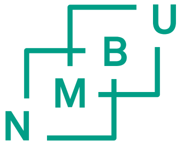
NMBU

ASSESSMENT OF A PROTOTYPE OF COMPOSTING TOILET.

Field scale study assessing the design, performance and potential of the prototype.

A Thesis submitted in partial satisfaction of the requirements for the degree

Master of Science

in

Environment and Natural Resources - Specialization Sustainable Water and Sanitation, Health and Development.

By

Mariya Evgenieva Kelova

Faculty of Environmental Science and Technology

Department of Environmental sciences (IMV)

Norwegian University of Life Sciences (NMBU)

Ås, Norway

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Foreword

The initial plan for this study was to assess the performance of the composting toilet system in regards to the composting process. Therefore, the preliminary research was done on composting toilets and that is reflected in the text. But due to delay in the construction and the low performance of the system, the focus was shifted to assessment of the overall performance and design. The study became a quest to better understand the system, to find the reasons for the malfunction and ways to improve it. That involved looking into the completely new to me fields of heat and energy transfer and design of solar heating systems. Even though it was challenging, I was motivated by the potential of the system to provide solution for some of the issues with the composting toilets and make them more attractive sanitation option.

Furthermore, I would like to express my deep appreciation and gratitude to everyone that help me on my way. First, I thank my supervisor professor Petter D. Jenssen for his inspirational personality, for the help and encouragement during the field work and support and guidance during the writing. I thank, Petter Heyerdahl for the time he committed to introduce to me, in an inspiring and understandable way, part of the physics concepts that I used in this study. My appreciation goes to Jørgen Kjørven for constructing the toilet system, for his useful insights and help with the field work.

Last but not the least, I would like to thank my family: my husband and my father for supporting me throughout writing this thesis, for their love and patience.

Mariya Kelova

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Abstract

Common problems with composting toilets are the appearance of odors, the control of the moisture content and the heat and energy demand. The objective of this study is to assess the performance of an innovative design of a composting toilet that targets to improve the performance for cold climate especially. Solar energy is utilized to optimize ventilation and provide temperature for better composting and evaporation control.

The system was conceptualized by Petter Jenssen, Petter Heyerdahl and Jon Fredrik Hanssen and was built by Jørgen Kjørven in Grua, Lunner municipality, Norway. The installation consist of solar air collector, gravel bed and composting chamber. The solar collector transforms the solar radiation to heat. The heat is transported by air that is sucked through the system by an exhaust fan. The gravel bed function as heat storage. The target of the design is to transport heat to the composting chamber to facilitate the degradation, evaporation and sanitization of the compost.

The system was optimized along with this study and modifications are described and assessed. The assessment is based on measurement of air temperature, light intensity, air flow, evaporation visual observations, and an interview with the users. The results are analyzed in terms of air and heat flow within the system, incoming solar radiation and heat storage capacity. Furthermore, the potential of the toilet system design is discussed and improvements suggested.

The performance of the system was correlated to airflow velocity and improved when air leakages and heat losses were reduced. The mean temperatures in the composting chamber during the period with the most optimal performance of the system were 10°C higher than the mean ambient temperatures. The temperatures in the solar collector reached up to 80°C. Comparison of the airflow at the inlet and outlet of the system showed that the air path was not sealed properly and when the leakages were sealed the airflow velocity was increased. The heat flow estimations in the system identified that only 20-25% of the solar energy was utilized and that during daytime the energy is transferred from the solar collector to the composting chamber. The energy flow in the system is as follows: energy is gained by the air in the solar collector, in the gravel bed this energy is transferred to the rocks, some of the residual energy is used to warm the compost chamber and some is lost with the exhaust air.

The results suggest that the present design will have beneficial effect on the composting process but the future development of the prototype theoretically have the potential to sanitize the compost in the warm months and to prolong the time without freezing in the cold months.

ACRONYMS

C – Carbon

C/N ratio – Carbon to Nitrogen ratio

CC - The composting chamber

CO_2 – Carbon dioxide

DEFRA - Department for Environment, Food & Rural Affairs

EPA - Environmental Protection Act

EU – European Union

GB - The gravel bed

H_2O – Water

K - Potassium

MDGs - Millennium Development Goals

N - Nitrogen

O_2 – oxygen

P - Phosphorous

PV – Photovoltaic

SC - Solar collector

SDGs - Sustainable Development Goals

SuSanA - Sustainable Sanitation Alliance

UN - United Nations

US EPA – United States Environmental Protection Agency

USA – United States of America

WHO – World Health Organization

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1. Introduction

In the last decades, overpopulation and climate change triggered the global attention to the polluted and disappearing natural resources. However, it were the industrialization and urbanization that brought to the western world today's standard for a comfortable living. Part of that comfort is the "flush and forget" system for disposal of excreta. This system was widely embraced in the western countries due to the many epidemics in the history, especially in Europe, caused by inadequate sanitation. It complies of a solution to carry the excreta out of our minds and houses and implies the notion of waste. It turned the topic of our excreta into something dirty and disgusting. At the other end of the pipe, however, our products are treated in an expensive, energy demanding and often a polluting manner (Van Der Ryn and Berry, 1999).

Today, centralized transport and treatment of wastewater in western countries is advanced and well developed in urban and semi-urban settlements. However, under the pressure of overpopulation and climate change the treatment plants struggle to clean the water sufficiently and to reuse the valuable nutrients in the wastewater in a sustainable way. Nitrogen, phosphorous and potassium, present in our excreta, are diluted with large amounts, in most cases drinking quality water, and transported throughout an extensive and expensive sewer system to the treatment plants. Those plants, furthermore, apply energy demanding technologies to separate the organic matter and nutrients from the water and reduce pathogenic organisms and are subject to failures. Failures in advanced treatment plants can result in millions of liters raw wastewater discharge per day into valuable water bodies (Dezenski and Ellement, 2013, Bousquet, 2009).

The urge to find more effective ways to preserve precious resources - water and plant nutrients, have shifted the focus of the future sanitation planning actors to a more sustainable alternatives and re-use options (SuSanA, 2015). One of those alternatives is the well-known but somehow often ignored composting toilet.

Composting toilet systems are predominantly dry systems and do not need water for flushing. The flush toilet is among the biggest consumers of water in a household (Jenssen, 2004a). Composting toilet systems reduce the wastewater load to a sewer system and handle the main source of pathogens that are otherwise flushed into the wastewater stream. Removal of pathogens in a centralized systems is a subject to an increasing stringency in the regulations (Heistad, 2014). Furthermore, composting systems are well known, regulated and commonly used in places or settings that does not allow for centralized treatment. At the global level more people are living in places without centralized treatment than with such (Corcoran E., 2010) and providing flush toilet systems to all will significantly endanger our scarce water resources and increase pollution. Composting toilet systems can provide the same comfort and clean experience as the flush toilet but it requires a shift in the mind-set regarding toilets.

The product of well-functioning composting toilet is a compost, which after an adequate handling and sanitization turns into a humus like substance that has many benefits for the soil and plants. In comparison with the wastewater sludge, the humus has more available plant nutrients and benefits for soil conditioning and plant growth.

The reuse of human excreta on agricultural fields can be traced back to ancient societies, and it has evolved as the agriculture evolved in different parts of the world. Most known examples of excreta composting are coming from ancient Asia and the use of night soil. In many parts of Asia some variance of this practice still exist and composting and reuse carry even cultural and traditional values (Oinam et al., 2008, WaterAid Nepal, 2008). The water shortage have been a driver for development and use of dry sanitation system in the 12 and 13 century throughout the Arab countries and among them the composting of dry feces even in a multi-story buildings by vertical drop shafts (Van Der Ryn and Berry, 1999). The first manufactured composting toilet was the earth closet developed in England by Henry Moule in 1800 (Del Porto and Steinfeld, 1999). The earth closet consist of seat and container where the user poured some soil after each visit. Later on, in 20th century in India and Vietnam several different applications of composting toilets have been recorded and at that time the technology had evolved and a chimney for ventilation became part of the toilet system (Del Porto and Steinfeld, 1999). The next major step in the technology development was undertaken in 1930 by the Swedish engineer Rickard Lindstrom, when he invented the Clivus Multrum - a sloped-bottom single chamber composter, containing two baffles and air ducts (Del Porto and Steinfeld, 1999).

During World War II a peat-earth toilet (Torfstreu-Trockenklosett) was in production and used in basements and bunkers in Germany. The products of those toilets were later used as fertilizer or fuel during the difficult times after the war (SuSanA Forum, 2015a). As the awareness of the effect untreated wastewater had on the water bodies increased, composting toilets were more widely promoted, used and manufactured (Del Porto and Steinfeld, 1999). However, they remain an option mainly for rural and unconnected to sewer areas.

The further development of the composting toilet technology and its wider implementation depend on improving the comfort of the user and creating a system that is a better fit for the modern standard of living. Today, many commercial and several homemade varieties of composting toilets exists. The basic design in all of them includes a toilet seat or squatting pan, chamber for composting and a ventilation pipe for aeration. The composting toilet can be sophisticated or simple (fig.5), but in all cases still require some commitment and labor from the user for proper maintenance. Most of the management of the toilet – as adding additives, turning the compost, control of aeration, moisture and heat, is mechanized in some of the available designs, but there is still a lot of room for improvement. Among the most common problems with composting toilets are the appearance of odors and the control of the moisture content and temperature and energy demand. In the last decade, with the increased focus on sustainability, the use of renewable energy sources became more important. The future development of the composting toilets needs to address those issues. The focus of this study is to assess the performance of an innovative design of a composting toilet that targets to reduce odors, and provide temperature and evaporation control utilizing solar energy. The first prototype of the composting toilet system and its modifications are assessed. The assessment focusses on air and heat flow. The potential of the toilet system is discussed and improvements suggested.

2. Literature review

Sustainable sanitation

In the past decade the humanity became more aware of the threats and limits of the ecological systems that sustain our existence. This increased the focus on better management of resources and sustainability. Sustainable development has been first defined in the Brundtland Commission report in 1987 and is addressed in the Millennium Development Goals (MDGs) (The World Bank Group, 2001, United Nations, 2015a). Formulated at the Millennium Summit of the United Nations (UN) in 2000, the MDGs outlined the main global targets that are to be achieved by the end of 2015. A continuation of those goals are the Sustainable Development Goals (SDGs) which are yet to be finalized and accepted by the end of the year (United Nations, 2015b). The SDGs promote more holistic approach in resolving global issues and have even greater focus on environmental protection and sustainable management of resources.

Sustainable sanitation is linked to several of the SDGs - those addressing: health and wellbeing, food security and sustainable agriculture, resilient infrastructure and settlements, conservation and sustainable use of water and energy resources, and is directly addressed in goal 6: “Ensure availability and sustainable management of water and sanitation for all.”(United Nations, 2015b).

In order to bring more focus on sanitation, UN declared 2008 as the International Year of Sanitation and triggered a joint reaction among the organizations working with sanitation to define the path towards sustainable sanitation. The joint effort resulted in the creation of the Sustainable Sanitation Alliance (SuSanA) and the definition of Sustainable Sanitation as:

“In order to be sustainable a sanitation system has to be not only economically viable, socially acceptable, and technically and institutionally appropriate, it should also protect the environment and the natural resources.” (SuSanA, 2008).

The Sustainable Sanitation theory is built upon the ecological sanitation concept but it integrates resource protection and the vision of excreta as a resource with the social and economic aspects.

Reuse of human urine and feces

The reuse of excreta closes the loop between agriculture and sanitation. Most nutrients needed for plant growth can be found in the household waste water stream (fig.1) One person excreta contain approximately the same amount of nutrients that this person consumes as food (Jonsson and Vinneras, 2013). Furthermore, one person excreta collected throughout a year contain approximately the amount of nutrients needed for the production of the cereal that would be enough to feed one person within a year (Heinonen-Tanski and Van Wijk-Sijbesma, 2005, Drangert, 1998). The compost or bio solids that are product of treated excreta contain valuable micro nutrients that improve the organic matter, the structure, water holding capacity and the biodiversity of the soil (Ronteltap et al., 2009). By acknowledging the resources in the excreta we are closing the loop and the nutrient cycle. When the toilet fraction is separated from the wastewater stream it reduces the burden on the wastewater plants, the water pollution from excessive nutrients, and the need for artificial fertilizers. The synthetic production of nitrogen is energy demanding and the production of phosphorus fertilizer is based on mineral phosphate. Mineral phosphate is a non-renewable resource and it is predicted that by 2033 its production will reach a peak, after which the demand will continue to increase but the additional production has to come from alternative sources (Cordell, 2013). In a sustainable future scenario, food waste, manure and human excreta are predicted to account for more than 80% of the supply of phosphorous after the year 2075 (Cordell et al., 2009).

Reuse of excreta has a long history in societies, like China and Vietnam, and is strictly rejected in other as a taboo. However, a more sustainable future implies reduced pollution and smart use of resources and entails that human excreta cannot be ignored as a resource. A treatment that uses natural processes, and utilizes the resources in the excreta by producing good quality organic soil conditioner is composting.

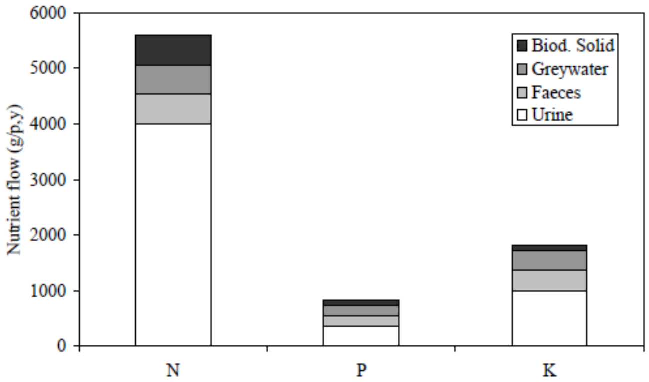


Figure 1. The content of Nitrogen (N), Phosphorous (P) and Potassium (K) in the different fractions of household wastewater, source – (Vinnerås, 2002).

Composting of excreta

Composting is controlled biological decomposition in aerobic conditions. It is a process, in which, aerobic microorganisms digest organic material and transfer it to a more stable biomass (Otterpohl R and Buzie C, 2013). In the process, oxygen is consumed and CO_2, water and heat are released

[C] + O_2 + microbial activity => New biomass + CO_2 + H_2O + Heat (Steintiford, 2013)

Stages:

Due to the released heat, the temperature of the compost changes with time (Fig.2) and three definite stages can be defined during the composting process. Those stages depend on the way the composting system is operated and the compost material (Hanssen et al., 2004). However, distinct stages are more visible in a municipal composter rather than in a domestic one. In the small domestic composting systems, those stages can occur simultaneously and are more difficult to detect (Jenkins, 2005).

1. Mesophilic stage – Temperature ranges between 20 - 45°C and duration is from few hours to few days (Fig.2). Mesophilic bacteria, actinomycetes and fungi, degrade the easily available organics and release heat until the increase in temperature start to inhibit their activity (Jenkins, 2005, Steintiford, 2013).
2. Thermophilic stage – Temperature ranges between 45 - 60°C and duration is from days to more than a week. The temperature rises above 44°C and thermophilic bacteria take over the process. Since, there is lower number of microorganisms tolerating these temperatures, the biodiversity is reduced and the easily available organic matter is exhausted, after which the biodegradation slows down and less heat is produced. The temperatures start to decrease and mesophilic microorganisms recolonize the compost to digest the more resistant organic material (Jenkins, 2005, Steintiford, 2013).
3. Maturation – Temperature ranges between 20 - 45°C and duration vary but minimum several months are required for complete maturation and sanitization. Hanssen et al, 2004 in their study on secondary composting found that stabilization can occur between 21 to 140 days after composting starts and greatly depends on additives and how the reactor is

operated. Within that stage mineralization and humification of lingo-cellulosic compounds occurs. The compost ages and matures at low temperatures, degrading the more resistant organic substances (Steintiford, 2013). The low temperatures and long residence time creates more suitable conditions for high biodiversity of microorganisms. High biodiversity have positive impact on degradation and improves the quality of the product as fertilizer (Jenkins, 2005, Steintiford, 2013). Pathogens that have survived the high temperatures are furthermore inactivated/killed by consumption and competition.

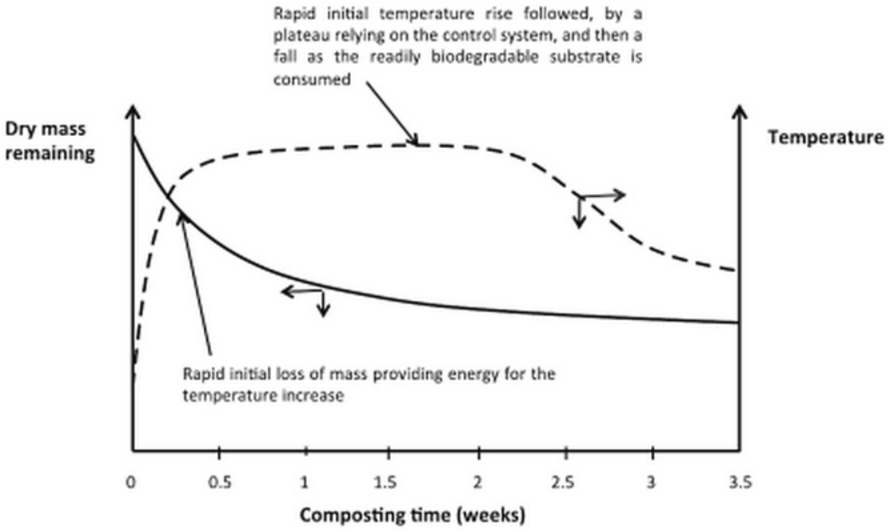


Figure 2. Changes in temperature over time in a controlled composting process and the mass-loss curve, source (Steintiford, 2013).

Benefits of composting

The compost benefits the soil. The compost-enriched soil releases nutrients more slowly, causing less nutrients to leach to ground and surface waters, increases soil porosity and water holding capacity. It balances the pH, increases soil darkness, thus improves heat absorption, and add valuable microorganisms. The compost increases the soil organic content and by that, it reduces erosion, increases the capacity of the soil to immobilize different pollutants and can be used in land restoration (Del Porto and Steinfeld, 1999, Jenkins, 2005). Microorganisms commonly found in a compost have indirect effect on plant growth by reducing the pH, by exercising control over plant pathogens and pests and by releasing valuable for the plant health and growth hormones (Matsui, 2010). If composting is used as method for treatment of excreta, it conserves fresh water by eliminating the need for flush water. Furthermore, it reduces the burden to wastewater treatment plants - it reduces the total load, the organic load and the pathogen load to the wastewater treatment plant. By composting, the nutrients in the excreta are recycled, reused and in some countries even marketed (Funamizu et al., 2010, Jenkins, 2005, Del Porto and Steinfeld, 1999). Recent research shows that it is a good alternative for treatment of pharmaceuticals and micro pollutants (Funamizu et al., 2010, Gunnarsdottir et al., 2013). “Composting is one means by which the power of microorganisms can be utilized for the betterment of humankind” p.27 (Jenkins, 2005).

Alternatives to composting for sanitization of excreta in a dry toilet system:

Dehydration

Dehydration is a process, which is used for treatment of feces when urine and feces are separated. The mass is reduced due to evaporation of the water content in the feces (feces have 82% water content). The solids must be stored in place where conditions facilitate drying – intensive ventilation, heating or solar radiation or often a combination of the above (Otterpohl R and Buzie C, 2013). The process is dependent on the ambient temperatures and airflow. Higher temperatures and air velocity speeds the desiccation. Because microorganisms do not thrive without moisture: 1) decomposition does not occur and odors are reduced and 2) pathogens are inactivated by desiccation and competition. However, recent research argue that good disinfection does not occur in the dehydration process (McKinley J and Guzman A, 2012, Schönning C. and Stenström T. A., 2004) and there is higher risk for recontamination after treatment (Otterpohl R and Buzie C, 2013). Disadvantages of the otherwise cheap and very applicable treatment is the unstable solids in the end product and that it does not have the benefits of the compost when applied to soil.

Pasteurization

Pasteurization is a process used in the disinfection of excreta. It is based on the Louis Pasteur discovery that high temperatures can eliminate pathogens. If the excreta are submitted to a temperature of 70°C for at least 30 minutes, they will be disinfected (Del Porto and Steinfeld, 1999, Otterpohl R and Buzie C, 2013). However, it is energy demanding and the end product does not have the same appearance and benefits as from composting.

Incineration

Incineration is a process of subjecting the excreta to very high temperatures to turn them into ash that is safe for disposal. Large amounts of energy is used in the process and according to USEPA incineration is only recommended as an option for very space restricted or sensitive areas (US EPA, 1999, BCDHE, 2015).

Freezing

The Finnish composting toilet producer Biolan offers dry toilets that freeze the content. The principle of operation is to lower the temperature to -15°C and prevent any biological activity that might produce smell. The toilet does not need ventilation and is both compact and mobile (Biolan, 2015). However, it is energy demanding and it does not treat or sanitize the excreta. Further treatment or disposal has to be performed in a composter or at a proper disposal site.

Factors affecting the composting process

Temperature

Temperature is a main factor controlling the decomposition process. If the moisture level is not controlled high temperatures, can cause dehydration and unfavorable conditions for microbial activity. Lower temperatures, on the other hand, can cause freezing and inhibit the microbial activity (Jenkins, 2005). The temperature range in which biological processes occur in the compost in the literature is commonly cited as 5°C to 71°C (Del Porto & Steinfield, 1998, Jenkins, 2005). However, Hanssen et. al, (2004) provided evidence for microbiological activity even at lower temperatures.

High temperatures in the compost are achieved by the heat released in decomposition or by ambient heat. It serves two purposes: maximizing the degradation rate and sanitizing. Each 10°C increase in temperature until 55°C doubles the reaction rate, speeding the process of degradation and stabilization (Steintiford, 2013). Different studies show different optimal temperatures for decomposition and biodiversity in general composting is between 35-65 °C (Del Porto and Steinfeld, 1999, Steintiford, 2013, Jenkins, 2005, Funamizu et al., 2010). A study in Japan on bio toilets, where they used controlled heating, found optimal temperature for excreta degradation to be around 60°C to 70°C, at higher temperature, the microbial activity is inhibited (Funamizu et al., 2010). According to Steintiford (2013), the optimum is between 45°C and 55°C (fig.3.) Due to the heat, the water is evaporated and for maintaining optimal moisture level, the compost has to be wetted. Temperatures higher than 45°C are effective in the pathogen reduction and as temperatures increase over 45°C, the time required for sanitization is reduced (Hanssen et. al, 2004, Funamizu et al., 2010).

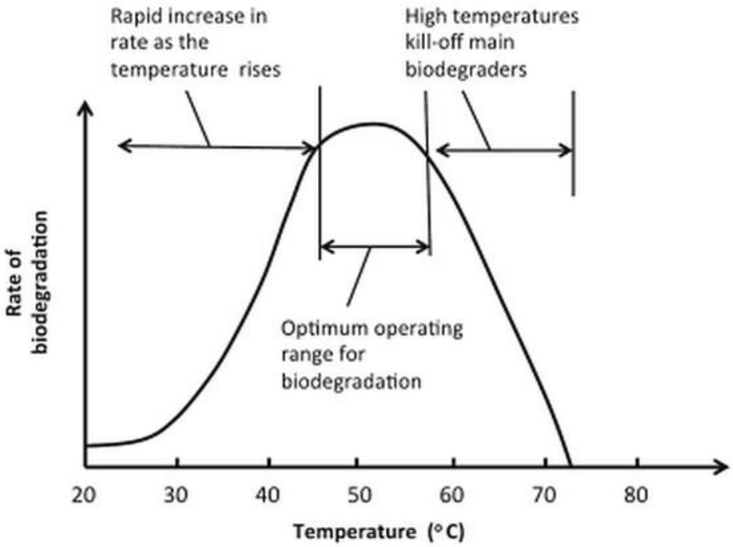


Figure 3. Typical curve representing the change of the rate of biodegradation with temperature, source (Steintiford, 2013)

Moisture content and evaporation

Appropriate moisture content in the compost ensures that the microorganisms will actively decompose the organic matter. Too dry conditions inhibit microbial activity and too wet conditions will cause anaerobic conditions. If the moisture is lower than 35-45%, the compost process is inhibited and moisture above 70% will drown the compost and cause anaerobic degradation and release of unpleasant odors (Del Porto & Steinfield, 1998, Steintiford, 2013). Water is lost all the time due to evaporation. The biggest loss of mass in the compost is not due to degradation but due evaporation of water (Steintiford, 2013). According to Jenkins, it is more likely that one has to add moisture rather than drain the compost to maintain optimal moisture. In most cases, the compost will have, enough moisture if urine is used and it is exposed to regular rainfall (Jenkins, 2005).

Study in Japan on a bio toilets found 65% moisture content to be the critical value above which anaerobic zones are appearing in the compost (Zavala and Funamizu, 2006). However, another study (Pui Ki Tsang, 2012) registered anaerobic processes even at 20-40% moisture. Higher moisture require additional attention to the operating conditions – ensuring adequate aeration and sufficient additives to absorb the excess moisture. Wet or liquid composting can be maintained by supplying air through the liquid but is energy demanding (Vinnerås, 2002). Higher moisture content results in odors due to the anaerobic degradation processes. Optimal moisture, when other parameters are controlled at optimum, was estimated to be 60% (Zavala and Funamizu, 2006).

Aeration

Aerobic microorganisms facilitate the decomposition process in the compost and oxygen/air has to be supplied within the compost. Two factors are important: 1) surface area that is in contact with air and 2) air-filled pores. The addition of bulking material prevents the compost to be submerged in liquid and provides structure that allows air to be trapped inside the pores of the compost (Del Porto & Steinfield, 1998; Jenkins, 2005). Turning or mixing the compost regularly increase the surface area and trap more air (Del Porto & Steinfield, 1998). However, according to Jenkins, 2005: “The perceived need to turn the compost is one of the myths of composting” p.48. Mixing with additives as wood chips, sawdust could provide the structure of the compost that traps air and provides free air passage through the material. If the compost mass becomes too compact the air supply will be reduced, bulk density above 600-700 kg/m3 is considered problematic (Steintiford, 2013).

C/N ratio

Microorganisms involved in the decomposition need nutrients to support their life and growth. Carbon is not only released, but also utilized in the growth and reproduction of microorganisms together with other nutrients, as Nitrogen, Potassium, and Phosphorous. For production of new cells, the microorganisms need carbon and nitrogen. The availability of C and N is expressed as C/N ratio. Optimum ratio for the decomposition in compost is 20-40 C per 1N (Jenkins, 2005, Del Porto & Steinfield, 1998; Steintiford, 2013). In the human fecal matter for one part N the microorganisms have 10 parts C (tabl.1), thus for decomposition to start, an additional carbon has to be added (Steintiford, 2013). Different bulking materials with slowly degradable carbon are used to compensate for the extra nitrogen in urine (tabl.1). Sawdust is a good carbon material to balance the extra nitrogen in the urine and feces (Jenkins, 2005). The availability of C and N is also a factor affecting the degradation, in some materials C and N are more readily degradable, than in others. Sugars, lipids and proteins are readily degradable, in contrast cellulose and lignin are very resistant and slowly to degrade (Steintiford, 2013).

Table 1: C/N ratios for different materials and substances found in excreta compost (adapted from Steintiford, 2013, Jenkins, 2005, (Gotaas, 1956) in Jenkins, 2005).

Material	C/N ratio
Sawdust	100-500
Paper/cardboard	200-500
Animal manure	15-25
Sewage sludge	5-15
Human fecal matter	5-10
Human urine	0.8

pH

The pH of the compost affects the decomposition rate. In the first stage of composting pH drops due to the presence of organic acids, it rises during the thermophilic stage and balances out to a neutral – pH 7, during the maturation (Atchley and Clark, 1979). Acidic or too basic conditions inhibit the microbial activity. Optimal pH range for compost microorganisms is 6.5-8 (Otterpohl R and Buzie C, 2013). The ammonia in the urine increases the pH and pH is difficult to control, but addition of sulfates and especially such containing magnesium may reduce the pH or enhance the formation of struvite (Zavala and Funamizu 2006). Another control can be addition of limestone or ash but this causes nitrogen loss as ammonia and reduces the value of the product as soil amendment. The pH like temperature is not equally dispersed throughout the mass of the compost.

Pathogen removal in the compost

The fate of human, animal and plant pathogens in the compost is determined by two main factors – temperature and interactions among microorganisms (Jenkins, 2005, Del Porto & Steinfield, 1998). In addition, environmental conditions as moisture, pH and residence time also have effect on their fate (Jenkins, 2005, Del Porto & Steinfield, 1998). Composting human feces is related to a greater health risk, in comparison with other composting materials. If a person is infected with a disease pathogen, a gram of his/her feces can contain billions of the pathogenic microorganism (tabl.2). However, most pathogens thrive best at body temperatures and high temperatures can eliminate them (fig 4).

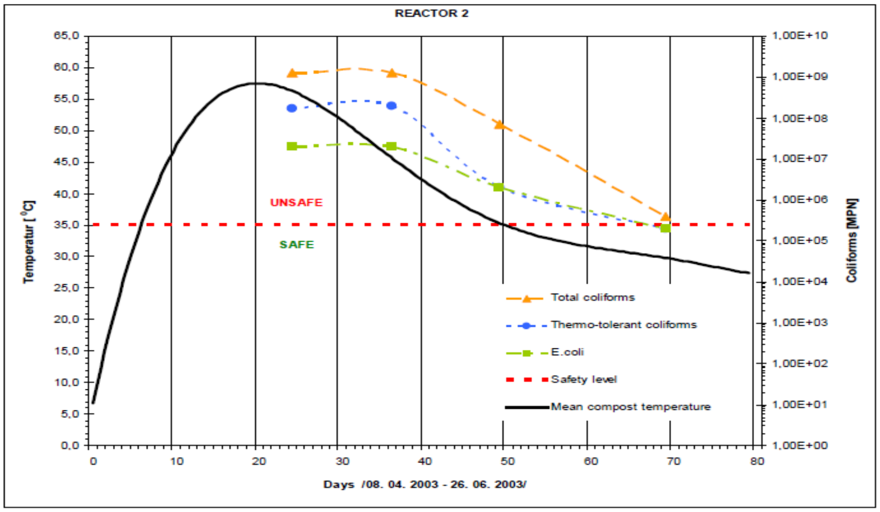
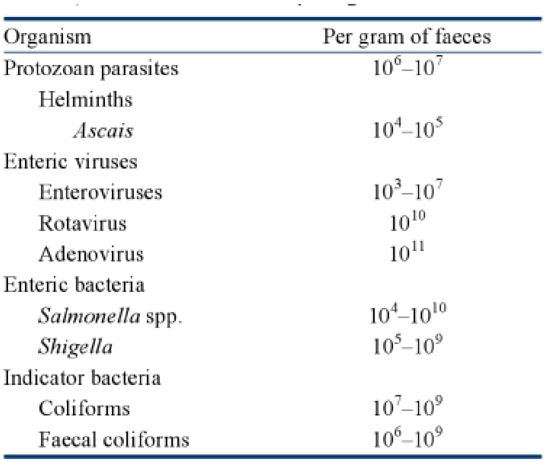


Figure 4. Higher reduction of pathogens occur at higher temperatures, source Hanssen et.al (2004)

Table 2. Concentrations of pathogens per gram human feces. Source: p.226 (Gebra, 2008)



Organism	Per gram of faeces
Protozoan parasites	10^6–10^7
Helminths	
Ascais	10^4–10^5
Enteric viruses	
Enteroviruses	10^3–10^7
Rotavirus	10^{10}
Adenovirus	10^{11}
Enteric bacteria	
Salmonella spp.	10^4–10^{10}
Shigella	10^5–10^9
Indicator bacteria	
Coliforms	10^7–10^9
Faecal coliforms	10^6–10^9

At 45°C, it will take approximately a week to eliminate the pathogens. If the temperature around 50 °C is maintained for 24 hours, all pathogens could be eliminated, with higher temperatures the required time for sanitization shortens (tabl.3). However, due to lack of homogeneity in the temperature distribution within the compost, it needs to be mixed regularly. In a secondary composting reactor, filled with mixture of human excreta, food waste and bark, Hanssen et. al (2004) found that mixing the material once a week improved the degradation and halved the time to reach thermophilic stage. Optimal rate for a bio toilet in Japan was estimated to be 15-20 times a day for 2-3 days after last use (Zavala and Funamizu 2006). The heat is important for pathogen elimination but if that is the only focus, it might keep the biodiversity in the compost low and prevent the main composting agents to thrive and biodegrade the material. If the biodiversity is diminished - the compost can be recolonized by harmful pathogens.

High biodiversity ensures removal of pathogens through different interactions between microorganisms:

"It is not only the heat of the compost that causes the destruction of human, animal and plant pathogens, it is a combination of factors including:

- competition for food from compost microorganisms;
- inhibition and antagonism by compost microorganisms;
- consumption by compost organisms;
- biological heat generated by compost microorganisms; and
- antibiotics produced by compost microorganisms." (Jenkins, 2005, p.44)

Table 3. Required time at certain temperature to sanitize the compost

Temperature °C	Time	Source
46	week	(Jenkins,2005)
48	week	(Feachem, 1983)
>50	week	(Niwagaba, 2009)
50	24h	(Jenkins,2005)
55	1 day	(Feachem, 1983)
62	1h	(Del Porto & Steinfield, 1998)
70	30min	(Otterpohl & Buzie, 2013)

Composting toilet systems

There is a great variety of composting toilet systems, both commercial and homemade (fig.5). Common categorization is based on design (Anand and Apul, 2014, Berger, 2011). The types according to design are separated into: self-contained, single and multiple chambered composting toilets. Furthermore, toilet systems are categorized based on: electricity – operating without electricity and with electricity; water – waterless or operating with water; urine diverting and mixed urine systems (Anand and Apul, 2014). A large variety of urine diverting toilets are promoted as composting toilets but their categorization is somehow controversial as some argue that without urine in the compost mix the optimal conditions for composting cannot be achieved and those toilet systems do not compost but dehydrate the fecal matter (SuSanA Forum, 2015b, Jenkins, 2005, Schönning C. and Stenström T. A., 2004). However, according to Del Porto & Steinfeld (1998) the diversion of urine is a beneficial for good composting. Composting toilet systems are also divided into site-build and manufactured.

Figure 5. Examples of different composting toilets. A – simple homemade composting toilet (Kathryn @ Farming My Backyard, 2014), B – Bio-Lux toilet (Japan)(Seiwa Denko, 2003), C - Enviro Loo - Waterless composting toilet system (South Africa)(SuSanA Secretariat, 2005), D – Naturum, model produced by Bioland (Finland)(Biolan, 2014).

It should be noted, that the label “composting toilet” could be misleading for some marketed and domestic toilet systems. It is disputable to what extent the process taking place in the different toilets is composting. In some, the goal for greater comfort - reduction of mass and odor, have led to the design of systems where the process is dehydration/desiccation rather than composting. Such systems need extensive residence time or secondary composting in order to achieve hygienically safe product applicable as fertilizer (Jenssen, 2004b). Many of the manufactured models in USA are not facilitating composting and further composting is required to assure a safe product (Jenkins, 2005). Omissions in the maintenance and operational conditions result in suboptimal performance and the temperature required for sanitization is rarely reached in such systems (Engen, 1991). Many composting toilets, especially small domestic units, do not treat the feces and urine by composting but by dehydration/desiccation, which results in lower pathogen reduction (Schönning C. and Stenström T. A., 2004). Storage at 20 ˚C leads to a slow reduction in some pathogens, but does not sanitize (Vinnerås, 2007). Composting toilets use a biological treatment process and if adequately maintained that process mimic the natural degradation of organic matter and provides safe and soil like end product. International research show that dry sanitation may give an equal or higher reduction of pathogens and a high reduction in risk of exposure (Schönning C. and Stenström T. A., 2004).

Existing regulations

There are no EU or USA regulations regarding domestic systems, when the product is collected within the premises and end product is used within the premises (Defra, 2008, Jenkins, 2005). However, the regulations for public facilities are stricter and often permissions are difficult to obtain (Jenssen, 2004b, Defra, 2008)

Solar energy collection, heat transfer and storage

Heat transfer

Heat is defined as “the form of energy that can be transferred from one system to another as a result of temperature difference” (p. 2, Cengel, 2006) and the rate at which the energy is transferred is the heat transfer. Heat describes the change in internal energy, in thermodynamic analysis it should be understood as energy in transition from a higher temperature object to a lower temperature object. When an object is heated, energy is transferred from the hotter object to the colder and that initiate higher molecular motion in the receiving object, thus increases its internal energy (Carl R. Nave, 2012). The molecular motion increases with the increase in the velocity and the degree of activity of the molecules and that is proportional to the temperature (Cengel, 2006). The driving force for heat transfer is the temperature difference and the flow is always from high to low temperature until equilibrium, when the energy flow is null.

The internal energy associated with the molecular motion is the sensible heat and the internal energy associated with the forces holding the molecules together is the latent heat. If the internal energy increases to a point when it is higher than the force binding the molecules, the system changes phase – from solid to liquid – melting, liquid to gas – vaporization, or the opposite if the internal energy decreases below a certain point. Common examples are the evaporation and condensation of water. Evaporation is a process in which, at the water surface, the molecules are more loosely connected and heating causes their escape until the air is saturated with water vapor. In the evaporation process a certain amount of energy is consumed for the vaporization of the molecules – that does not result in change of temperature. The internal energy of the water increases without changing the temperature and that is the latent heat of water. The energy for the process is transferred from the air and the air temperature drops. Condensation is the opposite process, when the water vapor loses energy during cooling, it condenses into clusters and form water droplets.

Change in the energy of a system can occur due to heat transfer or work. The energy can increase because the system is heated but could also be because a work is done on it and accordingly it will decrease if cooled or work is done by it. The energy that is due to heating is the thermal energy and includes the sensible and latent heat.

In flowing fluid as air, the internal energy of the fluid (U) is combined with the energy of the flow = absolute pressure (P)*specific volume (V). The combined energy is the enthalpy (h) = U+P*V (Cengel, 2006). The energy required to rise the temperature of a unit mass with one degree is the specific heat (C [kJ/kg.K]) and for gases it can be defined as specific heat at constant volume (Cv) or constant pressure (Cp). It depends on the temperature and the pressure for gases and only on temperature for liquids and solids. The changes in the internal energy and enthalpy can be expressed as:

$\Delta U\ [J] = m*C*\Delta T$, where m – is the mass of the system, ΔT – is the change in temperature.

Thermodynamic analysis describes the amount of energy (Q), or the total change in energy during a process in which at the start and the end of it, the system is in equilibrium. The heat transfer (Q', [J/s]) describes the rate at which the energy changes or it can be used to estimate the time in which that change will occur (Cengel, 2006).

$Q\ [J] = Q'*\Delta t$, where Δt is time interval

The rate of heat transfer per unit area normal to the direction of the transfer is the heat flux (q').

$q'\ [W/m^2] = Q' / A$, where A is the heat transfer area

A stationary system is characterized by a fixed mass for which it is assumed no change in time or position. The energy of the system remains constant and according to the first law of thermodynamics the energy entering the system will be equal to the energy leaving the system:

$E_{in} – E_{out} = \Delta U\ [J] = m*C*\Delta T$, with no work $\Rightarrow Q = m*C*\Delta T$

The net energy transfer by latent heat depends on the mass of a substance, temperature and the energy required for change in phase of the substance (L):

$Q'_{latent}\ [kJ/s] = m\ [kg] * L\ [kJ/kg]$

The net energy transfer if the substance change mass – phase change is then:

$Q'_{net\ change\ in\ thermal\ energy} = Q'_{sensible} + Q'_{latent} = m*C*\Delta T + m*L$

The energy in a steady flow system, with no change in phase, is described by controlled volumes for which it is assumed no change in time or position. The energy of a control volume remains constant and according to the first law of thermodynamics the energy entering the system will be equal to the energy leaving the system. The mass in the system, however, is not fixed and is characterized by a mass flow rate ($\dot{m}$ [kg/s]) (Cengel, 2006). The mass flow rate when the fluid flow is in one direction can be expressed as:

$\dot{m}\ [kg/s] = \rho*\nu*A_c$, where ρ [kg/m^3] is the fluid density, ν [m/s] is the fluid velocity and A_c [m^2] is the cross sectional area normal to the flow direction.

The net heat transfer in a steady flow system is equal to the rate of increase in the internal energy of a fluid as it flows through a control volume. It is expressed as:

$\dot{Q}$ [kJ/s] = $\dot{m}*C*\Delta T$

Heat transfer occur by different mechanisms of energy transfer – conduction, convection and radiation. In most cases radiation occur simultaneously with conduction or convection.

By conduction

The heat is transferred by conduction, due to the molecular activity in a substance. When within a substance there is a temperature difference - in the hotter part of a substance the molecular motion is more intense and by the molecular interactions the energy of the motion diffuses throughout the substance. The rate at which a substance conducts heat depends on its material, geometry, thickness and the temperature gradient (Cengel, 2006). It is expressed as:

$\dot{Q}_{conduction}$ [W] = $-k*A*(dT/dx)$,   where k [W/m.˚C] is the thermal conductivity of the substance, A [m^2] is the cross sectional area normal to the energy flow direction and dT/dx is the temperature gradient

By convection

The heat is transferred by convection when, beside the microscopic motion of the molecules, there is a macroscopic motion of a fluid. The thermal energy is transferred not only by diffusion from molecule to neighboring molecules but also by the bulk motion of the fluid.

When the heat is transferred in a system with still surface and fluid in motion, like in the case of air ducts or water pipes, the friction between the surface and the fluid have effect on the fluid motion and temperature. The friction results in slower fluid velocity and a temperature gradient on the border between the fluid and the surface. The layer between the fluid, with velocity and temperature, not affected by the surface and the surface is the boundary layer (Cengel, 2006).

Depending on the driving forces for the fluid motion, convection can be forced or natural. Forced convection is when the fluid flow is due to an external force like fan or pump and natural convection is when the fluid motion is due to the buoyancy forces emerging from difference in pressure or temperature.

The heat transfer by convection depends on the fluid properties, fluid velocity and type of flow, the area of transfer, and the temperature difference (Cengel, 2006). It is expressed by the Newton's law of cooling:

$Q'_{convection}$ [W] = $-h*A_s*(T_s - T_\infty)$, where h [W/m^2.˚C] is the convection heat transfer coefficient that depends on the fluid properties, velocity and flow, A_s [m^2] is the heat transfer area, T_s [˚C] is the temperature of the surface, and T_∞ [˚C] is the temperature of the fluid sufficiently far from the surface.

By radiation

Radiation is the electromagnetic waves or particles, in the case of non-ionizing radiation - photons, emitted by an object. This energy originates from changes in the electronic configurations of the atoms or molecules. In terms of radiation energy, objects are described by their emissivity (ε) and absorptivity (α). Absorptivity and emissivity are properties describing surfaces. Some surfaces absorb more radiation compared to other, black body is perfect absorber and $\alpha = 1$, for different surfaces the absorptivity is between 0 and 1. All known objects have temperature above the absolute zero and emit thermal radiation. This is a type of radiation caused by the temperature of a body and does not need a medium to be transferred. It travels as a waves, which are not interfered by a gas medium, it is a phenomena relevant for solids. To quantify the emitted radiation by a body, this body is compared to an idealized blackbody, which has maximum emissive power and it is expressed by the Stefan – Boltzmann law:

$Q'_{emitted}$ [W] = $\varepsilon*\sigma*A_s*T_s^4$, where ε is the emissivity of a real surface, it is a measure to how close a real surface approximate a blackbody; $\varepsilon_{blackbody} = 1$, σ [W/m^2.K^4] is the Stefan – Boltzmann constant, $\sigma = 5.67*10^{-8}$, A_s [m^2] is the radiating surface area, T_s [K] is the thermodynamic temperature (with reference to the absolute zero temperature) of the surface.

The radiation heat transfer between two objects with medium in between that does not interfere with the radiation (gas) depends on the properties of the surfaces, their orientation relative to each other and is expressed as:

$Q'_{radiation}$ [W] = $\varepsilon*\sigma*A_s*(T_{s1}^4 - T_{s2}^4)$, where T_{s1} [K] is the thermodynamic temperature of the surface 1 and T_{s1} [K] is the thermodynamic temperature of the surface 2

Heat storage

The heat storage capacity of a material depends on its properties and the change in temperature. The specific heat (C [kJ/kg. ˚C]) is a measurement of the capacity of a material to store heat. It indicates the amount of energy that can be stored in a unit mass when temperature rises with one degree. A material with higher values for C can store more energy per unit mass. The volumetric heat capacity of a material is expressed as = ρ*C [J/m^3. ˚C].

Solar energy

The sun emits radiation energy at a constant rate of $3.8*10^{26}$ W, from which very small part incidence on Earth but it is still sufficient to provide energy to sustain the life. The energy reaching the Earth's atmosphere is the total solar irradiance and is 1373 W/m^2, from that only a portion is reaching the surface. A fraction of the radiation is reflected, scattered and absorbed in the atmosphere. The amount reaching a specific surface depends on the atmospheric conditions and the length that the sun rays travel to reach it. The distance that the solar radiation travel varies with the position of the surface on Earth, the position of the Earth to the Sun and the angle at which the sun rays fall on the surface. The measure for the amount of solar radiation falling on a surface per unit area per unit time is the solar irradiance – G [W/m^2]. The solar irradiance coming on a specific surface depends on the geographical coordinates, time of the year, time of the day, the angle of the surface, the geographical direction it is facing and the atmospheric conditions (Goswami et al., 2000). Furthermore, any object standing in the way of the sunrays at a certain moment will cause a shadow and reduce the incoming solar irradiance. Thus, the amount of solar energy that can be utilized and transformed by a solar collector depends on the site and the design of the collector.

Air solar collector

Solar energy collectors are defined as: "sun-facing surface which transfers part of the energy it absorbs to a working fluid" (p.2, Goswami et al., 2000,). The design is based on three main elements – glazing, absorber and insulator. The glazing surface is commonly glass or Plexiglas that is transparent to visible and shortwave radiation but reflects the infrared (thermal) radiation coming from the absorber. The absorber has surface with high absorptivity and low emissivity, which transforms the solar radiation into thermal energy (Romdhane, 2007). The thermal energy is emitted in one direction and stopped by the insulation in the other direction.

The performance could be improved with addition of baffles. They increase the air velocity and turbulence and by forcing the air to take meandering trajectory increase the length of the airflow in the collector and increases the area of heat transfer by increasing the contact area with the absorber (Romdhane, 2007). The narrower air passage and increased surface increases the friction and cause greater resistance to the air flow in the collector (Romdhane, 2007).

3. Methods

Background information

The first prototype of the toilet system design was constructed at kindergarten “Småtjern naturbarnehage” in Grua, Lunner municipality, Norway. Geographic coordinates: latitude 60° 15' 37.7604", longitude 10° 38' 16.17". The area can be characterized as hilly, covered mainly by spruce forest, with history of mining. It is rich in natural resources and fresh water biodiversity. Rare and protected aquatic plant species can be found in the calcium rich lakes in the area. Fresh water protection is among the municipality goals (Gorset, 2013). Thus, the fresh waters are vulnerable to pollution with sewerage.

Climate

The area has humid continental climate zone. It is characterized by four seasons with cold winters and warm humid summers. Average monthly values for precipitation and temperature are listed in tabl. 4

Table 4. Average monthly temperatures and total precipitation from Grua metrological station, during the testing months. Source - (Meteorologisk institutt, 2015)

Month	**Temperature**			**Precipitation**
	Average	**Warmest**	**Coldest**	**Total for the month**
Jul-15	15.1° C	28.4 °C, 01. jul	4.1°C, 17. jul	96.4 mm
Jun-15	12,8° C	23,1°C, 30. jun	1,7°C, 15. jun	70,6 mm
Mai-15	7,7°C	16,8° C, 27. mai	-1,9°C, 9. mai	118,0 mm
Apr-15	5,4°C	23,5°C, 20. apr	-5,9°C, 1. apr	9,6 mm
Mar-15	1,5°C	11,7°C, 23. mar	-9,8°C, 5. mar	40,8 mm

Description of the kindergarten

The kindergarten is run by Jørgen Kjørven and have currently 20 children and 4 adults personal per day. It is placed outside the small city of Grua on a hillslope covered by a spruce forest. The kindergarten promotes close connection to the natural environment and sustainable living. The children spend their time entirely outside, enjoying outdoor activities in the area. They are engaged in activities that connect them to the nature and inspires them to learn more about it. Because of this focus, only few small buildings exist on the premises of the kindergarten. Among those buildings are three toilets, two of them were the existing old composting toilet systems and one is the newly build composting toilet system that this paper describes.

Description and design of the system

The system was conceptualized by Petter Jenssen, Petter Heyerdahl and Jon Fredrik Hanssen.The system was built by Jørgen Kjørven with the participation of the kindergarten staff and children. Some modifications were done by me and Petter Jenssen.

The toilet system construction is a small outdoor building – it is not a part of or connected to another building. It is a small room with two toilet seats placed on a coach-like boxed space along two of the walls. Under that space lies the gravel bed. For the building construction mainly wooden materials are used, except for the insulation, the water resistant membrane, the glazing part of the solar collector and the ventilation pipe.

Figure 7. The toilet building

To the wall facing South, Sought-East, a solar collector (SC) is attached. The SC consist of two rectangular plates of glazed Plexiglas sheets with sizes: 1.80m and 2.00m, mounted at 0.05m distance from a black painted wall. The air is to pass between the plates and the wall from the left to right and enter the gravel bed. Five baffles were mounted on the black wall to alter the air flow and increase the efficiency. During sunlight, the black wall heats up and air heats up as it passes through the collector and transports/conveys the heat to the storage unit – the gravel bed. An exhaust fan drives the air through the system. It can be connected to a solar cell and work only when there is sunlight or connected to the electricity grid, but then with a timer set to work only during daytime. In both cases, the air is sucked into the collector only during sunlight, so it can heat up. During night hours and no sunlight the collector is closed and the exhaust fan is not working. A closing valve is installed in the collector that is controlled by a thermal expander (fig.8). The thermal expander is commercially sold as automatic vent opener for greenhouse, when the temperature rises above certain limit the metal expands to open and when the temperatures fall below the limit it retracts back to original position (Hageweb, 2015). It starts to open at 15˚C and if fully opened at 30˚C, it is not recommended to use it at higher than 50˚C temperatures.

When the wall is heated by the incoming solar radiation, the expander heats up and expands pushing the closing valve to open. When the collector cools down, the expander also cools down and it subtracts itself back to initial position and pulls the valve to close.

Figure 8. The thermal expander (Hageweb, 2015) and the closing mechanism.

The gravel bed (GB) is a parallelepiped shaped wooden compartment with sizes Height: 0.3m, Width: 1m and Length: l.70m. It lies under the building and on top of it is the composting chamber with buckets for excreta collection, and the toilet room. It is filled with rock material, referred to as gravel in this thesis, and insulated from all sides beside the top where the composting chamber is. A wooden plate is separating the gravel bed from the composting chamber and several holes are drilled on it to allow air flow from gravel bed to the compost chamber. The gravel consists of spherical pebbles, metamorphic and volcanic stones – granite and gneiss, with approximate diameter of 0.1m. The stones are arranged normally – randomly placed with no additional compaction. Thus, a porosity of 0.4 ($\varepsilon = 0.4$) is assumed (Singh et al., 2013).

The toilet room has two seats placed on the composting chamber (CC) along two of the walls (fig.9 A). The composting chamber houses the collection buckets under the seats. It is partly insulated to allow air to flow trough but at the same time reducing the heat losses. Bottomless buckets – funnel like, are attached to the seats in order to restrict splashing out or excreta falling outside the buckets. Under them are the two collection buckets. The bottomless buckets and the collection buckets overlap as shown in fig.9 B. The top of the composting chamber can be taken out to access the buckets and the compartment.

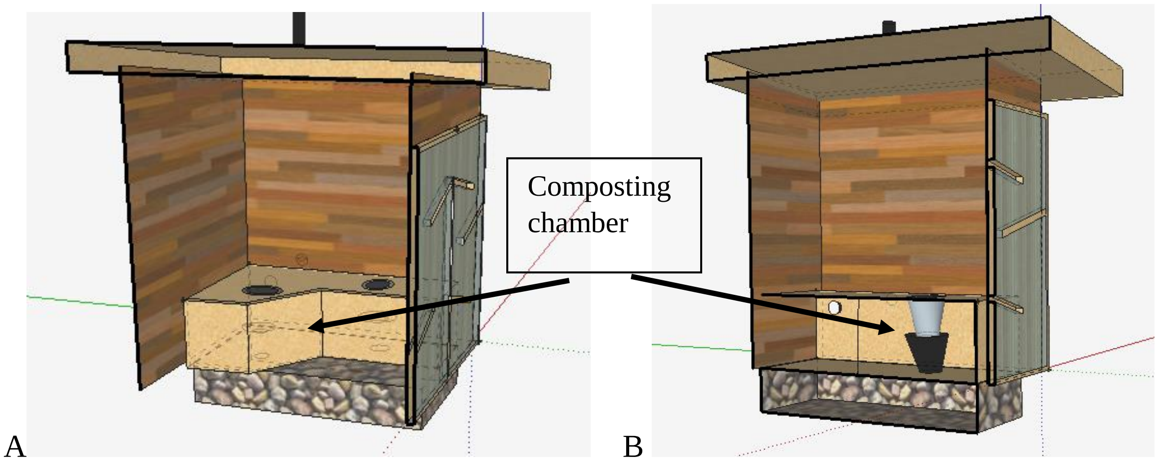


Figure 9. Drawings of the views inside the room and composting chamber. A - Cross sectional view of the room B - Cross sectional view of one of the collecting buckets and the exhaust fan.

For the analyzing the whole toilet system was conceptualized as having three main systems based on function, namely 1) the solar collector (SC), 2) the gravel bed and (GB) 3) the composting chamber (CC) and two main modes – 1) during sunlight and 2) during no sunlight. The modes are also referred to in the paper as day and night mode for simplicity and since they represent those conditions fig.10.

A fan is the driving force for the air, and if it is the powered by a solar cell, it is automatically regulated by the solar input, if it is powered by the grid a timer is regulating the hours of work. During sunlight, the SC is utilizing the solar radiation by transforming it into thermal energy, this thermal energy is conveyed to the gravel bed by forced convection driven by the fan. The function of the gravel bed is to store heat. Without heating the gravel will approximate the ambient temperature, and when heated air is forced through it, a heat transfer by convection occur from the hot air to the colder surface of the gravel. From the surface the energy is conducted within the stone by conduction. The residual thermal energy of the air, is then conveyed to the composting chamber where the higher temperatures should increase the evaporation rate of the excessive liquids, boost up the microbiological activity and increase the degradation rate. The air flow also takes out the odors. During no sunlight, when the sun does not heat the air in the collector, the temperature in the collector drops and the valve closes not allowing cold air to enter or the accumulated heat to escape. During night, the air in the whole system cools down and the accumulated thermal energy in the gravel becomes a heat source. Heat is transferred from the warm stones to the air. The wormer air rises forced by natural buoyancy forces and heats up the composting chamber that is placed above the gravel bed. In theory, an ideal system will be airtight, however, in practice that is very difficult and expensive to achieve and some losses of thermal energy can be expected through air leakages and as the moisture in the compost evaporates, some of the energy will be consumed as latent heat.

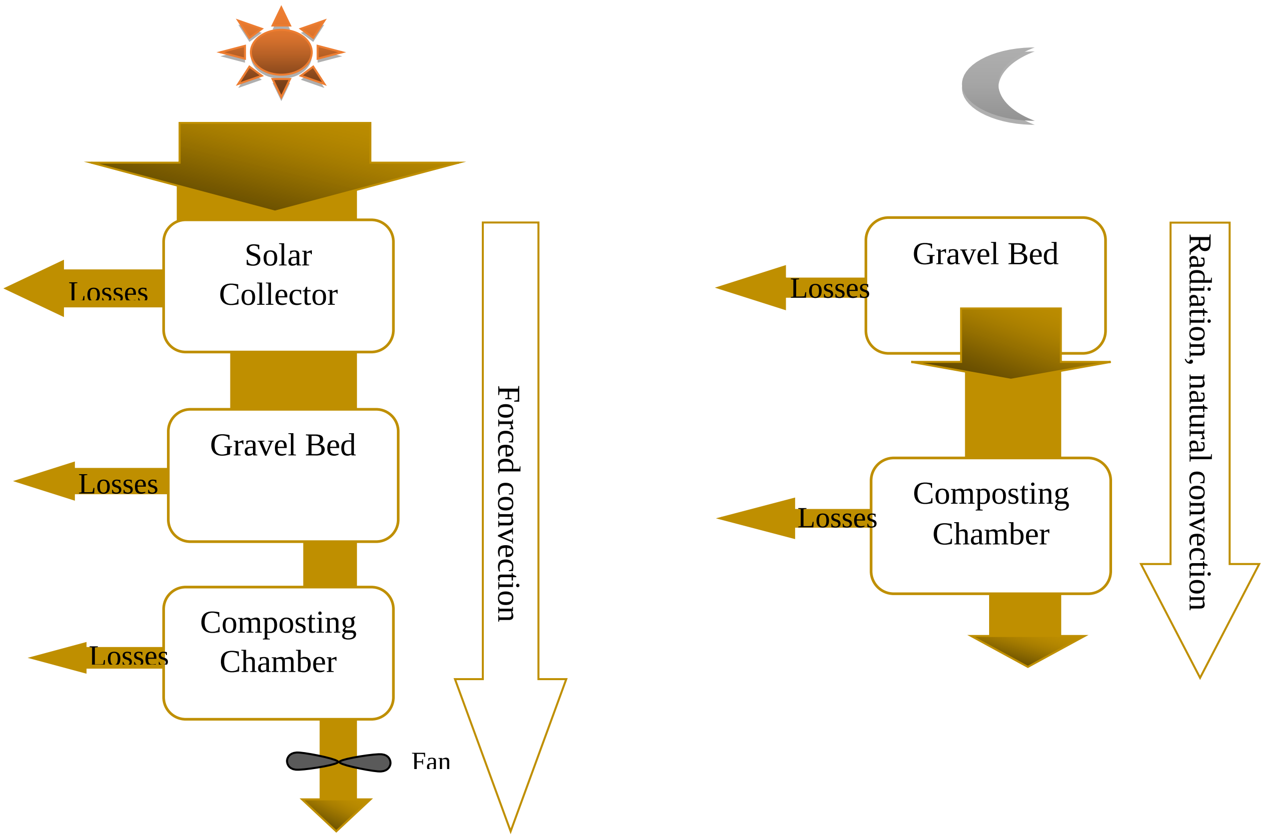


Figure 10. Energy flow diagram for the system, during sunlight – day and during no sunlight – night.

Assessment of heat, air flow and light intensity.

The assessment is based on air temperature measurements, light intensity, air flow, visual observations, mass measurements and interviews.

Heat

The heat was measured as temperature, which was measured with data loggers. The model used was HOBO Pendant Temperature/Light Data Logger model UA-002-xx (fig.1.1, annex 1) with optic USB Base Station for communication with computer. The loggers have operational range of -20 to 70 ˚C and response time for temperature changes of 10 min. The temperature accuracy is ± 0.53 ˚C when temperatures are between 0 and 50 ˚C (fig.1.2A, annex 1) and the time accuracy is ± 1 minute per month at 25 ˚C (fig.1.2B, annex 1).

The loggers were programmed through HOBO software to take measurement every 15 minutes. This time was chosen because it provides frequent readings and is more than the response time, thus the error from the adjusting of the logger to changes in temperature is reduced. They were all set to start recording at the same time. Before placing them in the toilet system it was checked if they were calibrated. This test was performed in dark, closed room at a plane surface, with no walls or any obstacles near them, and approximately no air movement. The result shows measurement discrepancies of approximately 0.2 ˚C (fig.2.1, annex 2).

The loggers were placed in the system, in such a way so they can capture the temperature in the different parts of the system, and to show the air temperature profile along the air path. Temperature measurements were recorded in the solar collector, the ambient air, at the entrance of the gravel bed, in the toilet room, in the composting chamber, and in the beginning of the chimney fig.11.

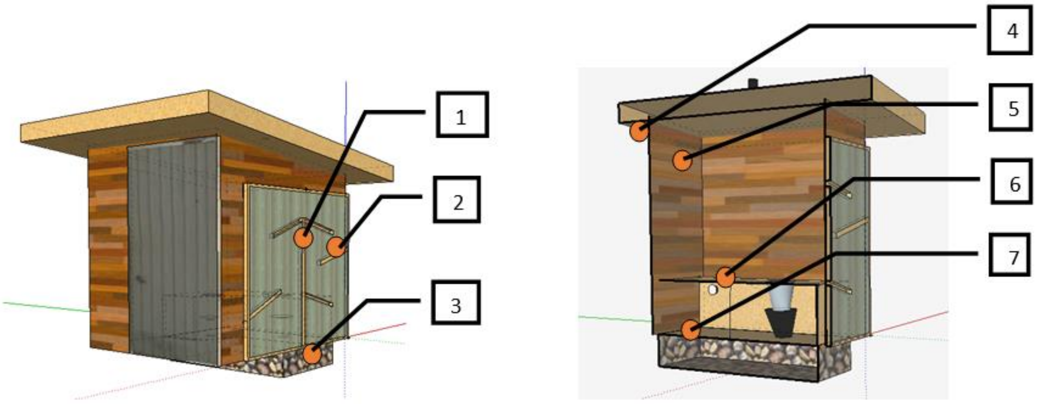


Figure 11. Placement of the sensors during period 28.07 – 05.08.2015. During different modifications some sensors were displaced and this figure represents the final placement of the sensors actual for the period 28.07 – 05.08.2015.

1 – Recording light intensity, it is placed outside, attached to the SC

2 – Recording temperature in the SC, placed inside and shadowed by an aluminum foil patch.

3 – Recording temperature between SC and GB, placed in a duct connecting the collector with the bed (Gravel bed inlet sensor).

4 – Recording ambient temperature, placed outside on the north side of the building, under constant shadow from the roof.

5 – Recording temperature in the toilet room, placed high, so the children would not be able to reach it.

6 – Recording temperature behind the fan, it is placed right after the fan in the exhaust pipe

7 – Recording temperature between the GB and the CC, it is places on the holes from which air from the GB enters the CC (Composting chamber sensor)

On dates: 16.04, 18.05, 23.06, 29.06, 15.07, 24.07 and 05.08.2015 the sensors were removed to read out and placed back to continue recording. Since, at the day of reading out they were removed from their location for approximately several minutes to half an hour for each one, the error from handling of the loggers during reading was avoided by eliminating the temperature records from the whole day of the reading.

Air flow and velocity

Initially the system was tested with smoke pallets – PH Smoke Pellets fig.12, to observe if there are obvious leaks in the ventilation system and to assess the air flow. After each modification concerning the air flow, the system was tested again with smoke pallets.

Figure 12. Testing with smoke pallets

The air flow was measured on 28.07.2015 with air velocity meter – VelociCalc, model 8345-M-S. All of the measurements were taken at distance at least five times the diameter of the channel from the start of the pipe in order to ensure that the flow is not turbulent and at ½ of the inner radius of the pipe to measure the average velocity of the flow. Due to the system design, at only one place was possible to take direct measurements – the exhaust pipe fig.13 – B. Additional channel, incorporating a pipe was constructed to measure at the inlet of the system fig.13 – A. Two measurement were taken in the pipe leading the exhaust air out through the chimney to measure flow at the outlet of the composting chamber. One before optimization of the system and one after modifications to improve the hydrodynamics of the system. Two measurements were taken at the inlet of the solar collector to measure inlet flow to the system, one before and one after the modifying the system.

Figure 13. Air velocity measurement. A- The additional channel constructed to measure the air velocity at the inlet of the system. B – Measurements of air flow in the exhaust pipe

Sunlight intensity, irradiance and duration

The light intensity was also measured by HOBO Pendant Temperature/Light Data Logger model UA-002-xx. The logger records light as relative light levels in lux. The light levels measured are relative to human eye sensitivity to light and correspond to measurement of the brightness experienced by a person – illuminance, a photometric measurement. Photometry units cannot be transferred directly to radiometric units, thus, it is not possible to estimate numerical solar energy input to the system only by them but they were correlated to measurements of the radiometric solar irradiation. The data logger used for light measurements was placed on the top of the collector facing the sun at the same angle as the solar collector. Since, at the day of reading out it was removed from its location for approximately several minutes to half an hour, the error from handling the logger during reading was avoided by eliminating the records from the whole day of the reading.

The radiometric solar irradiation was measured as millivolts with Fluke 10 Multimeter connected to SolData 881spc pyranometer with calibration factor 168mV/(kW/m^2). 99 measurements were taken at the same time, location and angle as photometric light intensity (fig.14) and these time paired measurements were used to create a correlation relationship. The measurements were taken at two locations, part were taken at Ås and part at the system location and they were correlated together. According to that relationship all photometric values were transformed to radiometric irradiation (fig.3.1, Annex3).

Figure 14. Placement of the SolData 881spc pyranometer and logger recording light intensity during measurement used for conversion from photometric intensity to radiometric irradiation.

Evaporation rate:

For calculation of drying rate the difference in weight over time was used:

Initial weight (m_1) – weight after a period of time (m_2) = lost weight during that period

$m_{(\text{lost mass})} = m_1 - m_2$

The buckets were weighed with a commercial bathroom scale two times during a period in which the toilets were not in use. First measurement was on 16.07.2015 and second on 24.07.2015

The lost weight was assumed to be due to evaporated water and by using the weight (m) and the density (ρ) the lost volume for a period was calculated:

$V_{(\text{lost mass})} = m_{(\text{lost mass})} / \rho_{\text{water}}$

ρ water ≈ 1 kg/m^3 when the temperature is between 0 - 20 ˚C

To calculate the evaporation rate the rate of volume loss was used - the volume was divided to the number of days in the period and that gave an approximation of water evaporation per day:

Evaporation rate = V/t

Assessment of the composting process

The excreta mass was assessed visually during the days in which the system was modified. It was clear that composting processes have not started and thus no further assessment was possible.

Assessment of user’s perceptions about the toilet

The children in the kindergarten are the main users of the toilet and a group interview was conducted to evaluate their experience with the toilet. The group interview was conducted on 29.06.2015, in a familiar for the kids setting in the kindergarten. Jørgen Kjørven (kindergarten manager) was translating between English and Norwegian as a person that is familiar to the children, their routines, and had shared experience and knowledge with them during the toilet construction. Ten kids were participating at age between four and seven years, however, the majority were six years old. The purpose of the interview and the idea behind constructing the toilet was explained to them and everyone was encouraged to answer. The questions were about their associations and experiences with the new toilet and a comparison between the older toilets in the kindergarten and the one they use at home, the list with questions and answers is in annex.4.

Modifications of the system per period

The modifications of the system and the placement of sensors during the field work are described as by period:

Period 1 – Dates: 17.04 – 04.05.2015

First tests of the system – trial placement of sensors, five sensors were placed: in the solar collector exposed to light, at the inlet of the gravel bed espoused to light, at the inlet of the gravel bed shadowed from direct light, in the composting chamber by the outlet of the gravel bed and one registering the ambient temperature, not exposed to direct sunlight. After realizing that sunlight exposure affects the sensor temperature readings only records from the shadowed sensors were used, thus the temperature records are from the three sensors not exposed to direct sun light. Light intensity was recorded by the one exposed to direct sun light in the solar collector. The toilet is not in use for the period. 220 V fan connected to the grid in combination with the wind fan drive the air through the system continuously day and night. There is no closing valve in place.

Period 2 – Dates: 06.05 – 17.05.2015

The placement of sensors is not changed but the electrical fan is changed with 20V solar cell driven fan (fig.15). The solar driven fan in combination with the wind fan drive the air through the system continuously day and night. The toilet is not in use for the period and there is no closing valve in place.

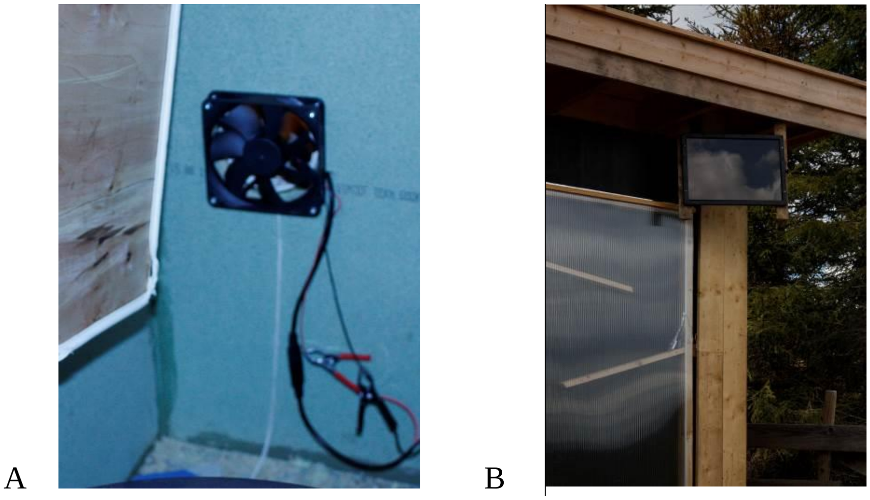


Figure 15. The solar driven fan. A- the fan, B - the solar cell

Period 3 – Dates: 01.06 – 22.06.2015

The toilet is in use and three additional sensors are added to the system. One sensor in the toilet room and one behind the exhaust fan for temperature registration. The sensor, placed in the collector was shadowed by an aluminum foil patch and an additional sensor was added at the top middle of the collector outside and exposed to direct sunlight for registration of the light intensity, but until 15.07.2015 (period 6 and 7) it was not noticed that in the evening hours the offset of the roof throws a shadow on the sensor. From the beginning of this period the toilet system is in use.

The solar driven fan in combination with the wind fan drive the air through the system continuously day and night. There is no closing mechanism in place.

Period 4 – Dates: 24.06 – 28.06.2015

The toilet is in use, temperature is recorded by 6 sensors and sunlight intensity by one.
The solar driven fan in combination with the wind fan drive the air through the system and a closing mechanism is added to the system fig.16. However, on 28.07 it was noticed that the

thermal expander of the closing valve was not functioning – it was not retracting and closing the valve. Thus the system cools down during the night.

Figure 16. The closing mechanism

Period 5 – Dates: 30.06 – 14.07.2015

The toilet is not in use, because of a vacation period during July, but there is a composting mass in the composting chamber. Temperature is recorded by 6 sensors and sunlight intensity by one. The solar driven fan in combination with the wind fan drive the air through the system and the closing valve is in place but not functioning. The sensor for the light intensity was misplaced in a way that makes the records not comparable to the other periods. It was not fixed until the next visit at the site at 15.07.2015, thus only temperature records are used for this period.

Period 6 – Dates: 17.07 – 23.07.2015

The toilet is not in use, because of a vacation period during July, but there is a composting mass in the composting chamber. Temperature is recorded by 5 sensors and sunlight intensity by one. The light intensity sensor was placed on the collector in a way that the roof shadow would not affect it. The solar driven fan is replaced by a 220V fan connected to the grid with timer. The timer is set to permit power from 7.00am to 19.00pm fig.17. The electric fan in combination with the wind fan drive the air through the system. The closing mechanism is in place but not functioning. The air channel between the solar collector and the gravel bed is modified to reduce leakages. Due to a mistake, the sensor for the toilet room was not recording.

Figure 17. The electric fan with timer

Period 7 – Dates: 29.07 – 05.08.2015

The toilet in use from 03.08.2015. Temperature is recorded by 6 sensors and sunlight intensity by one. The fan connected to the grid, with timer set on to permit power from 7.00am to 19.00pm in combination with the wind fan drive the air through the system. The closing mechanism was optimized (fig.18) and the thermal expander replaced. The expander was covered by insulation material to prevent overheating and the closing valve was made heavier, so when the expander is not heated, it can push it back to the initial position. In addition the mounting of the SC was replaced and the SC was better insulated. Noticed leaks were closed with glue. The flow through the gravel bed was optimized by covering the holes for the air, that were drilled in the begging of the bed and were allowing the air to short-circuit the bed, and enlarging the holes by the end of the bed, thus forcing the air to pass through the whole length of the bed.

Figure 18. The new closing mechanism

Statistical analysis

All statistics were done in R with package RcmdrPlugin.NMBU

For comparison between the ambient temperature and the temperature in the composting chamber a statistical analysis is applied. To test the hypothesis stating that: if the system work the compost chamber mean temperatures will be higher than ambient air temperature, the entire sets of the records for a period are summarized and the mean values are compared to test if the difference in the mean values (CC-A) is above zero with a two sample z test, assuming unequal variance. To test if the gravel chamber heats up the composting chamber during night hours, for each date all the records between first reach of light intensity above 2000lux and the last record of 2000lux or above are selected. It was observed in the data that this corresponds well with the daylight duration. Accordingly the mean difference during the day was based on the selection of the records from the first reach of 2000lux to the last for each date. For the night time records, the ambient temperatures are subtracted from the composting chamber temperature values and the difference (CC-A) is tested with a single sample z test, to test if the mean is above zero.

4. Results and discussion

Temperature and light intensity per period

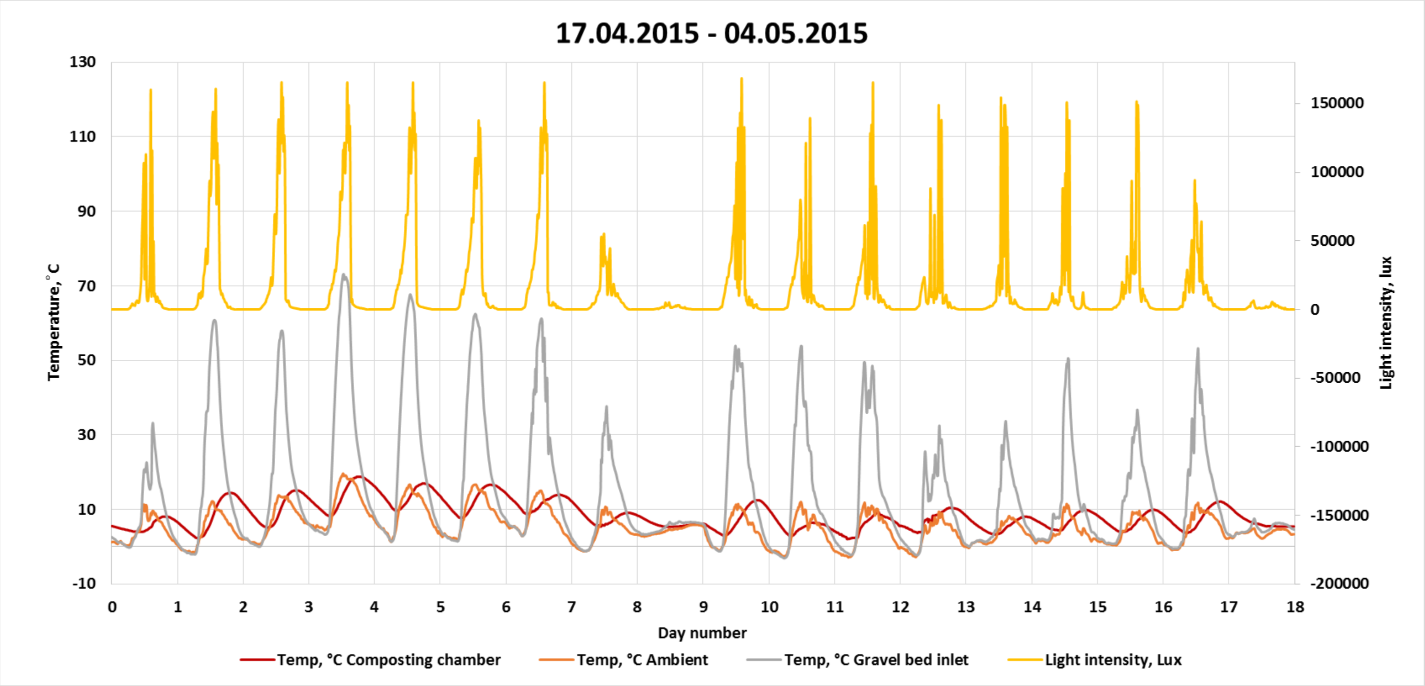


Figure 19. Temperature and light intensity variation recorded for period 1. The light intensity follows the diurnal changes in sunlight and peaks up at 150 000lux. The air coming to the gravel bed is heated during sunlight but it does not heat up notably the CC during the day. The CC is kept warmer than ambient temperatures during night.

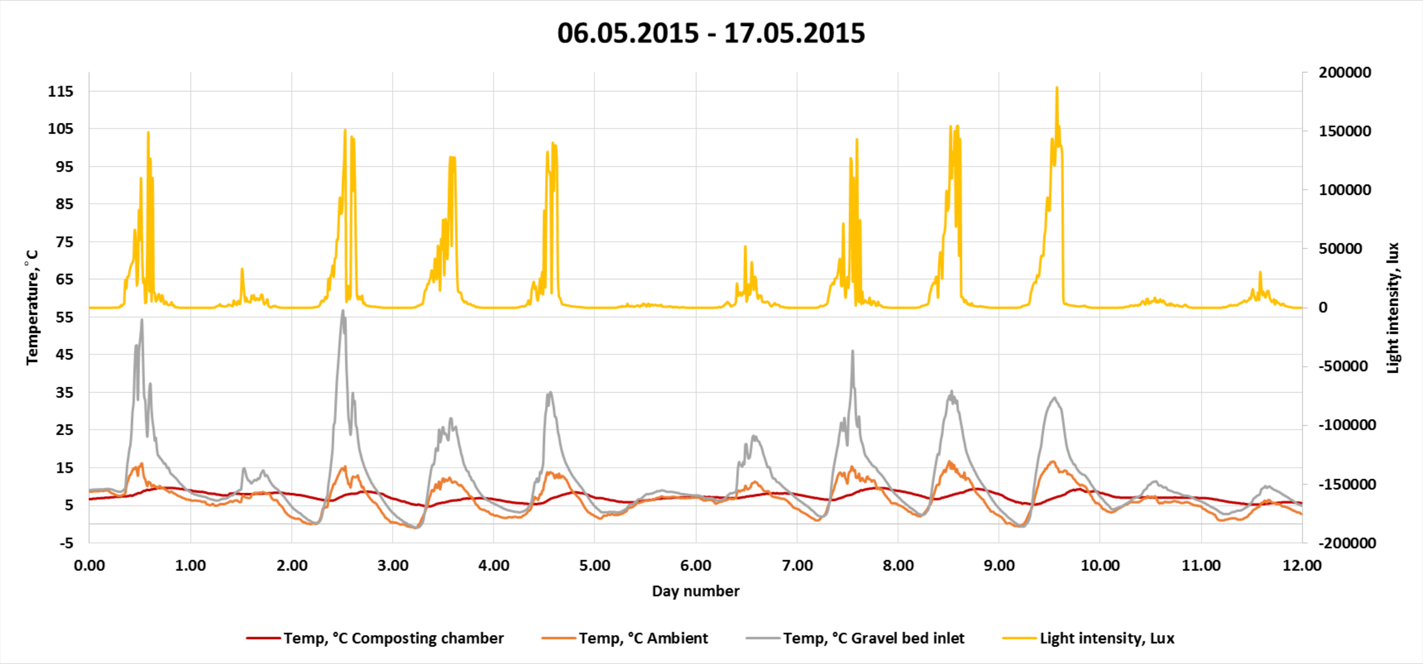


Figure 20. Temperature and light intensity variation recorded for period 2. The period has few cloudy days when the light intensity is significantly reduced. The air coming to the gravel bed is heated during sunlight and less heated when the sunlight is less. The composting chamber has more constant temperature and only shows slight rise during the day but is warmer than ambient temperatures during night.

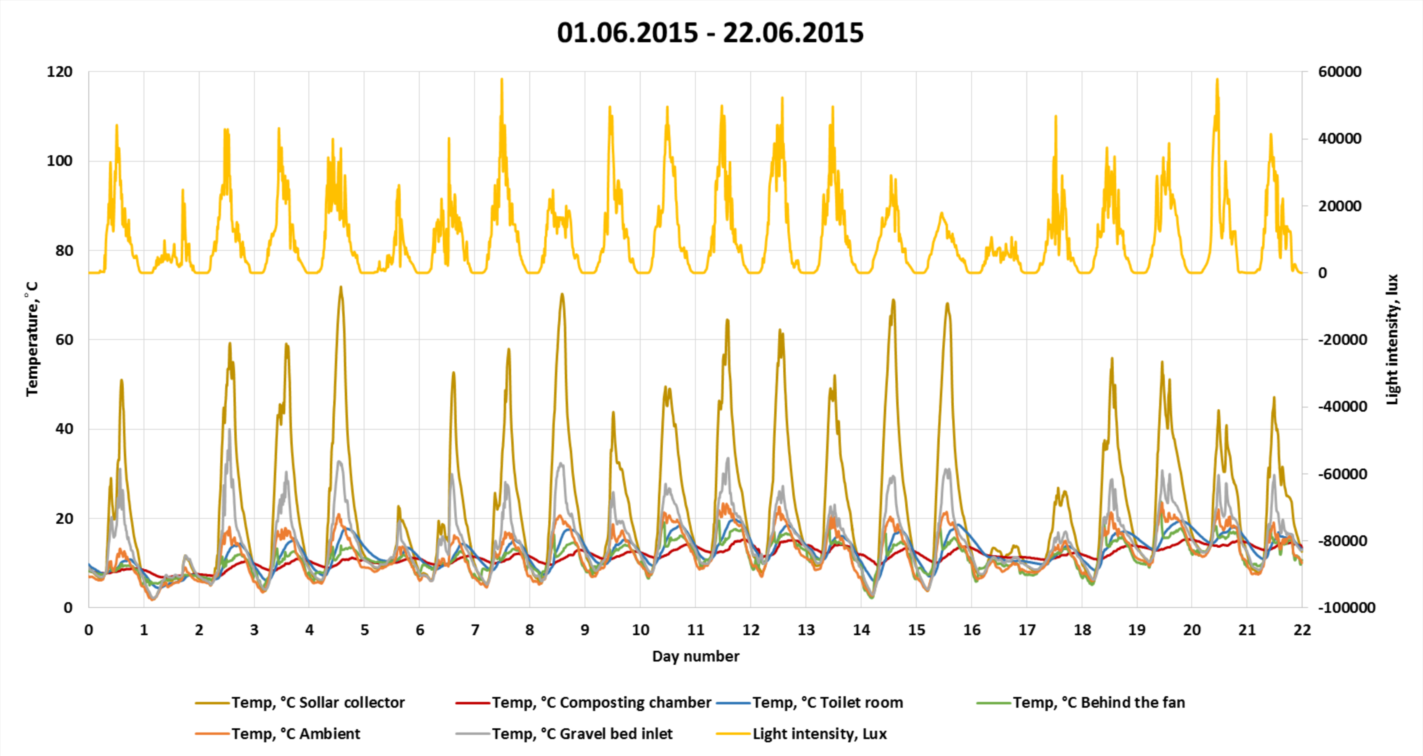


Figure 21. Temperature and light intensity variation recorded for period 3. The period is with sunny days, but the recorded light intensity peaks at only 60 000lux. The air in the solar collector heats up to 70 ˚C. The air temperature declines with 20 to 30 ˚C from the collector to the gravel bed entrance. The temperature at the gravel bed entrance fluctuate with the ambient. The composting chamber has relatively constant temperature and only shows slight rise during the day but is warmer than ambient temperatures during night. The temperatures in the toilet room and behind the fan are more correlated to the ambient temperatures than on the CC temperature.

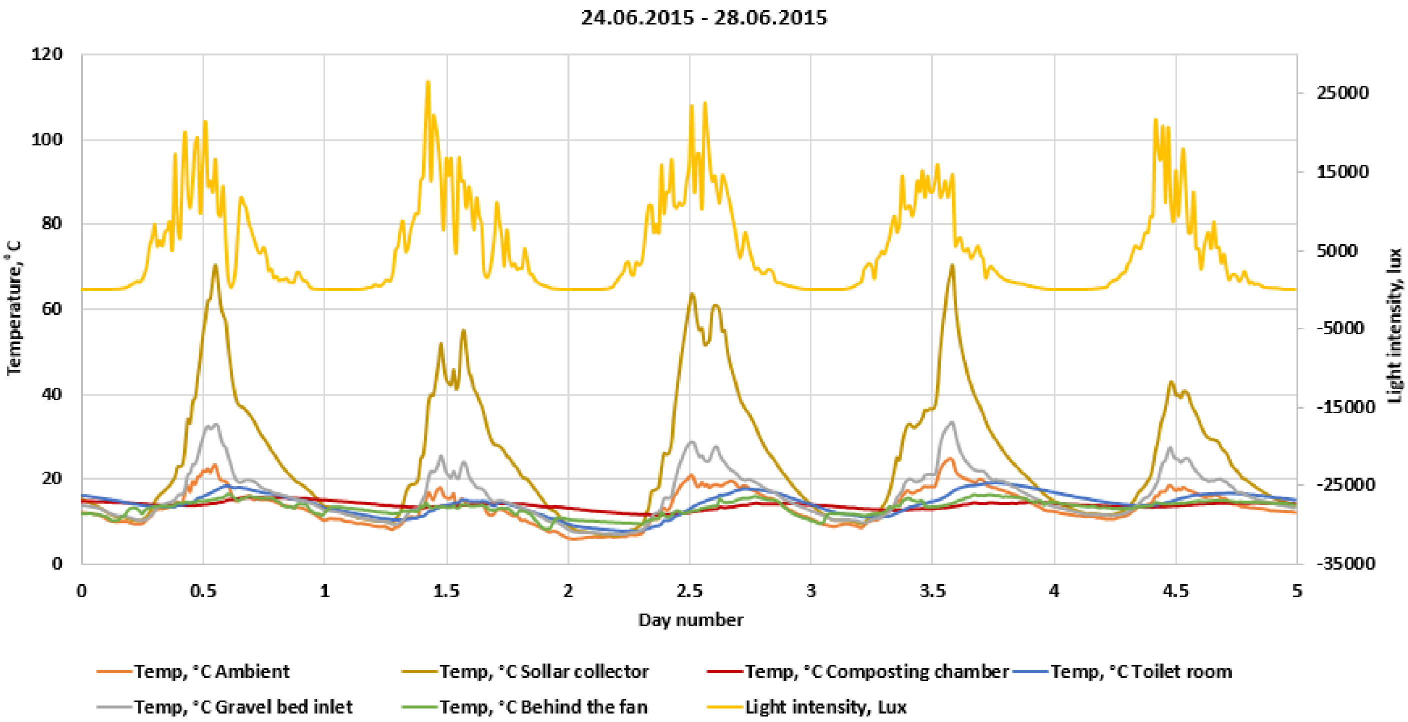


Figure 22. Temperature and light intensity variation recorded for period 4. The light intensity recorded for the period is low, however the air in the solar collector heats up to 70 ˚C but the air at the entrance of gravel bed peaks at 30 ˚C and fluctuates with the ambient temperature. The composting chamber has relatively constant temperature and only shows slight rise during the day but is warmer than ambient temperatures during night.

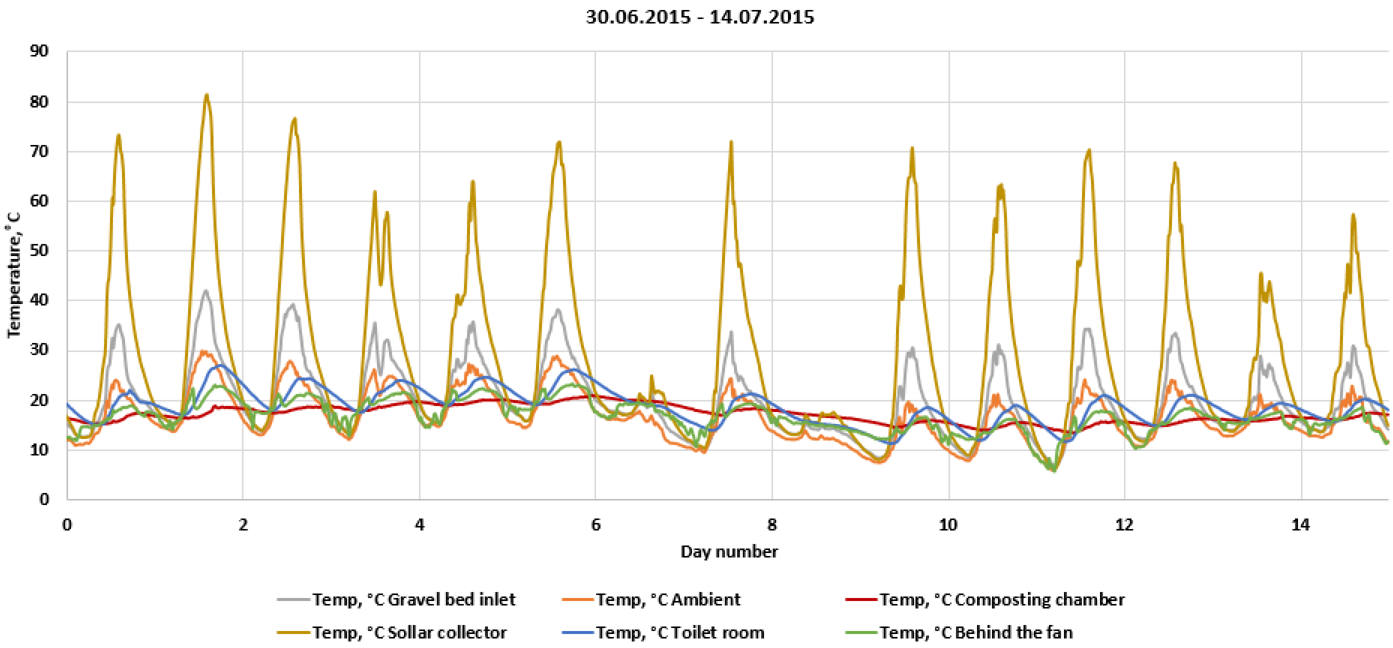


Figure 23. Temperature variations recorded for period 5. The temperature in the solar collector peak at 80˚C. This temperatures drops significantly at the gravel bed inlet. The ambient temperature fluctuate more than 10˚C between day and night time. The temperatures of the toilet room and behind the fan are following the variations in the ambient temperature. The CC temperature is relatively constant and remains lower during the day and higher during the night compared with the ambient.

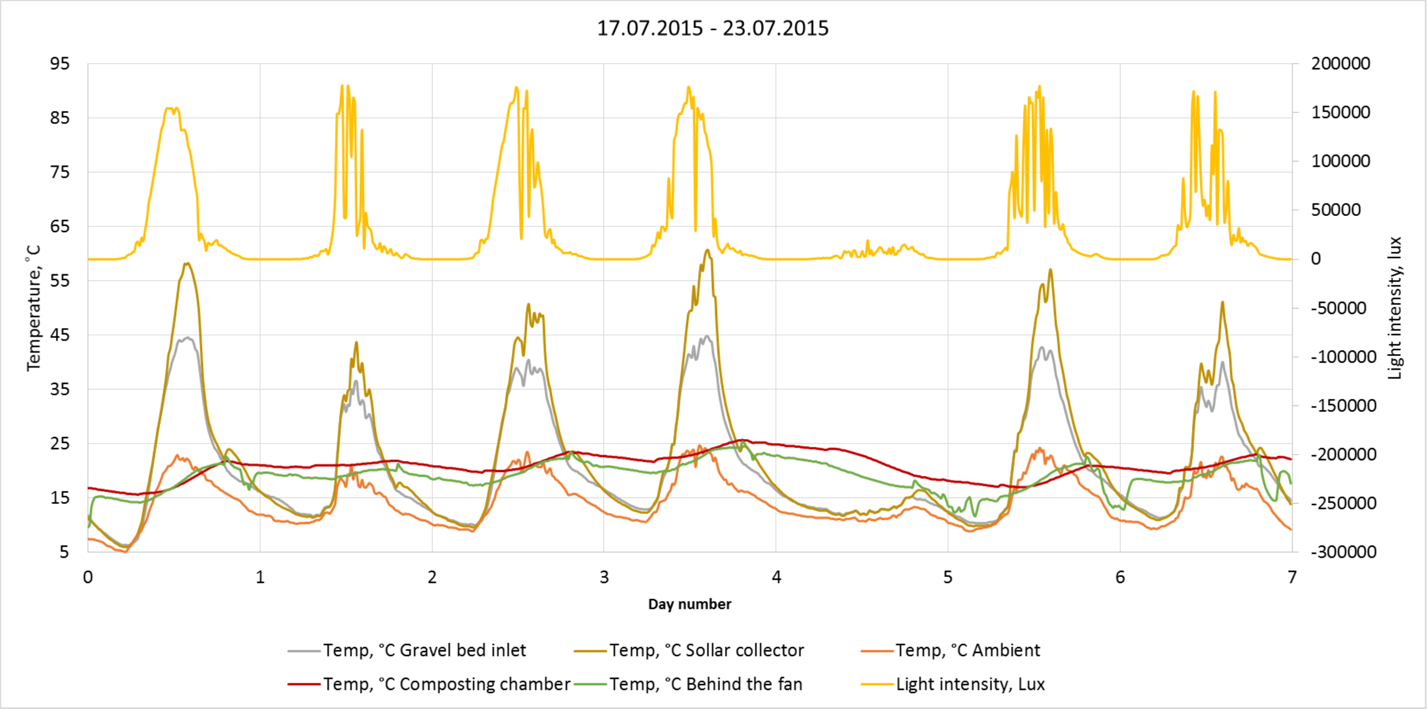


Figure 24. Temperature and light intensity variation recorded the period 6. The period is sunny and the light intensity peaks at around 180 000lux. The temperatures in the solar collector vary between 5˚C and 65˚C. The air temperature at the gravel bed inlet peaks at 45˚C and the drop in the temperatures from the collector to the bed inlet is not as noticeable as in previous periods. Thus, the air is not losing as much heat. The temperature of the composting chamber is relatively constant but for most time higher than ambient and the temperature behind the fan is correlated to the temperatures in the chamber.

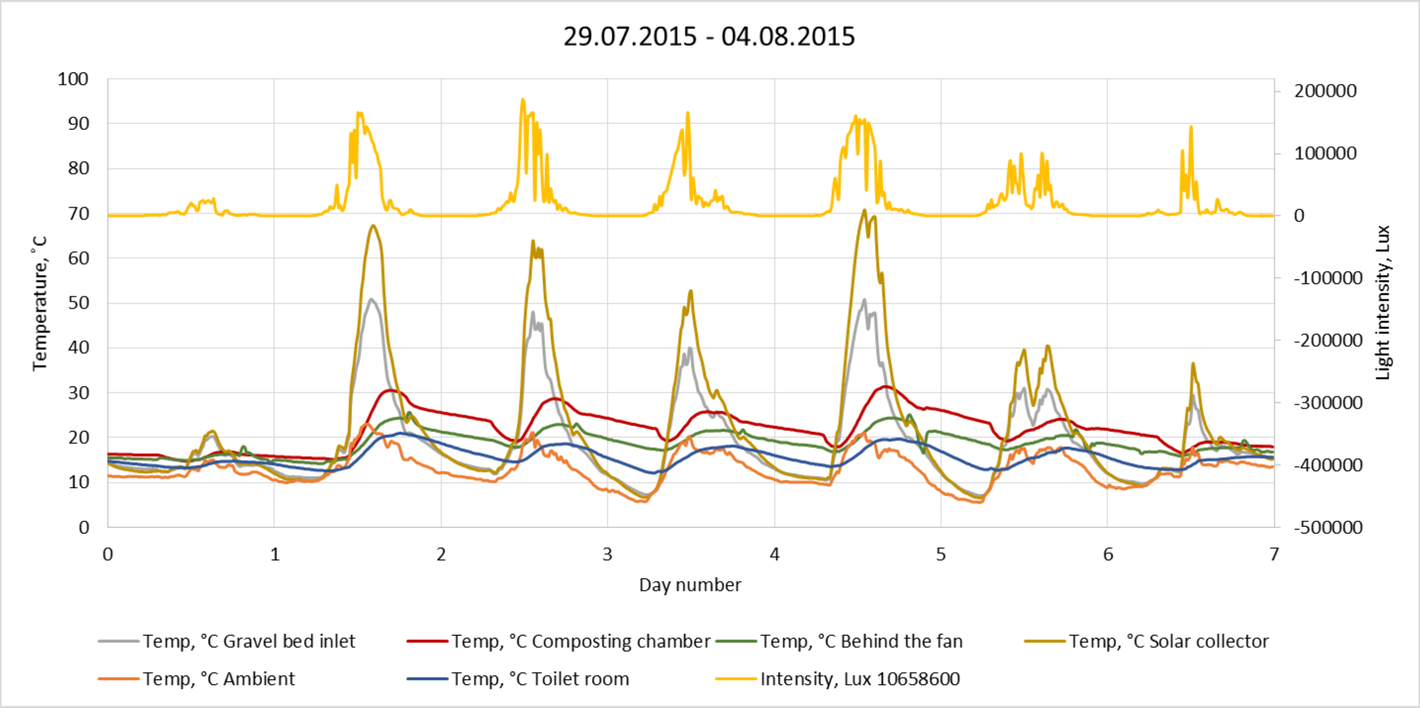


Figure 25. Temperature and light intensity variation recorded for period 7. The light intensity peaks at around 180 000lux. The temperatures in the solar collector vary between 10˚C and 70˚C. The air temperature at the gravel bed inlet peaks at 50˚C and the drop in the temperatures from the collector to the bed inlet is between 10˚C and 20˚C. The temperature of the composting chamber peaks up during the day, thus heat is transported to it during the day, and is higher than ambient at all times. The temperatures recorded behind the fan and in the toilet room are correlated to the temperatures in the chamber.

During the different modifications and as the understanding of the factors affecting the records increased, several of the sensor's places are changed. Both these changes and the system modifications have effect on the results and how periods can be compared.

The gravel bed inlet sensor was moved two times. Initially it was placed at the edge of the solar collector and then it was moved once at the start of period three, when it was moved 4-5 cm further from the solar collector and second time in the beginning of period 6, when it was moved 30-35 cm away from the collector in the channel connecting it with the bed. The temperature records in period 1 and 2 are higher compared to the next periods. Maximum temperatures in this initial periods for the gravel bed inlet are between 35-70 ˚C and later in periods 3, 4, and 5 it drops to 20-40 ˚C (fig.19-25). Explanation could be that the sensor initially was placed so close to the collector that it was recording the air temperature in the collector. However, when the sensor is moved further towards the GB for periods 6 and 7, an increase in peak temperatures can be observed rather than decrease and the reason could be that the channel has less leaks. The solar collector sensor was shaded from direct sunlight from period 3 and shows that temperatures drop significantly from the collector to gravel bed inlet. The SC sensor is very close to the black wall and the high temperature of the wall could affect the records of the sensor. The big difference in temperatures between the SC and the GB inlet is probably due to a combination of the effect of the wall, no insulation on the connecting channel and some heat losses from leakages. Furthermore, the sensor's accuracy is reduced with high temperatures (fig.1.2, annex 1) and the peak temperatures in SC are in several cases higher than sensor's operational range. The light intensity records in period 3 and 4 were affected by the roof shadow and have lower values compared to the records in other periods.

When the air in the system is driven by a 220V fan (periods 1, 6, 7) the temperatures in the CC are higher compared to when the less powerful solar fan – 20V, is driving the air. In periods 6 and 7 the timer is preventing the fan of sucking air through the night and cooling the system. In those periods the difference between the ambient temperatures and the temperatures in the system are greater. Thus, the toilet system modifications that have the greatest effect on the temperate profile in the system are those that optimize the air and heat flow when the sun is heating and reduce the airflow during night. The most noticeable increase in the heat flow in the GB and CC is when the air flow is increased during sunshine due to the electric fan and accordingly is prevented during the cold night by the closing valve and the timer. In addition, the elimination of leakages and the improvement of the air path through the gravel bed, in period 7, optimises the heat flow to the composting chamber and also could give additional rise to the temperatures in the chamber.

Comparison between the ambient temperatures and temperatures in the composting chamber

In both modes – day and night, energy as sensible heat should be delivered to the compost chamber. To analyze if the energy part of the system work as intended, it is hypothesized that:

1. The system works, if energy is transferred to CC. If that is true the mean temperature in the CC should be higher than the mean ambient.

2. The system works, if energy is stored in the gravel bed during the day and released during night. If that is true, the difference in mean temperature between the CC and ambient (CC – A) should be bigger during the night compared to the day.

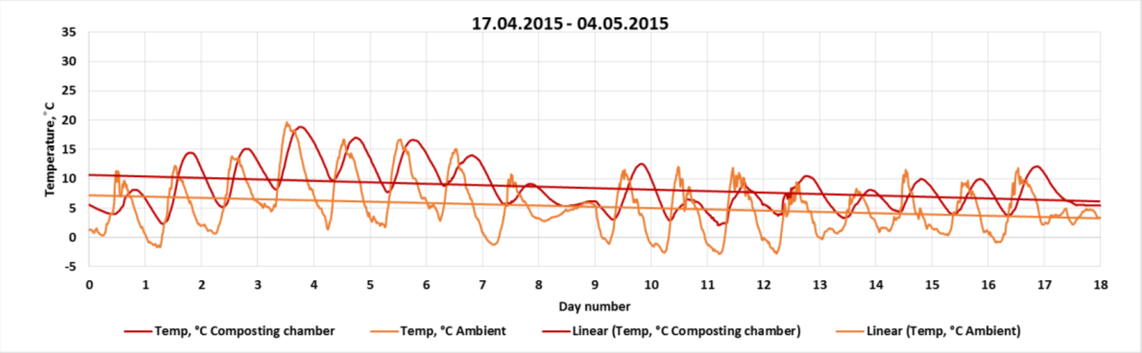
Table 5. Comparison between ambient temperatures and composting chamber temperatures per period. The p-values are the outcome of the statistical hypothesis testing (annex 5)

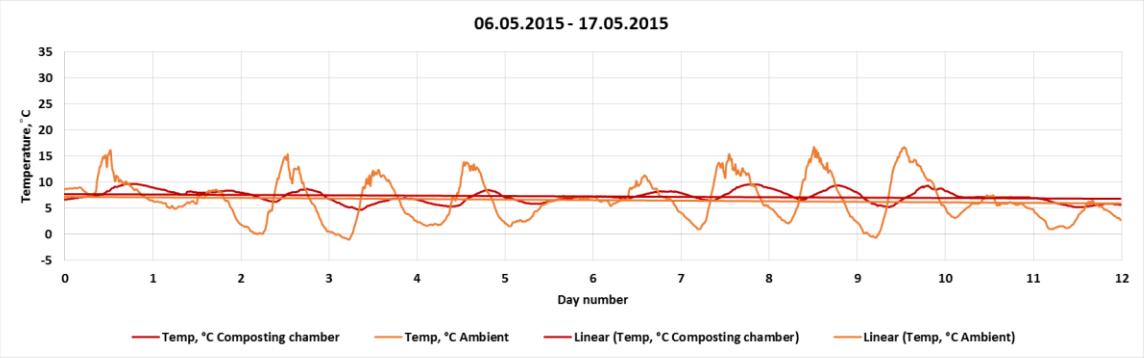
Modification	**Period**	**Ambient temperature °C**		**Composting chamber temperature °C**		**Mean temperature difference during day °C (>2000lux)**		**Mean temperature difference during night °C (<2000lux)**		**p-values CC-A >0**	**p-values D > 0 during no sunlight (CC-A)**
		Mean	**± St. dev**	**Mean**	**± St. dev**	**Mean**	**± St. dev**	**Mean**	**± St. dev**		
Electric fan, no timer, no closing mechanism, not in use	1	5.22	4.51	8.38	3.78	0.07	3.15	5.98	2.59	2.2E-16	2.2E-16
Solar cell driven fan, no closing mechanism, not in use	2	6.55	3.95	7.28	1.15	-1.71	3.33	2.99	2.37	9.7E-10	2.2E-16
Solar cell driven fan, no closing mechanism, in use	3	11.78	4.78	11.5	2.08	-2.23	3.74	3.63	1.61	9.9E-01	2.2E-16
Solar driven fan, closing mechanism, in use	4	13.43	4	13.96	0.88	-1.59	3.63	3.41	2.18	2.4E-03	2.2E-16
Solar driven fan, closing mechanism, not in use but with composting mass	5	16.66	5.11	17.28	1.83	/	/	/	/	7.3E-06	/
Electric fan with timer, closing mechanism, not in use but with composting mass	6	14.21	4.45	20.83	2.35	4.49	4.69	10.13	1.54	2.2E-16	2.2E-16
Electric fan with timer, optimized closing mechanism and gravel bed air flow, in use	7	12.93	3.62	21.63	4.28	6.49	4.25	10.09	4.76	2.2E-16	2.2E-16

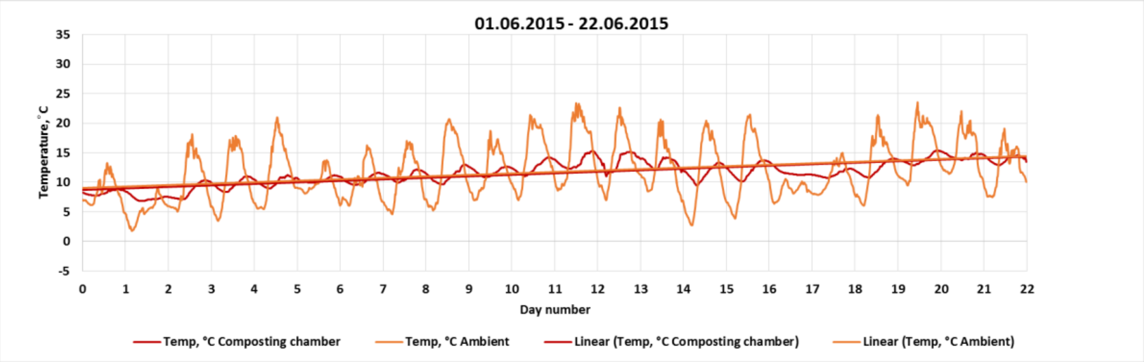
Based on the outcome of the hypothesis testing (tabl.5, p-values CC-A >0), with confidence interval of 95%, it is clear that heat is coming to CC, and accordingly CC temperature is higher than ambient, with only one exception – during the period 3 – 01.06-22.06.

The statistics shows that the mean temperature in the composting chamber is higher than the ambient for most periods. From the mean values (tabl.5) and fig.26 it is visible that the difference of the between CC and A for most modifications is around or less than 1˚C, this correspond to the sensors accuracy and thus cannot be considered as a good indication that the heating-ventilation system works and keeps the CC wormer. Only during periods 1, 6, 7, the mean composting chamber temperature is several degrees higher than the ambient. Thus, even though statistical results shows that the energy is transferred for all but one period, it is only during the periods with high air velocity due to more powerful 220V fan, that the system can be considered working and delivering heat to the compost chamber.

Furthermore, the outcome of the hypothesis testing for the difference between composting chamber and ambient temperatures during no sunlight (tabl.5, p-values D > 0 during no sunlight (CC-A)), shows with confidence interval of 95%, that the difference in mean temperature between the CC and ambient is greater during the night compared to the day. In all periods the probability of higher ambient temperatures than in the composting chamber, during no sunlight, is very low - P-value < 2.2e-16 and the difference between the composting chamber temperatures and ambient is on average several degrees (tabl.5). That can be considered an indication that the gravel bed is functioning as a heat storage. The modifications in periods 6 and 7 resulted in the greatest increase in the CC temperatures.







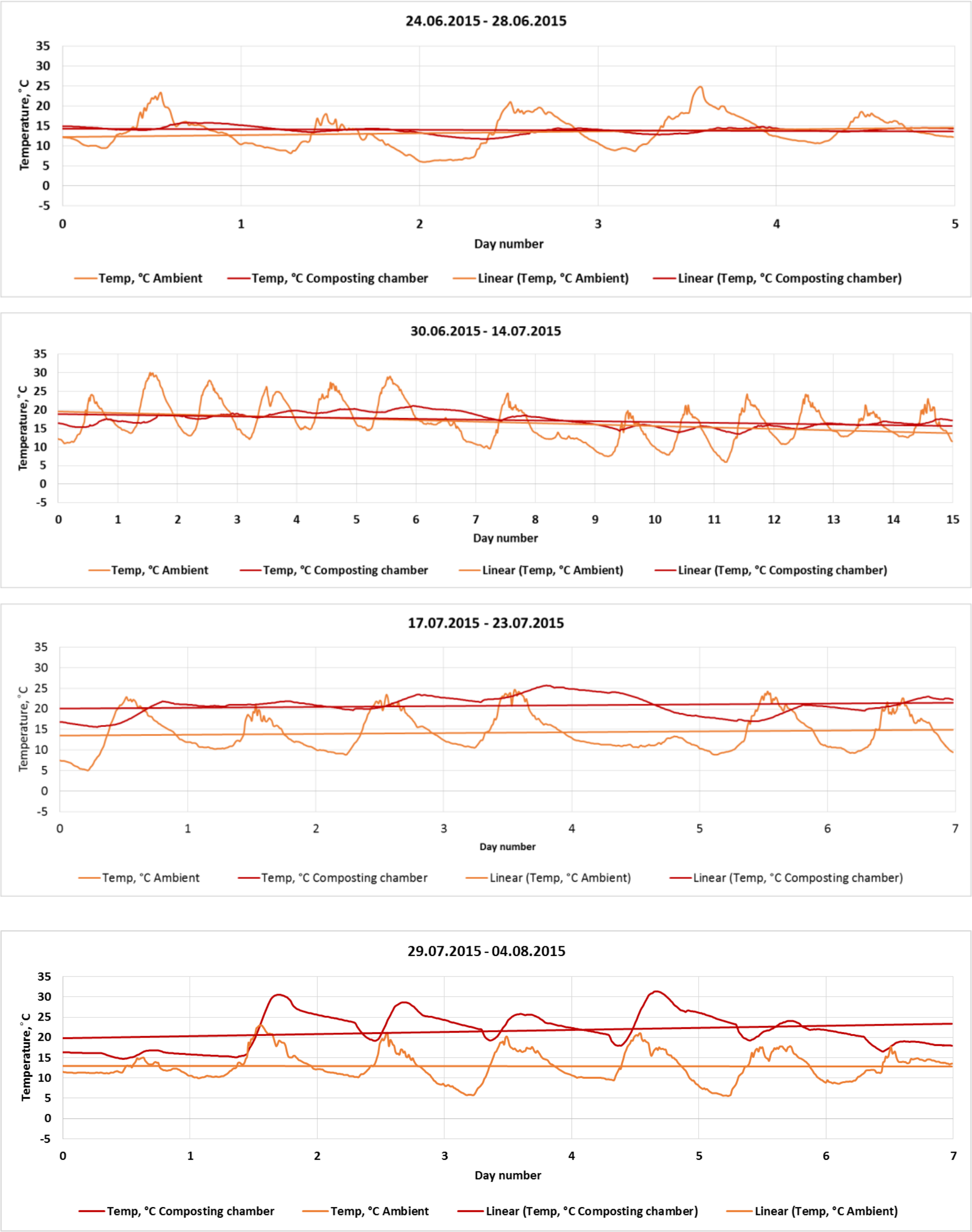


Figure 26. Temperature variation per period, comparison between the ambient temperatures and temperatures recorded in the composting chamber with trend lines to visualize the main trend in the temperatures over time and the average difference between the temperatures. The composting chamber temperature is higher in periods 1, 6 and 7

Air flow

Volume air flow q [m^3/s] = ν *A_c

ν - Measured

For circular pipe $A_c = \pi*D^2/4$

Mass flow $\dot{m}$ [kg/s] = q*ρ

$\dot{m}_{in}$ – mass flow at the inlet

$\dot{m}_{out}$ – mass flow at the outlet

ρ_{air} - from table .6.

Assumptions: The air is an ideal gas and the pressure is constant – 1 atm.

Measurements before modifications on 28.07.2015

Air velocity at the exhaust pipe outlet: ν_{out}= 3 m/s

Pipe diameter D = 0.1m

$A_c = 3.14*0.1^2/4 = 0.007854\ m^2$

$q = 3\ m/s*0.007854\ m^2 = 0.0236\ m^3/s$

At 20˚C, $\dot{m}_{out} = 0.024\ m^3/s*\ 1.2\ kg/m^3 = 0.028\ kg/s$

Air velocity at the solar collector inlet ν_{in} = 0.14 m/s

Pipe diameter D = 0.15m

$A_c = 3.14*0.15^2/4 = 0.017671\ m^2$

$q = 0.14\ m/s*0.017671\ m^2 = 0.0025\ m^3/s$

At 20˚C, $\dot{m}_{in} = 0.0025\ m^3/s*\ 1.2\ kg/m^3 = 0.003\ kg/s$

Measurements after modifications on 28.07.2015

Air velocity at the exhaust pipe outlet: ν_{out} = 3 m/s

Pipe diameter D = 0.1m

$A_c = 3.14*0.1^2/4 = 0.007854\ m^2$

$q = 3\ m/s*0.007854\ m^2 = 0.024\ m^3/s$

At 20˚C, $\dot{m}_{out} = 0.024\ m^3/s*\ 1.2\ kg/m^3 = 0.028\ kg/s$

Air velocity at the solar collector inlet ν_{in} = 1 m/s

Pipe diameter D = 0.1m

$A_c = 3.14*0.1^2/4 = 0.007854\ m^2$

$q = 1 \text{ m/s} * 0.007854 \text{ m}^2 = 0.0079 \text{ m}^3/\text{s}$

At 20˚C, $\dot{m}_{in} = 0.007854 \text{ m}^3/\text{s} * 1.2 \text{ kg/m}^3 = 0.009 \text{ kg/s}$

Table 6. Density of air at 1 atm pressure, adapted from Cengel, 2006

Temperature range ˚C	Air density kg/m^3
- 10 ˚C ~ + 10 ˚C	1.3
+ 10 ˚C ~ + 35 ˚C	1.2
+ 35 ˚C ~ + 60 ˚C	1.1
+60 ˚C ~ + 80 ˚C	1.0

The airflow at the outlet of the system – is measured after the fan, in the chimney pipe, thus is more stable and depends on the fan. In both cases - before the modification of the system and after it, the airflow is 0.024 m^3/s. At the inlet of the system, however, the airflow is higher after the modifications: before - 0.0025 m^3/s, after - 0.0079 m^3/s. At the inlet, the airflow depends more on the airtightness of the system – when the system is not sealed the fan is drawing air through the holes and the suction force at the inlet is reduced, but when it is airtight the airflow at the inlet should be equal to the outlet as there are no losses. The first measurement at the inlet shows approximately ten times lower airflow value than the outlet and reveals that the system is very poorly sealed. After several tests with smoke pallets, most holes were identified and sealed and the next outlet measurement reflects that. The inlet airflow was improved to 0.0079 m^3/s, which is approximately 1/3 of the outlet value.

Solar input

The irradiance (G) is based on estimated value by correlation with the light intensity.

$G = 4 * 10^{-6}$ * light intensity + 0.0462 (fig.3.1, annex 3)

Since, irradiance value of 0.01 [kW/m^2] corresponded to 2 153 lux, and 0 corresponded to values in the range of 32-162 lux and only few measurements were taken at low light, in order to avoid overestimating the total irradiance and considering that the error due to the correlation is higher than 1% the irradiance corresponding to light intensity below 2 000 lux was rounded to 0.

If light intensity > 2000 lux, $G = 4 * 10^{-6}$ * light intensity + 0.0462

If light intensity < 2000, G = 0

G_{SC} [kW] = G*$A_{SC,}$ where A_{SC} is the area of the solar collector

A_{SC} [m^2] = 1.8m*2m = 3.6 m^2

For the solar energy input (fig.27), it is assumed that for the time between measurements the irradiation is constant, thus G_{SC} *15min*60sec gives the irradiance for the time of one measurement to the next.

G_{SC} [kW]*15min*60sec/min = Solar energy input per 15 min [kJ]

The above equations are used to compute the results in Fig. 27. And in the example below shows the calculation of the solar energy input for one given 15 min interval. Example:

Solar energy $\text{input}_{\text{from 01:15:00 PM to 01:30:00 PM 07/30/15}}$ = $G_{\text{from 01:15:00 PM to 01:30:00 PM 07/30/15}}$ * A_{SC} * 15min * 60sec/min = 0.62 kW/m^2 *3.6 m^2 *15min*60sec/min = 2008.8 kJ

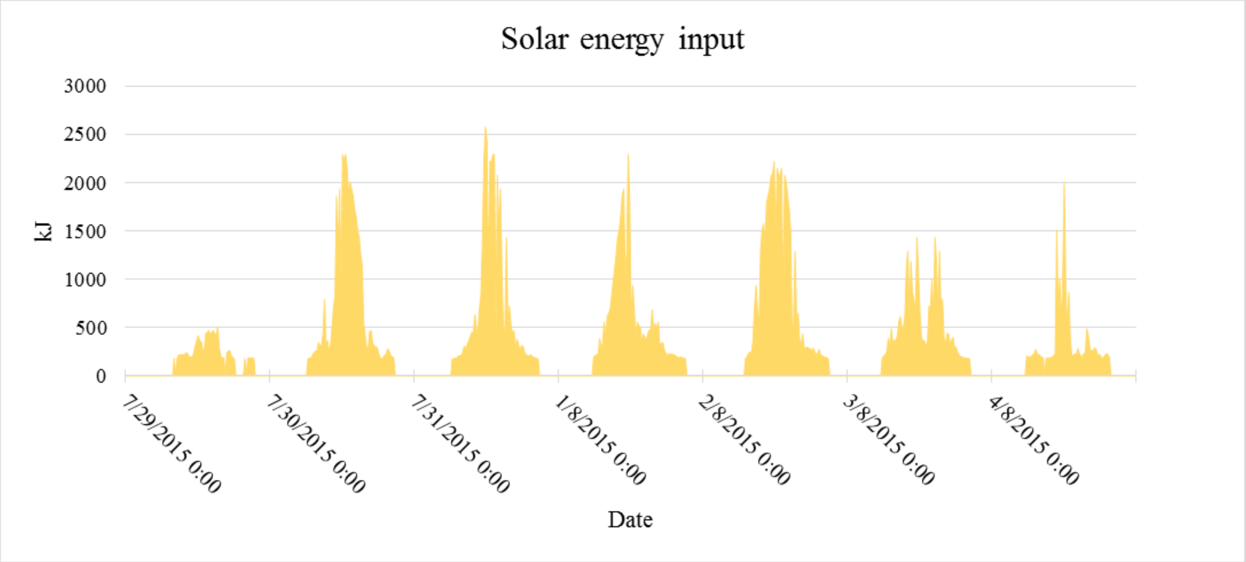


Figure 27. Solar energy input measured over 15 min intervals for period 7 - 29.07 – 04.08.2015

The solar energy falling on the collector area in period 7 peaks in the early afternoon hours and is at highest 2500kJ over 15 min interval.

Total solar energy input per period Gt is estimated as:

Gt [kJ] $_{\text{for a period}}$ = Σ (G_{SC} *15min*60sec/min)

Average solar energy input per day [kJ] = Σ (G_{SC} *15min*60sec/min) / number of days

Average solar energy input per day [kW] = Average solar energy input per day [kJ] / 3600 sec

Table 7. Day length, sunlight duration and solar input comparison between periods.

Period	**Number of days in a period**	**Average daylight***		**Total solar energy input kJ,**	**Average solar energy input per day kJ,**	**Average solar energy input per day kWh**	**Average solar energy input kWh/m²/day**
		hours	**% from 24hours**				
1	18	15h 10min	63%	400 213.57	22 235.09	6.18	1.72
2	12	17h	71%	230 077.33	19 173.11	5.33	1.48
3	22	18h 40 min	78%	422 585.93	19 208.45	5.34	1.48
4	5	18h 54 min	79%	601 75.82	12 035.16	3.34	0.93
5	14	18h 29 min	77%	/	/	/	/
6	7	17h 44 min	74%	284 359.36	40 622.77	11.28	3.13
7	7	16h 51min	67%	238 385.15	34 055.02	9.46	2.63

*Daylight - source - (Moesen, 2015)

The system is assessed in the period of the year with longest daylight – spring and summer. The periods include days with daylight between 15 to 19h, including the longest day in the year, and thus represent the time of the year that has the highest solar radiation input per day. The periods with high solar input are 1, 6 and 7. In periods 3 and 4 the light intensity sensor was shadowed by the roof and because of that the values for those periods are underestimated and not directly comparable to the rest of the periods. The large area of the collector, its orientation to south and the cleared landscape optimize the solar irradiance incidence on the collector. In comparison with data for Oslo (tabl.7) the irradiance falling on the collector is 80 to 90% of the irradiance falling onto a vertical surface facing south, south east in the Oslo area. The solar energy input on one square meter of the collector, can provide sufficient energy for heating. Theoretically, from equation Q = m*C*ΔT, 0.05kWh of energy can increase the temperature of 1m^3 air with density 1.2 kg/m^3 and C_{air} = 1.01 kJ/kg.˚C with 150 ˚C.

Table 8. Solar irradiance onto a vertical surface in Oslo, based on average monthly values over a period of 22 years, source: (The Solar Electricity Handbook website, 2015)

Month	April	May	June	July	August
Solar irradiance kWh/m²/day	3.05	3.51	3.27	3.41	3.17

Heat transfer

The toilet system is analyzed as three separate steady flow subsystems fig.28, for period 7 – 29.07-04.08.2015. Period 7 is with the most promising results in terms of increase in temperatures in CC and only in that period the heat flow in the system is analyzed.

The heat transfer is estimated only for the day time when the fan is driving the air and when the assumption of constant air mass flow is more valid.

The airflow can be assumed for constant if the system is airtight but for the calculation of the energy change it is assumed that:

- Constant air flow: 1) from SC inlet to GB outlet, measured at the SC inlet, which implies that the system is completely insulated between these two points and there is no losses to the walls or air leakages; 2) constant air flow between the CC inlet to the CC outlet, which implies that the system is completely insulated between these two points and there is no losses to the walls or air leakages.
- Constant air pressure throughout the system

Rate of net heat transfer: $\dot{Q}$ [kW] = $\dot{m} * C * \Delta T$
The mass flow is taken from the calculations on p58-59, for the flow measured after the system was modified on 28.07.2015,
Where: $\dot{m}_{in}$ – mass flow at the inlet
$\dot{m}_{out}$ – mass flow at the outlet

$\dot{m}_{SC} = \dot{m}_{in} = 0.021$ kg/s
$\dot{m}_{GB} = \dot{m}_{in} = 0.021$ kg/s
$\dot{m}_{CC} = \dot{m}_{out} = 0.028$ kg/s
$C_{air} = 1.01$ kJ/kg.˚C (Cengel, 2006)
$\Delta T = T_o - T_i$, where T_o is temperature at the outlet and T_i temperature at the inlet - fig.28.

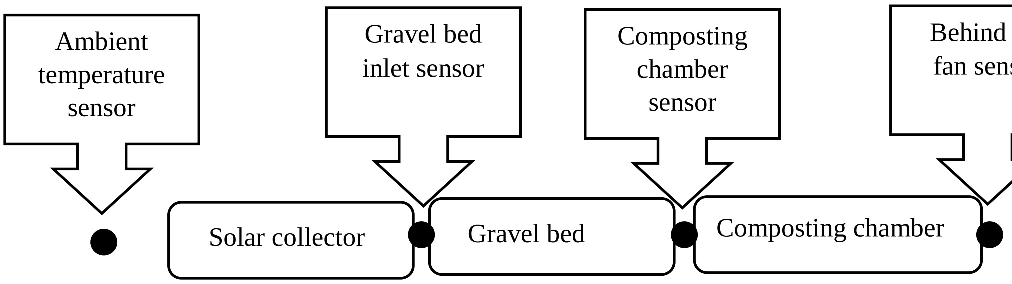


Figure 28. The conceptual division in the system and placement of sensors at inlets and outlets of the different subsystems.

- Ambient temperature sensor – air temperature at the solar collector inlet - $T_{i\ SC}$
- Gravel bed inlet sensor – outlet air temperature of the solar collector - $T_{o\ SC}$, inlet air temperature for the gravel bed - $T_{i\ GB}$
- Composting chamber sensor – outlet air temperature for the gravel bed - $T_{o\ GB}$, inlet air temperature for the composting chamber - $T_{i\ CC}$
- Behind the fan sensor – outlet air temperature for the composting chamber - $T_{o\ CC}$

Energy change in the system for the interval of one measurement to another:

$\Delta\dot{Q}$ net heat transfer [kJ] = $\dot{Q}$ [kW] * 15min * 60sec/min

$\Delta\dot{Q}_{SC} = \dot{m}_{SC} * C_{air} * \Delta T_{air\ (SC)}$ * 15min * 60sec/min

$\dot{m}_{SC} = \dot{m}_{in} = 0.009$ kg/s

$\Delta T_{air\ (SC)}$ = Outlet air temperature of the composting chamber $T_{o\ SC}$ – inlet air temperature $T_{i\ SC}$

$\Delta\dot{Q}_{GB} = \dot{m}_{GB} * C_{air} * \Delta T_{air\ (GB)}$ * 15min * 60sec/min

$\dot{m}_{GB} = \dot{m}_{in} = 0.009$ kg/s $\Delta T_{air\ (GB)}$ = Outlet air temperature of the composting chamber $T_{o\ GB}$ – inlet air temperature $T_{i\ GB}$

$\Delta\dot{Q}_{CC} = \dot{m}_{CC} * C_{air} * \Delta T_{air\ (CC)}$ * 15min * 60sec/min

$\dot{m}_{CC} = \dot{m}_{out} = 0.028$ kg/s

$\Delta T_{air\ (CC)}$ = Outlet air temperature of the composting chamber $T_{o\ CC}$ – inlet air temperature $T_{i\ CC}$

The above equations are used to compute the results in Fig. 29. And in the example below shows the calculation of the net energy change for one given 15 min interval. Example:

$\Delta\dot{Q}_{SC\ \text{from 01:15:00 PM to 01:30:00 PM 07/30/15}}$ = 0.009 kg/s * 1.01 kJ/kg.˚C *(48.2˚C - 23.0˚C)*15min*60sec/min = 206.16 kJ

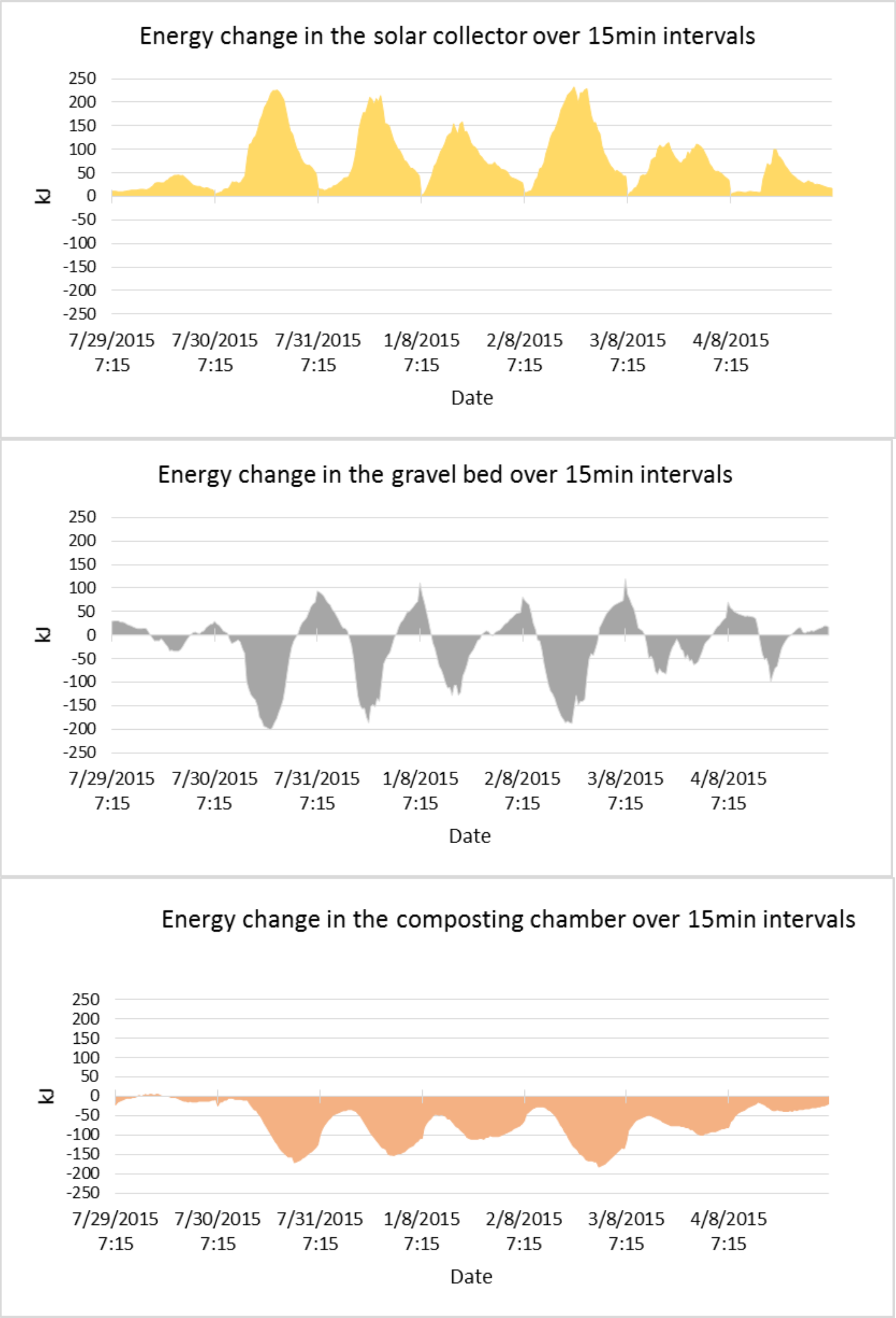


Figure 29. Increase or decrease in the energy of the air, over 15 min intervals, within the different subsystems during daytime, when the air flow velocity is determined by the fan for period 7.

Taking into account the imprecise measurements, the assumptions that cannot be validated, and the low values, the quantitative changes in the energy between the subsystems are subject to large error margin. The energy transfer is based on change in temperature that is recorded with sensors with accuracy of approximately 1˚C fig.0, annex 0, collective for the inlet and outlet sensor = 2˚C. Change in temperature (ΔT) of 2 ˚C can result in 38 to 51 kJ difference depending on the air flow (from $\dot{Q} = \dot{m} *1.01* (2)$). With values of energy change between 0 and 250 kJ, 51kJ represents substantial error margin. Furthermore, the air flow is subject to a large error due to the not validated assumptions for constant pressure and airflow, and due not considering the effect from the wind powered fan in the calculations. However, the energy changes in the system are useful to qualitatively describe the heat flow within the toilet system.

Figure 29 show that the heat in the SC during day time increases and decreases following the solar input. This energy is transferred to the GB with some losses where it is accumulated in the gravel during the hours of high energy input from the collector. In the beginning and the by the end of each day the energy in the GB increases instead of decreasing, an explanation can be that no heat is supplied to the bed and the temperature difference between the gravel and the air drive a thermal energy flow in the opposite direction - from the gravel to the air. In the CC energy is lost during day time. The energy flow in the system, during day time, correspond to the conceptualized energy flow in the system in fig.10. Energy is gained in the solar collector, it is transferred with some losses to the GB, where most of it is accumulated and some is transferred to the CC. Some losses can be assumed in the GB due to leaks. In the composting chamber the energy is lost to heat the air in the chamber and for evaporation. The highest energy lost from the CC is during evening hours. This could be explained by the increased temperature of the stones and as shown on fig. 29 the air is gaining energy from the stones in the evening and that energy is delivered to the CC. This results in bigger difference between the temperatures at the inlet and outlet of the chamber. The temperature in the gravel increases gradually during the day as the gravel accumulates energy and the temperature difference between the air and the gravel decrease. When the solar input is high the air heats the gravel, but during the morning and evening hours the stones heat the air.

Solar collector efficiency

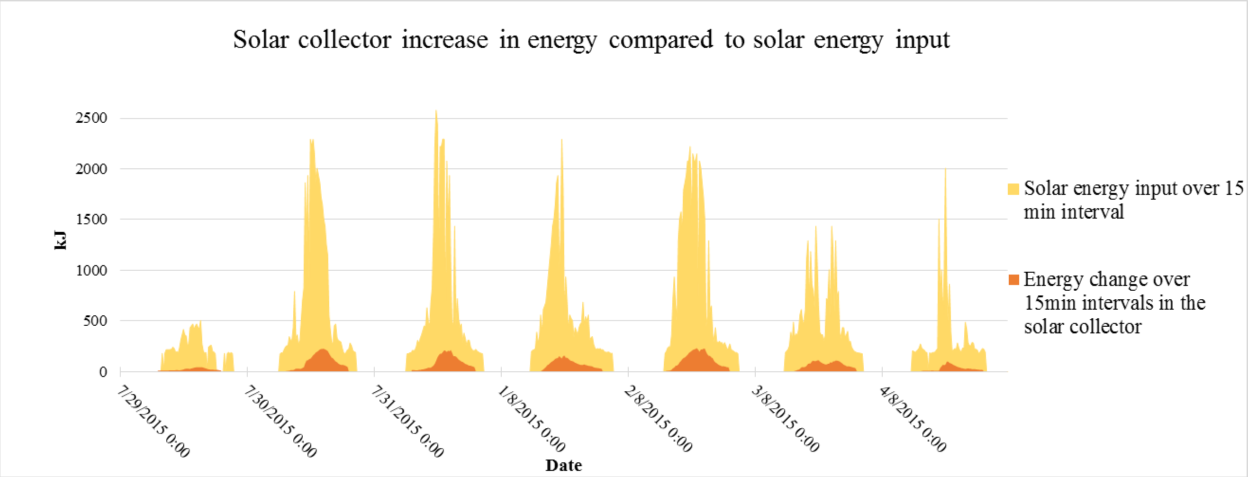


Figure 30. Comparison between incoming solar energy and the corresponding energy increase in the solar collector for period 7 – 29.07 – 04.08.2015. The solar energy input per 15 min is maximum 2500 kJ and the maximum energy increase in the collector reach 250kJ. From fig 30 it can be estimated that between 1-10% of the total the solar energy is captured by the solar collector as shown by the energy increase. In the morning hours a large fraction of the solar energy is used to increase the heat of the black plywood absorber plate of the collector. In contrast, in the evening hours when the wall has been heated up for several hours, heat is given off to the air even though the sun input has ceased.

The efficiency of the solar collector can be expressed as:

$$\text{Efficiency} = Q'_{\text{SC per 15 min}} / G_{\text{SC per 15 min}} * 100$$

The above equation is used to compute the results in Fig. 31. And in the example below shows the calculation of efficiency for one given 15 min interval. Example:

$$\text{Efficiency}_{\text{from 01:15:00 PM to 01:30:00 PM 07/30/15}} = \Delta Q'_{\text{SC from 01:15:00 PM to 01:30:00 PM 07/30/15}} / G_{\text{SC from 01:15:00 PM to 01:30:00 PM 07/30/15}} * 100 = 206.16\ \text{kJ} / 2006.72\ \text{kJ} * 100 = 10\ \%$$

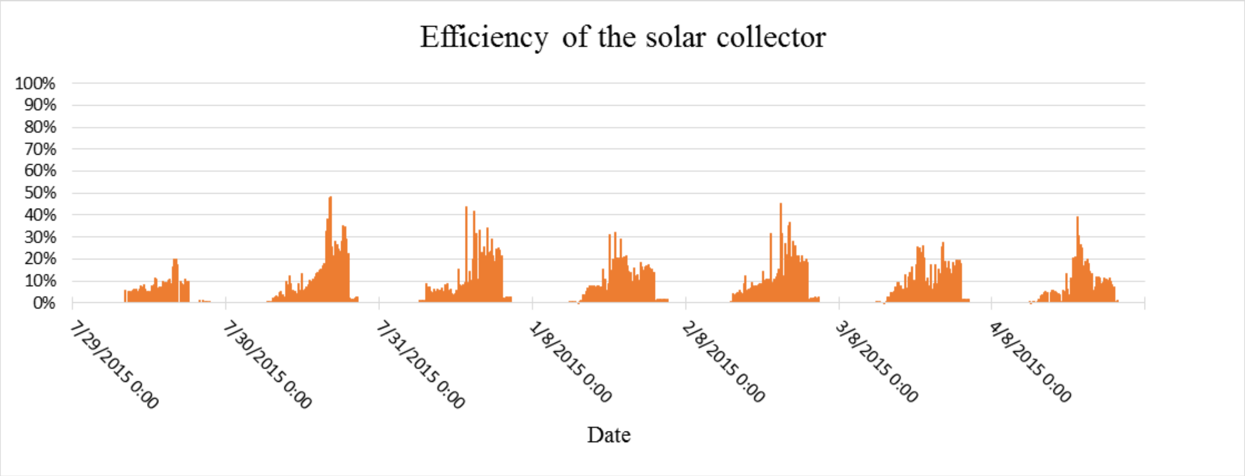


Figure 31. Efficiency of the solar collector for period 7 – 29.07 – 04.08.2015. For most of the time during the day the efficiency is between 5 and 10% except in the evening hours, when the heat accumulated in the wall increases the energy in SC air. The solar energy input in the evening is low but heat is still given off from the wall and results in a bias in the values in the evenings.

If a fan operated directly from a PV panel is used the running time of the fan is controlled by the sun intensity. However if the fan is operated from a battery or the grid better utilization of the solar input can be obtained by delaying the starting time in the morning until the black collector panel is heated and extending the fan operation into the evening until the collector panel has cooled off. This could be further optimized if the closing valve can be adjusted with the temperatures inside the SC, rather than ambient.

Storage capacity of the gravel bed

The storage capacity of the gravel bed is calculated from:

Heat storage capacity = volume (V) *density (ρ) *specific heat capacity (C) (Cengel, 2006)

Granite density – $\rho = 2.6\text{-}2.7 g/cm^3$

Gneiss density -$\rho = 2.6\text{-}2.9 g/cm^3$ (Harvey and London, 2005)

Thus on average for mix of granite and gneiss: $(2.65+2.75)/2 = 2.70\ g/cm^3 = 2700\ kg/m^3$

Granite and gneiss specific heat C = 800 J/kg°C (Harvey and London, 2005)

Volume of the gravel bed: size – 1m/1.m/0.3m

Assuming that the gravel bed was filled by random placing of spherical stones, the porosity can be expected to be 0.4 (Singh et al., 2013)

Thus, stones fraction of the volume = 1 - 0.4= 0.6

Stones volume V=0.6* 1*1.7*0.3= 0.306m^3

Heat storage capacity = V* ρ* C = 0.306 m^3*2700 kg/m^3*800 J/kg℃ = 660960 J/ ℃

660960 J/ ℃ /3600= 183.6 Wh for 1˚C change in temperature.

If the temperature of the gravel surface changes from 10 ˚C to 40 ˚C the stored heat will be:

183.6 Wh.℃ *(40℃ -10℃) = 5.508 kWh

Optimal storage size:

The optimal storage capacity of the gravel bed is calculated from:

Q' [kJ/s] = m*C*ΔT = V* ρ* C*ΔT (Dincer, 1999)

According to solar energy input:

The optimal volume of the storage needed to utilize the maximum solar input for a day to the system is:

Assuming: Q' = Solar energy input in a day (Q'_S)

V_{opt} = Q'_S / ρ* C*ΔT, where Q'_S is the maximum solar input per day registered in the period 17.07-24.07.2015 and ΔT is based on the maximum temperature difference that can be expected between the GB inlet and outlet. In this case, a temperature rise of 70℃ is considered – because, for most of the variation in ambient temperatures during the year, such increase will result in high enough temperatures for compost to be sanitized.

Q'_S [kJ] = $\Sigma_{\text{from 12.00am – 11.59pm}}$ (G_{SC} *15min*60sec/min)

Q'_S [kJ] = 59250 kJ = 59250000 J (registered for 17.07.2015)

ρ = 2700 kg/m^3

C = 800 J/kg℃

ΔT = 70℃ -0℃ = 70℃

V_{opt} = 59250000 J/ 2700 kg/m^3*800 J/kg℃*70℃ = 0.39m^3

The actual volume of the gravel is V = 0.306m^3.

According to the calculations given above the actual volume is slightly less than the optimal volume required to accumulate the solar input considered for an optimal energy input in a day.

The gravel bed volume, thus, is sufficient for short term storage if we consider the maximal daily input of solar energy. However, to utilize 100% of the solar input would be ideal and some energy will always be lost. Outside of the summer season the light input will be lower and thus the optimal volume is smaller. When considering the efficiency (Fig 31), the volume can be sufficient for long term storage in the case that it is not discharging the energy during each night but only accumulates. Since, 100% of the solar input will be rarely utilized, even a smaller volume can be considered as sufficient.

Evaporation rate and latent heat energy

The measurements are valid for period 6 – 17.07 – 23.07.2015

m_1 - Date - 16.07.2015, time – 15.00pm

m_2 - Date – 24.07.2015, time – 21.00pm

Bucket 1 – 60 l

$m_1 = 22$ kg

$m_2 = 20.5$ kg

$m_{\text{(lost mass)}} = m_1 - m_2 = 22 - 20.5 = 1.5$ kg

$V = m_{\text{(lost mass)}} / \rho = 1.5/1 = 1.5$l

$t = 9h + 6*24h + 21h = 174h$

Evaporation rate = V/t = 1.5/174 = 0.00862 l/h * 24 h = 0.21 l/day

Bucket 2 – 80l

$m_1 = 29$ kg

$m_2 = 26$ kg

$m_{\text{(lost mass)}} = m_1 - m_2 = 29 – 26 = 3$ kg

$V = m_{\text{(lost mass)}} / \rho = 3/1 = 3$l

$t = 9h + 6*24h+21h = 174h$

Evaporation rate = V/t = 3/174 = 0.041 l/h * 24 h = 0.98 l/day

Latent heat loss in the CC due to evaporation:

The CC mean air temperature for period 6 is 20.83˚C or ≈20˚C

$L_{\text{water at }20^{\circ}C} = 2454$ kJ/kg (Incropera, 2006)

m_1 = 0.00862 l/h = 0.00862 kg/h

m_2 = 0.041 l/h = 0.041 kg/h

Bucket 1: $Q'_{1\_latent\ at\ 20^\circ C}$ = 0.00862 kg/h * 2454 kJ/kg = 21.15 kJ/h

Bucket 2: $Q'_{2\_latent\ at\ 20^\circ C}$ = 0.041 kg/h * 2454 kJ/kg = 100.614 kJ/h

21.15 kJ/h / 4 = 5.29 kJ per 15 min

100.614 kJ/h / 4 = 25.15 kJ per 15 min

$Q'_{1\_latent} + Q'_{2\_latent}$ = 5.29 + 25.15 = 30.44 kJ per 15 min

The difference in the evaporation rate between the buckets could be explained by the difference in the moisture content and different surface area. The mass in bucket 2 has more liquid compared to bucket 1 by visual assessment that combined with the bigger size could explain the higher evaporation rate. The latent heat of evaporation represents some of the losses in energy in the composting chamber and judging from fig.29 on average it represents around 10-25% from the day time losses in the CC.

The estimations of evaporation rate and accordingly latent heat, is simplified with the assumption that the conditions in the composting chamber are constant during the period for which it is estimated. However, the evaporation depends on several factors, such as air flow, temperature, air humidity and surface area (Hendriks, 2010). Those conditions vary to some extend during the period, due to the variations in the microclimate of the chamber. Thus, the estimated values are not precise quantifications but are useful in assessing the overall system performance.

Perceptions

The interview was conducted after the children have used the toilet for a month – periods 3 and 4. The group interview results show that the children have positive attitude towards the new toilet. The older kids are familiar with use of manure for fertilizer and that the solar power is used to heat and ventilate the toilet. The children responses indicated that the “new toilet” still has malodors but that is very little compared to the old composting toilets on the kindergarten premises. They are excited about and enjoy the toilet because it has two seats and they use it two at the same time. The toilets at their homes are evaluated as cleaner and without any smell in comparison with the new toilet. However, they emphasize the fact that they can use it together as more important than the minor smell issues. The improvement they suggested are about making the room prettier, with light, paint and drawings.

In general the answers of the children indicate that they can accept and understand the concept of a composting toilet and that the new design reduces the odors. An interesting insight from the interview is that children can accept some of the drawbacks of a composting toilet better if they can enjoy their time in the toilet – in this case by having a company.

Compost quality

The toilet was in use from the beginning of June until the end and in the first days of August – period 3, 4 and period 7. In periods 5 and 6 the toilet is not in use. The mass from the mixed excreta, urine and toilet paper, was partly submerged in liquid throughout the study period. No bulking material is added at any time to increase the C/N ratio, absorb some of the liquid and create air pockets in the mass and thus a composting process cannot start. Furthermore, the excessive liquid indicates anaerobic conditions. Thus, no effects on the composting process could be observed or measured and there is no effect from the composting process on the temperature measurements in the CC. If the excreta mass is well aerated and additional carbon source is added regularly to maintain a C/N ratio above 15 (Steintiford, 2013), a composting process could start.

Potential of the toilet system

The idea behind the design of the toilet system is to increase temperature and evaporation, facilitating the compost process, and to increase the user’s comfort by reducing odor and operational control. The results show that the ventilation is working and heat is supplied to the composting chamber, thus the system reduces odors and the excreta mass is heated. However, the prototype assessed in this study has the potential for further optimization. The potential of the toilet system is then discussed to evaluate what the system can achieve if optimized.

The heat supplied in the system is transformed solar energy and is correlated to the amount of solar radiation and to what extend that amount is utilized.

The solar energy input at the current location and time period is sufficient to significantly increase the temperatures in the composting chamber. The results show that the temperatures in the composting chamber, for the final period, are on average 5-10 ˚C higher than ambient and the air entering the gravel bed at the peak hours of sunlight reaches up to 50˚C. By this stage of the prototype, the solar power is utilized with 5-10 % efficiency in the solar collector and even less in the CC due to losses. Thus, the potential for improvement is high and that should result in higher temperatures. If the system is airtight and the air flow velocity high, the heat losses will be minimal and that the temperatures registered at the gravel bed inlet could equalize with the temperatures in the compost chamber. This could happen, if the granite temperature equalizes with the air temperature in the bed, or if the air by-pass the GB, and no heat is lost to charge the stones. Therefore, the temperatures in the compost chamber can potentially be raised to 50˚C and higher. At 62 ˚C the compost will be sanitized in an hour, prolonged exposure to 50 ˚C (24h to a week) will also inactivate the pathogens in excreta and sanitize the compost (tabl. 3). Furthermore, with high temperatures, the degradation rate increase and the mass reduction and transformation will be faster (Steintiford, 2013). However, when considering conditions as in Norway, the potential discussed so far correspond to the spring and summer months and is lower during the rest of the year. If the fresh input to the toilet is separated from the sanitized, the latter can be left for maturation. This toilet system has theoretically the potential to sanitize the compost in the warm months and leave it to mature during the rest of the year. During the cold months, even small rise in temperatures can keep the compost away from freezing and allow longer time for maturation.

The system has potential to be designed for dehydration. If urine is collected separately and no additional moisture is added through the bulking material the faeces will desiccate with time. That could simplify the operation and maintenance but dehydration could result in less pathogen reduction and more unsafe end product. Furthermore, the energy input will be employed only for evaporation, which means that great amount of energy will not be utilized. Furthermore, the product will have lower quality due to the fact that it is dried excreta mass instead of soil like compost. This will make the system less sustainable but could be more attractive to a potential user.

Recommendations:

The toilet system is a prototype and this study identifies some non-optimal issues with the current construction and the possibilities for improvement. To improve the system performance the following recommendations are formulated.

- High flow velocity should be maintained when the system is receiving heat from the sun and the air-flow should cease during the time when the system does not receive solar heat. This condition can be fulfilled both with a timer controlled fan connected to the grid or a solar driven fan. A solar driven ventilation is recommended to avoid dependency on the grid and to increase the sustainability of the system.
- The timing of the high velocity forced airflow could be improved to account for the time it takes to heat the black absorber plate and the time it takes before cooling after sunset. Alternatively, a better insulated absorber with higher thermal conductivity giving quicker response, can be selected.
- Improved insulation of each part of the system can reduce the heat losses. Several places in the current system are identified to need better insulation as the air passage between the solar collector and the gravel bed, the chimney and the composting chamber.
- The air passage should be as airtight as possible to avoid losses of heat and reduction of air-flow velocity.
- The closing valve mechanism that controls the air-flow should be modified to be more sensitive to the range of temperatures that trigger opening and closing. It should be as airtight as possible when it is closed. The thermal expander should to be resistant to the high temperatures in the solar collector if it is placed inside the collector.

Some modifications that could improve the system but have not been investigated in this study:

- The air path in the gravel bed could be optimized by introducing a system that disperses the air more equally in the whole cross section of the bed.
- Smaller size of the pebbles could increase the surface area and the thermal performance of the bed (Singh et al., 2013).
- A more sophisticated air flow control mechanism could provide better control over when the heat should only to be supplied to the compost chamber or accumulated in the gravel bed. This could also facilitate the possibility to surpass the gravel bed and directly heat

the compost chamber, to achieve quicker sanitization of the compost during the warm months.

- A more tightly packed gravel bed has better thermo-hydraulic properties (Singh et al., 2013).
- Improvements on the natural convective flow in the system could reduce the flow resistance. Such modifications could be: increase in the height of the chimney, insulation of the chimney and the air flow in the solar collector could be only in the direction of natural convection.

5. Conclusions

The heat flow depends on the aerodynamics of the system – air flow velocity, air path and leakages. It can be improved by increasing the fan power and reducing/sealing leaks of the system. The modifications that:

- optimized the airflow velocity during the high solar energy input
- restricted the airflow during night
- improved the airtightness of the system
- and optimized the air path through the gravel bed,

increased the heat flow to the compost.

The energy flow in the system, during day-time, correspond to the conceptualized energy flow in the system. Energy is gained in the solar collector, it is transferred with some losses to the gravel bed, from where the energy is given off to heat the air in the compost chamber and for evaporation. The solar energy input is substantial but only 5-10% of that energy is captured by the solar collector. The gravel bed theoretically has the capacity to accumulate 100 % of the solar input per day, but since that would be rarely the case its size could be reduced.

The heat and air-flow estimates that are subject to a certain bias due to inaccuracy of the measuring equipment, thus, the measurements only crudely quantify the air and heat flow of the system. However they give a general picture of what is happening in the system. This picture helped to elucidate problems, their mitigation and how the system could be optimized.

The results suggest that the system has large potential, but that at this stage the potential is not fully utilized. The optimization of the toilet system prototype is a process and part of that process is described and done in this study. The results herein indicate that future development of the prototype theoretically have the potential to sanitize the compost, especially in periods with high sun intensity, and substantially increase the efficiency in the cold months. The system can also be modified for dehydration of the excreta. Based on the data collected and analyzed and on the experience from working with the toilet system it is recommended improve the system performance by: maintaining high airflow velocity synchronized with the time when the system is charged by the sun, better insulation to avoid heat losses and improved airtightness.

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Annex 1

Figure 1.1.HOBO Pendant Temperature/Light Data Logger model UA-002-xx.

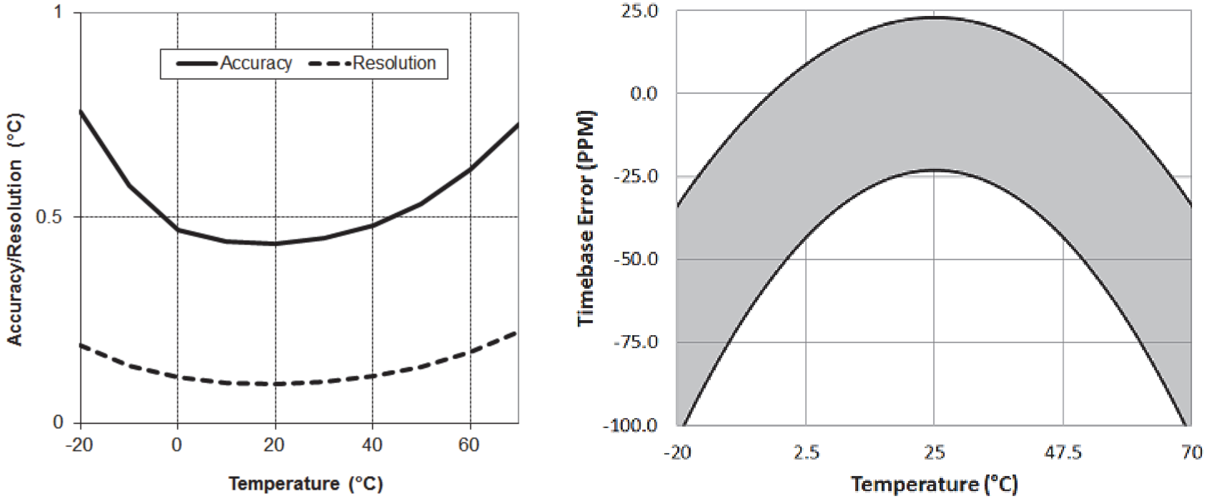

Figure 1.2. A Temperature accuracy and resolution Time accuracy of HOBO Pendant Temperature/Light Data Logger model UA-002-xx.

Annex 2

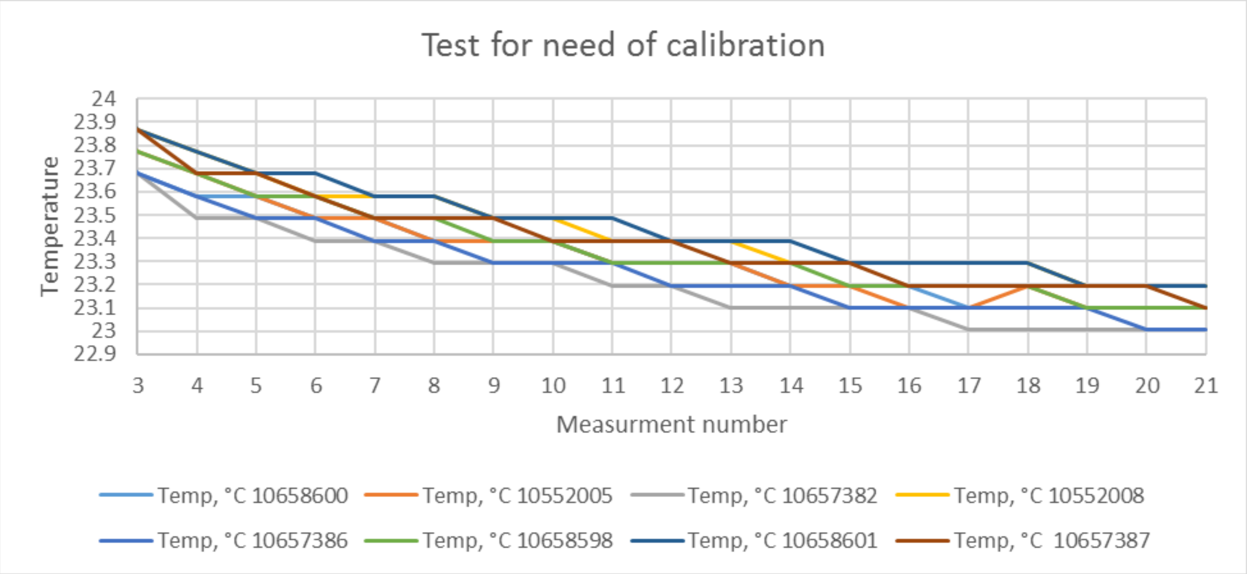

Figure 2.1 Results from the test performed to check if the sensors are calibrated. Each sensor has an eight digit identity number. The test shows that the sensors are calibrated. The measurement difference is maximum 0.3 ℃, which falls well into the 0.5 product accuracy.

Annex 3

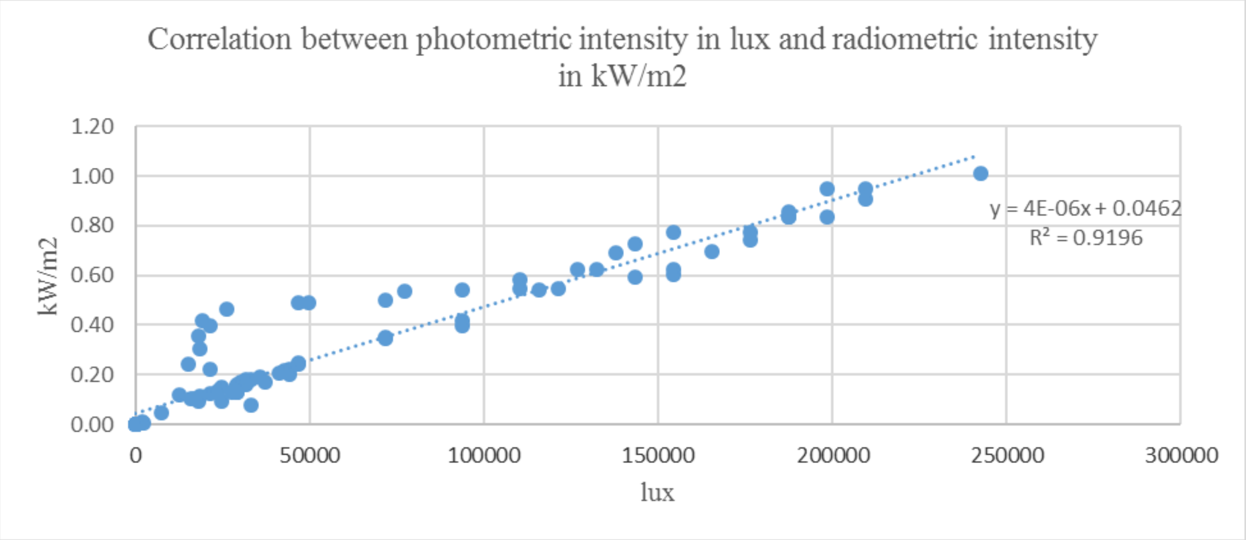

Figure 3.1 Correlation between photometric intensity in lux and radiometric intensity in kW/m^2

Annex 4

Group interview:

- How many toilets do you have in the kindergarten?

Answer: Three

- Have you used the “new toilet”?

Answer: Yes

- Who helped during construction?

Answer: Everyone participating in the interview

Can you come up with a name for the new toilet?

Answer: Ute do, nye do – Outside toilet, new toilet

- Now we will play a game called associations. I will say a word and you have to tell me the first word that comes to your mind - the “new toilet”.

Answer: Go to toilet, Sun, Fun, two seats

- Now, show me a face that you make when something smells bad. Are toilets smelly (which ones)? Is the new toilet smelly?

Answer: Better than the old ones but still a little smell

- Is the toilet clean or dirty?

Answer: It is clean, but there is some dirt on the walls

- Think about how you go to toilet in the new toilet. Is it easy to use? Is it comfortable to sit on?

Answer: It is comfortable to sit, they like very much that they can sit together

- What do you think we can do to make the toilet better, nicer, more fun?

Answer: To paint the walls, to have light, to draw princesses on the walls, to cut more trees, to have a star light throwing shadows on the walls.

- Think about the old and the “new” toilet. Which one do you prefer?

Answer: The new toilet is better, because is less smelly and they can sit together.

- Now, think about the toilet at home and the “new toilet”. Can you compare them, which one do you like better?

Answer: The toilet at their homes is cleaner and smells better but in the kindergarten they can sit together. They prefer the new toilet in the kindergarten because they can sit together.

Annex 5

Statistical analysis

Statistical ccomparison between ambient temperatures and the temperatures in the composting chamber 17.04 – 04.05.2015

Table 5.1 Statistical summary for the period 17.04 – 04.05.2015

	Mean	Standard deviation	Variance	N	Min	Max
Ambient	5.22	4.51	20.33	1728	-2.84	19.66
Compost chamber	8.38	3.78	14.28	1728	2.09	18.81

Hypothesis testing whether at all time the composting chamber temperatures are higher than the ambient.

Hull hypothesis – The composting chamber temperatures are no different than the ambient
Alternative hypothesis – The composting chamber temperatures higher than the ambient
Confidence interval - 95 %

Welch Two Sample z-test
Data: compost chamber and ambient 17.04 – 04.05.2015
P-value < 2.2e-16
Z obtained = 22.352 > Z critical= +1.65, thus:
Hull hypothesis rejected, there is significant positive difference between the ambient temperatures and the temperatures in the composting chamber. The temperatures in the compost chamber are higher than the ambient.

Hypothesis testing whether during the night composting chamber temperatures are higher than the ambient

Hull hypothesis – During night the composting chamber temperatures are no different than the ambient

Alternative hypothesis – During night the composting chamber temperatures are higher than the ambient

One Sample z-test

Confidence interval - 95 %

Data: difference between compost chamber and ambient during night 17.04 – 04.05.2015

P-value < 2.2e-16

Z obtained = 69.727 > Z critical= +1.65, thus:

Hull hypothesis rejected, the difference between the compost chamber temperatures and the ambient is significantly higher than zero. The temperatures in the compost chamber during night are higher than the ambient.

Statistical ccomparison between ambient temperatures and the temperatures in the composting chamber 06.05 – 17.05.2015

Table 5.2 Statistical summary for the period 06.05 – 17.05.2015

	Mean	Standard deviation	Variance	N	Min	Max
Ambient	6.55	3.95	15.61	1152	-1.00	16.71
Compost chamber	7.28	1.15	1.32	1152	4.73	9.67

Hypothesis testing whether at all time the composting chamber temperatures are higher than the ambient.

Hull hypothesis – The composting chamber temperatures are no different than the ambient

Alternative hypothesis – The composting chamber temperatures higher than the ambient

Confidence interval - 95 %

Welch Two Sample z-test

Data: compost chamber and ambient 06.05 – 17.05.2015

P-value = 9.662e-10

Z obtained = 6.0034 > Z critical= +1.65, thus:

Hull hypothesis rejected, there is significant positive difference between the ambient temperatures and the temperatures in the composting chamber. The temperatures in the compost chamber are higher than the ambient.

Hypothesis testing whether during the night composting chamber temperatures are higher than the ambient

Hull hypothesis – During night the composting chamber temperatures are no different than the ambient

Alternative hypothesis – During night the composting chamber temperatures are higher than the ambient

One Sample z-test

Confidence interval - 95 %

Data: difference between compost chamber and ambient during night 06.05 – 17.05.2015

P-value < 2.2e-16

Z obtained = 30.873 > Z critical= +1.65, thus:

Hull hypothesis rejected, the difference between the compost chamber temperatures and the ambient is significantly higher than zero. The temperatures in the compost chamber during night are higher than the ambient.

Statistical ccomparison between ambient temperatures and the temperatures in the composting chamber 01.06 – 22.06.2015

Table 5.3 Statistical summary for the period 01.06 – 22.06.2015

	Mean	Standard deviation	Variance	N	Min	Max
Ambient	11.78	4.78	22.80	2112	1.75	23.48
Compost chamber	11.5	2.08	4.32	2112	6.88	15.38

Hypothesis testing whether at all time the composting chamber temperatures are higher than the ambient.

Hull hypothesis – The composting chamber temperatures are no different than the ambient

Alternative hypothesis – The composting chamber temperatures higher than the ambient
Confidence interval - 95 %

Welch Two Sample z-test
Data: compost chamber and ambient 01.06 – 22.06.2015
P-value = 0.9939
Z obtained = -2.5073 < Z critical= +1.65, thus:
Hull hypothesis is not rejected, there is no significant positive difference between the ambient temperatures and the temperatures in the composting chamber. The temperatures in the compost chamber are not higher than the ambient.

One Sample z-test
Confidence interval - 95 %
Data: difference between compost chamber and ambient during night 17.04 – 04.05.2015
P-value < 2.2e-16
Z obtained = 59.774 > Z critical= +1.65, thus:
Hull hypothesis rejected, the difference between the compost chamber temperatures and the ambient is significantly higher than zero. The temperatures in the compost chamber during night are higher than the ambient.

Statistical ccomparison between ambient temperatures and the temperatures in the composting chamber 24.06 – 28.06.2015

Table 5.4 Statistical summary for the period 24.06 – 28.06.2015

	Mean	Standard deviation	Variance	N	Min	Max
Ambient	13.43	4.00	15.96	480	5.96	24.84
Compost chamber	13.96	0.88	0.77	480	11.72	15.86

Hypothesis testing whether at all time the composting chamber temperatures are higher than the ambient.
Hull hypothesis – The composting chamber temperatures are no different than the ambient

Alternative hypothesis – The composting chamber temperatures higher than the ambient
Confidence interval - 95 %

Welch Two Sample z-test
Data: compost chamber and ambient 24.06 – 28.06.2015
P-value = 0.002409
Z obtained = 2.819 > Z critical= +1.65, thus:
Hull hypothesis rejected, there is significant positive difference between the ambient temperatures and the temperatures in the composting chamber. The temperatures in the compost chamber are higher than the ambient.

Hypothesis testing whether during the night composting chamber temperatures are higher than the ambient
Hull hypothesis – During night the composting chamber temperatures are no different than the ambient
Alternative hypothesis – During night the composting chamber temperatures are higher than the ambient

One Sample z-test
Confidence interval - 95 %
Data: difference between compost chamber and ambient during night 17.04 – 04.05.2015
P-value < 2.2e-16
Z obtained = 22.28 > Z critical= +1.65, thus:
Hull hypothesis rejected, the difference between the compost chamber temperatures and the ambient is significantly higher than zero. The temperatures in the compost chamber during night are higher than the ambient.

Statistical ccomparison between ambient temperatures and the temperatures in the composting chamber 30.06 – 14.07.2015

Table 5.5 Statistical summary for the period 30.06 – 14.07.2015

	Mean	Standard deviation	Variance	N	Min	Max
Ambient	16.66	5.11	26.15	1440	5.96	30.05
Compost chamber	17.28	1.83	3.35	1440	13.46	21.09

Hypothesis testing whether at all time the composting chamber temperatures are higher than the ambient.

Hull hypothesis – The composting chamber temperatures are no different than the ambient

Alternative hypothesis – The composting chamber temperatures higher than the ambient

Confidence interval - 95 %

Welch Two Sample z-test

Data: compost chamber and ambient 30.06 – 14.07.2015

P-value = 7.266e-06

Z obtained = 4.3357 > Z critical= +1.65, thus:

Hull hypothesis rejected, there is significant positive difference between the ambient temperatures and the temperatures in the composting chamber. The temperatures in the compost chamber are higher than the ambient.

Statistical ccomparison between ambient temperatures and the temperatures in the composting chamber 17.07 – 23.07.2015

Table 5.6 Statistical summary for the period 17.07 – 23.07.2015

	Mean	Standard deviation	Variance	N	Min	Max
Ambient	14.21	4.45	19.81	672	5.04	24.64
Compost chamber	20.83	2.35	5.51	672	15.57	225.71

Hypothesis testing whether at all time the composting chamber temperatures are higher than the ambient.

Hull hypothesis – The composting chamber temperatures are no different than the ambient

Alternative hypothesis – The composting chamber temperatures higher than the ambient

Confidence interval - 95 %

Welch Two Sample z-test

Data: compost chamber and ambient 17.07 – 23.07.2015

P-value < 2.2e-16

Z obtained = 34.066 > Z critical= +1.65, thus:

Hull hypothesis rejected, there is significant positive difference between the ambient temperatures and the temperatures in the composting chamber. The temperatures in the compost chamber are higher than the ambient.

One Sample z-test

Confidence interval - 95 %

Data: difference between compost chamber and ambient during night 17.04 – 04.05.2015

P-value < 2.2e-16

Z obtained = 104.62 > Z critical= +1.65, thus:

Hull hypothesis rejected, the difference between the compost chamber temperatures and the ambient is significantly higher than zero. The temperatures in the compost chamber during night are higher than the ambient.

Statistical ccomparison between ambient temperatures and the temperatures in the composting chamber 29.07 – 04.08.2015

Table 5.7 Statistical summary for the period 29.07 – 04.08.2015

	Mean	Standard deviation	Variance	N	Min	Max
Ambient	12.93	3.62	13.07	672	5.55	23.00
Compost chamber	21.63	4.28	18.33	672	14.71	31.37

Hypothesis testing whether at all time the composting chamber temperatures are higher than the ambient.

Hull hypothesis – The composting chamber temperatures are no different than the ambient

Alternative hypothesis – The composting chamber temperatures higher than the ambient

Confidence interval - 95 %

Welch Two Sample z-test
Data: compost chamber and ambient 29.07 – 04.08.2015
P-value < 2.2e-16
Z obtained = 40.223> Z critical= +1.65, thus:
Hull hypothesis rejected, there is significant positive difference between the ambient temperatures and the temperatures in the composting chamber. The temperatures in the compost chamber are higher than the ambient.

One Sample z-test
Confidence interval - 95 %
Data: difference between compost chamber and ambient during night 29.07 – 04.08.2015
P-value < 2.2e-16
Z obtained = 43.038 > Z critical= +1.65, thus:
Hull hypothesis rejected, the difference between the compost chamber temperatures and the ambient is significantly higher than zero. The temperatures in the compost chamber during night are higher than the ambient.

Annex 6

Solar powered dry toilet for cold climate. Results from a pilot study.

Author contact information
Petter D. Jenssen (petter.jenssen@nmbu.no), Department Environmental Sciences Norwegian University of Life Sciences (NMBU)
Petter H. Heyerdahl (petter.heyerdahl@nmbu.no), Department Mathematical Sciences and Technology Norwegian University of Life Sciences (NMBU)
Jon Fredrik Hanssen (jon.hanssen@nmbu.no), Department Biotechnology, Norwegian University of Life Sciences (NMBU)
Mariya E. Kelova (mdoneva@abv.bg), Department Environmental Sciences, Norwegian University of Life Sciences (NMBU)

Background

The dry toilet is a common facility in cabins and remote areas throughout Scandinavia. However, the cold climate and extended periods of freezing temperatures reduce the compost processes' speed and efficiency. The result is suboptimal functioning of the toilet – slower composting rate, increased moisture and odors. Some of the existing dry toilet designs provide working solutions for cold climate but they commonly depend on electricity or extensive storage through the cold season.

In an on-going pilot study, an experimental design of a dry toilet is tested for its functionality. The objective of the study is to test the ability of the design to provide an improved solution for cold climate. Solar power is the driver of heat and electricity production in the toilet and a novel ventilation system provides an odorless toilet room and heat to the composting process.

The toilet

The toilet is based on a well insulated building containing the toilet room, the composting chamber and a unit for heat storage. Warm air is produced by a solar collector on the south wall of the toilet. The air flow is enhanced by a solar powered fan. The idea is that solar energy is collected and stored as heat during the day and given off during the night (Fig. 1).

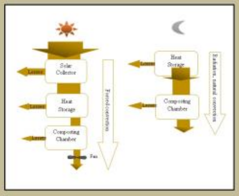

Figure 1. Energy flow of the system during sunlight – day, and during no sunlight - night.

Results

The air temperature, solar radiation, air flow and evaporation is measured. The solar radiation measurements indicate the energy input to the system. The temperature profiles show the heat variation in different parts of the system (Fig.2).

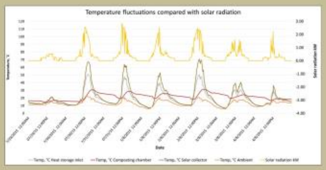

Figure 2. Temperature and solar radiation variation between July 29 and August 4 (adapted from Kelova, 2015).

Fig. 2 shows that the incoming solar radiation reaches up to 3 kW. The temperatures in the solar collector are correlated to the solar input and vary between 10˚C and 70˚C. The air temperature at the heat storage inlet reaches up to 50˚C. The temperature of the composting chamber is higher than the ambient at all times. This shows that heat is transported to the composting chamber during the day and that the accumulated heat is transferred during night.

For the period between July 29 and August 4, the average temperature in the compost chamber was 8.7˚C higher than the average ambient temperature. The maximum difference recorded was 18.9˚C at 2:30 am on August 3.

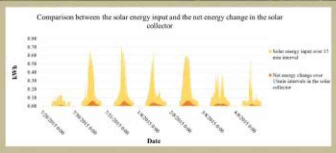

Figure 3. Comparison of the solar energy input and the net energy change in the solar collector over 15 min intervals in the period between July 29 and August 4 (adapted from Kelova, 2015).

The results from the initial tests of the prototype show that the solar energy input to the collector is substantial, but only a small fraction is transferred in the system (Fig.3). The amount of solar energy captured by the collector is 10-20% (Fig.3).

This indicates that the system has potential for improvement.

Conclusions

- The compost chamber has a higher temperature than the ambient at all times.
- The heat collection is more dependent on sun intensity than the ambient temperature.
- Only 10 – 20 % of the solar energy input is utilized by the current design, thus there is room for improvements.
- The prototype has potential to sanitize the compost, especially in periods with high sun intensity, and it can substantially increase the efficiency in the cold months.
- The system can be modified for dehydration of the excreta.

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Norwegian University of Life Sciences

Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no