Theoretical study of the potential to improve indoor comfort in Botswana using solar water heating, solar PV and PV/T

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Abstract

The possibility of improving indoor climate in residential buildings in Botswana was examined as the foundation of this Master's Thesis. Initially articles were studied to gain understanding of previous research in the field as well as to gain understanding of local energy related conditions. Furthermore, a software called TRNSYS was thoroughly studied as this was found to be a powerful tool able to perform wanted simulations. Through two months of field work the previously obtained parameters for the simulation were complimented with on sight observations, mostly of residential buildings. This provided the foundation to initiate actual simulations. It quickly surfaced that the way residential building are built in Botswana today did not allow for space heating or cooling as the current houses have an average U-value of 2.9 W/(m^2·K). It was found that with an average U-value of 0.5 W/(m^2·K), no space heating of any type is needed. However, as this meant warmer indoor climate during summer, the possibility of generating electricity to power AC units was studied. Two systems to solve this were studied and compared. Firstly a solar collector in combination with photovoltaics (PV) and secondly a hybrid PV/T system to generate both hot water and electricity. A 13.35 m^2 solar collector in combination with a 2 m^2 PV generated approximately the same amount as a 13.35 m^2 PV/T system, resulting in 84 % of the energy need being derived from solar energy assuming a household consumption of 5000 kWh.

Summary

Botswana has one of the highest solar irradiations in the world. However, they do not generate electricity from solar energy and they consume more electricity than they generate domestically. This leaves them dependent on foreign imports. Due to the desert climate, Botswana has hot summers that last from mid September until mid April and winters with cool nights that last from mid April to mid September. The three systems modelled are firstly a solar collector system for hot water generation and space heating. Secondly, a solar collector hot water system without heating but with added solar photovoltaic (PV) panels for electricity generation. Lastly, a system using a hybrid photovoltaic/thermal (PV/T) solar panel for both hot water and electricity generation. Fieldwork for the Master's Thesis was carried out in Gaborone, the capital of Botswana, in cooperation with a local research institute. Through this fieldwork parameters of an average residential house in Botswana could be found. An average residential building in Botswana was found to be a four person house. Furthermore, it has a floor area of 100 m^2, an average U-value of 2.9 W/(m^2·K) and a hot water consumption of 95 l/day. As all houses studied, from low to high income, were built in the same way, this average U-value of 2.9 W/(m^2·K) is used. These parameters among others were used when simulating the different systems and scenarios in a software called TRNSYS. It was early found that any heating system would have little affect due to the non-existent insulation in the houses. It was also found that the heating system worked optimally at an average U-value of 1.8 W/(m^2·K) where it could reduce the amount of hours under the chosen set point temperature of 19 °C by 82 %. Yet, a heating system is a large investment. Instead, by insulating further, to an average U-value of 0.5 W/(m^2·K) no heating of any type would be needed. However, while reducing the amount of heating hours, a large amount of cooling hours was needed during summer with such high insulation. Additional simulations found that an air conditioning unit (AC) worked more efficient with such high insulation although it at the end meant warmer summer indoor climate than before. However, this result was achieved when assuming that there was only one AC unit in the house. With the use of two or more AC units the indoor climate was improved also during summer. After having optimized the two systems without heating, it was found that both solutions resulted in a solar savings fraction of 0.84 when assuming a household consumption of 5 000 kWh/year. This includes both electricity for appliances and hot water generation. This number can be compared with the average Swedish house consumption of 25 000 kWh/year [1]. A solar collector of 2 m^2 could cover the hot water need with barely no heating element use, while the PV panels of 13.35 m^2 generated 3 008 kWh annually. The hybrid PV/T collector of 13.35 m^2 generated slightly more energy in total, while it used 2 m^2 less of roof space. However, PV/T collectors are in general more expensive per area unit compared to PV and in most cases, the regular thermal collector in combination with PV panels will be the most cost efficient solution [2]. To conclude, to avoid the cool nights during winter, insulation should be used instead of heating systems. This in combination with more than one AC unit in the house results in improved indoor climate during both winter and summer. Also, unless roof space is a limitation, a solar thermal system in combination with solar PV is the best solution for generation of hot water and electricity.

Keywords: Solar thermal collector, solar PV, PV/T hybrid, TRNSYS, Botswana, Gaborone, residential heating , residential cooling, electricity generation.

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SolarShop: Figure 3.2
Alpha Renewables: Figure 3.3
Kraftringen: Figure 3.5
APC Technology group: Figure 3.6

List of Abbreviations

AC – Air Conditioner
PV - PhotoVoltaic
BPC - Botswana Power Corporation
DMS – Demand Side Management
PV/T – Photovoltaic Thermal
DE - The Department of Energy
UB - University of Botswana
MMEWR - The Ministry of Minerals, Energy and Water Resources
EAD - Energy Affairs Department
BITRI - Botswana Institute for Technology Research and Innovation
SHW – Solar Hot Water
Kh - (Kelvin·hours)
DDH$_\mathrm{H}$ – Discomfort Degree Hours (Heating), measured in K·h
DDH$_\mathrm{C}$ – Discomfort Degree Hours (Cooling), measured in K·h
BWP - Botswana Pula (Currency) HEX - internal Heat Exchanger

Nomenclature

L	Metre	m
V	Litre	l
A	Area	m^2
η_{th}	Steady state thermal efficiency of solar collector	-
$\dot{Q}_u$	Useful collected heat of solar collector	W/m^2
$\dot{m}$	Mass flow rate of water	l/h
c_p	Specific heat capacity for water	kJ/(kg·K)
T_{in}	Inlet water temperature of collector	K
T_a	Ambient temperature	K
$\dot{Q}_{HEX}$	Useful energy into radiator	W/m^2
$T_{hot,in}$	Hot side inlet temperature for water	K
$T_{cold,in}$	Cold side inlet temperature for air	K
ΔT_{HEX}	Temperature difference of the water before and after passing the HEX in the tank	K
$C_{min} =$	Minumum capacity rate	KJ/(s·K)
η_{th}	Steady state thermal efficiency of solar collector	-
F_R	Overall collector heat removal efficiency factor	-
I_T	Global radiation incident on the solar collector (Tilted surface)	$kJ/(h \cdot m^2)$
$\tau\alpha_n$	Product of the cover transmittance and the absorber absorptance at normal incidence	-
$\tau\alpha_b$	Product of the cover transmittance and the absorber absorptance for beam radiation (depends on the incidence angle θ	-
ϵ	Heat exchanger effectiveness	-
U_L	Overall thermal loss coefficient of the collector per unit area	$kJ/(h \cdot m^2 \cdot K^2)$
$U_{L/T}$	Thermal loss coefficient dependency on T	$kJ/(h \cdot m^2 \cdot K)$
$b_0 =$	Negative of the 1st-order coefficient in the Incident Angle Modifier curve fit equation	-
$b_1 =$	Negative of the 2nd-order coefficient in the IAM curve fit equation	-
θ	Incidence angle for beam radiation	$^\circ$

Contents

1 Background

The Republic of Botswana is located in the southern part of Africa and consists mainly of the Kalahari Desert. Throughout the major part of the year the temperatures are high and indoor climate is uncomfortably warm. However, the semi-arid climate means that the temperature varies considerably between day and night. This applies in particular during winter when the night temperature can be as low as 0 °C [3]. Poorly insulated houses in combination with cool nights means that the indoor climate during this period is uncomfortably cold. Even during wintertime the country has a high amount of solar irradiance, which is why solar thermal in Botswana could be suitable for space heating. Furthermore, electricity is required all year round, mainly for heating up water, powering Air Conditioner (AC) units and for cooking. The major part of a household's electricity usage is consumed by the water geysers, i.e. electric water heaters, indicating that great energy savings could possibly be achieved with the use of solar thermal collectors [4]. With this in mind, a combined solution using both solar thermal collectors and solar PhotoVoltaics (PV) could be preferable, supplying both electricity, heat and hot water. According to local experts, solar thermal collectors in Botswana are currently quite commonly used while solar PV cells are not [5].

The electricity grid in Botswana is still a one-way, top-down network with no possibility to sell power back to utilities. This is a major obstacle for residential solar energy in Botswana as most electricity from PVs is generated during the day when people are at work. Without the possibility to sell the excess to the grid this electricity will be wasted. This could be solved through the use of batteries, but that would make the investment additionally expensive. The electricity consumption is high during the day as AC units, lighting and computers in office buildings are turned on. If electricity could be sold back to the grid the pay back of an investment in a solar PV or PV/T system would improve. While the country at the same time would become less dependent on foreign imports. It must be mentioned that such a system on residential houses could address the electricity problem from two sides: the household uses less of the grid electricity when people are home and it contributes to the grid when people are at work. Also, it would be desirable to exploit more solar thermal for hot water heating. Consequently, the high quality electric energy, today used for heating water, could be applied more effectively. As the hot water demand is highest during peak hours, the use of a Solar Hot Water (SHW) system would help lowering the peaks additionally. However, as of today electricity generated in the two government owned coal power plants is heavily subsidised, which gives a misleading payback time of any competing energy system. Several foreign international energy companies have tried to provide the government of Botswana with possible solar energy solutions [6]. Due to the high solar irradiation in Botswana, the investment looks good to the foreign energy companies as it is more profitable than installing the same system in most other places. However, when the business plan is presented to the government it is dismissed as the price per kWh is higher than the currently subsidised coal generated electricity [6]. The money put into subsidies of coal power could instead be invested in initiation of solar energy projects for residential houses. This is enforced by the fact that the fastest growing sector regarding energy consumption is the residential sector [7], [8], [9]. This would allow for a bonus in form of foreign investment now proving to be profitable when competing with un-subsidised energy generation. These facts form the foundation for the investigation of this report of the potential to improve indoor climate by using different types of solar energy systems.

In Botswana today there is a severe shortage of energy as the two existing larger power stations in the country, Morupule A and B, both are having difficulties [10]. Morupule A is old and the power output has decreased steadily for many years, whilst Morupule B is struggling with teething problems [11]. Botswana therefore have to rely heavily on electricity imports from mainly South Africa but also from Mozambique. The Orapa and Matshelagabedi diesel power plants, owned by Botswana Power Corporation (BPC), with a combined output of 160 MW, are used to cope with the demand during peak hours [12]. Additionally, rolling power outages occur throughout the country to meet the power shortage. Furthermore, a mere half of the population were grid connected in 2014 [10]. This indicates that even with an expansion of the power producing facilities in the country, it will still suffer from power shortages as more and more people gain access to electricity.

Affordable and clean energy is part of the UN sustainable development goals and is central to most major challenge and opportunity that the world faces today [13]. Providing this necessity is one of the most crucial aspects when it comes to increasing the standard of living in the world, and to fight poverty. With this in consideration, there are a couple of possible actions that needs to be taken. Demand Side Management (DSM) and more specifically load control is a strategy for alleviating the power supply problem that could be done independent on which major solution for the problem that is chosen. This could suggestively be done either through a comprehensive expansion of the existing power production facilities, although they are anything but clean, with an accompanying expansion of the national electricity grid. This is a costly option that would take long time to implement. Nonetheless it might be necessary for the future national development. Or the solution could be to reduce the dependence of centralised grid connected electricity by encouraging people to generate their own energy. With one of the highest solar irradiations in the world, the most viable solution for micro producers in Botswana could be the use of solar energy. All the factors above are opportunities for Botswana to improve the energy situation in a more long term and sustainable way.

1.1 Energy situation in Botswana

Botswana's primary energy sources are coal, fuel wood, liquefied petroleum gas, diesel and petroleum [14]. Only 1 % of the energy generation can be derived from renewable energy sources, which is about the same as the world as a whole. However, Botswana has excellent solar conditions with annual solar irradiation of 2 200 kWh/m^2 compared to northern Europe that gets approximately 1 100 kWh/m^2 [15]. The average electricity consumption per person and year in Botswana was about 1500 kWh in 2012, compared to a world average of about 3 350 kWh [16].

1.1.1 National Energy Policy for Botswana, 2009

The overall responsibility for the energy sector in Botswana is held by The Ministry of Minerals, Energy and Water Resources (MMEWR) through the Energy Affairs Department (EAD) [17]. Its mandate is to formulate, direct and coordinate the national energy policy, as well as to supervise the parastatal energy company Botswana Power Corporation (BPC). MMEWR has formulated the National Energy Policy for Botswana, with the overall policy goal for the energy sector to provide affordable, environmentally friendly and sustainable energy services in order to promote social and economic development. To meet this goal, there are several objectives defined [11]:

- Improve security and the reliability of energy supply to all economical sectors.
- Stimulate sustainable economic growth by promoting competition, efficiency and investment in the sector and thus achieve poverty reduction. This to make sure that energy services are supplied at the least cost.
- Improve capacity in the various players in the energy development and delivery chain.
- Improve the availability of energy information. There is a lack of energy related information when it comes to planning and policies. Hence, one of the missions with this energy policy is to gather information to a comprehensive data base, publicly available.

- Improve energy security through diversity in supply. This involves the promotion of more use of locally available sources such as coal and alternative energy sources (such as solar energy) instead of importing electricity. As for today, Botswana has no known petroleum reserves and the country has to import all its petroleum product requirements in refined form, mainly from South Africa.

Although there is an obvious necessity of setting goals, there has been criticism against the Ministry for their struggle to implement the policy. At present there is need for a more concrete plan to eradicate the lack of access for electricity in Botswana and more research and documentation regarding targets to improve the energy supply has been requested. As for now, there is a shortage of such documentation.

1.1.2 Electricity generation in Botswana

Botswana primarily generates its electricity in coal power plants, mainly because of the abundance of coal and its proven technology. Yet, only one coal mine, Morupule Colliery, provides coal used for electricity generation. Adjacent to the mine, Botswana's two power stations Morupule A and the recently built Morupule B are located. They are operated by the parastatal company BPC. Due to a constant decrease in operational capacity over the years, the current power output of Morupule A is only 40 MW [11]. Since year 2000, the power plant has supplied an average of 27 % of the electricity demand, but as a result of several refurbishments, the number in 2012 was as low as 7 % [11]. Consequently, the remaining electricity need had to be covered through imports, with 70 % from power company Eskom in South Africa and 23 % from other providers such as Mozambique and Namibia [11]. This overwhelming energy dependence creates insecurity in Botswana's fast growing economy. Further, it indirectly means that South Africa's and Mozambique's economical or social issues may become Botswana's problem since it will affect the energy exporting power of the two countries respectively. Moreover, it leads to increasing insecurities since Eskom in South Africa currently struggles to meet their own national electricity demand. In 2013 Botswana received a guarantee of 100 MW continuously from South Africa, and an additional 200 MW provided if possible, depending on South Africa's own need [11]. Botswana's decline in power generation has led BPC to take action for peak shaving, mentioned before as rolling power outages. Cities in Botswana now have their own load shedding schedule. As can be seen in Figure 1.1, the electricity usage has increased over the 13-year period since year 2000.

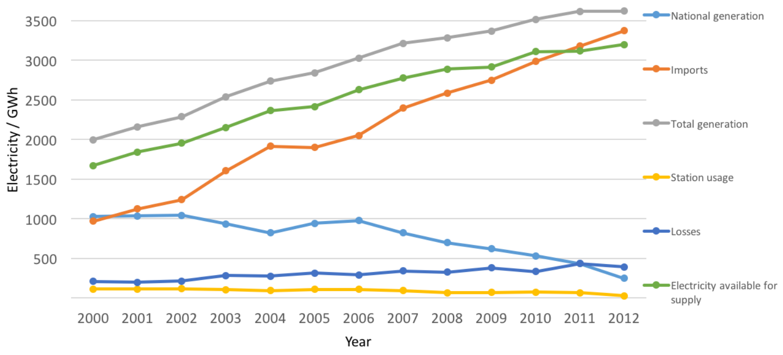


Figure 1.1: Electricity generation trends for different areas in Botswana [7], [8], [9].

Furthermore, with national energy generation decreasing, an increasing part of this increment can be derived from imports. To decrease the dependence of imported electricity, a decision was made to build a new power station. Hence, the Morupule B power station was projected, consisting of eight 150 MW units power plants that all were supposed to be completed in 2014 [10]. The new power station was anticipated to increase the total amount of installed energy in Botswana tenfold. However, in 2014 only four out of the total eight units were completed with a total of 600 MW power output, generating 2 210 GWh, as can be seen in Table 1. The electricity imports in 2014 amounted to 1 780 GWh, a decrease by 59 % from previous year [10]. In 2014, Morupule A was also taken out of operation for maintenance but is now back online. The average selling price per kWh has increased by 180 % since 2010, reaching 0.65 BWP in 2014, where 1.00 BWP is about 0.75 SEK [18]. This is slightly less compared to the average generation cost which has increased by 182 %, from 0.57 BWP in 2010 to 1.04 BWP in 2014. Evidently, the coal power plant cannot bear its own costs for generating electricity, which is why there is a need for heavy subsidies from the government. In 2014 the operating loss before revenue grant for BPC landed on 1.326 billion BWP, compared to a 1.623 billion BWP loss reported in 2013 [10].

Table 1: Breakdown of electricity generation from Morupule A and B over the last five years in combination with selling price and cost for the same period [10]

Year	**2014**	**2013**	**2012**	**2011**	**2010**
Morupule A, annual generated electricity /GWh	0	46.0	250	437	532
Morupule B, annual generated electricity/GWh	2 210	714	0	0	0
Annual imported electricity /GWh	1 780	2 980	3 370	3 180	2 980
Average selling price per unit /(Thebe*/kWh)	64.5	60.0	57.0	48.0	36.0
Average cost per unit /(Thebe/kWh)	104	109	85.0	68.0	57.0

* 100 Thebe = 1 BWP

The electricity consumption for the domestic sector is increasing the most, as can be seen in Figure 1.2 below. It can be seen that Botswana's total electricity consumption in 2012 was approximately 3200 GWh.

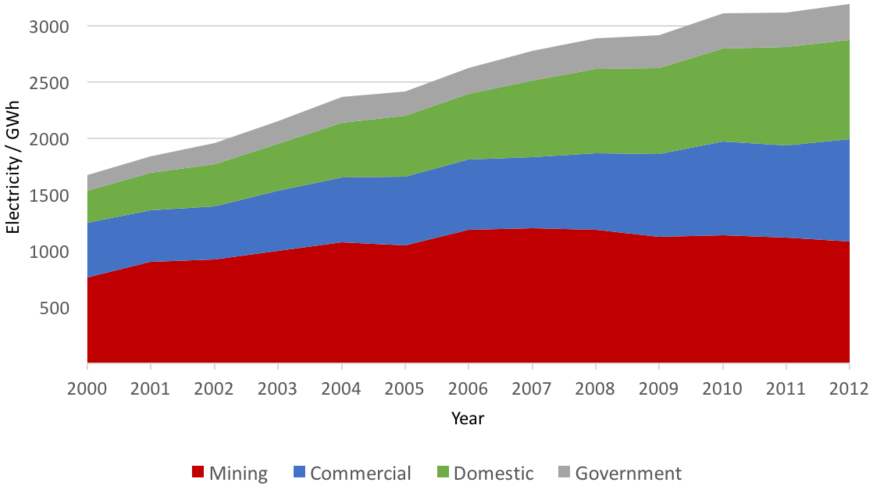


Figure 1.2: Botswana final electricity consumption trends by sector during the years 2000–2012 [7], [8], [9].

1.1.3 Solar energy in Botswana today

The following section will present an assessment of solar heating in Botswana today, its constraints and difficulties as well as practical examples based on the report *Evaluation of Solar Water Heating Systems in Botswana* by MT Oladiran and E Ossenburg [19].

The government has invested large sums in domestic solar water heating in order to conserve energy that previously has been used in electric or petrol heaters. However, due to little knowledge about maintenance of solar water heating systems among the consumers, many of these installations have been unsuccessful. This study is based on the problems with the systems that have been of various nature, although many of them have been reoccurring. For example, the pumps are often made of cast iron, which works well if the system is active 24 hours a day. However, the SHW system is not active during night which means that it has to be stopped and restarted. The start/stop cycle introduces oxygen in the system which allows for corrosion. This problem is easily solved by replacing the cast iron pump with a pump made from brass or stainless steel, either from the beginning or as a retrofit. Yet, the price for such a pump is higher, which may discourage many potential buyers. Corrosion occurs on other parts of the system as well. Accumulator tanks, pumps and collector housing are also often made of cast iron and due to the many inlets and outlets that may leak, they also corrode. Leaking air relief vents is another common problem. Air relief vents are used to empty the system of air after having been filled with water.

According to Oladiran and Ossenburg, issues with air relief vents are a major maintenance problem. They especially recommends that storage tanks should be flushed at least annually to get rid of sediments that increases resistance to heat transfer. Furthermore, the authors found that more than 50 % of analysed solar collectors were partially covered with dust due to dusty seasonal winds in combination with wrongly inclined collectors. This affects the heat transfer negatively since solar rays has to penetrate the layer of dust before reaching the actual collector. Sideways sloping, i.e. tilting, which is used to prevent air locks in SHW systems was found to be another frequent problem. According to the analysis, as few as one in ten solar collectors were installed using the correct tilt. Oladiran and Ossenburg suggests that none of the investigated electrical backup elements, i. e. the heating elements, were functioning correctly or at all as their lifetime was approaching nine years. Due to lime stone deposit, many of the heating elements were completely washed-out while others were malfunctioning. Moreover, some of them were constantly turned on, even when there was no water flow, thereby increasing the electrical bill at no use. A main reason for the different failures of the system is that unlicensed people offer to install the system at a low cost. In other words, for most people, the problems are traced back to the lack of expertize with the installers rather than problems with the system itself.

1.2 Urban houses in Botswana

Houses in Botswana are non-insulated and a similar structure is used in all urban areas [20]. Inner walls are made up of one layer of one 115 mm brick. Outer walls are made up of two layers of 115 mm bricks, which means a total thickness of 230 mm, on which a thin layer of coating is placed [20]. The roof is the only part of the building structure that has any insulation. Is consists of a thin layer, about 80 mm thick, of glass fibre in between the ceiling and the roof. However, some roofs are built using a frame on which a thatched roof is placed as seen in Figure 1.3. Furthermore, regarding size and floor area, a typical house can be considered to have a floor area of about 100 m^2 and about 15 m^2 of windows [20].

Figure 1.3: Inspection of a residential house under construction in Gaborone led by Dr. Rakgati.

1.3 Climate in Botswana

Botswana is a warm country with a predominantly semi-arid climate with large seasonal differences. This partly due to the fact that more than 70 % of the land consists of the Kalahari Dessert [21]. The rainy season normally occur between December and March when the weather alternates frequently.

During the hot season, mid September to mid April, the average temperature range between 27 °C and 24 °C and even though evening temperatures are lower it never gets cool [22]. However, during winter season, mid April to mid September, the average night temperature is 8 °C and rarely gets below 0 °C [23].

1.4 Objectives

The main objective of this thesis is to make a feasibility study of the use of solar energy to improve indoor comfort levels in residential houses in Gaborone, Botswana. The aim is to evaluate if solar thermal collectors in combination with PV are technically and economically viable. The solar collectors will be dimensioned to cover space heating during wintertime as well as hot water consumption all year round. Lastly, a hybrid solution consisting of a Photovoltaic Thermal collector (PV/T) will be investigated. The following research questions will be asked:

- What solar energy based solutions, thermal and/or photovoltaic, would increase the indoor comfort in residential houses in Botswana the most?
- How does the building properties of such houses affect the possibilities to improve indoor climate using these solar energy solutions?
- Which solar energy solution is the most cost efficient?

1.5 Constraints

The region investigated has been Gaborone and it's surroundings and the focus were on the residential sector, specifically private single family houses. A simplification of the house model has been made, using a single zone building with calculated average U-values.

No scientific conclusions based on the residential energy consumption can be drawn, due to limited number of households investigated in the BPC report used as foundation.

The investment calculations in the report are somewhat limited due to lack of information available regarding pricing of PV/T systems in Botswana. Furthermore, in the comparison of the different systems all maintenance costs have been assumed to be the same.

The targeted group in this study is middle- and high income earners and the presented recommendations only applies to new constructions, not retrofitting.

When evaluating the indoor comfort, dry-bulb temperature has been the parameter taken into consideration.

Initially, social aspects of solar energy solutions were to be studied but with lack of data in combination with lack of time, this was not done. It was listed in the target document.

No passive methods were investigated when looking into space cooling.

2 Method

In this chapter, the necessary tools to conduct this study will be presented and explained.

2.1 Literature study

The foundation of this study was achieved by studying articles about the current energy situation in Botswana combined with literature of different solar energy solutions. This in order to make theory backed comparisons and eventually be able to draw qualified conclusions about the results. Additional information regarding energy related questions in Botswana and nation wide reasoning was studied to get a broad perspective. Subsequently, building techniques and building materials in Botswana were studied and interviews with experts within the field were carried out to get an understanding of the topic and to obtain necessary parameters. Furthermore, evaluations of solar water heating systems installed in Botswana have been studied to gain understanding of what has previously been done in the field. This has also included to investigate what kind of difficulties an installation faces as well as problems that occur after a couple of years.

2.2 Methodology - TRNSYS simulation

To simulate a system as complex as SHW requires a complex simulation software. For this thesis, TRNSYS 17 was used [24]. TRNSYS is an energy simulation program, commonly used to simulate SHW systems, solar PV systems and PV/T systems among other things. The learning of the software involved studying components, coupling, inputs and outputs as well as how to create graphs. Each of the components, or so called types, has parameters, inputs and outputs. Parameters are fixed values that remain the same throughout the simulation. Inputs, on the other hand, are in most cases outputs from other types and thereby calculated as the simulation runs. Consequently, outputs are also calculated as the simulation runs. Most of these components are included in the regular TRNSYS library, although some of them are chosen from the so called TESS library that is an add-on due to development of the software [25]. All types in the system are calculated separately but in sequential order in TRNSYS, and they often depend on each other. The tank temperature for example, is dependent on the mass flow in the solar collector loop. TRNSYS is using an iterative method, limited by a predefined tolerance limit, to complete the computations. If the iteration fails somewhere along the simulation, the simulation is interrupted. Information about errors can be found in the so called list file that can be accessed through the TRNSYS interface. Additionally, the list file provides information about what component the error can be traced to, which allows for simplified problem solving. In other words, TRNSYS simulations are a powerful tool. However, if not used with knowledge of the underlying physics and mathematical expressions the output may be completely wrong. In order to avoid such cases, two main techniques are used, not uncommonly as a complement to each other. Energy equations are often calculated by hand, and is then compared to the result given by the TRNSYS calculation. The other common way to ensure that one is not misunderstanding an output is to use a so called printer to plot the output. This is especially effective for checking energy balances and mass flows in different parts of a system.

When determining the indoor comfort in the Botswana residential houses a discomfort unit was declared, referred to as Discomfort Degree Hours (DDH). It is a parameter created solely for this report, that quantifies the level of temperature uncomfortableness in a building. It is calculated as the amount of hours where the temperature is below the set point temperature of 19 °C, multiplied by the amount of degrees under 19 °C that they were associated with. These are referred to as $\mathrm{DDH_H}$ when it regards heating. In the same way $\mathrm{DDH_C}$ describes the discomfort associated with temperatures above the cooling set point of 25 °C. It is further explained in Figure 2.1 below, where the red columns display the $\mathrm{DDH_H}$ and the blue columns display the $\mathrm{DDH_C}$. The span in between 19 °C and 25 °C was considered to be a comfortable indoor temperature. Furthermore, DDH was believed to be a more tangible parameter than for example the amount of power consumed by the system as the main focus of the report is on indoor comfort, not energy consumption.

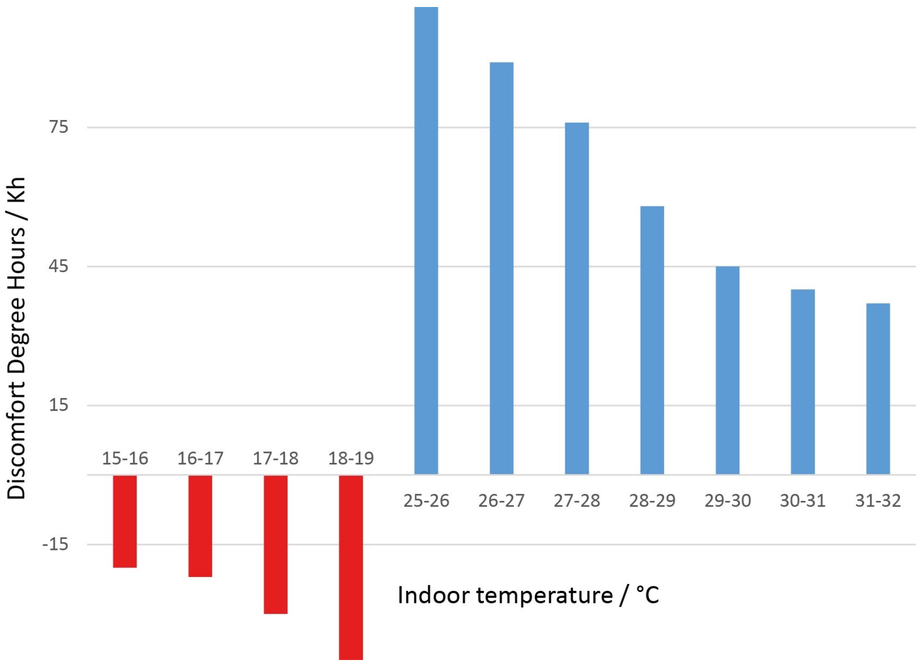


Figure 2.1: Example of a histogram showing the discomfort degree hours

2.3 Field work

Through 8 weeks of field work in Gaborone, Botswana, the necessary parameters and inputs could be obtained through different processes. The field work that was carried out consisted of two major parts. Firstly, interviews with qualified individuals in the areas of interest were held. These involved people from the Department of Energy (DE), BPC, University of Botswana (UB) and managers at local solar energy companies. Secondly, on sight measurements and observations in residential buildings as well as on construction sites were performed. This to get an understanding of how the houses are built, of what material they are built, in which cardinal points the windows are placed and what size the windows are. In addition, size and placement of accumulator tank as well as the type of heating element that were used was also assessed. The information received from building material experts could thereby be complemented with first hand observations.

3 Energy technologies

This part of the report will explain different energy technologies that are currently used or could be used for heating, cooling and/or hot water generation in Botswana.

3.1 Electric water heaters (geysers)

Electric water heaters, locally referred to as geysers, is the most common way to generate hot water in Botswana. Furthermore, while the electric water heaters in many other countries are fuelled by natural gas, in Botswana they use electricity as their only mean of primary energy [11]. An electric heater is a simple construction mainly consisting of a tank in which one or several heating elements are placed as seen in Figure 3.1 below. The elements, commonly a pair, are surrounded by filler material, contained in an outer shell of either stainless steel or copper. Furthermore, a high-limit cut-off temperature is used in order to prevent unnecessarily high temperatures, which may damage components in the hot water system [26].

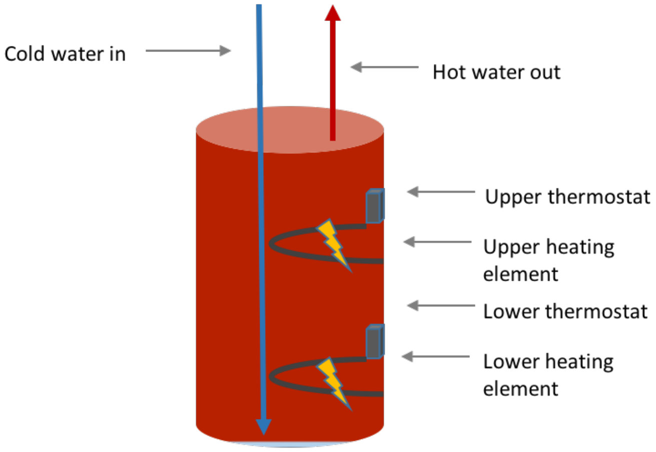


Figure 3.1: Electric geyser with the electric elements as well as the thermostats typically placed

3.2 Different types of solar energy systems and system layout

There are currently two main types of solar thermal heaters for private use; flat-plate collectors and evacuated tube collectors. They can both be used in either a regular tank system or in a thermosiphon system which will be explained in Section 3.5 [27]. Common for all types are that they use the radiation from the sun to heat up a working fluid that then can be used for heating the house or as a hot water source. The working fluid is normally a mixture of water and glycol which prevents it from freezing. However, in Botswana this is not needed as the temperature rarely goes below 0 °C. There are high performing panels that can collect heat even during cloudy days since they do not require direct sunshine to work properly [27]. However, the use of the lower temperature water that is provided on cloudy days is somewhat limited although one can lower the pump flow to get more heat. In addition to the solar collector itself, there are several other components required to successfully harvest the sun. A pump is connected to sensors located on the collector and the storage tank that keeps the flow in the system at an optimal rate. The storage tank is where the hot water is accumulated and with the use of pumps it is distributed to the different consumers in the house [28]. Due to the fact that most solar panels either generate very small amounts of hot water during rainy or cloudy days, a heating element is connected to the storage tank. This insures that hot water is available even during such days, while it also assists the solar thermal collector in achieving a more reliable water temperature [29].

3.3 Flat plate collector

Solar thermal collectors, especially flat plate collectors, are relatively simple in their nature, collecting heat from the solar radiation to heat up a working fluid [30]. A solar thermal collector can be seen in Figure 3.2, and is essentially made up of two parts. Firstly, there is shallow metal box and secondly the pipes, called collector pipes, in which the working fluid flows. Inside the box there is an absorber plate, commonly in black chrome, collecting the heat. The box, usually made of aluminium alloy or galvanized steel, is covered with a glass that protects the absorber plate as well as prevent loss of the absorbed heat [30]. In other words, the box collects and traps the heat, a function very similar that of a greenhouse. The absorbed heat is then transferred to the pipes, usually made of copper, and thereby transferred to the working fluid. The pipes are made of copper, not only due to the material's extraordinary thermal conductivity properties but also due to the fact that copper is highly resistant to both aquatic and atmospheric corrosion [30].

Figure 3.2: Typical installation of flate plate collectors on a roof. Photo: SolarShop [31]

The performance of a thermal collector is dependent on more complex parameters than a regular solar PV module. The thermal collector has the same dependency on climate factors such as temperature and irradiance, but the performance also depends on parameters such as the fluid flow rate and the size of the accumulator tank. Moreover, the hot water usage of the household also has a great effect on the performance of the solar collector.

3.4 Evacuated tube collectors

Evacuated tube collectors consists of vacuum tubes in which copper pipes run [32]. The copper pipes inside of the tubes are connected to the so called manifold found at the top of the tubes. To ensure minimal heat losses from the manifold to the air, the manifold is placed in an extremely well insulated housing made of aluminium as seen in Figure 3.3. The rest of the system, regarding overall function, is the same as for a flat-plate collector [32]. Due to vacuum inside of the tubes, the incoming solar radiation is trapped in a more efficient way than in flat-plate collectors. This is possible since the vacuum provides superb insulation due to smaller convection losses. However, since the design and technical properties of an evacuated tube collector is more sophisticated they are also more expensive [32].

Figure 3.3: An evacuated tubes installation on a roof where the cold inlet and warm outlet are visible as they enter the roof. Photo: Alpha Renewables [33]

3.5 Thermosiphon system

What constitutes a thermosiphon system is that the storage tank is located directly above the solar panel as seen in Figure 3.4. This allows for a natural flow due to density differences in heated and unheated water, which means that no circulating pump is needed for the system. This type of system is common in Botswana, both in combination with flat plate collectors and evacuated tubes [29].

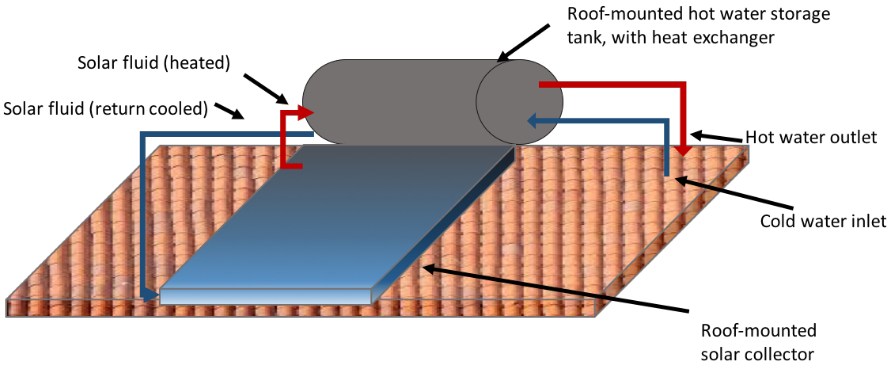


Figure 3.4: A thermosiphon system installed on a roof where the in- and outlets of the solar fluid and the water are displayed

3.6 Solar PV

In 1839 it was found that certain materials generate an electric current when they are exposed to light, an effect known as the photovoltaic effect [34]. This is the basis of the way a solar cell operates. The most common solar cells today are made of silicon, which is a semiconducting material. A silicon solar cell is essentially a jointing where a p-type and an n-type silicon is placed side by side. P-type, or positive type, means that the material has been doped with atoms that has one less electron than silicon, which in turn means that the material becomes positively charged. N-type, or negative type, means that the material instead has been doped with atoms that has one more electron than silicon, which means that the material becomes negatively charged. When light hits the silicon atoms in the solar cell, their energy is transferred to the excess of electrons in the n-type. This will push the electrons of the atoms of the n-type and makes them jump over to fill the gaps in the p-type, making the n-type more positively charged and the p-type negatively charged. In other words, an electric current has been created [34]. These cells are placed in panels which when placed in series form an array as can be seen in Figure 3.5.

Figure 3.5: A large array of solar panels installed on a roof. Photo: Kraftringen [35]

3.7 PhotoVoltaic/Thermal system (PV/T)

A Photovoltaic/Thermal collector is a module that combines the two techniques of solar thermal collectors and PV cells. This hybrid solution thereby generates heat and electricity simultaneously, resulting in higher overall efficiency per unit area for the device compared to PV cells or solar thermal. The research on PV/T collectors started in the mid 1970s with the aim to increase the PV efficiency [36]. The issue with conventional PV cells is that they suffer from a decrease in efficiency with higher temperature [34]. In other words the original idea with PV/T collectors is to lower the cell temperature by circulating a fluid at the back of the PV cells, thus removing heat. Today, several system designs exist with both air and liquid as a cooling fluid for PV/T collectors as well as concentrated photovoltaics thermal [36]. Seen in Figure 3.6 below, PV cells are placed on top of a regular solar collector. There is a cold water inlet, a hot water outlet as well as a connection for electricity output.

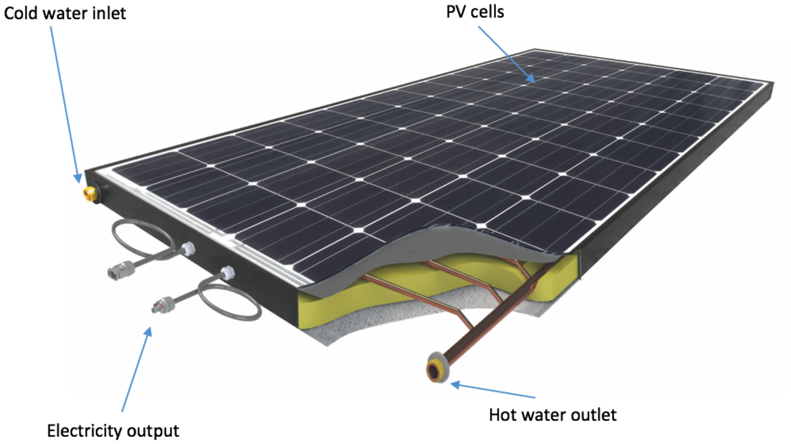


Figure 3.6: Hybrid PV/T panel in cross section. Photo: APC Technology Group [37]

4 Execution

This chapter will explain the course of action for the components in TRNSYS, the three different systems as well as when applying AC units to the latter two systems.

4.1 The TRNSYS deck

The so called TRNSYS deck contains many different components where the most decisive ones are presented below.

Tank

Type 60c was chosen due to suitable parameters, inputs and outputs in TRNSYS. The tank has multiple inlets and outlets as well as an internal heat exchanger (HEX) for tap water. The inlet from the solar collector is referred to as inlet 1. The outlet to the radiator is referred to as outlet 2. Furthermore, the tank is divided into 5 nodes where different placements within a node are considered to be the same by the software. The size of the tank is a parameter that turned out to have a noticeable affect on the efficiency of the SHW system. Hence, it was further investigated in a parametric study. A too small volume will increase the temperature in the system as the tank is more often fully loaded. This will lead to destratification thereby reducing the usefulness of the solar collector. An excess tank volume would mean problems with reaching the desired temperature due to a large water volume with severe thermal heat losses. The tank geometry is a crucial parameter as an overly elongated tank means large thermal losses, while a tank that is too compact will lead to insufficient stratification. For each given tank volume, a specific tank height was determined by using the same dimensions as a certain conventional tank producer. Aquasol produces accumulator tanks with a height of tank to tank diameter ratio of 8/3 which was used in all cases. According to *Solenergiboken*, [38] a tank volume of 50 $\mathrm{l/m^2}$ to 100 $\mathrm{l/m^2}$ of solar collector area should be used for Swedish conditions. This theory will be applied to the tanks in all of the three systems, but with some modifications in order to suit the warmer Botswana conditions. Geysers in Botswana are commonly placed outdoors to avoid thermal heat losses from the tank to further increase the usually warm indoor temperature. The tank environment has therefore been set to the outdoor conditions. Furthermore, the use of one heating element was chosen. There was little information to be found regarding current tank systems in Botswana. Thermosyphon systems are most commonly used for not more than water heating. Therefore, a regular tank with pump system was used. In order to not change the conditions for the two latter systems compared to the first, this layout was used in those cases as well.

Hot water consumption

Non of the local entities could provide definite numbers of hot water consumption in Botswana. However, BPC were able to provide information about the peak hours when the consumption are the highest. According to BPC, the hot water usage peak hours are between 7.00 − 9.00 a.m and 18.00 − 21.00 p.m [4]. Without any known average hot water load, an estimation was made based on a typical Swedish hot water consumption, which ranges from 35 l/person to 120 l/person and day [39]. Due to the heat in Botswana, showering is more often used as a mean to cool off and for this reason the hot water load was estimated to be approximately 50 % of low Swedish consumption. Since the estimation was done for a four person family home, the value had to be multiplied by four resulting in a daily water load ranging between 140 l/day to 480 l/day. A low value from this range of 190 l/day was chosen. After taking all the factors mentioned above into consideration the average hot water consumption for a typical urban household was assumption at 95 l/day at a temperature of 55 °C. More specifically, the hot water consumption was set to 25 l/h during morning peak hours and 15 l/h during evening peak hours. Furthermore, the water outlet temperature from the tank was also studied in order to make sure that legionella bacteria development was avoided. The hot water consumption was the same for all three systems. The values above greatly affects the system and although the estimation was qualified it allows for a certain margin of error. If the hot water demand is too high for the system, desired temperatures may not be reached. If the demand is too low for the system, the whole tank will eventually get warm, which means that the inlet water temperature to the solar collector will increase. In turn, this results in a reduction of the solar collector efficiency since it is dependent on a large temperature difference, according to Equation 1 and 2. The required energy for heating the water in a solar collector, $\dot{Q}_u$, is calculated by

$$\dot{Q}_u = \eta_{th} \cdot A \cdot I_T, [40] \tag{1}$$

where η_{th} is calculated by

$$\eta_{th} = F_R \cdot (\tau \cdot \alpha)_n - F_R \cdot U_L \cdot \frac{(T_{in} + T_a)}{I_T} - F_R \cdot U_{L/T} \cdot \frac{(T_{in} + T_a)^2}{I_T}, [40] \tag{2}$$

where

- η_{th} = Steady state thermal efficiency of solar collector
- A = Solar collector area, measured in m^2
- I_T = Global radiation incident on the solar collector (Tilted surface)
- F_R = Overall collector heat removal efficiency factor
- $\tau\alpha_n$ = Product of the cover transmittance and the absorber absorptance at normal incidence
- U_L = Overall thermal loss coefficient of the collector per unit area, measured in $\mathrm{kJ/(h{\cdot}m^2K)}$
- T_{in} = Inlet water temperature of collector, measured in K
- T_a = Ambient temperature, measured in K
- $U_{L/T}$ = Thermal loss coefficient dependency on T, $\mathrm{kJ/(h{\cdot}m^2K^2)}$

The intercept efficiency, $F_R(\tau\alpha)_n$, is corrected for non-normal solar incidence by the factor $(\tau\alpha)/(\tau\alpha)_n$. By definition, $(\tau\alpha)$ is the ratio of the total absorbed radiation to the incident radiation. Thus, a general expression for $(\tau\alpha)/(\tau\alpha)_n$ is:

$$\frac{(\tau \cdot \alpha)_b}{(\tau \cdot \alpha)_n} = 1 - b_0 \cdot (\frac{1}{cos\theta} - 1) - b_1 \cdot (\frac{1}{cos\theta} - 1)^2, [40] \tag{3}$$

where

- $\tau\alpha_n$ = For beam radiation (depends on the incidence angle θ)
- θ = Incidence angle for beam radiation, measured in °
- b_0 = Negative of the 1st-order coefficient in the Incident Angle Modifier curve fit equation
- b_1 = Negative of the 2nd-order coefficient in the IAM curve fit equation

Pump/Pump flow

There are two pumps used in the SHW heating system. One for circulating the fluid in the solar collector loop and one for the radiator loop. Pump flow rate in low flow systems in Sweden usually range between 0.15 l/(min·m^2) to 0.2 l/(min·m^2), while conventional volume flow rates commonly range between 0.4 l/(min·m^2) to 0.6 l/(min·m^2) [38]. After discussions, the pump flow assessed further was the lower range of 0.15 l/(min·m^2) to 0.2 l/(min·m^2). Too low flow might lead to high thermal losses in the tank as well as dangerously high temperature and pressure in the solar collector, while too large pump flow will lead to destratification both decreasing the energy gain in the tank [41]. Furthermore, the circulating pumps in this model does not add any energy to the water.

Windows

An add-on software program called TRNBUILD was used to determine the heat transfer coefficient (U-value) of an average double paned window to 2.9 W/(m^2·K). Furthermore, 15 m^2 of window area was used in the simulation. Infiltration air was set to 250 kg/h, in order to simulate air flowing through an open window. The airing was set after a schedule to when people were at home, during summer months. The ideal and more realistic thing would have been to set the schedule to airing when indoor temperature exceeded the outdoor temperature. However, this would have been too complicated to simulate and a simplification had to be made in TRNSYS. Furthermore, no window shading was used in the model.

Weather Data

TRNSYS 17 comes with an optional, comprehensive set of weather data files including 1000 locations in 140 countries. However, Gaborone was not included as one of those locations. The nearest locations were Johannesburg, about 280 km to the south, and Maun, about 580 km to the north. These cities have similar climates but for this study to be as accurate as possible it was decided that a weather file for Gaborone had to be created. Erik Johansson, assistant professor at the Department of Architecture and Built Environment, did through interpolation of locations create an accurate weather file for Gaborone. The weather file contained all weather data needed as input for the components in TRNSYS.

House

The house called Type 88 has been used. It is a simplified single zone building which uses an average U-value for the entire construction. The average U-values were calculated in TRNBUILD using the different individual U-values for the walls, windows, roof and floor weighed by their areas respectively. Through this method, the average U-values for houses in Botswana today were found to be 2.9 W/(m^2·K). The dimensions of the house used for the simulations are $(12.5 \cdot 8 \cdot 2.5) \Rightarrow$ 302.5 m^2 building envelope area and 250 m^3 house volume.

Radiator

To illustrate a radiator, the heat exchanger Type 5c was used. The amount of heat transferred per unit time by the radiator, $\dot{Q}_{HEX}$, is calculated according to Equation 4 below

$$\dot{Q}_{HEX} = \epsilon \cdot C_{min} \cdot (T_{hot,in} - T_{cold,in}), [40] \tag{4}$$

where

- ϵ = heat exchanger effectiveness
- C_{min} = minimum capacity rate, measured in kJ/(s·K)
- $T_{hot,in}$ = inlet water temperature of radiator, measured in K
- $T_{hot,out}$ = outlet water temperature radiator, measured in K

Where the difference $(T_{hot,in} - T_{hot,out})$ depends on the temperature and mass flow of the air flowing across the radiator. A suitable size of the radiator for this residential house was assumed to be 1 kW. To design this system, a couple of prerequisites were developed. It was decided that a reasonable water temperature decrease in the radiator would be from 55 °C to 40 °C. This prerequisite allowed for less options for the remaining parameters of the radiator. By iterations of the two mass flows it was found that with 80 kg/h of hot water and 120 kg/h of cold air, the radiator would generate 1 kW of heat. A high limit cut-out temperature of 23 °C was used. This means that the radiator kept heating the house until the indoor temperature of 23 °C was reached.

Internal gain

Electricity usage in the house, heat gained by residents' metabolism as well as radiation let into the house through windows has been added as internal gains for the building. The thermal storage tank is located outdoors and will thereby not contribute to any internal gains. The internal gains are assumed to be 450 W [42].

Solar Collector

There are a large amount of solar collectors in the TRNSYS standard library. After having evaluated several different Types, Type 1b was found to have well suited parameters and outputs for this project. This was crucial as the solar collector is the heart of the simulations for the two first systems. Type 1b is a flat plate collector that is used in both the heating system as well as the system presented in Section 4.3.

PV/T collector

In the TRNSYS library there are several different PV/T types. The type with the right outputs and parameters was found after discussion with the TRNSYS support team. This resulted in Type 50 d being used in the simulations. The PV/T collector module area was set to 0.89 m^2.

PV type

As a comparison was to be made it was decided that the same type as in the case of the PV/T above should be used. This since a PV/T collector with no fluid flow basically is a regular PV panel. Through this method the very same parameters and settings for the PV unit could be used in the two cases of PV/T and PV, which allowed for a correct and exact comparison. The PV collector module area was set to 0.89 m^2.

4.2 SHW system for heating and hot water generation

The layout of the SHW system with heating and hot water generation can be seen in Figure 4.1 below. It can be seen how the hot water runs from the solar collector to the inlet in the upper part of the tank and how the cold water is pumped back up into the collector from the bottom of the tank. Furthermore, cold water from the municipality runs into the heat exchanger in the bottom of the tank. The hot water from the tank supplies both the hot water needs as well as the radiator where it cools off and runs back into the bottom of the tank.

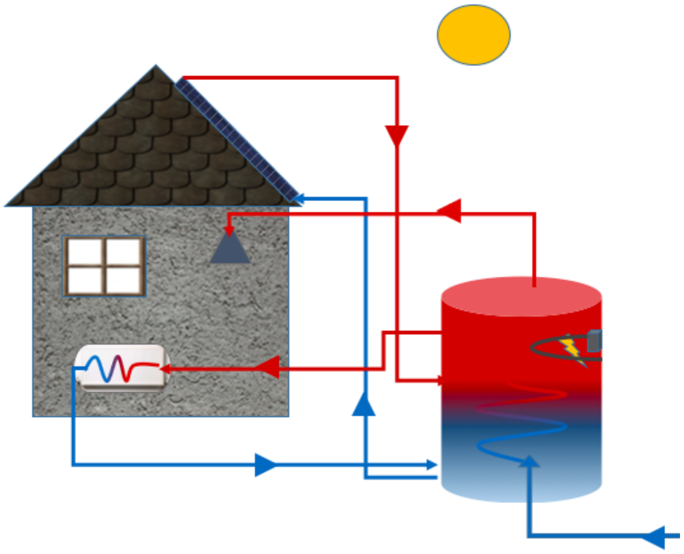


Figure 4.1: System design for the scenario with solar thermal collectors for space heating and hot tap water generation

Firstly, to be able to perform a parametric study a key parameter had to be decided on, which after discussions of different possibilities became the amount of ($\mathrm{DDH_H}$) under a certain set point temperature. In order to optimize the SHW system, all parameters which had an impact on the performance of the system had to be identified. All components were analysed and their associated parameters were listed. This list was systematically analyzed where the parameters were divided into two groups. The ones that had great impact and/or were dependent on other parameters and those who could be varied without an advanced parametric study. It was shown that with the current building insulation for the houses in Botswana, the heat transfer through walls would be to comprehensive. However, through TRNSYS simulations it became clear that with a certain amount of insulation, there would be no need for space heating to keep the house warm even during the cool winter months. In other words, the heating system was in between two cases where it would either have very little impact on the indoor comfort, or not be needed at all. The amount of insulation was optimized before the actual performance of the system could be determined. This as there were two cases for which the heating either had little effect due to no insulation or were not needed due to good insulation. Between these two cases there was a state where the system would have the highest effect on improving the indoor climate. A parametric study of the average U-value was performed where the amount of $\mathrm{DDH_H}$ was studied, in order to determine for what average U-value the SHW system had the highest effect. The values of the parameters of the second group had now been decided on. After having found the optimal value for the parameters of the second group, it was decided that the current state of the system was a good foundation for initiating an advanced study of the first group of parameters.

In order to decide the necessary size of the solar collector, the approximate energy demand had to be determined. This meant finding the sum of the energy required for the hot water as well as the space heating. The hot tap water energy demand was determined according to Equation 5 below

$$Q_{tap} = m \cdot \Delta T \cdot c_p, [43] \tag{5}$$

where

- m = mass of the water for the entire year, measured in kg
- ΔT = temperature difference of the water before and after passing the HEX in the tank, measured in K
- c_p = specific heat capacity for water, measured in kJ/(kg·K)

Next, the heating energy demand was calculated by Equation 6 below

$$Q_{heating} = DDH_{\mathrm{H}} \cdot A \cdot U_{average} \tag{6}$$

where

- $\mathrm{DDH_H}$ = amount of discomfort degree hours (heating), measured in K·h
- A = building envelope area, measured in m^2
- $U_{average}$ = average U-value for the building, measured in $\mathrm{W/(m^2{\cdot}K)}$

The average U-value is an average heat loss coefficient for the entire building calculated using Equation 7 below,

$$U_{average} = \frac{\sum U_i \cdot A_i}{\sum A_i} = 1.8\ W/(m^2 \cdot K) \tag{7}$$

where

- U_i = U-value for part i, measured in $\mathrm{W/(m^2{\cdot}K)}$
- A_i = Area of part i, measured in m^2

The UA-value is then calculated by Equation 8 below:

$$U_{Average}A = 1.8 \cdot 302.5 = 544.5\ W/K \tag{8}$$

By combining Equation 8 with Equation 6, the amount of energy required, $Q_{heating}$, to eliminate all $\mathrm{DDH_H}$ could be obtained. The next step meant finding a collector area that could handle the hot water demand without using the heating element excessively. When the right area was found, optimization of the tank size and mass flow for the collector loop was the next step. This was based on theory from *Solenergiboken* regarding what values tank size and mass flow should be in between to achieve optimal energy transfer. After having completed the above, it was found that the effect from the system had included effect from the heating element. The plan was to make the solar system as good as possible which meant turning the heating element off and redoing the optimization. As the optimal system had been found, the optimal slope for the solar collector was to be determined. As the heating system only would operate if the indoor temperature was under 19 °C the collector slope was optimized for the whole year. However, the interesting part of the graphs would be during the time in which the system was operating. This meant that the Botswana winter had to be defined. In this report, the winter period is specified to range between 16th of April until 16th of September. The optimization of the system was followed by a sensitivity analysis of the key parameters in order to determine the sensitivity of the system.

4.3 SHW system in combination with PV for hot water and electricity generation (PV+T)

The layout of the SHW system in combination with PV for hot water and electricity generation can be seen in Figure 4.2 below. In similarity with the case of the SHW system for heating there is a solar collector, but also a PV panel generating electricity. In addition, there was no heating in this system.

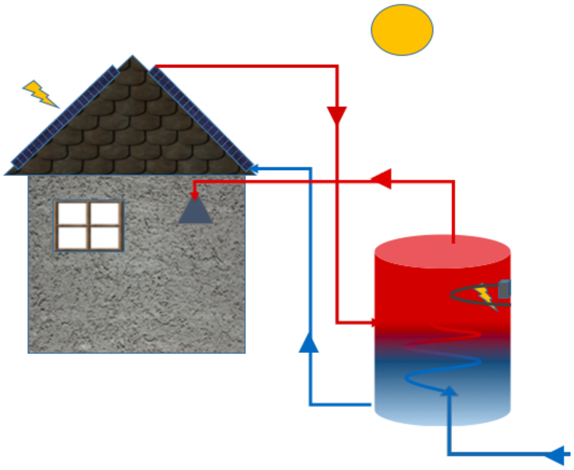


Figure 4.2: System design for the scenario with solar thermal collectors for hot water generation in combination with PV panels for electricity generation

What follows is an optimization of the SHW system to specifically fit the hot water demand, which still is the same as in chapter 4.2. Three different tank sizes were investigated further: 100 l, 150 l and 200 l. This is all according to conventional solar thermal theory in *Solenergiboken* saying that 50 $\mathrm{l/m^2}$ to 100 $\mathrm{l/m^2}$ of solar collector area should be used. However, these are recommendations for Swedish conditions and might not be fully accurate in Botswana conditions. Yet, in this report they are used as intitial guidelines. According to the sum of results from Equation 5 and Equation 6 areas from 4 $\mathrm{m^2}$ to 8 $\mathrm{m^2}$ were assessed. Regarding optimization of the collector slope, the whole year was studied in case there are some occasions under 19 °C that would require heating. The parameter that was studied was the amount of $\mathrm{DDH_H}$. Furthermore, the same tank height to diameter ratio of 8/3 as presented before is used. The analysis was made to show what tank size in combination with pump flow that would generate the most energy, and at the same time generate the least amount of thermal losses. In all cases, the energy at the ordinate is calculated as energy gained by solar collector subtracted by the thermal losses in the tank. According to theory regarding recommended pump flows presented in *Solenergiboken*, flows between 18 l/h and 24 l/h were chosen for this solar collector area and the analysis has been carried out with this in mind. Furthermore, the placement of the heating was examined, and tested at four different heights. To avoid overusing the heating element and to enable the solar collector to work towards low temperatures the heating element in conventional solar tanks is placed close to the top. The optimal height was balanced to use the heating element as little as possible, while still generating enough energy. In order to determine the optimal height of inlet 1, the same technique as for the heating element placement was used. The solar collector slope angle was optimized with intent to supply hot water on an even basis throughout the year. The total net energy was plotted against the collector slope angle. The electricity generation for the solar PV panel was optimized in the same way. The PV panel area is a multiple of the PV module area. In this case, 15 modules were used, resulting in a total PV area of 13.35 m^2.

4.4 Photovoltaic/Thermal system (PV/T)

The layout of the hybrid PV/T system can be seen in Figure 4.3 below. The layout of this system is similar to the one for the SHW system in combination with PV, although now there is only one panel generating both hot water and electricity. Also, there was no heating in this system.

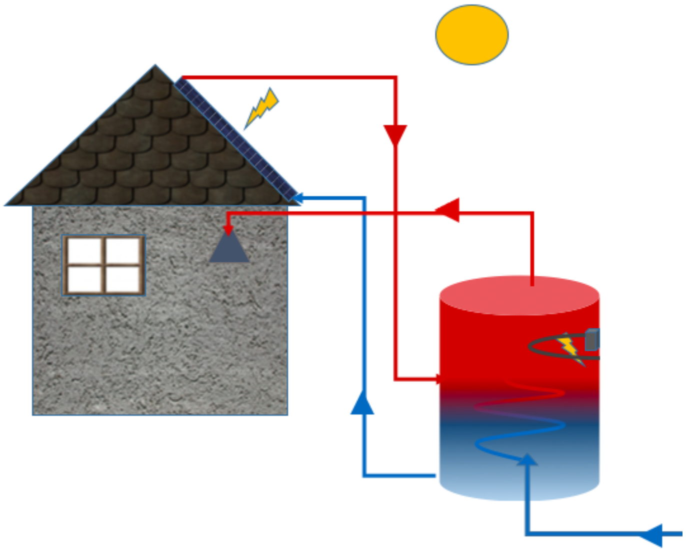


Figure 4.3: System design for the scenario with a PV/T collector for hot water and for electricity generation

It is known that the efficiency of PV panels decrease with increasing cell temperature and thereby with increasing ambient temperature. The manufacturers have measured the efficiency in standard test conditions of 25 °C and 1000 W/m^2 [44]. In other words, this is the reference efficiency. Furthermore, in order to perform a fair comparison between the electricity generation from a PV panel and a PV/T collector the same component was used in both cases. In the case of the PV the mass flow of water in the panel was set to zero. The optimization was followed by a sensitivity analysis of the key parameters in order to determine the sensitivity of the system. To reach an optimal indoor climate during summer would require cooling, and thereby electricity. Hence, an optimization of the electrical output from both a solar PV + T and PV/T system is made in this report. Since different settings generate more electricity from the panel, while they at the same time require more input from the heating element, the combined net value of these two outputs was considered the key parameter. Furthermore, the same tank height to diameter ratio of 8/3 as in previous studies was used. Regarding choice of size, it was early found that a PV/T system is rather poor when regarding hot water generation, as the temperature of the water exiting the PV/T collector is significantly lower than that of a regular SHW collector. Furthermore, two parameters of the PV/T model are worth further mentioning. The first one, the packing factor, is the fraction of absorber area covered by solar cells, thereby ranging from 0-1. For this study, the packing factor was set to 1, as electricity generation was prioritized. The second parameter, the temperature loss coefficient for the PV cell, defined as the percentage loss in efficiency for every degree Kelvin above 298.15 K was set to –0.4 % [34]. As all parameters were decided on, the optimization followed the same order as for the previous studies beginning with the mass flow and tank size, followed by placements of inlet 1 and the heating element. The optimization was followed by a sensitivity analysis of the key parameters in order to determine the sensitivity of the system. The PV/T collector area was decided to be the same as the PV area, 13.35 m^2.

4.5 Applying an AC unit to the systems

Even if one can get rid of the cold climate during winter through insulating their house, it has to be weighed in proportion to the price of even warmer summer indoor climate. AC units are a common solution of improving indoor climate in residential buildings in Botswana. Consequently, the effect that the 60 mm insulation has on both the AC unit energy consumption and performance was of interest. Therefore the effect that a typical AC unit has on the indoor temperature using different average U-values also had to be studied. A reference volume flow from the AC unit of 600 m^3/h was studied at first [45], while a volume flow of 1 200 m^3/h was further studied. As a relative comparison between the two cases is wanted, the AC unit was turned on 24 hours a day in order to eliminate misleading results. The indoor temperature during the day when people were not home would get much higher with improved insulation. As no one is at home it does not matter if the temperature is high during the day and it would therefore give misleading results. For this reason, the AC unit is turned on throughout the day as well although it only operates if the indoor temperature is above 23 °C. This was reasoned to be the most fair comparison between the two cases.

5 Results

This chapter will present all the results from the three different systems as well as the applied AC.

5.1 Optimization of SHW system for heating and hot water generation

The base case for the heating system is a 6 m^2 solar collector, average U-value of 1.8 W/(m^2·K), tank size of 600 l and a mass flow of 63 l/h. Furthermore, the placement of inlet 1 was set to 1.3 m, the placement of outlet 2 to 1.7 m and the placement for the heating element to 1.5 m. The tank height was set to 1.89 m. As seen in Figure 5.1, the U-value for which the system can mitigate the highest amount of DDH_H is 1.8 W/(m^2·K). This was optimized by measuring the amount of DDH_H that could be reduced for the different U-values with the system on, compared to with the heating system off. With the use of insulation equivalent to 10 mm of rock wool, an average U-value of 1.8 W/(m^2·K) can be obtained, see Appendix for calculations. For the scenario with a well insulated building the average U-value of 0.5 W/(m^2·K) was used. This meant that space heating was no more necessary as a 99 % reduction of DDH_H was achieved.

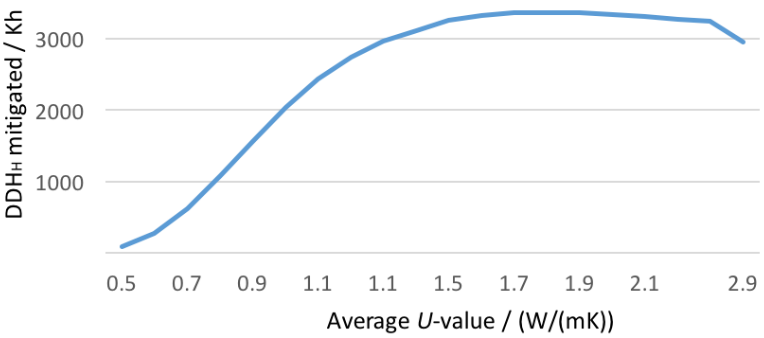


Figure 5.1: Optimization of the amount of DDH_H mitigated by the system with respect to the average U-value of the building.

The result can be seen in Figure 5.2 below, presenting that with a set up of a 48 ° slope angle, 2 368 DDH_H will be achieved. Regarding the water temperature out of the heat exchanger, there are a few occasions where the temperature is below 50 °C although it still was more than 48 °C. However, none of these occasions ever happened following another occasion below 50 °C. Therefore, it was reasoned that the chances for development of legionella are insignificant. This way of reasoning has been applied to all the systems.

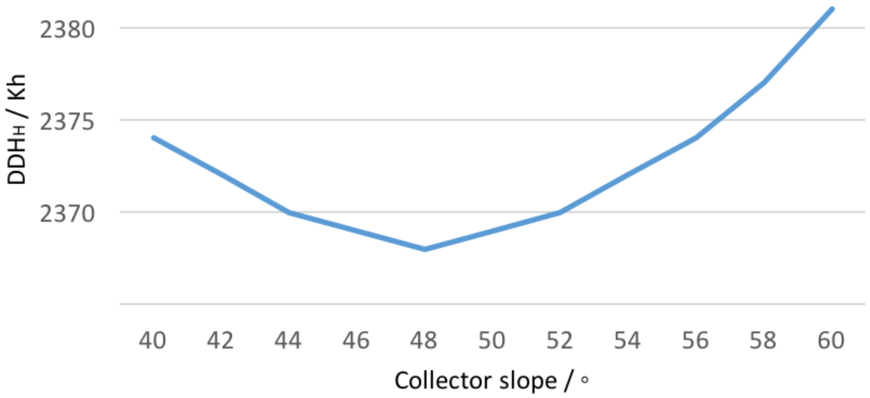


Figure 5.2: Optimization of the amount of $\mathrm{DDH_H}$ with respect to the slope angle of the solar collector.

As can be seen in Figure 5.3 below, the pump flow and tank size were optimized at the same time. Tank sizes of 300 l, 450 l and 600 l were investigated according to theory of a recommended 50 $\mathrm{l/m^2}$ to 100 $\mathrm{l/m^2}$ of solar collector area in *Solenergiboken*, where 75 $\mathrm{l/m^2}$ was chosen as an average value. Furthermore, the recommendations for low-flow systems does in this case correspond to 54 l/h to 72 l/h. However, it was found that the optimal mass flows were to be higher in Botswana than recommended for Swedish conditions. The optimal flows were 108 l/min, 126 l/min and 144 l/min respectively for tank sizes 300 l, 450 l and 600 l. The combination of a 600 l tank and a 144 l/h mass flow resulted in the least amount of $\mathrm{DDH_H}$ under 19 °C and was therefore chosen. Approximately 50 $\mathrm{DDH_H}$ can be mitigated through use of the larger tank compared to the smaller one, an improvement of 2 %.

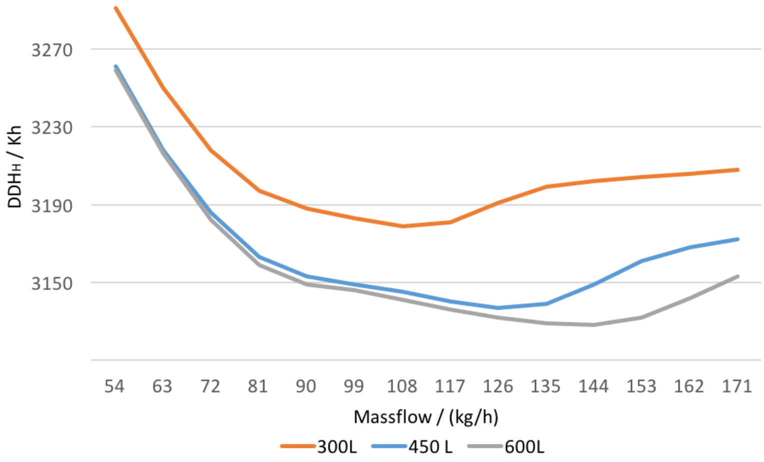


Figure 5.3: Optimization of mass flow and tank size with respect to the amount of $\mathrm{DDH_H}$.

The following optimization of placements of heating element, inlet 1 from the solar collector and outlet 2 to the radiator will be done with respect to two parameters. Firstly the heating element consumption and secondly the amount of $\mathrm{DDH_H}$. In order to be able to make a decision based on the amount of kWh consumed by the heating element compared to the amount of $\mathrm{DDH_H}$ reduced, a ratio between the two had to be found. In TRNSYS, this was found by adding a certain amount of kWh of thermal heat during a certain period of time and investigating how this affected the amount of $\mathrm{DDH_H}$. The ratio between the amount of kWh and the amount of $\mathrm{DDH_H}$ was found to be 2.1, and is from now on referred to as translation factor. In others words, by adding 2.1 kWh of thermal energy the amount of $\mathrm{DDH_H}$ will be lowered by 1 K·h. However, this translation factor is only valid for this specific house and time of the year. This is due to the fact that the UA-value along with the outdoor temperature at the given time are the only two values that affect the translation factor.

Based on the reasoning above in combination with Figure 5.4 below, the heating element is optimally placed at a height of 1.6 m to 1.8 m whereas the tank height is 1.89 m. Yet, the heating element can increase the amount of energy transferred to the tank by being placed further down. As can be seen in Figure 5.4 below, by placing the heating element further down, the amount of $\mathrm{DDH_H}$ are lowered. However, this also means that the heating element consumes more electricity. The decision was made that lowering the amount of $\mathrm{DDH_H}$ by 97 by moving to a height of 1.4 m at the cost of a consumption increase of 228 kWh was not preferable according to the ratio between the parameters. The placement of the heating element was chosen to be at a height of 1.6 m.

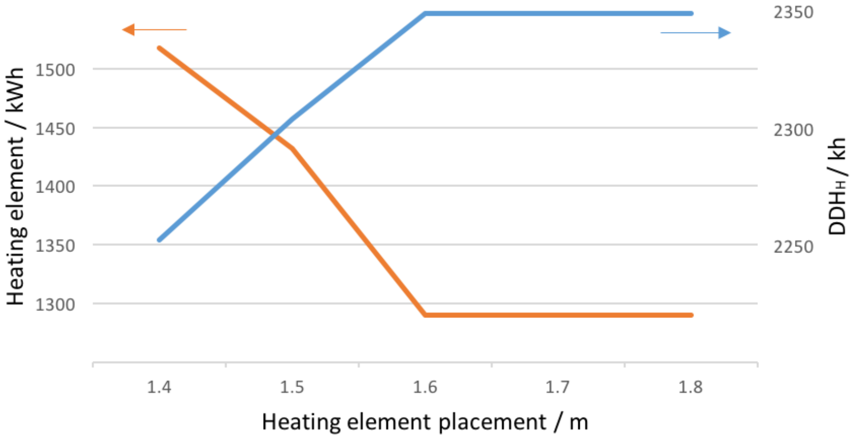


Figure 5.4: Optimization of heating element placement with respect to annual energy consumption.

As seen in Figure 5.5 below, the amount of $\mathrm{DDH_H}$ can be lowered from 2 370 to 2 356, down 24 $\mathrm{DDH_H}$, while also saving 9 kWh, which was considered preferable. This can be achieved by moving the inlet 1 placement from between 0.8 m and 1.1 m up to between 1.2 m and 1.5 m, represented as the orange horizontal line to the left. By increasing the height to between 1.6 m and 1.8 m the amount of $\mathrm{DDH_H}$ can be lowered further to 2 340 $\mathrm{DDH_H}$ at a cost of 27 kWh. In other words 16 $\mathrm{DDH_H}$ can be eliminated at a cost of 27 kWh, which with the ratio between the two is considered preferable. However, in practice an inlet is never placed at the same height as the heating element. Following the arguments above, an inlet placement of 1.4 m is chosen.

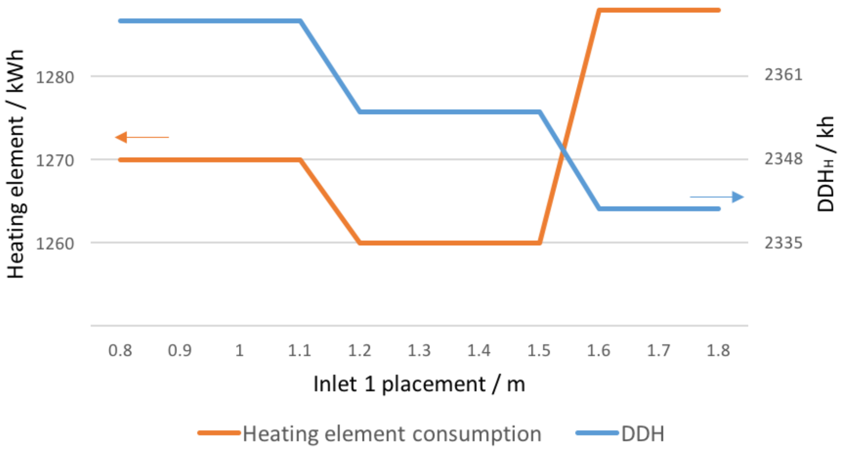


Figure 5.5: Optimization of inlet 1 placement with respect to annual energy consumption.

The placement of outlet 2 has the largest effect on the amount of DDH_H. As seen in Figure 5.6 below, by varying the placement of outlet 2 from a height of 0.8 m to a height of 1.8 m the amount of DDH_H varies from 3 334 to 2 355 while the heating element consumption increases from 55 kWh to 1 260 kWh. This means that 979 DDH_H are mitigated at the cost of 1 205 kWh. With the ratio between the parameters in mind it is preferable to place outlet 2 at a height of 1.6 m or above. It is placed at 1.6 m.

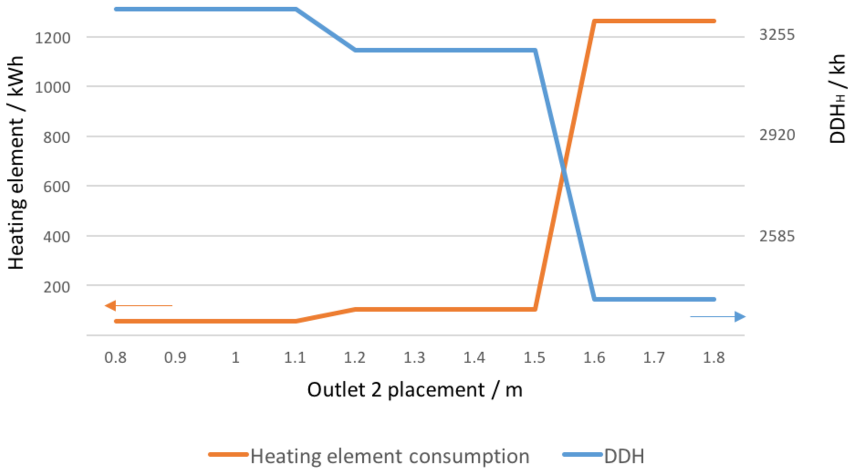


Figure 5.6: Optimization of outlet 2 placement with respect to annual energy consumption.

To get an average U-value of 1.8 W/(m^2·K) an equivalent of 10 mm of rock wool insulation is required while for an average U-value of 0.5 W/(m^2·K) an equivalent of 60 mm is required, see Appendix. Below are graphs showing the temperature in the house with the system turned on and off for the three different scenarios: the average U-value set to 2.9 W/(m^2·K) meaning todays houses in Botswana, an average U-value of 1.8 W/(m^2·K) meaning the scenario where the system has the highest effect, and an average U-value of 0.5 W/(m^2·K) meaning enough insulation to eliminate most of the cold hours. Figures 5.7, 5.9 and 5.11 show the indoor temperature for the whole winter, and Figures 5.8, 5.10 and 5.12 represent only a few weeks in late June to early July which is in the middle of the winter. Furthermore, a certain overshoot can be seen in Figures 5.7, 5.9 and 5.11. The indoor temperature in the case where the heating system is on begins at a higher temperature than for the non heated case. This due to the fact that the temperature never reaches as low as it does without heating. This in combination with the fact that the solar radiation through the windows is the same with or without heating creates the overshoot.

In Figure 5.7 below, can be seen that in a house with an average U-value of 2.9 W/(m^2·K) most of the hours during the winter are under the desired lower set point temperature of 19 °C. Furthermore, the small impact from the system can be seen as the graph generated with the system turned off almost covers the graph from when the system is turned on.

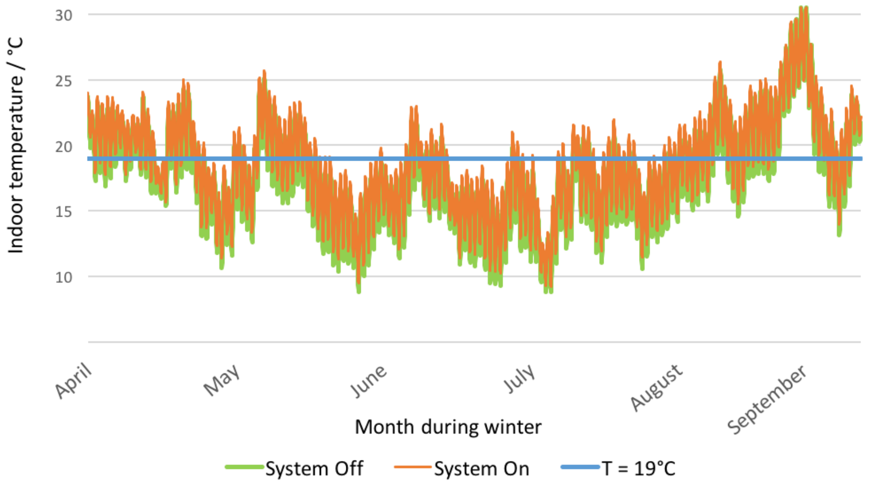


Figure 5.7: Indoor temperature during winter with an average U-value of 2.9 W/(m^2·K).

Figure 5.8 below shows a more detailed version of Figure 5.7, due to shorter time interval. It can be seen that the increment with the system turned on is mostly not more than about 1 °C.

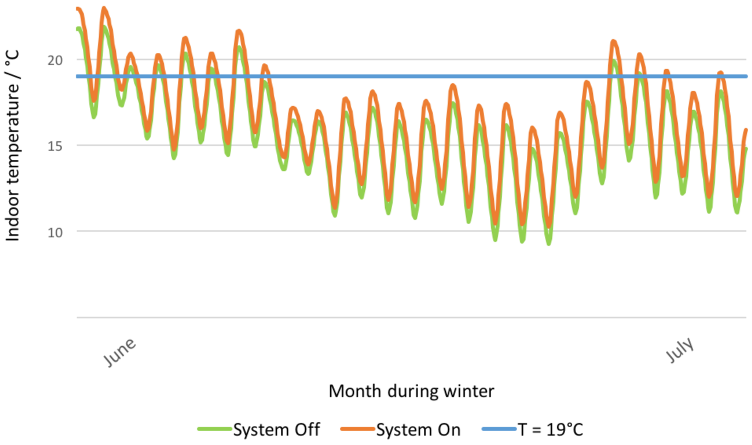


Figure 5.8: Indoor temperature during 20 days mid-winter with an average U-value of 2.9 W/(m^2·K)

With an average U-value of 1.8 W/(m^2·K) the largest decrease in DDH$_\mathrm{H}$ is produced by the system. As seen in Figure 5.9 the orange part of the graph representing the system being turned on is now more visible. The reason for the difference between the graphs even above 19 °C in Figures 5.9 and 5.10 is due to the fact that the radiator keeps heating until the high limit cut-out at 23 °C.

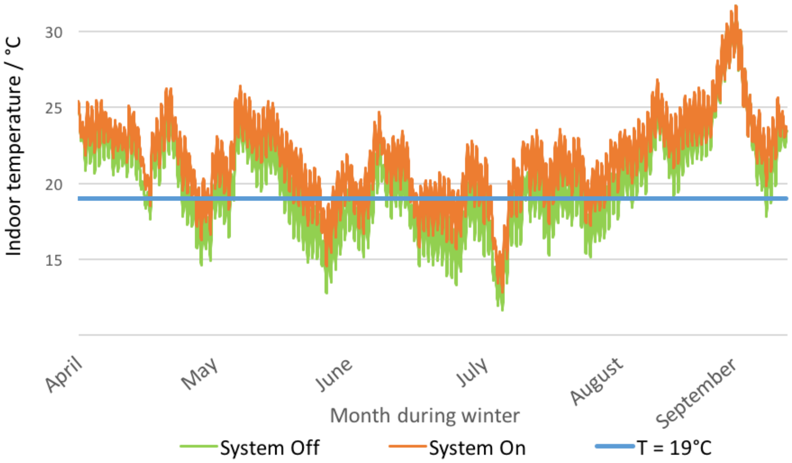


Figure 5.9: Indoor temperature with an average U-value of 1.8 W/(m^2·K) during winter

As can be seen in Figure 5.10 below, the increase of the indoor temperature with the average U-value of 1.8 W/(m^2·K) is a bit more than 2 °C continuously.

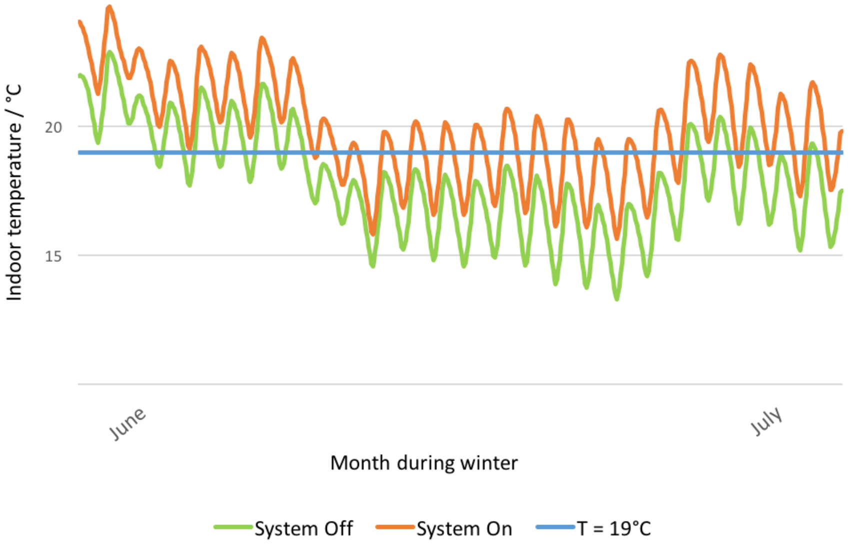


Figure 5.10: Indoor temperature with an average U-value of 1.8 W/(m^2·K) during 20 days mid-winter

In Figure 5.11 below, is the case where the average U-value value of 0.5 W/(m^2·K) without heating is displayed. As can be seen, by insulating to this level is sufficient to eliminate almost all of the DDH$_\mathrm{H}$, which leaves the heating system unnecessary.

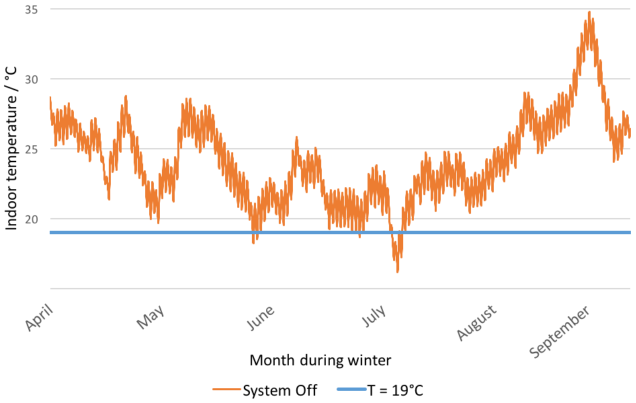


Figure 5.11: Indoor temperature with an average U-value of 0.5 W/(m^2·K) during winter

Figure 5.12 below shows how the temperature in a house during mid-winter with an average U value of 0.5 W/(m^2·K) almost never goes below the desired temperature of 19 °C. This partially due to the fact that the temperature, because of the higher insulation, decreases slower thereby aiding the system in maintaining the desired temperature.

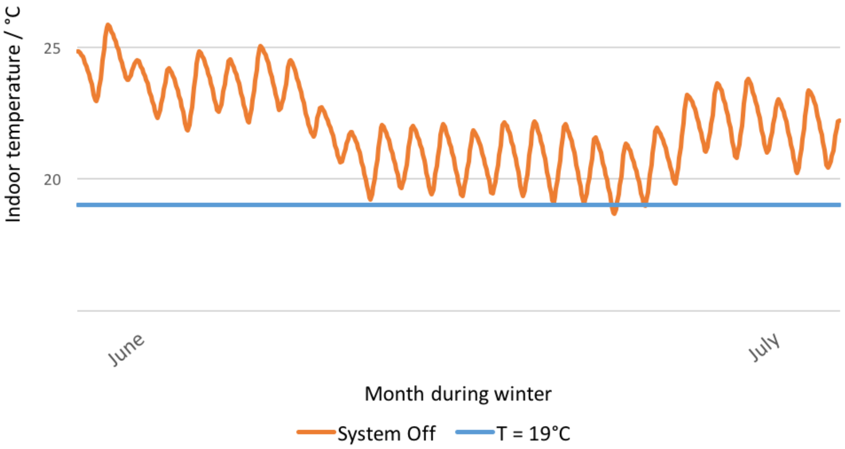


Figure 5.12: Indoor temperature with an average U-value of 0.5 W/(m^2·K) during 20 days mid-winter

In Figure 5.13 below, the distribution and amount of DDH for each of the three cases with different U-values can be seen. For the case with an average U-value of 2.9 W/(m^2·K) it is obvious how there are many DDH$_\text{H}$ below 19 °C while there also are a large amount of DDH$_\text{C}$ above 25 °C. For the case with an average U-value of 1.8 W/(m^2·K) there are significantly fewer DDH$_\text{H}$ below 19 °C although there is a larger amount of DDH$_\text{C}$ above 25 °C. For the case with an average U-value of 0.5 W/(m^2·K) it is obvious how there are barely any DDH$_\text{H}$ below 19 °C while there is a considerable amount of DDH$_\text{C}$ above 25 °C.

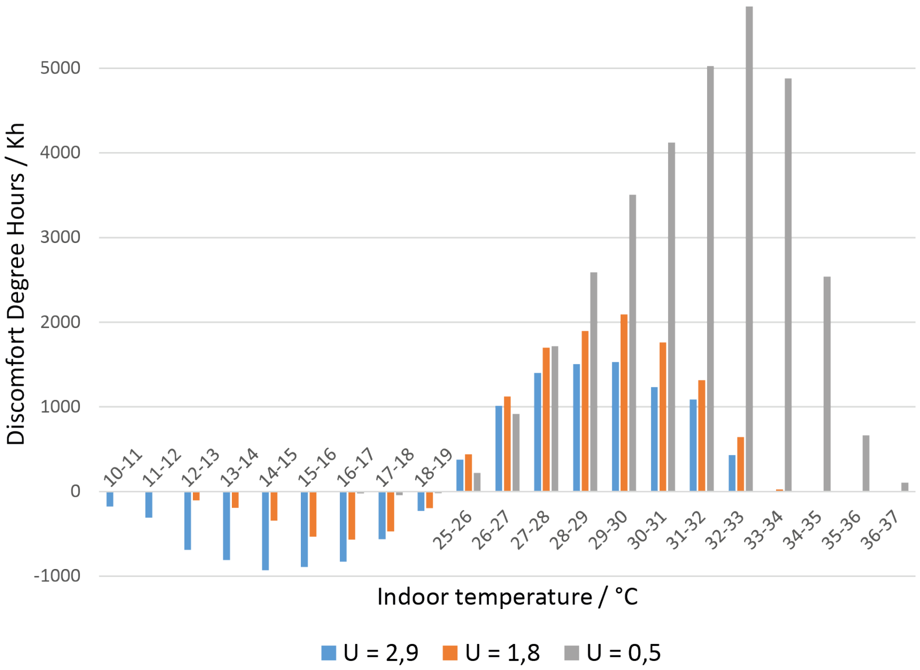
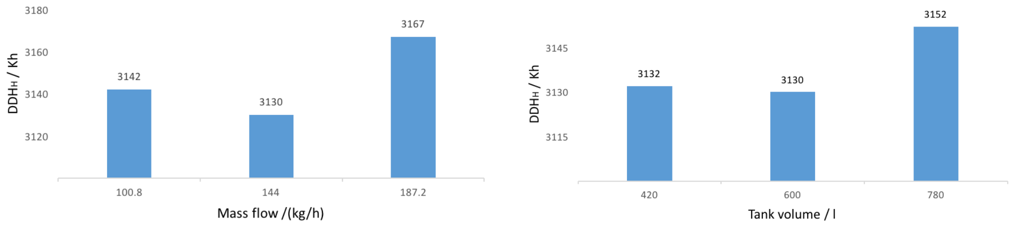


Figure 5.13: Histogram of the distribution and amount of DDH throughout the year for the three different U-values

Sensitivity analysis

To expose the stability of the system, a sensitivity analysis was performed. Each key parameter was adjusted ±30 % of its original optimized value and the number of $\mathrm{DDH_H}$ was once again calculated. The results can be seen in Figures 5.14 to 5.16 below. For the sensitivity analysis of the pump flow and the tank volume, seen in the Figures 5.14(a) and 5.14(b), the heating element was turned off. This since the heating element was turned off when optimizing those parameters in order to be able to maximize the solar collector output without interference from the heating element. In the case when testing the height of the inlet of the tank from the solar collector, the height of the heating element as well as the height of the outlet to the radiator, seen in Figures 5.15(a), 5.15(b) and 5.16, the heating element was turned on. This due to the fact that the placement of the heating element, in combination with the placements of the inlet and outlet had large impact on each other.

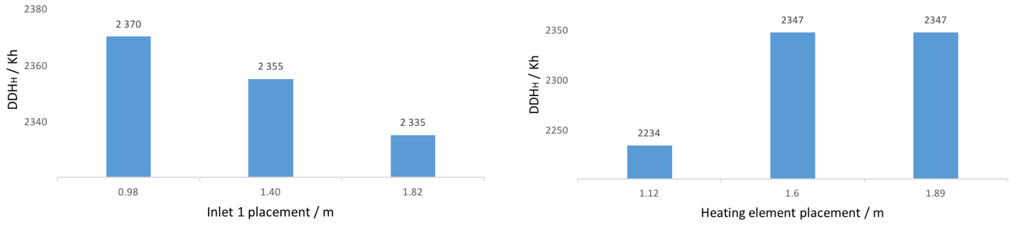
Figure 5.14(a) below, shows the impact of the pump flow on the system, altered by ±30 % to 100.8 l/h, 144 l/h and 187.2 l/h. In this test the heating element was turned off. An increase of the pump flow by 30 % led to an increase of the $\mathrm{DDH_H}$ to 3 167, 1.2 % more than the original value. A decrease of the pump flow by 30 % led to a 0.4 % increase of the $\mathrm{DDH_H}$ to 3 142. The pump flow can therefore be considered to have a small impact on this system. In Figure 5.14(b) below, the system sensitivity depending of the accumulator tank volume is shown. As can be seen in the figure, decreasing the tank volume by 30 % to 420 l has no significant impact and the $\mathrm{DDH_H}$ are increased by less than 0.1 %. However, by increasing the tank volume by 30 % to 780 l a more negative impact was found although it only leads to an increase of 0.7 % of the $\mathrm{DDH_H}$. The tank volume can therefore be considered to have little impact on the amount of $\mathrm{DDH_H}$.



(a) (b)

Figure 5.14: Sensitivity analysis of mass flow (a) and tank volume (b), altered by ±30 % with respect to the amount of DDH_H

In Figure 5.15(a) below, the height of inlet 1 was lowered by 30 % to 0.98 m and raised by 30 % to 1.82 m. The figure indicates that a high inlet would be preferable, lowering the DDH_H by 20, or less than 1 %. However, as shown in the parametric study in Figure 5.5, by doing so the heating element energy consumption increases significantly. The height of inlet 1 can therefore be considered to have little impact on the amount of DDH_H. Figure 5.15(b) below shows the amount of DDH_H with three different heights of the heating element. Lowering the height by 30 % to 1.19 m will reduce the amount of DDH_H by 5 %. Yet, this would mean that the heating element will have to work towards unnecessarily low temperatures, thereby decreasing the energy gained by the solar collector. Placing the heating element slightly further up in the top of the tank at 1.89 m has no impact on the system. This as it still remains in the same node of the tank. Except for when placed in the same node, the placement of the heating element can therefore be considered to have a certain impact on the amount of DDH_H.



(a) (b)

Figure 5.15: Sensitivity analysis of placements of inlet 1 (a) and heating element (b), altered by ±30 % with respect to the amount of DDH_H

In Figure 5.16 below, the height of the outlet leading to the radiator has been altered. Lowering the outlet height by 30 % to 1.19 m, meant an increase in $\mathrm{DDH_H}$ of 26 %. By raising the outlet to the top, at 1.89 m, has no effect on the system. Accordingly this parameter has a far greater impact on the system than any other and is hence considered most crucial.

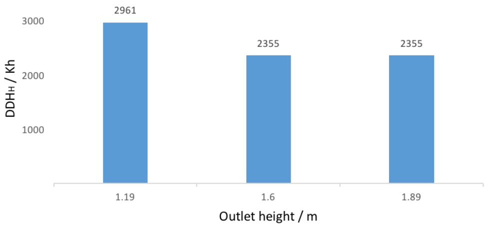


Figure 5.16: Sensitivity analysis of outlet placement, altered by ±30 % with respect to the amount of $\mathrm{DDH_H}$.

Table 2: Breakdown of the amount of $\mathrm{DDH_H}$ achieved with the system turned on and off for the two average U-values of 2.9 $\mathrm{W/(m^2{\cdot}K)}$ and 1.8 $\mathrm{W/(m^2{\cdot}K)}$

Average *U*-value / $\mathrm{W/(m^2{\cdot}K)}$	**System off, $\mathbf{DDH_H}$** /(K·h)	**System on, $\mathbf{DDH_H}$** /(K·h)	**Difference, $\mathbf{DDH_H}$** /(K·h)
2.9	8 271	5 395	2 876
1.8	5 657	2 369	3 288

In Table 2 above, one can read that by just insulating in order to get an average U-value of 1.8 $\mathrm{W/(m^2{\cdot}K)}$, about the same effect is achieved as when using the heating system having an average U-value of 2.9 $\mathrm{W/(m^2{\cdot}K)}$. Furthermore, and more interestingly, the difference between the current houses today in Botswana with no heating and the house with an average U-value of 1.8 $\mathrm{W/(m^2{\cdot}K)}$ with heating is 5 902 $\mathrm{DDH_H}$. In other words, about 70 % of the $\mathrm{DDH_H}$ can be eliminated using this combination. As can be seen in Figure 5.1 below, the amount of $\mathrm{DDH_H}$ mitigated by the system is highly dependent on the average U-value. With an average U-value of 2.9 $\mathrm{W/(m^2{\cdot}K)}$ as is the reality of houses today in Botswana, the system can eliminate 2 876 $\mathrm{DDH_H}$. This means that the house can only eliminate 35 % of the $\mathrm{DDH_H}$ below 19 °C.

As seen in Table 3 of the final outputs, the energy input from the 6 $\mathrm{m^2}$ solar collector is 5 404 kWh. With heating element output of 1 260 kWh and thermal losses of 1 562 kWh, this results in the final energy available for space heating and hot water generation of 5 197 kWh. This results in 2 369 $\mathrm{DDH_H}$ below the set point temperature of 19 °C, compared to 5 657 $\mathrm{DDH_H}$ without using the system. In other words, the SHW heating system is capable of eliminating 3 288 $\mathrm{DDH_H}$, or 58 %, through space heating. As a comparison, by using the same system on a current Botswana house with an average U-value of 2.9 $\mathrm{W/(m^2{\cdot}K)}$ the mitigation is 2 876 $\mathrm{DDH_H}$, or 35 %.

Table 3: SHW system with heating.

(a) Final settings for the SHW heating system.

Parameter	Value
Average U-value	1.8 W/(m^2·K)
Mass flow	144 l/h
Tank volume	600 l
Tank height	1.6 m
Inlet 1 placement	1.4 m
Heating element	1.6 m
Outlet height	1.6 m
Slope angle	48°C

(b) Final output values for the SHW heating system.

Energy outputs	Value
Energy in from solar collector	5 404 kWh
Energy required to HEX*	1 211 kWh
Heating element output	1 260 kWh
Thermal losses	1 562 kWh
Energy net out	5 197 kWh

*Energy required to annually supply the hot water need was calculated through Equation 5 in Section 4.2.

5.2 Optimization of SHW system in combination with PV for hot water and electricity generation (PV+T)

The following chapter is about the second system. As can be seen in Figure 5.17 below, the energy generation to the internal heat exchanger is dependent on the tank size although the dependency is weak. The difference in energy generation between the optimal mass flow of 13 l/h for the 100 l tank and the optimal mass flow of 16 l/h for the 200 l tank is only 14 kWh or approximately 1 %. A difference nonetheless and the largest energy generation of 1250 kWh is obtained with a mass flow of 13 l/h for a 100 l tank. It is possible that an even smaller tank could result in a higher energy generation. However, the fact that the test below examines the recommended span of litres of tank based on a 2 m^2 solar collector in combination with the difference being insignificant, a decision was made not to examine further. According to the method of calculating the hot water energy need presented in Section 4.2, the 2 m^2 of solar collector area was chosen for this system. This is also the same area as the local supplier SolaHart is using for its smallest thermosiphon system [6].

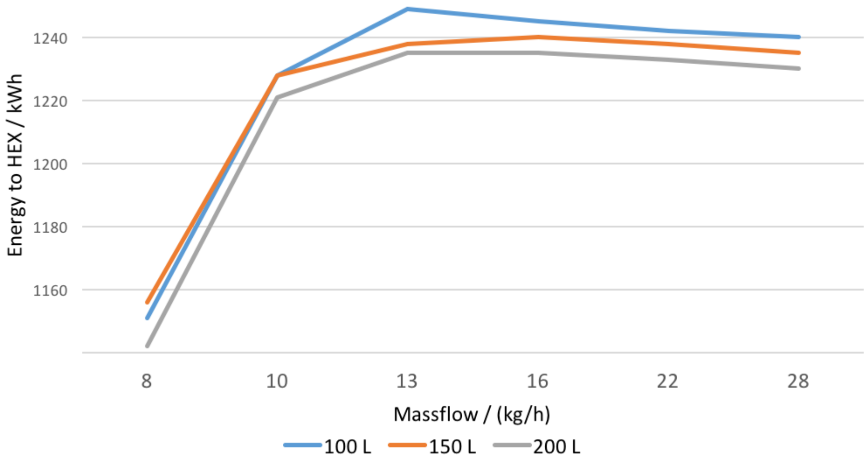


Figure 5.17: Optimization of mass flow and tank size from the 2 m^2 solar collector with respect to energy generation to the internal heat exchanger.

In Figure 5.18 below, it can be seen how placement of the heating element affects not only the energy output to the heat exchanger but also the amount of energy consumed by the heating element. More specifically, it can be seen that if the heating element for example is placed at 0.7 m it consumes 35 kWh over the course of a year. However, if placed at 0.8 m it consumes only 33 kWh while the net energy generation is 16 kWh higher than the previous example of placement. With these arguments in consideration, the heating element was placed at a height of 0.8 m.

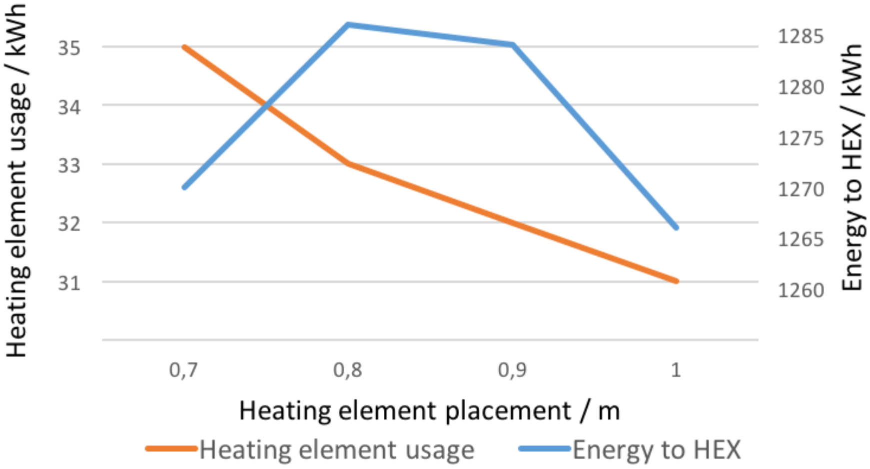


Figure 5.18: Optimization of heating element placement with respect to heating element consumption as well as energy generated to the internal heat exchanger.

In Figure 5.19 below, it can be seen how the placement of inlet 1 affects the energy generation to the internal heat exchanger. By moving the inlet from a height between 0.6 m and 0.7 m to a height of between 0.8 m and 0.9 m the energy generation can be increased by approximately 1 %, from 1267 kWh to 1286 kWh. Heights 0.6 m, 0.7 m and 0.8 m, 0.9 m are in the same nodes respectively which is the reason for the partial linearity of the graph. However, as the change in net energy output happens at 0.8 m this is the chosen height of inlet 1.

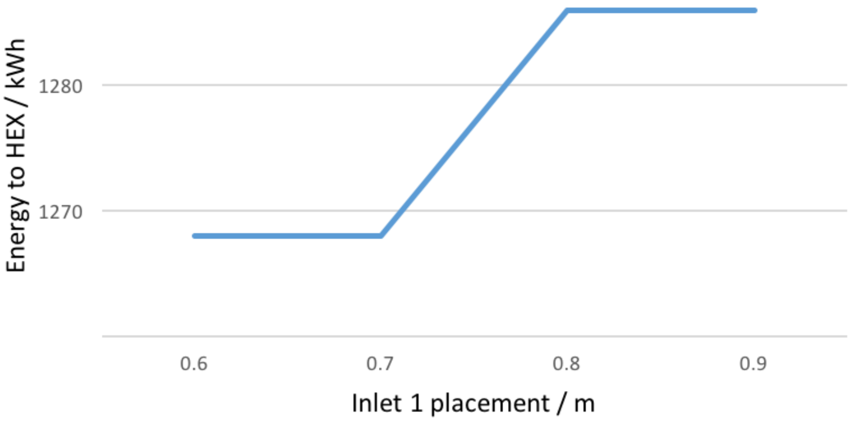


Figure 5.19: Optimization of heating element placement with respect to net energy generation to the internal heat exchanger.

In Figure 5.20 below, the energy generation to the heat exchanger as a function of the collector slope can be seen represented by the blue line. This parameter considers the fact that an increased amount of heat implies more thermal losses from the tank. A slope angle of 26° is optimal to receive the highest amount of energy to the hot water generation. It is interesting how this angle differs from the optimal angle for the heating system in the previous chapter. This is due to the fact that the heating system is optimized to have maximal energy generation during winter when the heating is needed. If the optimal angle for the system in this chapter would be used for the heating system, the thermal losses during summer would be much greater while energy generation during winter would be lower.

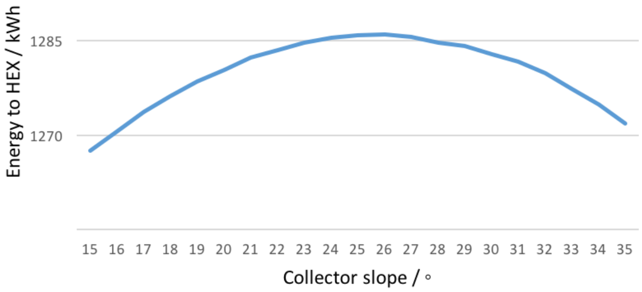


Figure 5.20: Optimization of the 2 m^2 solar collector angle with respect to energy output to the internal heat exchanger.

As seen in Figure 5.21 below, the optimal angle for the solar PV panel is the same as the optimal angle for the solar collector. A difference due to thermal losses was expected to shift the optimal angle for the thermal collector. However, as the results show, the gain in additional energy added to the tank is not outweighed by the thermal losses.

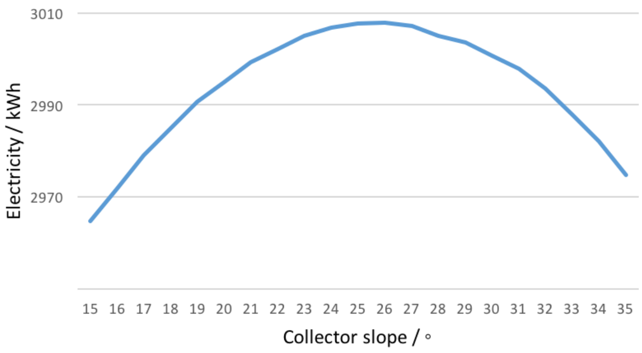
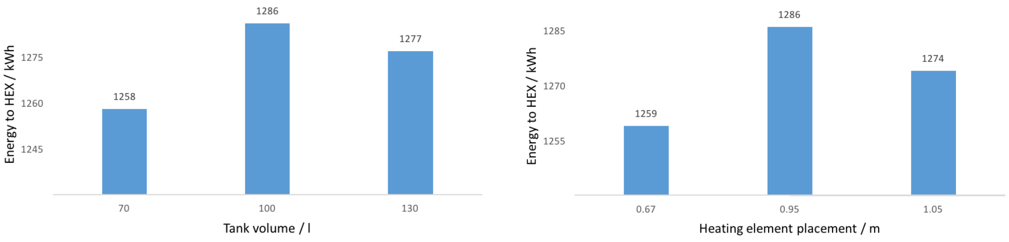


Figure 5.21: Optimization of the 13.35 m^2 solar PV array angle with respect to electricity generation.

Sensitivity analysis

To expose the stability of the system, a sensitivity analysis was performed where each key parameter was adjusted by ±30 % of its original optimized value. The results can be seen in Figure 5.22 and 5.23. Furthermore, the hot water usage pattern was also adjusted to demonstrate the sensitivity of future changes.

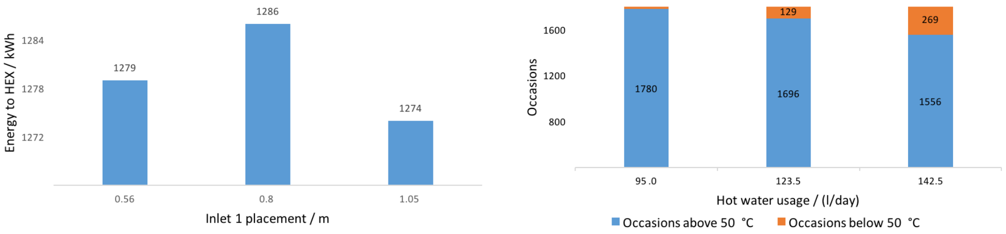
As seen in Figure 5.22(a) below, with a 30 % smaller tank volume of 70 l, the amount of energy to the heat exchanger decreases by 2 %. For a 30 % larger tank volume of 130 l, the amount of energy to the heat exchanger decreases by 0.7 %. The tank volume is therefore considered to have a small impact on the system. As seen in Figure 5.22(b) below, by decreasing the height of the heating element placement by 30 % to 0.67 m, resulted in a decrease in the amount of energy to the heat exchanger by approximately 2 %. For the maximum height of the heating element placement, at the top of the tank at 1.05 m, the amount of energy to the heat exchanger decreases with 0.7 %. The height of the heating element placement is therefore considered to have a small impact on the system.



(a) (b)

Figure 5.22: Sensitivity analysis of tank volume (a) and heating element placement (b), altered by ±30 % with respect to energy output to the internal heat exchanger.

As seen in Figure 5.23(a) below, with a 30 % decrease of the height of inlet 1 to 0.56 m, the energy to the heat exchanger decreases by 0.5 %. For the maximum height of the inlet 1, at 1.05 m, the energy to the heat exchanger decreases by 0.9 %. The height of inlet 1 is therefore considered to have a small impact on the system. In Figure 5.23(b) below, the amount of occasions where the water temperature going to the tap water falls below 50 °C can be seen. The amount of occasion where the water temperature going to the shower falls below 50 °C is highly dependent on the consumption. A 50 % consumption increase results in a 600 % increase in occasions under 50 °C. However, after studying the occasions in relation to each other, the same conclusion as before is drawn: they do not happen in succession.



(a) (b)

Figure 5.23: Sensitivity analysis of inlet 1 placement (a) and hot water consumption (b), altered by ±30 % with respect to energy output to the internal heat exchanger and occasions below 50 °C for the tap water respectively.

In Table 4 below, the final settings (a) and outputs (b) of the SHW system in combination with PV for hot water and electricity generation can be seen.

Table 4: SHW system with a PV panel + a thermal collector.

(a) Final settings for the PV+T-system.

Parameter	**Value**
Mass flow	13 l/h
Tank volume	100 l
Tank height	1.6 m
Inlet 1 placement	0.8 m
Heating element placement	0.8 m
Tank height	1.05 m
Slope angle*	26°C

(b) Final values for the PV+T-system.

Energy ouputs	**Value**
Energy to HEX	1 286 kWh
Energy required to HEX*	1 211 kWh
Heating element output	33 kWh
Thermal losses	554 kWh
Electricity generated	3 008 kWh

*Same values as for previous system

5.3 Optimization of PV/T-system

The system has been optimized with both the net electricity and the energy transferred to the internal heat exchanger as key parameters. As seen in Figure 5.24 below, four different sizes of the accumulator tank were tested, varying from 300 l to 500 l with increments of 100 l. Each tank size was further tested with altered pump flow, varying from 10 to 140 l/hr with an increment of 10 l/hr. As evident, the combination of a 600 l tank and a mass flow of 140 l/h generates the most energy. However, the combination of a 300 l tank and a mass flow of 113 l/h generates only 20 kWh, or approximately 1 %, less. With price differences associated with different tank sizes in consideration, the smaller tank was preferred. The same optimal slope angle of 26° used for the PV+T system was used in this optimization as the PV/T collector is both a PV and thermal collector.

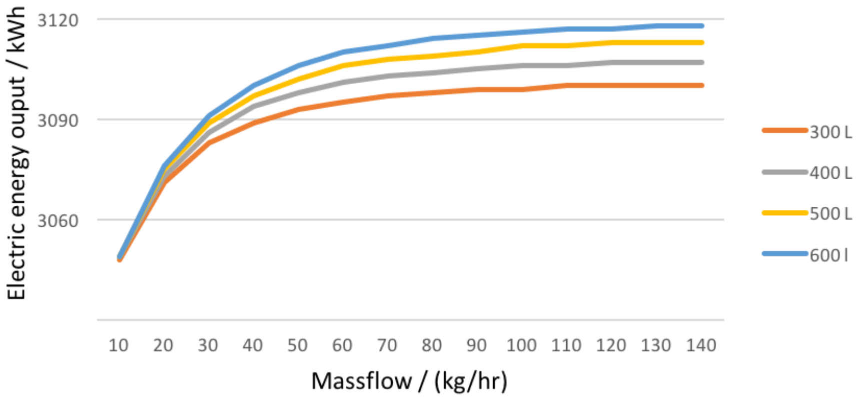


Figure 5.24: Optimization of the tank volume and pump flow with respect to electricity output.

In Figure 5.25 below, it can be seen how the placement of the heating element affects not only the amount of energy generated to the heat exchanger but also the amount of energy consumed by the heating element. More specifically, it can be seen that if the heating element is placed between 1.1

m and 1.2 m it consumes 301 kWh over the course of a year while the energy output to the heat exchanger is 1175 kWh. However, if placed between 1.3 m and 1.4 m it consumes only 147 kWh while the energy output to the heat exchanger is 1 163 kWh. In other words, getting 12 kWh more to the heat exchanger would cost 154 kWh in heating element consumption, which is not preferable. With this argument in consideration, the heating element was placed at a height of 1.3 m.

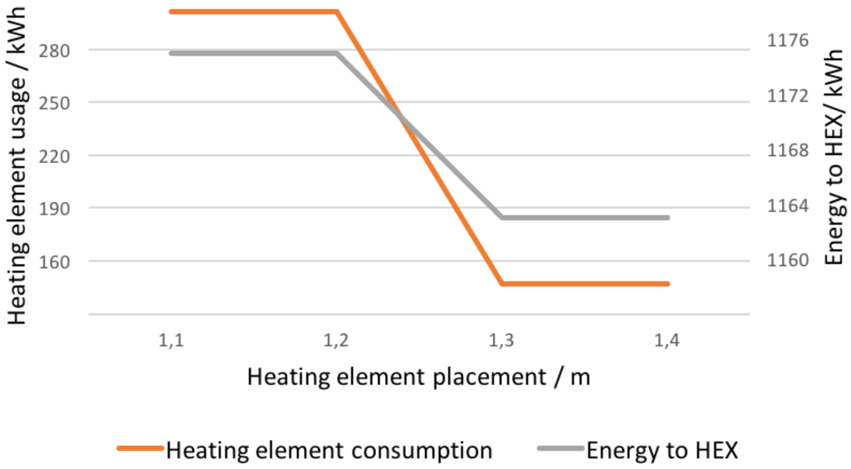


Figure 5.25: Optimization of the heating element placement with respect to energy output to the internal heat exchanger.

In Figure 5.26 below, the height of inlet 1 was altered from 0.6 m to 1.4 m, with an increment of 0.1 m. The inlet placement proved to have little impact on the energy transferred as it differed by 2 % for the different placements. As the highest energy output is reached with an inlet placement of 1 m and up, 1 m has been chosen as the optimal height of inlet 1.

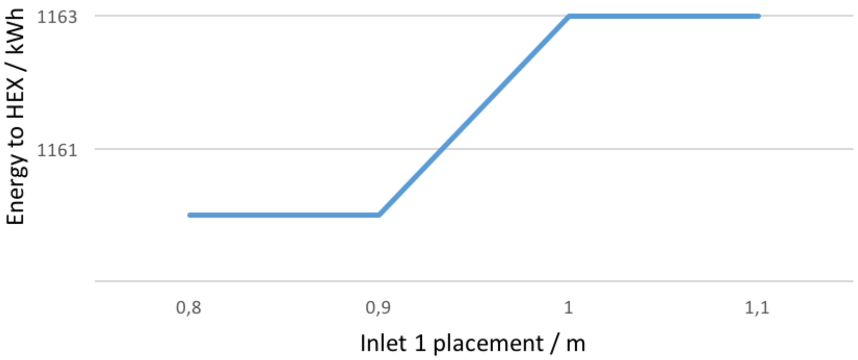
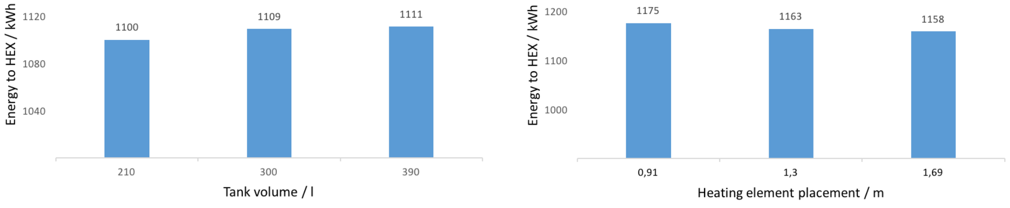


Figure 5.26: Optimization of inlet 1 placement with respect to energy output to the heat exchanger.

Sensitivity analysis

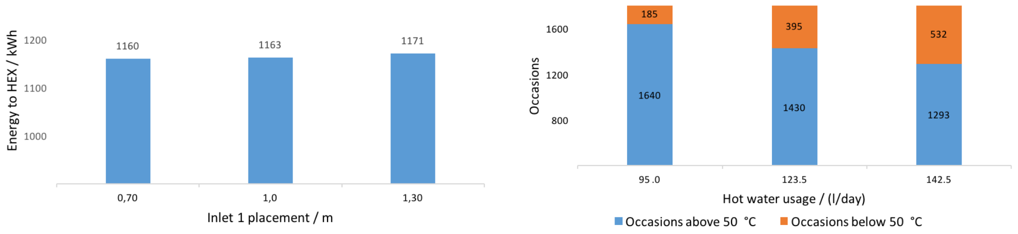
To expose the stability of the system, a sensitivity analysis was performed where each key parameter was adjusted by ±30 % of its original optimized value. The results can be seen in Figures 5.27 and 5.28. As seen in Figure 5.27(a) below, with a 30 % decrease of the tank volume to 210 l, the generated electricity decreases by less than 1 %. Furthermore, by increasing the volume by 30 %, to 390 l, the energy to the internal heat exchanger decreases by less than 1 %. The tank volume is therefore considered to have a small impact on the amount of energy to the heat exchanger. As seen in Figure 5.27(b) below, by lowering the heating element placement by 30 %, a 1 % increase of the amount of energy to the heat exchanger, from 1 163 kWh to 1 175 kWh is achieved. By raising the heating element placement by 30 %, a less than 1 % decrease of the amount of energy to the heat exchanger, from 1 163 kWh to 1 158 kWh is achieved. The heating element placement is therefore considered to have a small impact on the energy output to the heat exchanger.



(a) (b)

Figure 5.27: Sensitivity analysis of tank volume (a) and heating element placement (b), altered by ±30 % with respect to energy output to the heat exchanger.

As seen in Figure 5.28 below, with a 30 % decrease of the inlet 1 placement height to 0.7 m, the generated electricity decreases by less than 1 % from 1163 kWh to 1160 kWh. Also, by increasing the inlet 1 placement height by 30 %, to 1.43 m, the generated energy output to the heat exchanger increases by less than 1 % from 1163 kWh to 1171 kWh. The inlet 1 placement is therefore considered to have a small impact on the amount of energy transferred to the heat exchanger. As seen in Figure 5.28(b), the impact of a 30 % and 50 % increase respectively is much greater on the PV/T system than on the PV+T system. The amount of occasions where the water temperature out of the internal heat exchanger falls below 50 °C is as can be seen highly dependent on the consumption. A 50 % increase results in a 280 % increase in occasions under 50 °C. However, after studying the occasions in relation to each other, the same conclusion as before is drawn: they do not happen in succession.



(a) (b)

Figure 5.28: Sensitivity analysis of inlet 1 placement (a) and hot water consumption (b), altered by ±30 % with respect to the of energy output to the heat exchanger and occasions below 50 °C for the shower respectively.

In Table 5 below, the final settings (a) and outputs (b) of the PV/T system for hot water and electricity generation can be seen.

Table 5: SHW system with a PV/T collector.

(a) Final settings for the PV/T-system.

Parameter	**Value**
Mass flow	110 l/h
Tank volume	300 l
Tank height	1.6 m
Inlet 1 placement	1 m
Heating element placement	1.3 m
Tank height	1.51 m
Slope angle*	26°C

(b) Final values for the PV/T-system.

Energy outputs	**Value**
Energy to HEX	1 163 kWh
Energy required to HEX*	1 211 kWh
Heating element output	147 kWh
Thermal losses	1 150 kWh
Electricity generated	3 100 kWh

*Same values as for previous systems

5.4 Applying an AC unit to the systems

The AC unit used in the simulations had a set point temperature, i.e. an outlet dry-bulb temperature, of 21 °C. As seen in the first column in Figure 5.29 below, the amount of DDH_C above 25 °C was 8 300. This applies to an existing building with an average U-value of 2.9 $\text{W}/(\text{m}^2{\cdot}\text{K})$, before installing the AC unit. The indoor temperature for this system strongly correlates to the ambient outdoor temperature. With insulation and an average U-value of 0.5 $\text{W}/(\text{m}^2{\cdot}\text{K})$, the annual indoor temperature increased severely, with the amount of DDH_C raised to 32 000. With a typical conventional AC unit [45] applied to the system, the amount of DDH_C decreased by 72 % to 9 038 for the insulated house and by 32 % to 5 604 for the house with the average U-value of 2.9 $\text{W}/(\text{m}^2{\cdot}\text{K})$. According to these results it would not be beneficial to insulate the house, as the better working AC unit does not compensate for the amount of added DDH_C. However, what also can be seen is how the amount of DDH_C get significantly lower for the case with the better insulation when two AC units are used. The Figure 5.29 further shows that with just one standard AC unit installed, the indoor comfort will be better without insulation. However, with two AC units or more, and an air flow of 1 200 kg/h in a 100 m^2 house, indoor comfort will be improved significantly also during summer with the recommended insulation of 0.5 W/(m^2·K). The three different yellow nuances in the graph below are the three different cases with an average U-value of 2.9 W/(m^2·K), where either no AC unit, one or two AC units are used in combination. The three different blue nuances symbolizes the same three different cases used, but in combination with an average U-value of 0.5 W/(m^2·K).

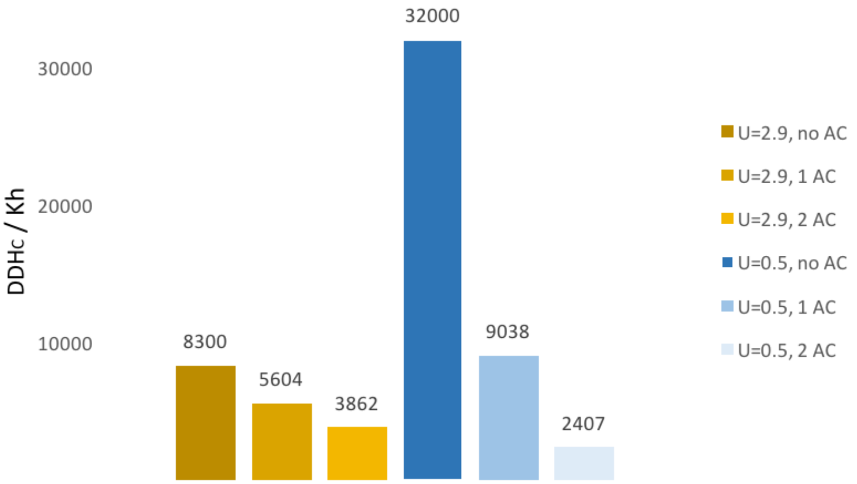


Figure 5.29: Amount of DDH$_C$ for the two different average U-values dependent on whether none, one or two AC units are used.

As can be seen below in Figure 5.30, the improvements regarding amount of DDH$_C$ from the AC unit is significantly higher when the improved insulation is used. However, a better performing solution is also associated with a higher cost in energy. For the case with an average U-value of 2.9 W/(m^2·K), 1 459 kWh is required to reach a 32 % improvement. To reach a 53 % improvement, 2 540 kWh is required. For the case with an average U-value of 0.5 W/(m^2·K), 2 334 kWh is required to reach a 72 % improvement. To reach a 92 % improvement, 3 267 kWh is required. In other words, improved indoor comfort can be achieved through the combination of good insulation and more than one AC unit, although at a higher cost in energy.

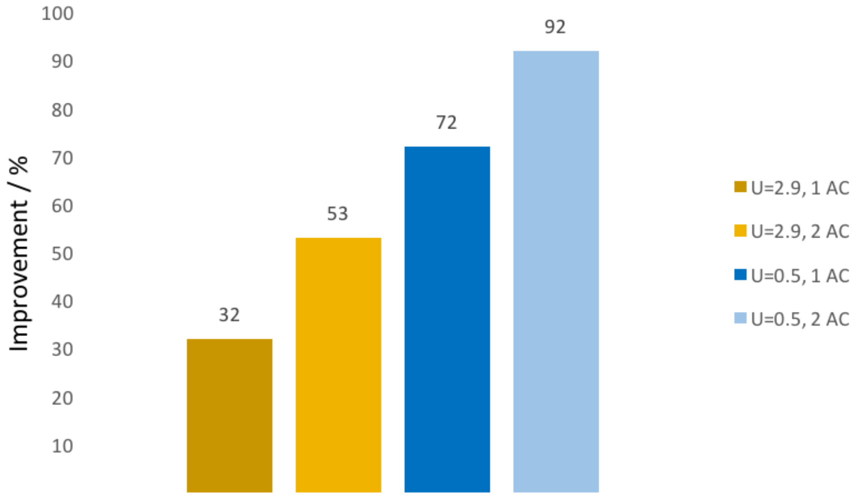


Figure 5.30: Improvements in % compared to no use of AC unit for the two systems with either one or two AC units installed.

From Figure 5.31 below, it can be seen what insignificant impact the AC unit has in the case with no insulation and an average *U*-value of 2.9 W/(m^2·K). The temperature with and without an AC unit is not that different although the peaks are shaved off. Furthermore, the AC unit does almost no work during winter although there are a few peaks that are affected. This due to the fact that the indoor temperature never reach 21 °C, which is the trigger for the AC unit to start.

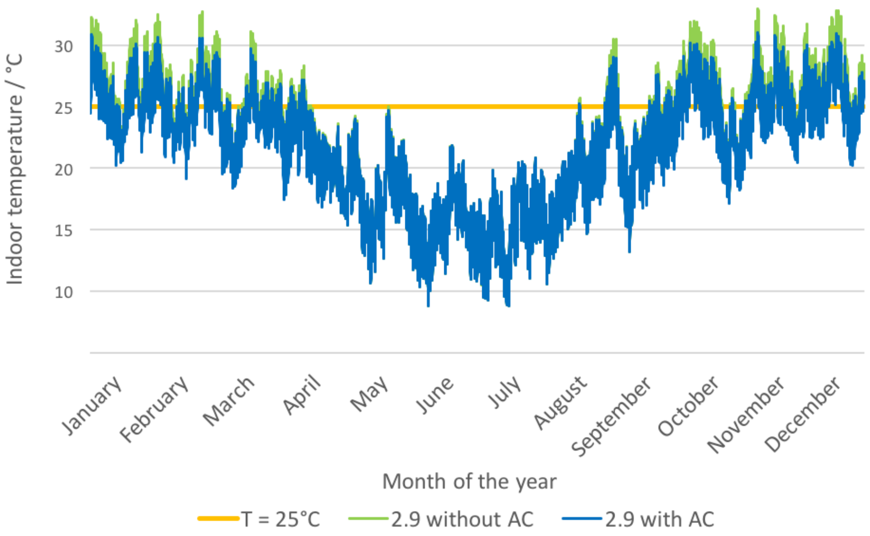


Figure 5.31: Indoor temperature as a function of time, with an average *U*-value of 2.9 W/(m^2·K), dependent on whether the AC unit is on or off.

From Figure 5.32 below, it becomes clear how the AC unit affects the indoor temperature in the case with an average U-value of 0.5 W/(m^2·K). It is pushed towards the desirable 25 °C line and the oscillations are decreased. It even does some work during winter as the indoor temperatures sometimes reach 21 °C which triggers the AC unit to start.

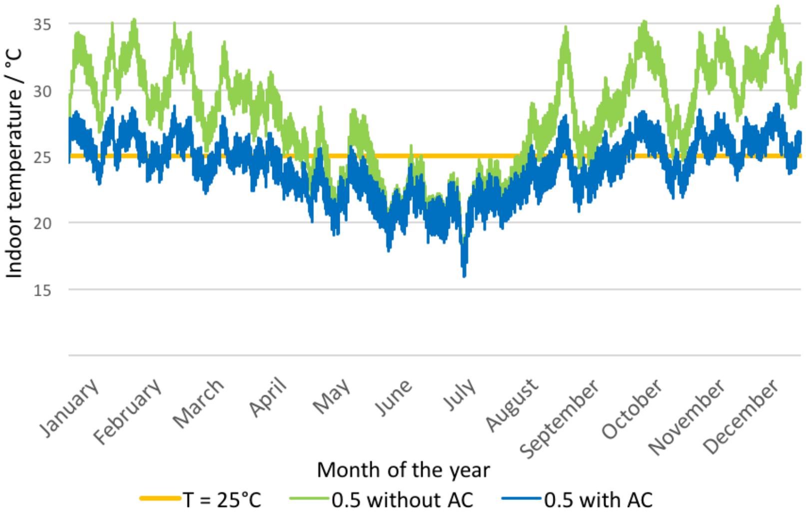


Figure 5.32: Indoor temperature as a function of time, with an average U-value of 0.5 W/(m^2·K), dependent on whether the AC unit is on or off.

5.5 Final results

In Figure 5.33 below, the annual indoor temperature of a typical four person residential house in Botswana, without any heating during winter, but with an AC unit during summer can be seen. For the case with an average U-value of 2.9 W/(m^2·K), seen as the green line, it results in 8 271 DDH$_\mathrm{H}$ during winter and 4 604 DDH$_\mathrm{C}$ during summer. For the case with an average U-value of 0.5 W/(m^2·K), seen as the blue line, it results in 82 DDH$_\mathrm{H}$ during winter and 9 038 DDH$_\mathrm{C}$ during summer. As can be seen, the indoor temperature is clearly improved during winter and even though the summers in general will be somewhat warmer, the worst heat peaks are smaller. Furthermore, after having optimized the two systems without heating, it was found that both solutions resulted in a solar savings fraction of 0.84 when assuming a household consumption of 5 000 kWh/year. The data from BPC used to calculate this household consumption may in some cases include an AC unit and in some not, as it depends on the households investigated. This assumption was based on data of costumer energy consumption provided by BPC.

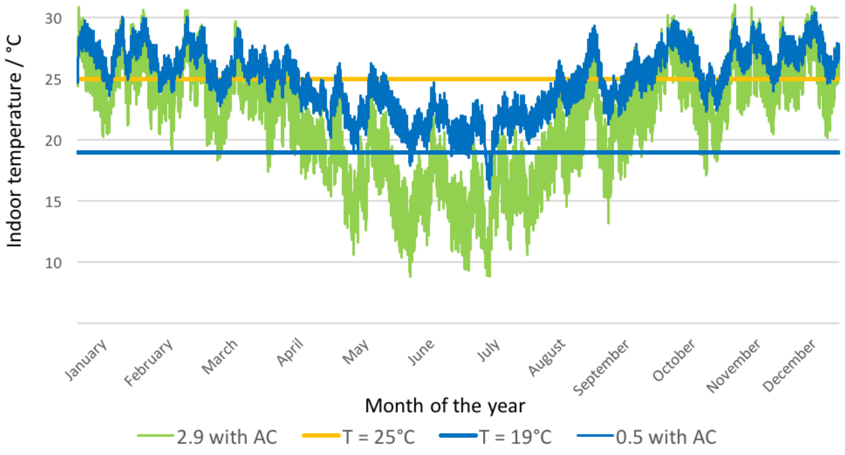


Figure 5.33: Indoor temperature without heating but with an AC unit, for an average U-value of 2.9 W/(m^2·K) and 0.5 W/(m^2·K) respectively.

5.6 Cost analysis

As the heating system proved not to be viable due to low effect on the indoor temperature in combination with very specific requirements for needed insulation, it was not considered in this cost analysis. The analysis is an economical comparison between the PV+T system and the hybrid PV/T system. Components considered in this calculation are listed in the table below:

Table 6: Component costs for the different systems.

Component	**PV + T 13.35 m^2+2 m^2**	**PV/T (13.35 m^2)**
Panel	21 500 SEK [1]	85 800 SEK [2]
Tank	8 200 SEK (100 l) [3]	10 400 (300 l)
Heating element	290 SEK 2.4 kW[6]	320 SEK 3.6 kW[6]
Insulation	14 000 SEK	14 000 SEK
Total	44 000 SEK	110 500 SEK

The market price of hybrid PV/T collectors range between 450 €/m^2 to 950 €/m^2 [47]. Consequently, the average price of 690 €/m^2 has been used in the comparison. For standard glazed solar thermal collectors, the costs are considered to be 350 €/m^2 and 120 €/m^2 for photovoltaic polycrystalline modules. These prices are all in accordance with a study conducted by Tomas Matuska at the *University Centre for Energy Efficient Buildings, Czech Technical University in Prague* [47]. The study was conducted in 2013 and the prices of PV panels have since decreased. Likely, so have prices of solar thermal collectors and PV/T collectors as well. However, as the price change of PV/T collectors is scarcely studied, the values above are considered to give the most fair comparison. The study further declares that if the market price of selective glazed PV/T collectors would be maintained under 420 €/m^2, large application potential would open up for standard solar

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[1] PV: 13.35 m^2 ·120 €/m^2+2 m^2 ·350 €/m^2= 2 302 € ⇒ 21 500 SEK

[2] PV/T: 13.35 m^2 ·650 €/m^2= 9 212 € ⇒ 85 800 SEK

[3] Tank prices estimated based on prices from *My Solar Shop* [46]

thermal applications in buildings for domestic hot water and space heating systems. Other than the ones above are costs related to components like piping, valves, controllers, thermostats, pumps as well as installation costs. However, these costs are considered to be the same or very similar for the two systems and will therefore not be further evaluated. Also, for this cost analysis it is estimated that the maintenance cost for both the systems are the same. Different sizes of heating elements was used since the PV/T system required additional heating to keep the set point temperature. Furthermore, an estimation of the additional material and installation cost for the insulation in a new building construction can be seen below: Area needed for insulation A_{tot} is calculated by:

$$A_{tot,insulation} = A_{walls} + A_{roof} - A_{windows} = 187.5\ m^2 \tag{9}$$

With a 60 mm insulation thickness, resulting in an average U-value of 0.5 W/(m^2·K), a cost of approximately 14 000 SEK is expected [48].

6 Discussion

This chapter will bring out discussions about the report as a whole as well as the individual chapters. There are two ways of improving indoor climate through improved temperature. Either to raise the temperature during winter when it is too cold, or by lowering the temperature during summer when it is too hot. Thereby, one strive to achieve a more stable temperature that does not go too high nor too low. This has been the goal throughout the process when the three systems have been studied. The sensitivity analyses for all three systems proved the optimization processes in combination with assumptions made to be correct. Common for all sensitivity analyses was that they proved the differences in the chosen interval to be small. This proved that the optimization processes in combination with the assumptions was correct. Furthermore, there are many other ways to improve indoor climate in the same way that has been done in this report regarding improved indoor temperature. Mechanical ventilation can be used to increase the air flow inside the building. Today natural ventilation is the only mean of ventilation implemented. A substantial contribution of the indoor temperature increase can be derived from direct solar irradiation, i.e. beam radiation. This can be prevented through the use of solar shading in the form of for example blinds.

The results in this thesis are much in line with the National Energy Policy presented in 1.1.1. The government of Botswana are expressing their will to diversify, and thereby secure, domestic energy generation. The PV+T system and the PV/T system addresses this need from two sides. Firstly, it would reduce the electricity need from the grid. Secondly, with possible policy changes allowing for private individuals to sell excess electricity generation back to the grid, less import dependence could be expected.

6.1 Optimization of SHW system for heating and hot water generation

It has been shown to be complicated when designing a SHW system to cover both the space heating demand as well as the hot water demand. Normally, the heating demand is highly seasonal while the hot water usage is quite constant all year round. This proved to be difficult when determining the size of the system, both regarding the accumulator tank and the solar collector. Considering the substantial cost associated with a SHW system for heating, this is not a viable solution to the space heating problem. There is no reason to insulate a house in order to be able to use such a system when better insulation will leave heating unnecessary. During the field study it became clear that upfront cost is a very crucial aspect and people in Botswana therefore consider a 5 year to 8 year pay back time as far too long. Maintenance is another issue as there is a lack of knowledge and qualified technicians in the matter. The reason for the small difference between slope angles for winter compared to the whole year is believed to be due to higher thermal losses that were found.

The translation factor chosen in chapter 5.1 is only valid for this specific time and house. By performing the investigation during another period of time, the value of the translation factor would be altered. Furthermore, if another translation factor had been chosen, the simulations would have given different results. For example, the heating element placement might have differed, which then would affect the rest of the optimization. For an even more accurate optimization based on energy use, the auxiliary energy use should be minimized instead.

6.2 Optimization of SHW system in combination with PV for hot water and electricity generation

The comprehensive thermal losses for the tank is possibly a result of an oversized system. However, to evaluate a smaller solar collector area is not of interest. Such a system would be considered too sensitive to an increase of hot water consumption and unnecessarily expensive per kWh. Furthermore, it is the same collector area as the smallest system sold by local supplier Solahart, which enforces that decision further. By adjusting the hot water profile, the heating system could prove its strength as well as its insensitivity against future variations for the user profile. As seen in the results, more specifically Figure 5.23, the system is robust and can handle increased hot water consumption of up to 50 % without any risk of development of legionella worth mentioning. It also became clear that tampering with the tank volume, heating element and inlet placement by ±30 % had little effect as non of them increased or decreased the system output more than 2 %. Furthermore, it is a well designed system as the heating element only consumes 33 kWh per year. This extra heat is used exclusively to raise the temperature at the top of the tank from approximately 48 °C – 49.5 °C to just over 50 °C.

6.3 Optimization of PV/T

When optimizing the PV/T system, a packing factor of 1 was used which means that solar cells cover the entire area of the solar collector, thereby prioritizing electricity generation. This was to address the electricity deficit in Botswana, reducing the amount of electricity needed from the grid. By using a lower value of the packing factor, thereby allowing more sunlight to directly hit the solar collector, a larger hot water output would be achieved. It was proven that 2 m^2 of solar collectors is enough to provide hot water for the consumption decided upon. This means that in case more hot water is prioritized for a certain house, PV/T collectors with a lower packing factor can be used without changing the size of the panels. Compared to the PV+T system, this system is not as robust when it comes to handling a higher hot water consumption. However, even this system can handle it with respect to risk for development of legionella. It became clear that by just notifying the amount of times where the temperature to the shower drops below 50 °C is misleading as a tool to determine risk for legionella development. It is about the time these occasions occur rather than how many they are in number that will determine that risk. Changes in the hot water consumption in this PV/T system has a larger effect than it has on the PV+T system. This since the PV/T collector proved to provide the tank with lower temperature water than a regular solar collector. This has to do with the high packing factor of 1. Thereby the water gets no direct heat from the sun and only heat from the hot PV cells. Consequently, the heating element has to do more work in order to reach the required water temperature. The heating element consumption is five times larger than for the PV+T case, but the difference is still only 114 kWh. With the electricity prices of 2014 it would cost approximately 75 BWP or 57 SEK and would therefore not likely be an important factor in a decision between one or the other. Furthermore, a regular PV installation is a more common procedure in Botswana than a PV/T installation. This is an advantage that is not visible in either the performance analysis or the cost analysis. An obstacle that is however not sufficiently researched in this report in order to quantify it. The electricity output from the PV/T collector was expected to generate more than it did. With output of 3100 kWh from the PV/T collector compared to 3008 kWh from the PV panel, a moderate 3 % increase was achieved.

6.4 Applying an AC unit to the systems

The large amount of DDH_C received in the case with the 60 mm insulation is strongly connected to the fact that the direct solar irradiation through the windows remain the same. However, in this case the heat gets trapped by the high insulation in the walls, which leads to the large increase in amount of DDH_C. This could have been partially avoided by using passive methods such as solar shading, reducing the solar heat gains. Yet, due to lack of time, passive methods were not studied in this report. The results show how the effect of the AC unit on the indoor comfort improves significantly with the improved insulation. Depending on whether one or two AC units are used the improvement of indoor climate is either 72 % or 92 % when an average U-value of 0.5 W/(m^2·K) is used. These are clearly noticeable improvements and with two AC units the temperature scarcely go above 25 °C. This can be compared to improvements of 32 % and 53 % respectively when an average U-value of 2.9 W/(m^2·K) is used, seen in Section 5.4. However, a higher energy consumption is associated with this improved performance. More specifically, when one AC unit is used, the case with the average U-value of 0.5 W/(m^2·K) results in an increase in energy consumption of 60 %. The same comparison but with two AC units show a smaller 29 % increase in energy consumption. It is interesting how the difference is smaller for the case when two AC units are used. This can be related to the fact that the last 1000 $\mathrm{DDH_C}$ are more difficult to eliminate than the first 1000 $\mathrm{DDH_C}$. In other words, if a curve would be fitted to the bars in Figure 5.29 for the two cases the curves would flatten out. This can be compared to how 10 mm of rock wool insulation decreases the average U-value by 38 % from 2.9 W/(m^2·K) to 1.8 W/(m^2·K). A 60 mm of rock wool insulation results in a decrease in average U-value of 83 % from 2.9 W/(m^2·K) to 0.5 W/(m^2·K). This is not a six times as large decrease as with the six times thinner insulation. To conclude, it will come down to whether one is willing to pay slightly more for highly improved indoor comfort during summer or not. Regular residential AC units are in the interval of about 500 m^3/h to 830 m^3/h [45] where it for this report was chosen to simulate using an average at 600 m^3/h. For this reason, one AC unit does not give enough to compensate for the amount of $\mathrm{DDH_C}$ added by the improved insulation. Consequently, two AC units does compensate for it but reaching a 92 % improvement might not be needed. However, one could either use a more powerful AC unit or two smaller ones to prevent costs of both initial investment and energy consumption to increase unnecessarily much. Yet, the difference of using for example two 450 m^3/h AC units instead of one 900 m^3/h AC units has not been studied. Furthermore, the results above were made as a relative comparison between the two cases with either an average U-value of 0.5 W/(m^2·K) or an average U-value of 2.9 W/(m^2·K) . The AC units have been running as long as the indoor temperature has been above the set point temperature of 21 °C. This even if people during most of the week are at work during the day. However, this still allowed for the most fair comparison between the two cases. Worth mentioning is that another automatic control could lower the consumption. Yet, this was only meant to make a comparison to prove that the large amount of added $\mathrm{DDH_C}$ can be handled easier with the improved insulation.

6.5 Cost analysis

As costs have not been able to be retrieved locally in Botswana, no pay back times have been calculated. However, a hypothetical discussion of the pay back times was made. As seen in Table 1 in Section 1.1.2, the average selling prices increased from 0.36 BWP to 0.65 BWP per kWh between 2010 and 2014, which results in a 180 % increase. With solar collectors, PVs, or PV/T the electricity price is constant throughout the years. Although one would have to account for the slight decrease in panel efficiency as well as maintenance over the years. Two scenarios can be considered, in which the first one, electricity prices keep increasing at the same pace as for the last four years. In the second scenario, the price trend slows down by 50 %. Depending on which scenario is closest to reality, the price in 10 years from 2014 is either 2.80 BWP or 1.50 BWP per kWh. Although these scenarios are hypothetical they are not unrealistic as the power output of the Moropule A is still zero. Possible problems or costs associated with introducing a new type of panel, the hybrid PV/T, to the market and thereby the installers, are difficult to predict and quantify and have therefore not been applied in the comparison calculations.

7 Conclusion

Regarding raising the temperature during winter, the results show that the solar heating system is not a viable solution. This is due to the way houses are built in Botswana today where most of the added heat escapes through the non-insulated walls and roof. In the other case where insulation is added, the heating system is no longer needed. In other words, it is not realistic to believe that someone with the option to insulate in a fashion that makes them require no heating would instead insulate less only in order to be able to use a SHW heating system. Thereby the conclusion that SHW heating, or any type of heating for that matter, in Botswana is not a viable solution due to poorly insulated houses can be drawn. However, the poor indoor climate during winter can be solved by adding reasonable amounts of insulation to the houses.

Regarding lowering the temperature during summer, the results show that better insulation used to improve climate during winter, resulting in a U-value of 0.5 W/(m^2·K), adds a large amount of DDH$_\mathrm{C}$. However, the improved insulation does at the same time make the AC work substantially more efficient as 72 % of the DDH$_\mathrm{C}$ could be removed compared to 32 % with houses as they are today in Botswana. Yet, with an air mass flow of 600 kg/h achieved in a typical AC unit, the improved performance from the AC due to the better insulation does not compensate for the amount of added DDH$_\mathrm{C}$. Worth mentioning though is that this result is based on the assumption that a residential house only has one AC unit. In the case where there are two or more AC units, the indoor climate is improved also during summer with the use of the better insulation although at a higher cost in electricity consumption. In this report, the two latter systems generate both electricity to reduce the use of the grid as well as hot water to almost fully sustain that need. It was shown that both the system with thermal collector in combination with PV as well as hybrid PV/T system can provide electricity and enough hot water to meet the domestic hot water consumption. Yet, the PV/T system generates 3 100 kWh of electricity compared to 3 008 kWh from the PV+T system, which is approximately 3 % more. In other words, if electricity is prioritized and roof space is limited, the PV/T is preferable. However, due to the high current market price of the PV/T system, the PV+T system is the most viable solution.

The overall recommendations based on this report are summarized below. As houses today are poorly insulated, heating systems are not really viable. Instead, by insulating houses to a level where an average U-value of 0.5 W/(m^2·K) is achieved, 99 % of DDH$_\mathrm{H}$ during winter are removed, thereby making heating unnecessary. This requires insulation equivalent to 60 mm of rock wool insulation when applied to a building under construction. Such an installation would result in an additional cost of materials of comparatively 14 000 SEK or 1 700 USD. A system that generates both electricity and hot water can be used to partially meet the needs of a typical four family house. By the use of a 2 m^2 solar collector in combination with 13.35 m^2 of PV a solar savings fraction of 0.84 can be achieved. The same solar savings fraction can also be achieved through 13.35 m^2 of hybrid PV/T collectors, although at a significantly higher cost.

8 Suggestions for future work

There are several suggestions for future work based on this report. In the report, a suggestion for a good value insulation was chosen where 99 % of the $\mathrm{DDH_H}$ were removed without paying to much attention to the amount of $\mathrm{DDH_C}$ added. Therefore, an analysis where a product of the amount of $\mathrm{DDH_H}$ and $\mathrm{DDH_C}$ is considered for an optimization of the amount of insulation could be of interest.

Another suggestion is to perform and study the same simulations made on a more detailed model of a typical Botswana residential house. As mentioned previously in Constraints, the house mode used in this report is simplified, which consequently allows for a certain error margin of the results. TRNSYS is compatible with another software called SketchUp where a perfectly detailed model of a building can be created, the only limitation for this is time.

An investigation of the expected improvement of indoor comfort from the use of for example mechanical ventilation and blinds for direct solar radiation could be made. This could work as a great complement to this report. It might show that by the use of such methods, either energy savings could be made or indoor comfort might improve further.

Furthermore, as the suggested solution in this report has been considered only for new buildings, a study on the possibilities of applying insulation retrospectively could be done. This would make the solution more applicable as it removes the requirement of a new building.

Additionally, a more detailed and well researched cost analysis based on possible prices of transporting the needed material to Botswana could be performed, which would make it more commercially interesting.

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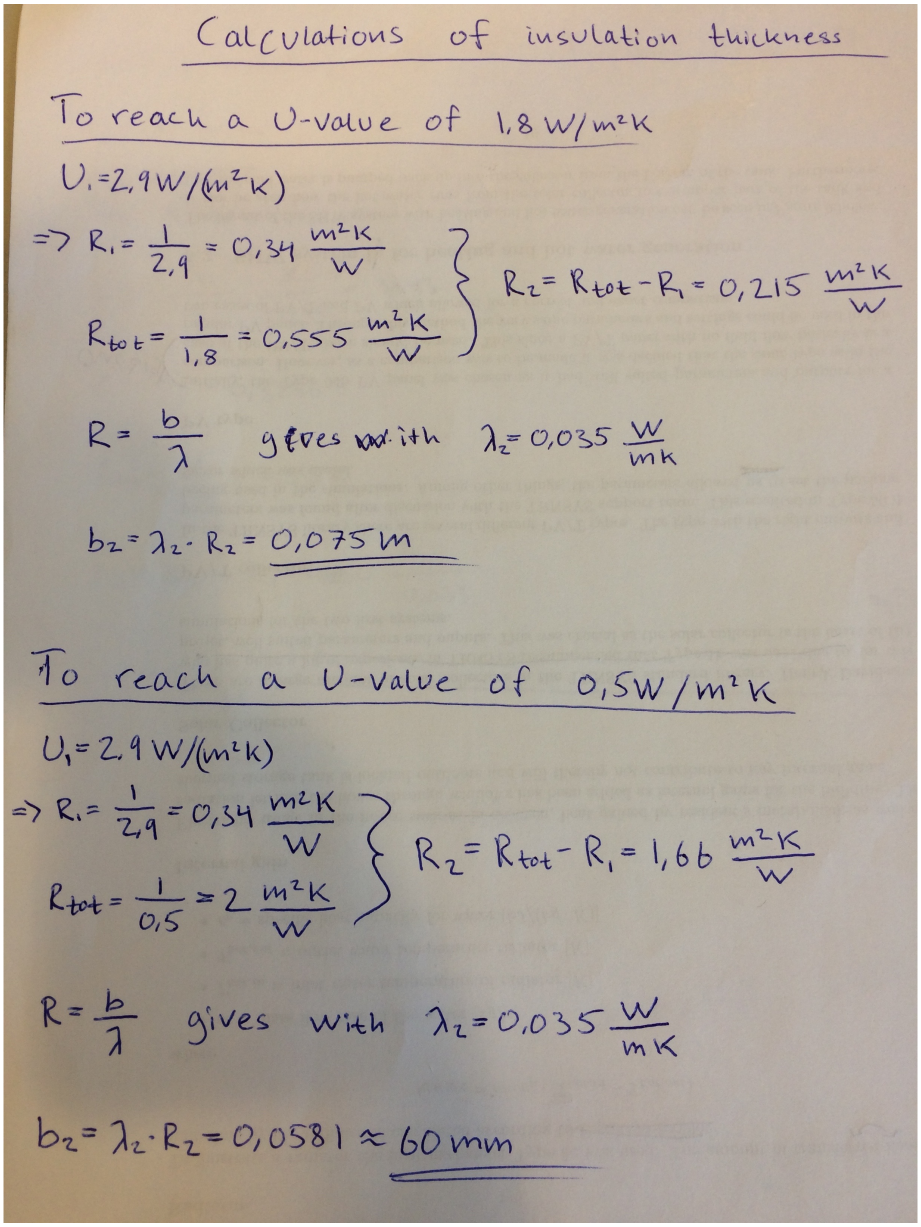

Calculations of insulation thickness

To reach a U-value of 1,8 W/m²K

$U_1 = 2{,}9\,W/(m^2K)$

$$\left.\begin{array}{l} \Rightarrow R_1 = \dfrac{1}{2{,}9} = 0{,}34\,\dfrac{m^2K}{W} \\[2ex] R_{tot} = \dfrac{1}{1{,}8} = 0{,}555\,\dfrac{m^2K}{W} \end{array}\right\} R_2 = R_{tot} - R_1 = 0{,}215\,\dfrac{m^2K}{W}$$

$R = \dfrac{b}{\lambda}$ gives with $\lambda_2 = 0{,}035\,\dfrac{W}{mK}$

$$b_2 = \lambda_2 \cdot R_2 = \underline{\underline{0{,}075\,m}}$$

To reach a U-value of 0,5 W/m²K

$U_1 = 2{,}9\,W/(m^2K)$

$$\left.\begin{array}{l} \Rightarrow R_1 = \dfrac{1}{2{,}9} = 0{,}34\,\dfrac{m^2K}{W} \\[2ex] R_{tot} = \dfrac{1}{0{,}5} = 2\,\dfrac{m^2K}{W} \end{array}\right\} R_2 = R_{tot} - R_1 = 1{,}66\,\dfrac{m^2K}{W}$$

$R = \dfrac{b}{\lambda}$ gives with $\lambda_2 = 0{,}035\,\dfrac{W}{mK}$

$$b_2 = \lambda_2 \cdot R_2 = 0{,}0581 \approx \underline{\underline{60\,mm}}$$