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Power to the Philippines

- A life cycle assessment study comparing renewable and non-renewable off-grid energy supply systems

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Sammandrag

Filippinerna är ö-nation i Sydostasien beståendes av mer än 7 000 separata öar. Filippinerna är det landet i världen som oftast blir drabbat av tropiska stormar; varje år når mellan 6 och 9 tyfoner land i Filippinerna. I november 2013 slog super-tyfonen Haiyan till mot nationen, och lämnade 10 000 döda och massiv förstörelse av delar av infrastrukturen (inklusive det nationella elnätet). Det är särskilt viktigt med tillgång till elektricitet under de första månaderna som följer en katastrof av denna magnitud så att framgångsrik katastrofhjälp kan bedrivas (så att kylning av medicin, rent vatten, telekommunikation och ljus kan erbjudas). Stora delar av det Filippinska folket bor på landsbygden utan tillgång till det nationella elnätet, och förlitar sig främst på dieselgeneratorer för elproduktion.

Det Svenska företaget InnoVentum har startat ett projekt som heter "Power to the Philippines" med syftet att förse en barnby driven av Barnmissionen i Filippinerna med förnybar energi från deras förnybara energi-lösning "Dali Powertower". Dali Powertower är en förnybar hybrid som kombinerar vind- och solenergi. Denna studie avser att undersöka InnoVentums projekt "Power to the Philippines" om det realiseras i sin fullskaliga form - när barnbyn till fullo blir försedd med förnybar energi för att kunna utföra sina basala behov - och jämföra det med ett dieselgenerator-system (som är vanligt idag). En kombination av dessa två energiförsörjningssystem (en förnybar/diesel hybrid) undersöks även. Dessa tre energiförsörjningssytem undersöks och jämförs ur en ekonomisk och miljömässig synvinkel för att komma fram till vilka fördelar, och nackdelar, som projektet "Power to the Philippines" kan ha.

Miljöpåverkan som dessa tre system har jämförs genom att en livscykelanalys (LCA) genomförs, som tar hänsyn till alla aspekter av energiförsörjningssystemen, vanligtvis hela vägen från råvaruutvinning till avfallshantering. LCA-studien kommer främst fokusera på miljöpåverkanskategorierna växthusgaserpåverkan och användning av primärenergi. Den ekonomiska analysen av de olika systemen görs med hjälp av annuitetsmetoden, vilket resulterar i ett pris per kilowattimme producerad energi. Denna analys görs för tre olika kalkylräntor (3, 8 och 13 %), för att simulera hur olika investerares avkastningskrav påverkar resultatet av den ekonomiska analysen.

Resultatet från LCA-studien visade att Powertower-systemet hade den minsta miljöpåverkan per använd kilowattimme av de tre studerade systemen, både gällande växthusgaspåverkan (89 g CO_2/kWh) och användning av primär energi (0.33 kWh/kWh). Dieselgenerator-systemet hade störst miljöpåverkan, då det hade ungefär 21 gånger högre miljöpåverkan (både gällande utsläpp av växthusgaser och användning av primär energi) jämfört med Powertower-systemet. Hybrid-systemet hade den näst lägsta miljöpåverkan, med ungefär 6 gånger högre miljöpåverkan (både gällande utsläpp av växthusgaser och användning av primär energi) jämfört med Powertower-systemet.

Resultatet från den ekonomiska analysen visar att när all producerad energi används, så producerar Powertower-systemet den billigaste elektriciteten vid den låga och den mellersta kalkylräntan (0.31 respektive 0.44 $/kWh) medan dieselgeneratorn (med platt prisutvecklings-struktur) producerade den billigaste elektriciteten vid den höga kalkylräntan (0.57 $/kWh). Däremot, om enbart elektricitet som används av barnbyn utnyttjas, så blir hybrid-systemet det billigaste alternativet med ett elpris på 0.56 $/kWh (att jämföra med 0.75 $/kWh för Powertower-systemet). Vid den mellersta nivån av kalkylränta blir dieselgenerator-systemet det billigaste alternativet (0.53 $/kWh), tätt följt av Powertower- och hybrid-systemet som kostar ungefär 10 cent mer per kilowattimme. Vid den höga kalkylräntan blir dieselgenerator-systemet ännu billigare (0.57 $/kWh) i jämförelse med sina konkurrenter.

Slutsatsen från studien var att hybrid-systemet är det bästa alternativet för barnbyn, då det kan producera billig energi med hög energisäkerhet och en relativt låg miljöpåverkan. Därför kan projektet "Power to the Philippines" anses vara av intresse för hjälporganisationer, så länge som deras energiförsörjning inte enbart kommer från Powertowers. En hybridisering av Powertowers med de dieselgeneratorer som används idag i barnbyarna kan sänka miljöpåverkan av det existerande energisystemet, samtidigt som det sänker kostnaden för elektriciteten (vid den låga och mellersta nivån av kalkylränta).

Nyckelord

Livscykelanalys; Filippinerna; Förnybart; Icke-förnybart; Vindkraft; Solenergi

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Power to the Philippines – A life cycle assessment study comparing renewable and non-renewable off-grid energy supply systems

Abstract

The Philippines is an island nation in South East Asia consisting of more than 7 000 separate islands. The Philippines is the country in the world that is most often struck by tropical storm; every year between 6 and 9 typhoons hit land in the Philippines. In November 2013 the super typhoon Haiyan hit the nation, killing 10 000 people and causing massive destruction to parts of the infrastructure (including the national electric grid). Especially in the first months following a disaster of this magnitude it is crucial for a successful disaster recovery to give the people access to electricity to enable refrigeration, clean water generation, telecommunication and lighting. Large portions of the Philippine people living in rural areas are left without access to the national grid, and are mostly relying on diesel generators for power generation.

The Swedish company InnoVentum has started a project called "Power to the Philippines" which intends to provide humanitarian aid villages run by the Children's mission that are active in the area with renewable energy using their power generation solution, the "Dali Powertower". The Dali Powertower is a renewable hybrid power generation system combining wind and solar power. This study investigates InnoVentums project "Power to the Philippines" if realized in its full-scale form - being able to completely power a humanitarian aid village with renewable energy to meet its basic needs - and compares it to a diesel generator system (as is commonly used today). A combination of the two systems (a renewable/diesel hybrid system) is also studied. These three energy supply systems are studied and compared from an environmental and economic perspective to see what advantages, or disadvantages, there might be to the "Power to the Philippines"-project.

The environmental impact of these three systems will be compared by conducting a life cycle assessment (LCA) study, which takes into account all aspects of the life cycles of the energy supply systems, usually ranging from raw-material acquisition to the end-of-life treatment. The LCA study is mainly focusing on the environmental impact categories global warming potential (GWP) and primary energy demand. The economic performance of the different systems is assessed by using the equivalent annual cost method, which results in a price per kWh of produced energy. This analysis is done for three different discount rates (3, 8 and 13 %) with the aim of simulating how different investors required rates of return affect the result of the economic analysis.

The results of the LCA study showed that the Powertower system has the least amount of environmental impact per kWh of used energy out of the studied systems, both regarding GWP (89 gCO2/kWh) and primary energy demand (0.33 kWh/kWh). The diesel generator is the system with the highest amount of environmental impact, having about 21 times higher environmental impact (both regarding global warming potential and primary energy demand) than the Powertower system. The renewable/diesel hybrid system had the second lowest environmental impact, with about 6 times higher environmental impact (both regarding global warming potential and primary energy demand) than the Powertower system.

The results from the economic analysis show that when the all the electricity is utilized, the Powertower system produces the cheapest electricity at a low and medium discount-rate (0.31 and 0.44 $/kWh respectively) while the diesel generator system (flat-rate diesel price) produces the cheapest electricity at a high discount-rate (0.57 $/kWh). However, if only the electricity used by the humanitarian aid village is considered, the hybrid system becomes the cheapest alternative, costing 0.56 $/kWh compared to the 0.75 $/kWh of the Powertower system. At the medium discount-rate the diesel generator system produces the cheapest energy (0.53 $/kWh), closely followed by the Powertower and hybrid system costing about 10 cents more per kWh. At the high discount-rate the diesel generator system becomes even cheaper (0.57 $/kWh) compared to its competitors while the leap to the competitors simultaneously becomes larger.

The conclusion is made that the hybrid system is the best alternative for the humanitarian aid village, as it can provide cheap energy with high energy security at a relatively low environmental impact. Therefore, the "Power to the Philippines" project can be deemed to be of interest to the humanitarian aid villages, as long as the energy load of the humanitarian aid village is not solely provided by Powertowers. A hybridization of Powertowers with the existing diesel generators can help lower the environmental impact of the existing energy system, while simultaneously lowering the cost of electricity.

Keywords

Life cycle assessment; The Philippines; Renewable; Non-renewable; Wind power; Solar power

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Foreword

This master thesis has been conducted at the department of Environmental and Energy systems studies at the faculty of engineering at Lund University. The project is done for the company InnoVentum, and mediated by the non-profit organization Miljöbron Skåne.

The authors want to send special thanks to our supervisors at the department of Environmental and Energy system studies, Per Svenningsson and Mikael Lantz, as well as InnoVentum and Miljöbron Skåne for the opportunity and support enabling us to conduct this study.

Lund, December 2014

Simon Berglund and Sebastian Engström

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1 Introduction

1.1 Background

1.1.1 The situation in the Philippines

The Philippines is an island country situated in Southeast Asia consisting of more than 7 000 separate islands. The Philippines, with its population of about 100 million people, is the 12th most populated country in the world (CIA, 2014). The Philippines is the country in the world that is most often struck by tropical storms. Every year the Philippines are hit by 19 typhoons of which six to nine hit land (Wingard & Brändlin, 2014). In November of 2013 the super typhoon Haiyan hit the nation which led to the destruction of portions of society and its infrastructure, including parts of the electrical grid. Haiyan was one of the worst typhoons to ever hit the Philippines, with an estimated 10 000 people killed and 14.5 billion USD worth of property destroyed (Rupp, 2014).

Figure 1. Example of the destruction following the super typhoon "Haiyan" (InnoVentum, 2014b)

An integral part of rebuilding society after a disaster of this magnitude is establishing a reliable, long-term supply of energy for the people. Especially in the first months following the disaster it is crucial for a successful disaster recovery to give the people access to electricity to enable refrigeration (of food, medicine and vaccines), clean water generation, telecommunication and lighting (among other services). Within the Philippine society there are big differences in living standards and the quality of infrastructure. The Philippines consists of 42 000 “barangays” which is one of the smallest administrative division in the Philippines (referring to a village or district). As of 2005, about 8 % of these barangays were without access to electricity. About half of these districts were in remote rural areas, leaving 1700 rural barangays unserved (Grewal et al, 2006).

The main electrical grid of the Philippines is divided into three separate grids with a total installed capacity of 16.8 Gigawatts (World bank, 2002). It’s not an economically viable alternative to expand the grid to the more remote islands, where instead small diesel plants (run by a subdivision of the National Power Corporation) commonly are used for electricity generation. These diesel plants are economically inefficient, partly due to their small scale and the high diesel costs. This electricity is then sold to local or regional electricity cooperatives which distribute it to its consumers (Grewal et al, 2006). The population in these remote rural areas are poorer than the general population, their income is less than 2 USD/day which is less than half of the national average. These conditions, coupled with poor management of the regional electricity cooperatives (World bank, 2002) has, despite implementation of subsidies, led to big financial difficulties for the National Power Corporation (Grewal et al, 2006).

1.1.2 InnoVentums work in the Philippines

InnoVentum is a Swedish small-scale wind turbine solutions manufacturer based out of Malmö, Sweden. InnoVentum has started the project “Power to the Philippines” with the aim of providing their renewable energy solutions to the Philippines. The project is a collaborative effort involving the Children’s Mission, a help organization active in 8 different countries around the world. The Children’s Mission runs humanitarian aid villages, called children’s villages, of varying sizes for children that come from exposed social backgrounds (Barnmissonen, 2014). These children’s villages are commonly powered by small-scale diesel generators (InnoVentum, 2014b).

The project intends to set up energy supply systems utilizing InnoVentums renewable sun/wind-hybrid the Dali Powertower that will be able to provide renewable energy to the Philippine children’s villages with no connection to the grid (InnoVentum, 2014b). As a first step of the project InnoVentum installed their first Dali Powertower in the Philippines in July of 2014 at the Hills of grace, a Children’s village situated outside of Manila, enabling the village to be run partly on renewable energy.

Figure 2. The PowerTower installed in Manila, the Philippines (InnoVentum, 2014b)

Another potential location for installing the Powertower-solution is the “Scandinavian village” just outside of Tacloban on the island of Leyte, which is located in the mid-east part of the Philippines. It is the administrative headquarter of the island and inhabits around 220 000 inhabitants (Head, 2013). This part of the Philippines was hit particularly hard by the typhoon and the area is in great need of humanitarian help and energy. After the typhoon the Scandinavian village lost their energy supply and is in need of a new stable energy solution. The village bought a 4,5 kW diesel electric generator which runs 4 hours a day to be able to light their LED-lights and charge cell phones, but it’s not able to keep fridges and freezers running (Daligault, 2014).

This study will focus around a humanitarian aid village very similar to the Scandinavian village regarding population size, living standards, energy use patterns and currently used energy supply system (diesel generator). This study intends to investigate InnoVentums project “Power to the Philippines” if realized in its full-scale form - being able to completely power a humanitarian aid village with renewable energy - and compare it to a diesel generator system dimensioned to be able to provide the village with the same amount of energy. A combination of the two systems (a renewable/diesel hybrid system) will also be studied. These three energy supply systems will be studied and compared from an environmental and economic perspective to see what advantages and disadvantages there might be to the different alternatives.

Figure 3. The Scandinavian village (after being rebuilt after typhoon) (InnoVentum, 2014b)

1.2 Problem description

After several disasters in the Philippines, large portions of the country's infrastructure are damaged. Because of the geographic location of the Philippines, it is highly probable that more disasters will strike in the future. The national electric grid in the Philippines only reaches about 70 % of the population (World bank, 2002) which has created a demand for decentralized energy systems in order to supply the parts of the Philippine people with no connection to the electrical grid with the energy they need to meet their basic needs. The most common solution to this problem is using diesel generators for producing energy, mainly because of the simplicity of use and low initial investment cost.

In the long term, it might be preferable for the Philippine society to restrict the dependence upon energy supply systems using fossil fuels for electricity generation. There are some negative aspects to the widespread use of diesel generators for off-grid energy generation. For example, it brings about a dependence on fossil fuels, which are expensive and have negative effects on both the local and global environment. Renewable energy technologies are viable alternatives to diesel generators that might help decrease both the cost and environmental impact of the off-grid power generation, but these alternatives are not utilized in any larger scale today.

1.3 Aim

The aim of this master thesis project is to study InnoVentums project "Power to the Philippines" and examine how economically and environmentally viable it is when realized in its full scale form (when the sun/wind-hybrid system is able to completely power a humanitarian aid village in a developing country inhabiting 500 people during 20 years). The sun/wind-hybrid system will be compared to a diesel generator system as well as a hybridization of the two aforementioned energy supply systems; a renewable/diesel hybrid system. All three systems will be dimensioned to be to be able to supply the humanitarian aid village with the same amount of energy for 20 years. A life cycle assessment will be carried out to examine and compare the environmental impact of the energy supply systems during their whole life cycle. An economic analysis will investigate which energy supply system is the most economically viable.

Furthermore, the project intends to study where the conditions for a switch from diesel generator to sun/wind-hybrid is the most environmentally favorable. This will be done by studying 4 other humanitarian aid villages at different locations around the world, assumed to be similar to the Philippine humanitarian aid village, the Scandinavian village, regarding population size, living standards, energy use patterns and current energy supply system (diesel generator).

1.4 Delimitations

The life cycle assessment will only cover three different energy supply systems; the diesel generator system, the sun/wind-hybrid system and the renewable/diesel hybrid system, no alternative solutions will be investigated. The sun/wind-hybrid system investigated in the study will only be the Dali Powertower created by InnoVentum. We have chosen to delimit the studied energy systems to be able to supply a village inhabiting 500 people with energy.

2 Energy systems - description and calculations

2.1 Description of the energy supply systems

2.1.1 The sun/wind hybrid system

Figure 4. The Dali Powertower with 6 PV cells (Innoventum, 2014a)

The Dali Powertower is a renewable hybrid power generation system combining wind and solar power that is developed by InnoVentum. The wind turbine is mounted at the top of the 12 meter high wooden tower, while the 6 solar panels are mounted at the base of tower. The tilt and direction of the solar panels is adapted to the specific conditions of the location where the Powertower is to be used. Coupled to the Powertower is an off-grid cabinet containing the electrical components necessary for producing and storing electricity such as batteries, a solar charge regulator, a wind charge regulator, inverters and a DC to AC converter. The system has 4 different available turbine configurations, for this study the HY Energy IV Lite turbine is used.

A factor that has to be taken into account when working with the Philippines is the previously mentioned destructive typhoons that are frequent in this area. In order to be able to withstand the rough meteorological conditions in the Philippines, the Dali Powertower has been designed to be able to go into a “safe-mode”. This is achieved by pulling out one of the legs from the tower, causing it to go into a split, collapsing closer to the ground. In this position the Powertower will be able to handle high wind speeds better than in the upright operational position.

The different components of the Dali Powertower are described in more depth in the following section.

The wind turbine

The Dali Powertower in this study uses the HY-3000 IV Lite turbine, which has a rated output of 3 kW at wind speeds of 12 m/s. The spec sheet of the HY-3000 Lite turbine can be seen in Table 1 and the Power curve of the turbine in Figure 5.

Table 1. The specification sheet for the HYE IV lite turbine (Innoventum, 2014a) .

Model	IV Lite - Off Grid
Rated Power	3000W
Max. Power	3500W
Rated Voltage	48Vdc
Rated rotation speed	700rpm
Start-up Wind Speed	2.0m/s
Cut-in Wind Speed	2.5m/s
Rated Wind Speed	12m/s
Survival Wind Speed	50m/s
Rotor Diameter	3m
Blades Quantity	5
Swept area	7.3m²
Noise Level	<30 dB (5m behind turbine @5m/s gusting)
Generator Type	Three phase PMA
Wind Turbine Type	Upwind
Tower connection	Flange connection
Temperature	-40°C~60°C
Strong wind protection mode	electromagnetic brake, blades aerodynamic brake
Service life	15 years
Net weight	70kg
Gross weight	84kg
Package size	153.5×64.5×32.5CM, 60.5×65.5×30CM

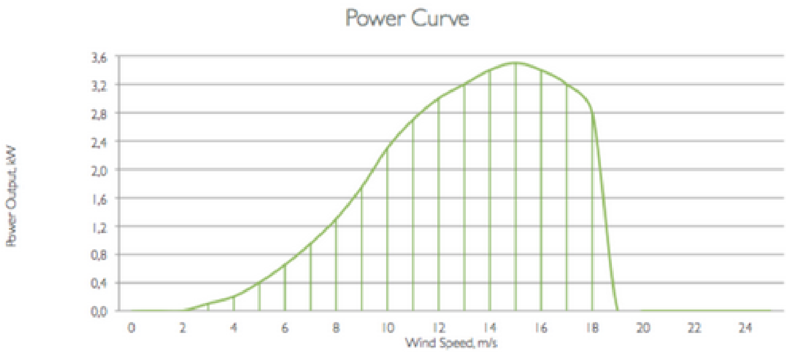

Figure 5. The power curve of the HYE IV Lite turbine (Innoventum, 2014a)

The solar panels

The type of solar panels used in the Dali Powertower is called EcoPlus and they are exclusively produced in Sweden by InnoTech Solar. Every Powertower will have 6 panels, each with a power of 250 Wp mounted onto the tower in a row. Each panel contains 60 multi-crystalline Silicon cells with the dimensions 156 x 156 x 180 microns. It contains a special glass with an anti-reflective surface which allows for higher output power during scattered and low light conditions. InnoTech tries to make their solar panels as environmentally adaptable as possible. According to calculations by an independent institute, InnoTech Solar has a 50 % smaller carbon footprint than conventional producers. The EcoPlus solar panel has a 25 year "linear performance warranty" (Innotech Solar, 2014). In the case of the Philippines, InnoVentum has decided to mount the solar panels as can be seen in Figure 6, rather than as in Figure 4.

Figure 6. The photovoltaic cells (Innoventum, 2014a)

The off-grid cabinet

The off-grid cabinet contains the following components; batteries, maximum power point tracker (MPPT), solar charge controller, wind charge controller and inverter. The different components vary in quantity depending upon the amount of Powertowers in the system. InnoVentum dimensions the system so that there is one off-grid cabinet per 3 Powertowers (Innoventum, 2014a). One off-grid cabinet (for 3 Powertowers) contains the quantities shown in Table 2 below.

Table 2. The components and their respective quantities contained in 1 off-grid cabinet (for 3 Powertowers)

Component	Quantity
Batteries	8
MPPT	3
Inverter	1
Solar charge controller	1
Wind charge controller	3

As can be seen in Table 2 the quantity of the MPPT and the wind charge controller are equal to the amount of Powertowers and the Inverter, and solar charge controller are equal to the amount of off-grid cabinets (which can be seen in Figure 7). Since the amount of Powertowers are not always in even 3's, a method for dimensioning the amount of off-grid cabinets where the number of off-grid cabinets are rounded off to a third of the closest number that is dividable with 3 was chosen. As an example, a system with 10 Powertowers will have 3 off-grid cabinets, and a system with 11 Powertowers will have 4 off-grid cabinets. This will affect the amount of batteries, inverters and solar charge controller, but not the amount of wind charge controllers and MPPTs (since these are dependent upon the amount of Powertowers).

Figure 7. The off-grid cabinet (Innoventum, 2014a)

The batteries.

The type of batteries that is used in the Dali Powertower is Sonnenschein SB6/200A which is produced by Exide Technologies (Figure 8). It is a gel lead-acid battery, commonly known as a VRLA-battery (Valve Regulated Lead-Acid battery). The VRLA battery technology has some advantages such as a low need for maintenance and it also needs less amount of electrolyte than other types of batteries (GS Battery, 2014). One battery has a storage capacity of 1.2 kWh, making the capacity of an off-grid cabinet containing 8 batteries 9.6 kWh.

Figure 8. The Sonnenschein batteries (Innoventum, 2014a)

Maximum power point tracker

The maximum power point tracker used in the Powertower is Morningstar Tristar MPPT 60 (Figure 9). The MPPT control the battery and prevent it from taking damage when system failures occur. It optimizes the charging process to maximize the battery's life length.

Figure 9. The maximum power point tracker (Innoventum, 2014a)

Solar charge controller

The solar charge controller is made by Echelon and is called iLON smartserver 2.0 (Figure 10). The controller monitors the energy use and production and manages the system to prevent malfunctioning.

Figure 10. The solar charge controller (Innoventum, 2014a)

DC to AC converter / Inverter

The DC to AC converter used in the Powertower is Studer XTender XTM 4000 – 48 (Figure 11). A DC to AV converter converts the electricity produced by the PV from DC to AC so the electricity is usable for electrical devices.

Figure 11. The DC to AC converter (Innoventum, 2014a)

Wind charge controller

The wind charge controller is produced by HY energy in Guangdong, China (Figure 12). The wind charge controller helps control the production of the wind turbine by automatically braking so that electricity is produced safely without reaching over-current or over-voltage states. It also helps protect the battery against over-discharging or over-charging.

Figure 12. The wind charge controller (Innoventum, 2014a)

2.1.2 The diesel generator system

The diesel electric generator that is used today in the Scandinavian Village is a Navigator NDG5000SE with a rated output of 4500 Watts. This diesel generator alone will not able to provide the village with energy correspondent to the continuous energy load. Therefore a theoretical diesel generator system that is actually able to supply enough power to meet the load of the village. The diesel generator chosen is a Kohler Power systems 7EFKOZD generator with an effect of 7 kW, as can be seen in Figure 13.

Figure 13. The Kohler 7EFKOZD diesel generator used in the theoretical diesel generator system (Kohler Co, 2014)

2.1.3 The renewable/diesel hybrid system

The renewable/diesel hybrid will be a combination of the sun/wind hybrid system and the diesel generator system. It will contain 1 diesel generator of the same type as described in chapter 2.1.2, a number of Powertowers and a battery tank. The system will also contain off-grid cabinets to regulate the energy produced by the Powertowers. The combination of diesel generator and Powertowers will allow for a reduction in consumed diesel, as well as a lower number of Powertowers required for meeting the load. Because of the lower number of Powertowers, the system will generate a lower amount of over-production. How the dimensioning of the renewable/diesel hybrid system was performed can be found in chapter 0.

2.2 Energy calculations

2.2.1 Energy demand of the humanitarian aid village

The village consists of 50 houses with 10 persons in each house. The inhabitants of the village need energy for everyday use such as charging cell phones and powering fans, fridges and lights which can be seen in Table 3.

Table 3. The appliances of one household.

Appliances	Fridge	Fan	LED light	Cellphone
Quantity	1	1	3	1
Power rating	29	60	10	5
Hours of use	1-24	11-20	19-23	1-24

All appliances, except for the refrigerator, continuously consume the amount of power that is stated in the power rating row in Table 3 above. The refrigerator has more of a variable energy consumption which causes the daily energy consumption to be less than what it would be if the power is multiplied by the number of hours per day (125 W * 24 h = 3 kWh). For this study, a refrigerator known to be used in a similar children's village outside of Manila in the Philippines (Daligault, 2014) was used. This refrigerator consumes 0.69 kWh/day, making the hourly average power use 28.75 W. This amount to a yearly energy consumption of the village is approximately 28.5 MWh, which during the assumed 20 year life time of the system will amount to 570 MWh. This energy load is assumed to be the same during all days of the year. A graph of the energy load profile can be seen in Figure 14.

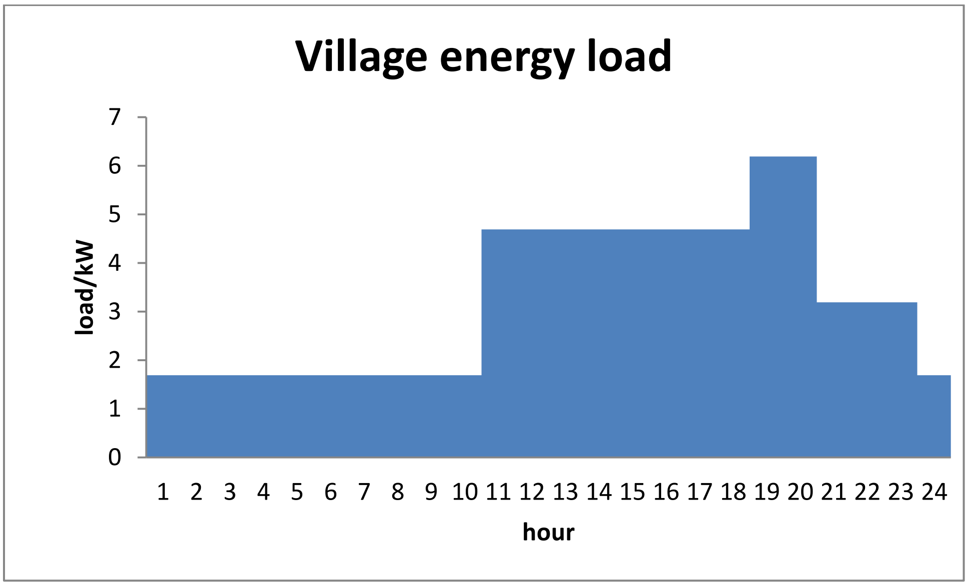

Figure 14, Total energy load (in kW) for a typical day in the village with 500 inhabitants

2.2.2 Solar energy calculations

The amount of electricity produced from the solar panels is calculated by gathering daily measures of insolation on the horizontal surface and diffuse insolation from the years 2001 to 2004 from a website owned by NASA (NASA, 2014). From these measures an average insolation value for each day of the year, later summed up to each month, were calculated. The solar energy resources can be seen below in Table 4.

Table 4 Monthly average insolation in kWh/m^2 in Tacloban, Philippines (NASA, 2014).

Month	J	F	M	A	M	J	J	A	S	O	N	D
Insolation, kWh	142	150	186	215	195	175	178	179	184	172	148	140

The average monthly insolation values, G, are then put into the following equation to calculate the electricity generated the solar panels.

$$E = A * r * G * PR$$

The A is the area of the solar panels, r is the solar panels yield, G is the solar irradiation and PR is the solar panels performance ration. The yield from a solar panel with a Watt peak of 250 and an area of 1.6 m^2 is 15.6 % and the standard efficiency is 75 % (Photovoltaic-software.com, 2014). This is considered to be close enough the area of the solar panels used by the Powertower which is 1.67 m^2. The total number of solar panels per Powertower is 6 which add up to an area of 10.02 m^2.

Table 5. Input values for electricity production of solar panels.

	Value
Area, A (m^2)	10.02
Efficiency, r	0.75
Yield, PR	0.15

The total amount of electricity produced by the solar panels of one Powertower is estimated to approximately 2060 kWh and the continuous production over the year can be seen in Figure 15.

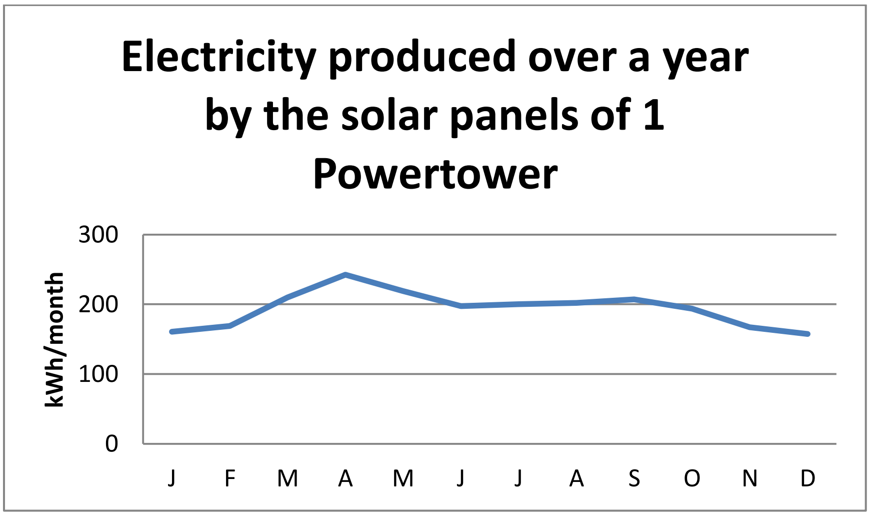

Figure 15. The electricity produced per month by the solar panels of 1 Power Tower over a year.

2.2.3 Wind energy calculations

In order to calculate the amount of wind power that a Powertower is able to produce over a year an appropriate wind data resource has to be utilized. The ideal would be to have a dataset from Tacloban with hourly values of wind speed, but since this was not available another dataset had to be used. A dataset containing daily average wind speed measurements collected over the years 2005 to 2012 from a weather station was found on the website Typhoon2000 (Padua, 2014). The website (and weather station) is driven by an individual in the Naga city region of the Philippines, about 400 km from Tacloban. This dataset was deemed to be a good enough representative of the wind speed in Tacloban. The average of the daily measurements over the years 2005 to 2012 can be seen in Figure 16 below. The wind speed is measured at a height of 30 meters.

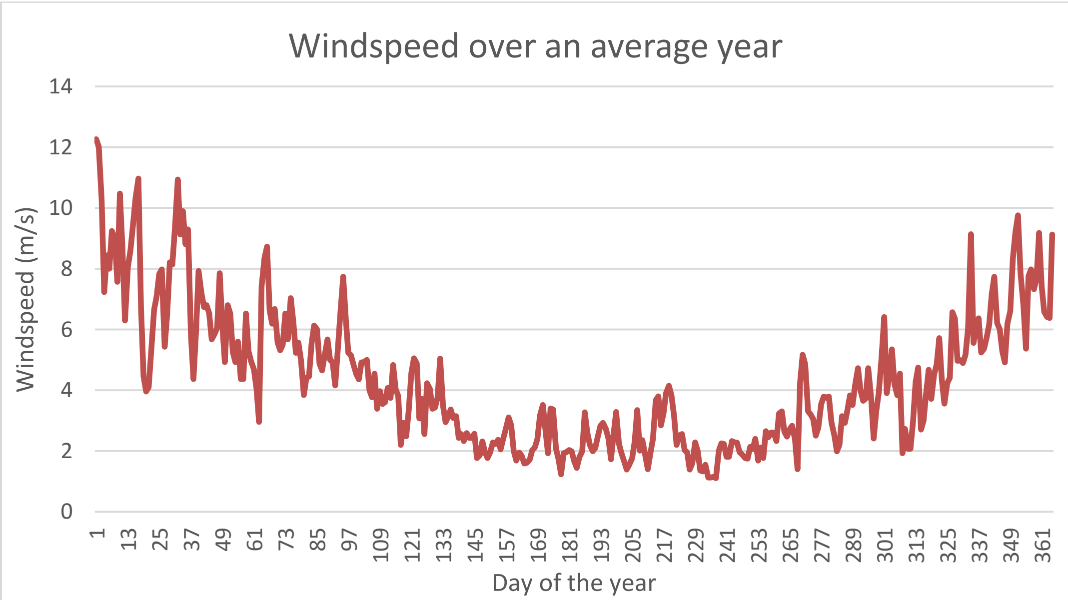

Figure 16. Daily wind speed measurements over a year (Padua, 2014).

These daily wind speed values are good, but in order to be able to perform a more advanced analysis of the energy system, hourly wind speed values are preferred. In order to convert the daily wind speed average into hourly values the following formula (where W_{ave} is the daily average wind speed, and n is the hour of the day (ranging from 0 to 23)) was used;

$$W_n = W_{ave} + \frac{1}{2} * W_{ave} * COS(\frac{n * \pi}{12})$$ (Zhongling, 2005)

These hourly values where then matched against the power curve of the wind turbine, as is seen in Figure 5 in chapter 2.1.1 The sun/wind hybrid system. This produces a line of the continuous yearly production as is seen in Figure 17 below. The total production over a year using this dataset amounts to approximately 3.54 MWh.

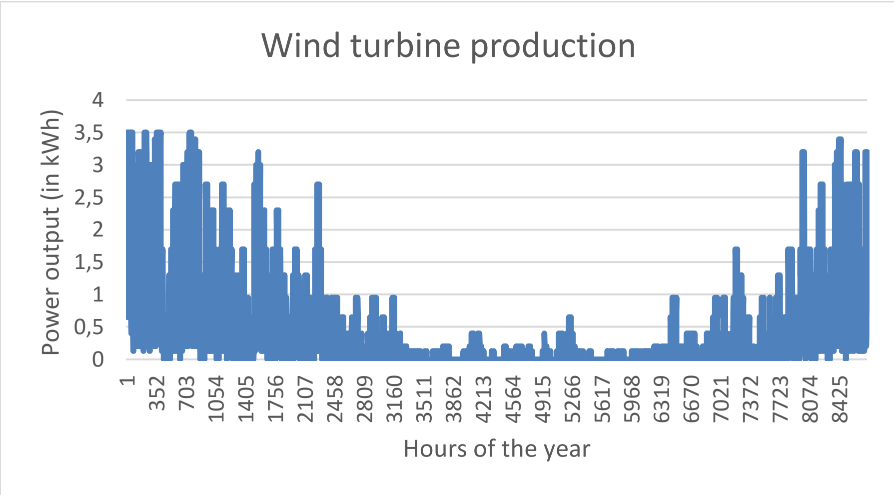

Figure 17. The wind turbine production over an average year

2.2.4 State of charge simulation

In order to dimension the sun/wind-hybrid system in such a fashion that it continuously meets the load a simulation of the state-of-charge (SOC) was carried out. The SOC is a measure describing what amount of energy that is stored in the battery tank relative to its full storage capacity, and is expressed as a percentage (similar to a fuel gage in a car). The state-of-charge simulation intends to simulate how the energy supply system and the load interact with the battery tank. The simulation is set up so that It simulates the SOC over a year using hourly values of energy production, load and calculates what the hourly value of the SOC is (while taking the different efficiencies involved into consideration). Limitations are imposed on the SOC so that it can't go below 0 % or above 100 %. Figure 18 below illustrates the system that the SOC simulation intends to simulate.

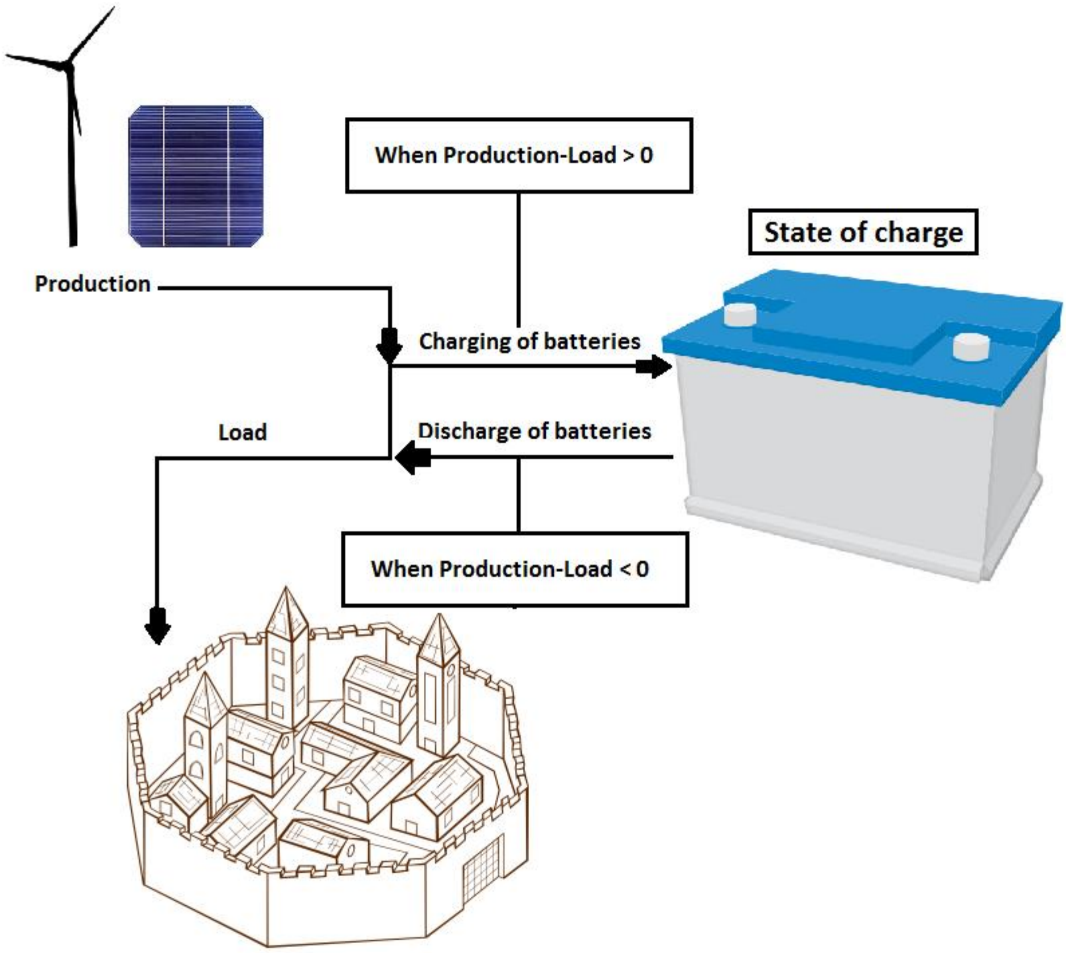

Figure 18. An illustration of the system that the SOC-simulation intends to simulate (the sun/wind hybrid system)

A self-discharge rate of the batteries of 0.2 % per day, as well as the following efficiencies were used in the simulation (Zhou, 2008);

$\eta_{Inverter}$ = 92 %

$\eta_{rectifier}$ = 95 %

η_{charge} = 90 %

$\eta_{discharge}$ = 100 %

One of the key figures is the percentage of time that the system is able to sustain the SOC above 0 %. Another key figure is the number of “deep discharges”. Having the state of charge level dip below 40 % is considered as a deep discharge by the battery manufacturer. A high number of deep discharges are generally considered to lower the life-time of the battery. Also, the yearly amount of over-production is displayed.

The dimensioning process is dependent on the criterion that the state of charge of the battery tank shall stay above 0 % more than 95 % of the time. The number of Powertowers and the corresponding amount of batteries are increased until this percentage is above 95 %. At this point, the system is considered to be properly dimensioned to meet the load.

2.2.5 Dimensioning the sun/wind-hybrid system

The sun/wind-hybrid system will supply power to a village of 500 inhabitants. To do that it must provide at least as much electricity as the village consumes, which over the year amounts to approximately 28.5 MWh. When the hybrid system does not produce electricity the batteries will provide the village with electricity. The batteries are charged when the hybrid system is producing more electricity than the village consumes. When charging and withdrawing electricity from the batteries, losses in efficiency are inevitable.

In one year the solar cells of one Powertower in the Philippines produces approximately 2.32 MWh and the wind turbine produces approximately 3.54 MWh, giving a combined total of approximately 5.86 MWh. According to the state-of-charge simulation that was carried out, the required number of Powertowers is 13 with a corresponding 4 off-grid cabinets containing a total of 32 batteries. The total quantities of the different components in the off-grid cabinets of the Powertower system in the Philippines are described by Table 6 below.

Table 6. The quantity of the components in the off-grid cabinet of the Philippine Powertower system

Component	Batteries	MPPT	Inverter	solar charge controller	Wind charge controller
Quantity	32	13	4	4	13

2.2.6 Dimensioning the diesel generator system

To be able to compare the current energy system in the village with the sun/wind-hybrid system the diesel generator system is assumed to produce enough energy to cover for the energy load of the village even if this is not the case today. The diesel generator currently used for electric production in the village has a rated output of 4.5 kW, but in order to match the load of the system a generator with a rated power output of 7 kW was instead chosen. The efficiency of the studied diesel generator at different loads can be seen in Table 7.

Table 7. The diesel consumption at different loads. 100 % equals 7 kW of power output. (KohlerPower, 2014)

Load (in %)	Diesel consumption (in liters)
100%	2,6
75%	1,9
50%	1,5
25%	1,1

In order to calculate the total amount of diesel consumed in one year the diesel consumption is calculated from the hourly values of the energy load (in %) which then is matched to the diesel consumption in Table 7. In order to get the diesel consumption at all the loads which are not stated in Table 7, an interpolation was performed, ranging from 0 -25 %, 25 % - 50 %, and so on. This results in a total amount of diesel needed to supply the village with energy for one year of approximately 12 700 liters.

2.2.7 Dimensioning the renewable/diesel hybrid system

The renewable/diesel hybrid system will be dimensioned to cover the yearly energy consumption of the village. This can be achieved with many different setups. Each set up will holds one diesel generator (the same type as in the diesel generator system) while the number of Power Towers will be varied between 1 and 5 and the capacity of the battery tank will be varied between 0-48 kWh. The different setups will lead to varying amounts of yearly diesel consumption, which also will be calculated.

In order to find the most suitable setup both environmental and economic aspects will be taken into consideration, and the setup with what is deemed to be the best compromise between these two aspects will then be chosen. The environmental performance is calculated according to the procedure as described in Chapter 4 while the economic performance is calculated according to the procedure as described in Chapter 5. The environmental performance is measured in g CO^2-eq/kWh and primary energy/kWh while the economic performance is measured in USD/kWh. How the dimensioning of the renewable/diesel hybrid system was performed can be seen in Appendix H.

3 Introduction to life cycle assessment

"LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)" (The Institute for Environment and Sustainibility, 2010)

Life cycle assessment, LCA, is a method used for measuring the environmental impact that a product, system or service has during its whole life-cycle. It can help us increase the understanding of a product, system or service's overall impact regarding different environmental aspects, such as the emission of greenhouse gases, acidification and eutrophication. By taking the product's whole life cycle into account from "cradle to grave", e.g. from raw material acquisition, transports, production, use to recycling and disposal, a holistic description of the impacts from the different stages of the life cycle is achieved. The results from a LCA can have many uses, for example it can be used for strategic planning, advertising and shaping public policy, as well as for developing and enhancing products. The guidelines for how a life cycle assessment should be performed are internationally standardized by the International Organization for Standardization organization (ISO), mainly governed by the standards ISO 14040 and 14044 (The Institute for Environment and Sustainibility, 2010).

A life cycle assessment consists of four different phases, namely (Figure 19);

- The goal and scope definition phase
- The inventory analysis phase
- The impact assessment phase
- The interpretation phase

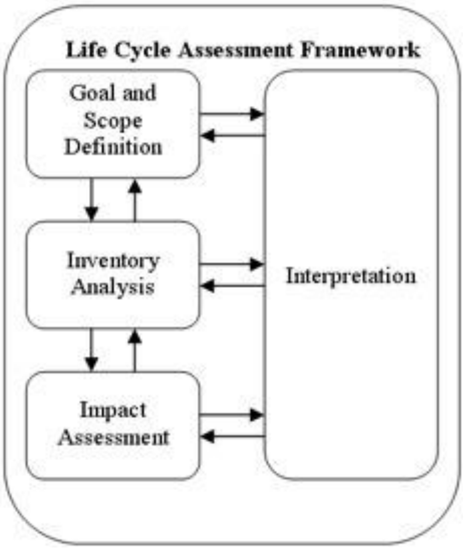

Figure 19. The framework of life cycle assessment (The Institute for Environment and Sustainibility, 2010)

These 4 phases, along with some common concepts related to the life cycle assessment methodology, are described in the following section.

Goal and scope definition

The goal definition is the first part of a life cycle assessment, and it affects all subsequent parts. The goal definition shall explain what the purpose of the LCA is, what the results are to be used for, as well as the targeted audience. The limitations of the study stemming from the method, choice of assumptions and the impact categories that are included shall also be stated. Depending on if the results of the LCA for example are going to be used internally in a company or publicly as advertising, the LCA will have different requirements on the quality of data and execution of the study.

The scope of the LCA shall identify and describe the system to be studied more in depth. In the scope section the requirements on methodology, quality and reporting and review shall be stated, and they must harmonize with the previously stated goals and the intended use of the LCA. The scope definition forms the framework for how the study will be performed in the latter stages of the LCA. The scope section shall define what type of results the study will produce as well as the systems function, functional unit and reference flow. It shall include a definition of the system boundaries, and what cut-off rules are used (if there are any).

The scope should describe what environmental impact categories that are to be included in the life cycle impact assessment (LCIA) phase of the study and state what LCIA-methods that are to be applied. It shall also state which types of data are used for the life cycle inventory (LCI) phase, from what sources, what quality it is and also what the data quality requirements are from a technological, geographical and time-related perspective.

Functional unit

The functional unit is an important element of a life cycle analysis. It gives a quantitative description of the function of the studied system, which will make it easy to compare the result of the LCA with a different system that fulfills the same function. The functional unit is used as a reference to quantify the collected data of the in- and outflows of materials and energy so that they adequately fulfill the function of the system. A detailed functional unit shall answer the questions “what?” “how much?” “how well?” and “for how long?” regarding the function and its satisfaction. A common example is 1 kWh of produced electricity.

System boundaries

The system boundaries defines which processes that are to be included in the LCA. The general system boundaries can be deduced from the goal and scope definition. A “perfect LCA” would have system boundaries that didn’t exclude any processes, but this makes the execution of the LCA study far too complex. Therefore, an assessment of what the relevant in- and outflows are, is carried out when defining the boundaries. This assessment must take into account the intended use of the study, the goal and scope, the assumptions that have been made and what delimitations there are concerning time and money. The system boundaries are commonly illustrated in a so called flow chart.

Cut-off principles

Using cut-off rules means excluding less relevant parts from the system, such as elementary flows, processes or complete life cycle stages. The cut-off criterion is a quantitative definition of the system boundaries, usually defined as the percentage of the total environmental impact (or material weight) that is included. A cut-off criterion of 95 % therefore means that 5 % of the total environmental impact is excluded. A cut-off criterion can also state how large portion of the total weight that a material has to constitute in order to be included in the system boundaries. How much these 100 % of the environmental impact really are is just an approximation, as if this was known, no cut-off would be needed. The bigger the cut-off, the more incomplete the data is and the lower the environmental impact will be. A big cut-off decreases the adequacy of using the results of the LCA for comparisons.

Life cycle inventory

The life cycle inventory (LCI) phase includes identifying the processes included in the studied system and collection and calculation of data to quantify the relevant in and out flows to the functional unit. The results from the LCI phase are what is used as input data for the next phase, the life cycle impact assessment. The data collection is one of the most time-consuming activities involved in a LCA study. The data is collected continuously and the more that gets known about the system the more limitations of the data can be revealed. These limitations can force changes in the method to meet the conditions set up in the goal and scope definition. Sometimes the changes in the method don't lead to an adequate satisfaction of the goal and instead the goals must be changed. In this way the LCA methodology enforces an iterative approach.

Allocation

Processes often produce more than one end product. Therefore their environmental impacts can be divided, or allocated, between the products. There are two different commonly used allocations; economic- and weight allocation. Economical allocation is made through weighting the products economic value to the environmental impact and the weight allocation is made through weighting the weight of the product to the environmental impact. If any allocation is used, the applied allocation method shall be described. System expansion is a method for avoiding the need to allocate processes in multi-functional system, and this is achieved by expanding the boundaries of the system so that all functions of the system are included. System expansion is generally the preferred method for dealing with multi-functional systems.

Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase the elementary flow data of the product or service's life cycle collected in the LCI phase are categorized into different impact categories. This process is known as classification. Next comes the characterization step, which leads to a unifying of the unit of the individual elementary flows relevant to an impact category. As an example, methane contributes 25 times more to global warming than CO_2, therefore it has to be multiplied by the impact factor 25 in order to get the contribution measured in CO_2-equivalents. Usually these steps are not performed by the LCA practitioners, as they have already been performed and built into the different LCA databases that are available.

Life cycle interpretation

The interpretation phase includes the interpretation of the inventory and the impact assessment phases. The interpretation phase should give results that are well matched according to the goals and scope, and also include conclusions, a description of limitations and recommendations. The interpretation phase is supposed to be a continuous process that ensures the harmonization of all parts of the study (see Figure 19. The framework of life cycle assessment), such as the goal definition, intended use and data quality requirements. In that sense, the interpretation aspect of a LCA is included in all phases as a sort of self-controlling mechanism. The interpretation phase includes sensitivity analyses which can bring about a deeper understanding of the results.

4 Life cycle assessment of different off-grid energy supply systems

4.1 Goal and scope definition

Goal

The aim of this study is to perform a life cycle assessment of three different energy supply systems along the lines of the requirements stated in ISO 14040-14044, but not strictly adhering to them. The study will be a comparative life cycle analysis, meaning its aim is to compare different systems performing the same function. It will compare the environmental impact that three different energy supply systems (supplying the same amounts of energy to a humanitarian aid village) have from the cradle-to-gate of their life cycle (including the operational phase). The three systems to be studied are a diesel generator system, a sun/wind hybrid system, and a combination of these two energy supply systems known as a renewable/diesel hybrid system.

The study can be used to motivate the use of these sun/wind hybrid systems for off-grid use by illustrating what reductions in emissions a shift from a diesel generator to a either a sun/wind hybrid system or a renewable/diesel hybrid system will result in. More so, the study will help InnoVentum get a more in depth understanding of their Dali Powertowers regarding eventual hot spots in the products life cycle. This can help them in their work of making their products as environmentally adaptable as possible. The intended audience of the study is university students and professors, as well as InnoVentum and its potential customers. Since the study includes a comparative assertion, it is planned to be disclosed to the public.

Scope

The three studied energy supply systems are;
1) The sun/wind hybrid system
2) The diesel generator system
3) The renewable/diesel hybrid system

These three systems will be studied and compared by carrying out a cradle-to-gate life cycle assessment (including the operational phase) which means that the study will include the environmental impact caused by the systems during all the stages of their life cycle up to the operational phase, but excluding the end of life treatment. In order to also study the environmental impact of the systems from a cradle-to-grave perspective, a sensitivity analysis will be performed in the life cycle interpretation phase of this study. The studied energy supply systems will be dimensioned to supply equal amounts of energy to a humanitarian aid village. The main case is to perform this study for an off-grid energy supply system dimensioned to supply a Philippine humanitarian aid village in Tacloban, the Philippines.

In order to deepen the analysis, 6 different sensitivity analyses will be performed, which include the following aspects;
- Localization
- End of life treatment
- Higher wind turbine production
- Different set up (8 solar cells)
- Higher load
- Utilization of 50 % of the over-production

The localization analysis will be carried out by performing the same study for 4 other locations around the world to investigate if an implementation of the Powertower solution is more (or less) environmentally beneficial in these places compared to the main case. All the 4 other studied locations are situated in developing countries with an actual humanitarian aid village operating in the area (not necessarily run by the Children's mission) and a relatively low level of rural electrification. The 4 other locations are;

1. Santo, Haiti
2. Mogadishu, Somalia
3. Santa Cruz, Bolivia
4. Srinagar, Uttar Pradesh, India

The end of life treatment sensitivity analysis will take end of life treatment into account, which is something that the main case of this study does not do. This sensitivity analysis will simulate what results this study would have had if it had been a cradle-to-grave study. The higher wind turbine production sensitivity analysis will account for the higher wind turbine production that the placement of the Powertower system on a hill close to the humanitarian aid village in Tacloban will lead to. The different setup sensitivity analysis will study how another setup of the Dali Powertower (containing 8 solar panels instead of the setup with 6 solar panels that is used in the main case) compares to the main case. The higher load sensitivity analysis will study how a higher load affects the environmental performance of the system. The utilization of 50 % of the over-production will study how utilization of 50 % of the over-production will affect the results.

The function of the system

The humanitarian aid villages that are run by the Children's mission are in need of energy to care for the basic needs of their inhabitants (such as refrigeration, lighting and powering fans) and carry out their humanitarian activities. The energy load of the village in this study is assumed to be similar to the Scandinavian village regarding energy use patterns, but with a smaller population of 500 inhabitants. It is estimated that the studied village needs approximately 78 kWh per day and 28.5 MWh per year (see chapter 2.2.1 for these calculations). The function of the studied energy supply systems is to successfully supply the village with this amount of energy.

Functional unit

"The electricity needed to continuously supply a humanitarian aid village in a developing country, inhabiting 500 people, with the energy they need to meet their basic needs during 20 years."
In order to make the results easily comparable to other life cycle assessments, an alternate functional unit of "kWh electricity" will also be used.

Cut off criterion

In this LCA a cut-off criterion of 95 % (based on mass) is used.

Environmental impact categories

The environmental impact categories that are to be included in the environmental impact assessment of this study are the following;

- Global warming potential, GWP-100 (measured in CO_2-equivalents)
- Primary energy use (measured in Joule)
- Eutrophication potential (measured in NO_x-equivalents)
- Acidification potential (measured in SO_2-equivalens)
- Photochemical ozone depletion potential (measured in C_2H_4-equivalents)

The impact categories GWP-100 and primary energy use will be displayed in the results section of the main study, and the others can be found in Appendix E. This decision was made because these two impact categories are the most relevant when analyzing energy supply systems, and also in order to make the results of the study more comprehensive by limiting the amount of graphs displayed.

System boundaries

This life cycle assessment includes all the processes from cradle-to-gate. A full cradle-to-grave analysis is performed in the sensitivity analysis found in one of the sensitivity analyses. The energy, emissions and resources used for making or transporting process equipment or vehicles is not included in the study. Figure 20 illustrates the system boundaries.

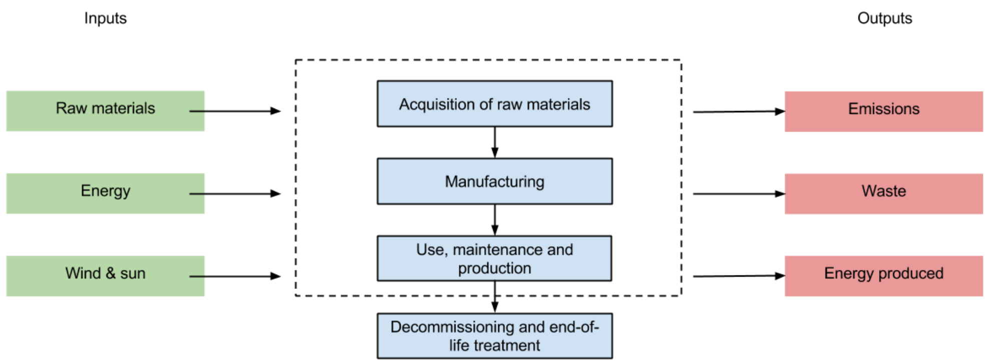

Figure 20. The system boundaries of the energy supply systems studied in the main case

Data quality

The data used in the environmental impact assessment were taken from EcoInvent version 2.2. When no data was available in the EcoInvent database other sources were sought out, such as other life cycle assessments. When no other sources were found, approximations were made. One example of this is for the diesel generator, where the material 'plastics' was assumed to be Polyethylene Terephthalate (PET), since this is a common plastic material.

The data used in the life cycle inventory phase were collected from a multitude of sources. When a model-specific life cycle assessment was available for a component (such as for the photovoltaic cells used in the Powertower) that data was preferably used. If there's no model-specific life cycle assessment available for a component, the next best approach is to find generic data for that type of component. This was done for the diesel generator where a life cycle assessment specifying the weight distribution of the different materials used in the generator (in percent) was used. When there's no generic data available, approximations were made in order to account for at least part of the environmental impact of the component. This was done for the solar charge controller, which was approximated to have the same material composition as the inverter.

4.2 Life cycle inventory

In this section of the life cycle assessment the different energy supply systems are inventoried with regards to the material composition and weight of the constituting materials. If data regarding the energy consumption associated with the production of the component is available, this is also presented.

4.2.1 The Powertower system

In the life cycle inventory phase data for the different components of the Dali Powertower is collected. The study includes raw material acquisition, material processing, transports and installation. The different components will be dimensioned according to the quantities described in Table 4. A schematic overview of the Powertower system inventory can be seen in **Fel! Hittar inte referenskälla.**.

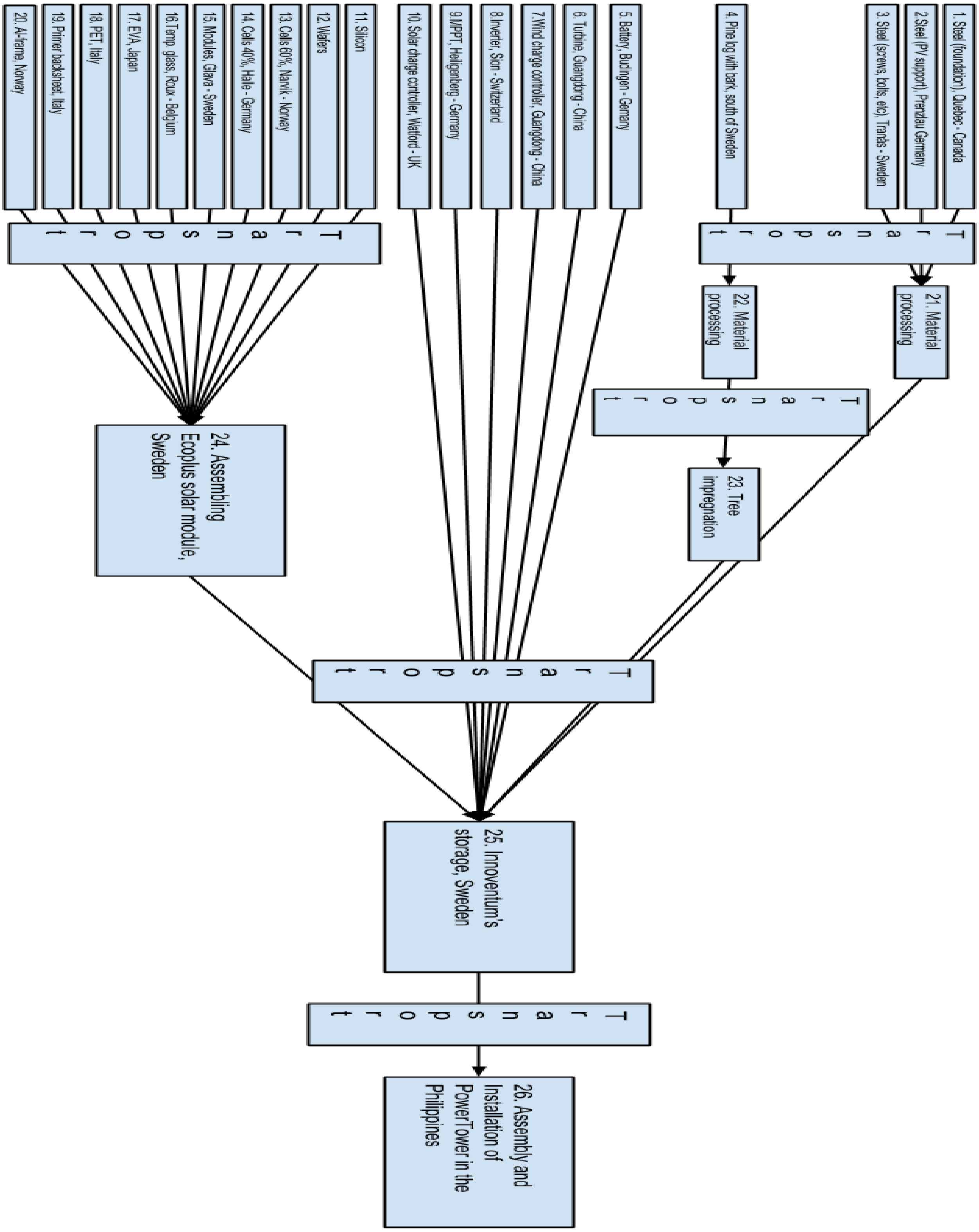

Figure 21. A combined flowchart of the Powertower system

Dali Tower

The inventory data of the Dali Tower is received from a LCA studying the tower of the Dali Powertower (Stoica, 2014). The data regards the production of one impregnated wooden tower, including the steel billet for the PV support structure, but excluding the turbine. The wooden tower is made of pine which is taken from plantations in the south of Sweden. The pine is manufactured by Derome Träteknik located in the Scania region and then impregnated by Woodtech located in Varberg 19 km from Derome Träteknik.

The production of the PV support structure is located in Prenzlau near Berlin in Germany by the company Hera Metall. The steel for the manufacturing is supplied by the local steel manufacturer, Thyssen Krupp, located 150 km from the PV support structure manufacturer. The bolts, washers, nuts and screws are from a company called SWEbolt located in Jönköping and Stockholm County. The energy used for the production of these components was not taken into consideration by the source because of data gaps (but the raw material production was).

The metal foundation screws are produced in Canada by the company Techno Pieux which also secures the installation of the tower. The screws are made of Canadian steel which is produced by Canadian steel mill King in Hamilton, Ontario, Canada. The manufacturing of the screw parts takes place at two other locations by two other companies, Acier Nova, located in LaSalle, Québec, Canada and Megantic Metal, located in Thetford Mines, Québec.

The components are then transported to InnoVentums storage in Malmö, except the screws from Techno Pieux which is directly transported to the customer, and packaged in a carton box on a wooden pallet. The material for the package is not taken in consideration since the environmental impact of this stage is very low. The installation of the tower, which is done by Techno Pieux, is done with the help of special equipment. The special equipment is run by a fuel generator. The assembly and erection of the tower can be done by manpower and electrical drills.

The processed wood is transported by truck to InnoVentums warehouse from Varberg. The metal from Prenzlau is transported by truck to Copenhagen and from there by boat to Malmö. The bolts are transported from SWEbolt by truck. In the use phase maintenance is necessary every fifth year. The maintenance consists of applying a wood saturation to prevent the wood from injuries.

The end of life treatment comprises the care of the components after the usage. The tower is taken down by manpower in the same way as the installation. The metal parts of the tower are handed over to the municipality for recycling as is the wooden tower. The wooden tower is impregnated with a water-copper solution and should ideally be treated to get rid of the water-copper solution before incineration.

The weight of the raw materials that are required for the production of one Power Tower are shown in Table 8.

.

Table 8. The materials and their respective quantity used in the production of 1 Dali tower (gross weights) (Stoica, 2014).

Input	Quantity
Pine log	1590 kg
Steel billet for PV support	100 kg
Steel billet for foundation	242 kg
Gasoline for installation machinery	3.29 kg
Cutting and drilling lubricant for foundation pieces	4.62 kg
Process water for steel manufacturing	0.115 kg
Argon liquid	72.7 kg
Carbon dioxide	2.99 kg
Boric acid	1.2 kg
Diethanolamine	4.8 kg
Propiconazole	0.12 kg
Copper carbonate	4.92 kg
Surfactants	1.2 kg
Tebuconazole	0.12 kg
Water	5.64 kg
Polyethyleneamine	4.8 kg
Organic acid	1.2 kg
Steel billet for Bolts/washers/nuts/wood screws	80 kg

The turbine

The turbine used in the studied Powertower is a HYE Lite turbine, produced in China by HY energy. The turbine consists of 5 blades made out of reinforced nylon fiberglass. Information about the weight of the different turbine parts was received through email correspondence with the producer in China (Daligault, 2014), but the exact details of the material distribution was not revealed due to company secrecy. In order to account for the material distribution of the generator approximations were made with the help of other information found about the turbine and mail conversation with the producer (Daligault, 2014).

Table 9. The turbine weight and material distribution. (Daligault, 2014)

Component	Weight [kg]	Material distribution
Generator	27.5	
		50 % Copper
		10 % neodynium magnet
		30 % aluminium alloy
		10 % Stainless steel
Blades	22	Reinforced nylon glass-fiber
Tail	11.6	Steel
Hub	3.5	Steel
Backseat	5	Steel

The solar panels

The inventory data for the solar panels was collected from an existing carbon footprint evaluation examining the same solar panel that are used in the Powertower configuration, The InnoTech EcoPlus. This study was performed by the independent institute called Smart green scans (Wild-Scholten, 2012). The EcoPlus solar panels are manufactured in Glava, Sweden, but the different components are produced in a wide range of countries. InnoTech performs an upgrade of their cells which improves their performance in Halle, Germany. This upgrade requires 0.45 MJ additional energy per cell. The 0.292 mm primer back sheet consists of Coveme dyMat PYE, 50 micron PET/125 micron PET/100 micron primer (without flouropolymers). The energy used for production of the primer in the back sheet was estimated by using the approximation Chemicals organic, at plant, GLO. Cutting losses during production of EVA (1%) and PET (4%) were included. All the components of the PV panels and their respective country of production are illustrated in the flowchart in **Fel! Hittar inte referenskälla.**

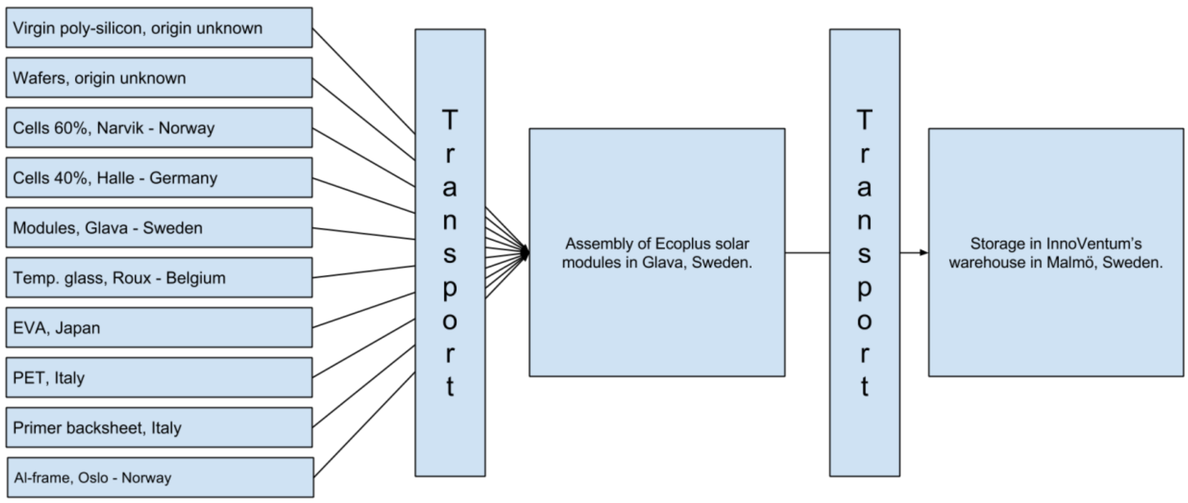

Figure 22. Flowchart of the PV production chain

The inventory data gathered from the carbon footprint evaluation is presented in Table 10 below.

Table 10. Weight distribution and energy consumption of the constituting parts of the PV module. (Wild-Scholten, 2012)

Component/material	Quantities for 6 modules (1.5 kWp)
Poly-silicon [kg] virgin	5.99
Wafers [numbers]	382
Cells [numbers]	369
Upgrading of cells [numbers]	369
Modules [m2] 1665 mm x 991 mm	9.9
Temp. glass [kg]	77.4
EVA [kg]	11.4
PET [kg]	2.36
Primer backsheet [kg] incl. Loss	1.35

Battery

As no specific life cycle data was found for the Sonnenschein SB6 - 200 A battery, generalized data for the weight distribution of materials used in lead-acid batteries was used instead (Rydh, 1999). This weight distribution can be found in Table 11 below.

Table 11. The weight distribution of the constituting materials of the lead-acid battery. (Rydh, 1999)

Material	Component	Weight %	1 battery (31 kg)
Lead	Active material, grids and poles	61.2	19.0
Water	Electrolyte (dilution to 1.295 s.g.)	13.3	4.1
Sulphuric acid (pure)	Electrolyte	9.6	3.0
Polypropylene	Cases and covers	8.2	2.5
Sb,Sn, As	Grid alloys	2.1	0.7
Polyethylene, PET	Separators	2	0.6
Polyester	Tubular mats	0.3	0.09
Copper	Connectors	0.3	0.09
Others	Expander and oxygen in PbO_2	3	0.9
Total		100	31

Other electrical components

The other electrical components featured in the Powertower are the inverter, the maximum power point tracker, the solar charge controller and the wind charge controller. For the inverter, data for a general 2500 W (weighing 18.5 kg) inverter was taken from EcoInvent and scaled up to the weight of the Studer XTender inverter used in the Powertower. Because good, specific LCA or material data was not found for the other electrical components in the off-grid cabinet, they were approximated to have the same composition and environmental impact as the inverter, but scaled to their respective weights.

Table 12. The weights of the electrical components.

	Weight (kg)	Source
Inverter	23	(Studer, 2014)
Smartserver	0.42	(NEX-G Energy Ltd, 2012)
MPPT	4.14	(Morningstar, 2010)
Wind charge controller	16	(Listnewenergy, 2014)

4.2.2 The Diesel generator system

As no specific life cycle data was found for the diesel generator, generalized data for the weight distribution of materials used in diesel generators was instead used. This weight distribution can be found in Table 13 below.

Table 13. The weight distribution of materials in the diesel generator. (Bondesson, 2010)

Material	Weight %	Weight (kg)
Aluminium	0.32	80.8
Copper	0.045	11.2
Steel	0.54	135
Plastic	0.090	22.4
Total	1	249

4.2.3 Impact from transportation

All the different components of the Powertower were assumed to be transported from their respective production facility to InnoVentums warehouse in Malmö, Sweden. From there the Powertower is transported by container ship to the port nearest to the location of use. The transport from the port to the actual place of use was neglected in order to make a fair comparison. Since the locations within the countries were randomly selected, the exclusion of this transport will negate the importance of the choice of location, but still include the freight by container ship to the country. Since the wind turbine and the wind charge controller are produced by the same company, they are assumed to be transported at the same time. In the case of the diesel generator it was assumed to be transported from Singapore where KohlerPower has a production facility.

When the place of production was not known, locations where it is probable that the production may have taken place where instead used. This was the example in the case of the Echelon solar charge controller where specific data on where it is produced was unavailable. A production facility in Watford, UK where it might have been produced was therefore used as an approximation. These approximations can be motivated because the environmental impact from the transport of these components will have a relatively small impact on the overall result. The approximated components also constitute a relatively small portion of the total weight of the Powertower, which further decreases the importance of the approximation on the results.

The port-to-port distance was calculated by using the SeaRates "port-to-port calculator" (SeaRates, 2014). The environmental impact of the different transports was calculated by using the network for transport measures (NTM) basic freight calculator (NTM, 2014). The transports by road were all assumed to be carried out by truck with trailer able to carry 28-34 tonnes. The transports over sea were all assumed to be carried out by container ship.

A table showing data for the different transports that take place during the life cycle of the two energy supply systems can be seen in appendix D. The overall results of the transport emissions of the two different energy supply systems have in the main case of this study can be seen below in Table 14. It is obvious that the Powertower System has a lot higher transport emissions than the Diesel generator system.

Table 14. The total transport emissions of the two energy supply systems for the main case of the study

Environmental impact category	Transport emissions of Powertowers	Transport emissions of Diesel generator
Total CO_2-eqv (kg)	8620	24.4
Total energy (MJ)	113000	275
Total acidification potential (kg SO_2-eqv)	273	1.46
Total eutrophication potential (kg NO_x-eqv)	22.4	0.14
Total photochemical oxidation potential (kg POCP-eqv)	0.31	0.002

4.3 Life cycle impact assessment

In this section the environmental impact factors (that convert the life cycle inventory data into results regarding environmental impact) are displayed. Table 15 shows a list of the different materials that are found in the life cycle inventory phase and their respective environmental impact factors (displayed as impact per kg of material). These impact categories are the following;

- Global warming potential, GWP-100 (measured in CO_2-equivalents)
- Primary energy use (measured in Joule)
- Eutrophication potential (measured in NO_x-equivalents)
- Acidification potential (measured in SO_2-equivalens)
- Photochemical ozone depletion potential (measured in C_2H_4-equivalents)

These impact categories are then multiplied with the quantities of the different materials used in the different energy supply systems in order to get a measure of the total environmental impact that the life cycles of the systems result in. The environmental impact factors used in this study can be seen in Table 15.

Table 15. The life cycle impact assessment data used in this analysis. All data is expressed as kg emission / kg material (except for the inverter, smartserver, MPPT and wind controller). The data Is mainly gathered from EcoInvent 2.2 but also other sources such as LCA's were used.

Material	GWP-100 kg CO_2-eq/kg	Eutrophication kg PO_4^{-3}-eq/kg	Acidiphication kg SO_2-eq/kg	Photochemical oxidation kg C_2H_4-eq/kg	Primary energy MJ/kg	Source
Aluminum	11.97	1822	487.2	39.8	64.70	Ecoinvent 2.2, Aluminium, primary, at plant
Copper	1.86	8587	546.9	15	11.49	Ecoinvent 2.2, Copper, primary, at refinery, RER
Steel	1.60	779	213.3	1.6	19.6	(World Steel Association, 2011)
Plastic	2.88	353	93.3	14.3	86.27	Ecoinvent 2.2, PET, granulate, bottle grade, at plant
Argon liquid	0.31	11	1.4	0	6.86	Ecoinvent 2.2, Argon, liquid
Boric acid	0.71	17	17.9	0.2	13.01	Ecoinvent 2.2, Boric acid, inorganic chemicals
Diethanolamine	3.65	48	14	2.2	96.59	Ecoinvent 2.2, Diethanolamine, organic chemical

Propiconazole	10.56	253	49.8	4.1	201.96	Ecoinvent 2.2, fungicides, at regional storehouse
Copper carbonate	1.88	1032	88.7	1.2	34.48	Ecoinvent 2.2, Copper carbonate, at plant
Tebuconazole	10.56	253	49.8	4.1	201.96	Ecoinvent 2.2, Fungicides, at regional storehouse
Organic acid	2.49	34	9	1.4	64.97	Ecoinvent 2.2, Formic acid, at plant
Concrete	0.12	0	120.1	0	0.67	(Sjunnesson, 2005)
Diesel	3.52	1	3515.9	0.2	46.98	(Gode, o.a., 2011)
Gasoline	3.73	1	8.2	2.1	48.12	(Gode, o.a., 2011)
Impregnated pine	0.14	3760	109.7	10.7	3.63	(Jildestedt, 2007)
Neodynium magnet	27.00	190	440	17	0.00	(Sprecher, o.a., 2014)
Reinforced nylon fibre glass	2.63	45	15.5	0.5	45.87	EcoInvent 2.2, Glass fibre, at plant, RER
Inverter	869.01	92348	7649.8	845.7	15923.69	Ecoinvent 2.2, Inverter, 2500W, at plant
Smartserver	7.59	807	66.8	7.4	139.07	Ecoinvent 2.2, Inverter, 2500W, at plant
MPPT	670.92	71297	5906.1	652.9	12293.92	Ecoinvent 2.2, Inverter, 2500W, at plant
Wind controller	1973.30	209698	17370.8	1920.3	36158.59	Ecoinvent 2.2, Inverter, 2500W, at plant
Lead, Primary	2.12	137	48.5	0.8	42.49	Ecoinvent 2.2, Lead, primary, at plant
Lead, Secondary	0.66	16	14.1	0.3	11.94	Ecoinvent 2.2, Lead, secondary, at plant
Water	0.00	0	0	0	0.00	Ecoinvent 2.2, Tap water, at user, RER

Sulphuric Acid	0,12	3	13.5	0	2,12	Ecoinvent 2.2, Sulphuric acid, liquid, at plant
Polypropylene	1,97	7	6.2	1.8	75,12	Ecoinvent 2.2, Polypropylene, granulate, at plant

4.4 Life cycle interpretation

4.4.1 Results of the LCA study

Table 166 shows a summary of the results from the main case of this study, expressed as impact per used kWh. The results presented in Table 16 are only regarding global warming potential and primary energy use as these impact categories are most relevant for energy supply systems.

As can be seen two alternatives named Powertower- and renewable/diesel hybrid system 100 % are included. These alternatives are included in order to make a fair comparison of the different alternatives. Because of the model used in this study where the energy supply systems are dimensioned to meet the load of the humanitarian aid village, portions of the electricity will be considered as "over-production", and therefore will not be utilized. These two other alternatives are included in order to simulate what the environmental impact would be if the energy supply systems were used for regular power generation.

Table 16. A summary of the results, expressed as impact per kWh electricity.

Energy supply system	Global warming potential (g CO2-eq)	Primary energy use (kWh)
Powertower system	89	0.33
Diesel generator system	1867	6.94
Renewable/diesel hybrid system	549	2.05
Powertower system 100 %	35	0.13
Renewable/diesel hybrid system 100 %	423	1.58

Global warming potential

Figure 23 shows the total amount of CO_2-equivalents (GWP-100) that are emitted during the life cycles of the three different energy supply systems. It can be seen that the Powertower system has about 21 times lower emissions of greenhouse gases compared to the diesel generator system, and about 6 times lower compared to the hybrid system (regarding global warming potential).

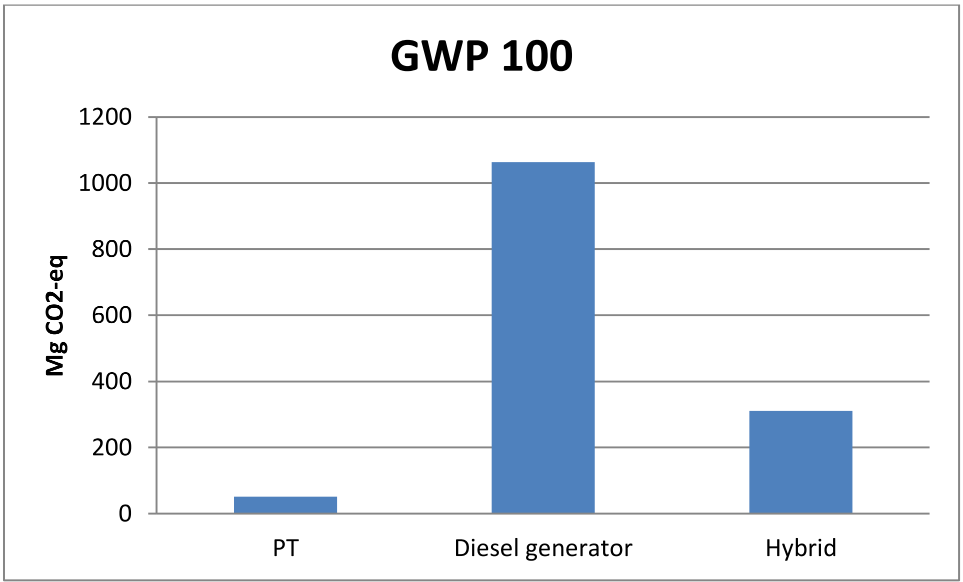

Figure 23. The total GWP emissions over 20 years for the three different energy supply system

Figure 24 illustrates how the GWP emissions are distributed between the different components of the Powertower system. The tower is the component that has the highest amount of emissions, and has about 25 % higher amount of greenhouse gas emissions compared to the concrete portion of the Powertower system (which has the second highest environmental impact).

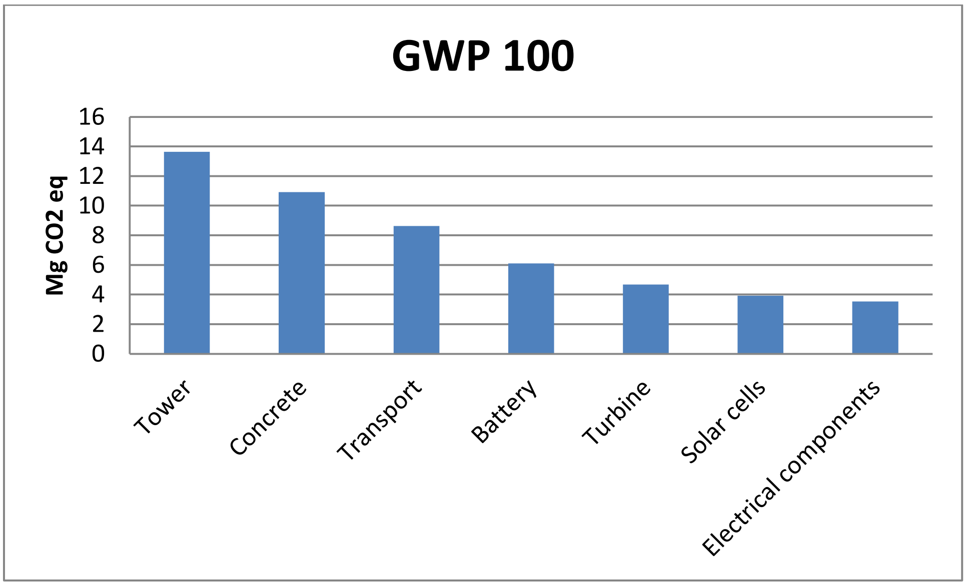

Figure 24. The distribution of the GWP emissions between the different components of the Powertower system

Primary energy consumption

Figure 25 shows the total amount of primary energy use that is required during the life cycles of the three different energy supply systems. The two best alternatives (PT and hybrid) have significantly lower primary energy use than the worst alternative (diesel generator). It can be seen that the Powertower system has about 21 times lower primary energy use compared to the diesel generator system, and about 2 times lower compared to the hybrid system.

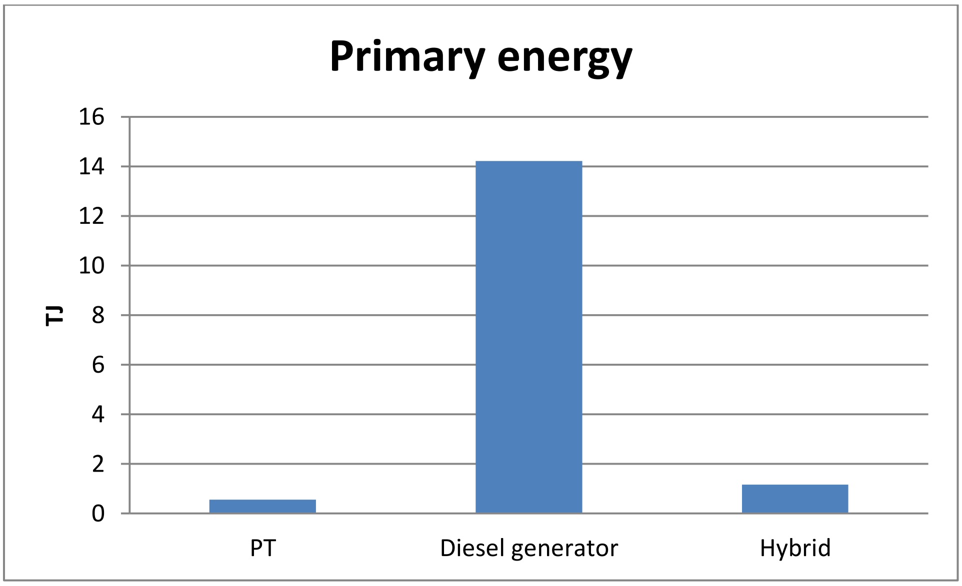

Figure 25. The total primary energy use over 20 years for the three different energy supply system

Other environmental impact categories

Regarding the eutrophication potential the diesel generator system had the lowest amount of impact with a total of about 600 kg NOx-equivalents. The hybrid system had the second lowest amount of impact with about 4 times higher emissions than the diesel generator system. The Powertower system had the clearly highest emissions with 20 tonnes of NOx-equivalents emitted (about 33 times higher than the diesel generator system).

Regarding the acidification potential the hybrid system had the lowest amount of impact with a total of about 680 kg SO_2-equivalents. The diesel generator system had the second lowest amount of impact with about 3.5 times higher emissions than the hybrid system. The Powertower system had the highest acidification potential with about 6 times higher emissions than the hybrid system.

Regarding the photochemical oxidation potential the diesel generator- and hybrid system had the lowest impact with about 60 and 80 kg C_2H_4-equivalents emitted respectively. The Powertower system clearly had the highest amount of impact with about 12 times higher than the diesel generator system.

The results regarding the other environmental impact categories are presented in more detail with graphs in appendix E.

4.4.2 Identification of significant issues

Contribution analysis

The contribution that the different stages in the life cycle have out of the total impact varies between the different energy supply systems. The percentage of contribution that the different stages have can be seen in Figure 26 below. The end of life treatment stage is excluded from this analysis.

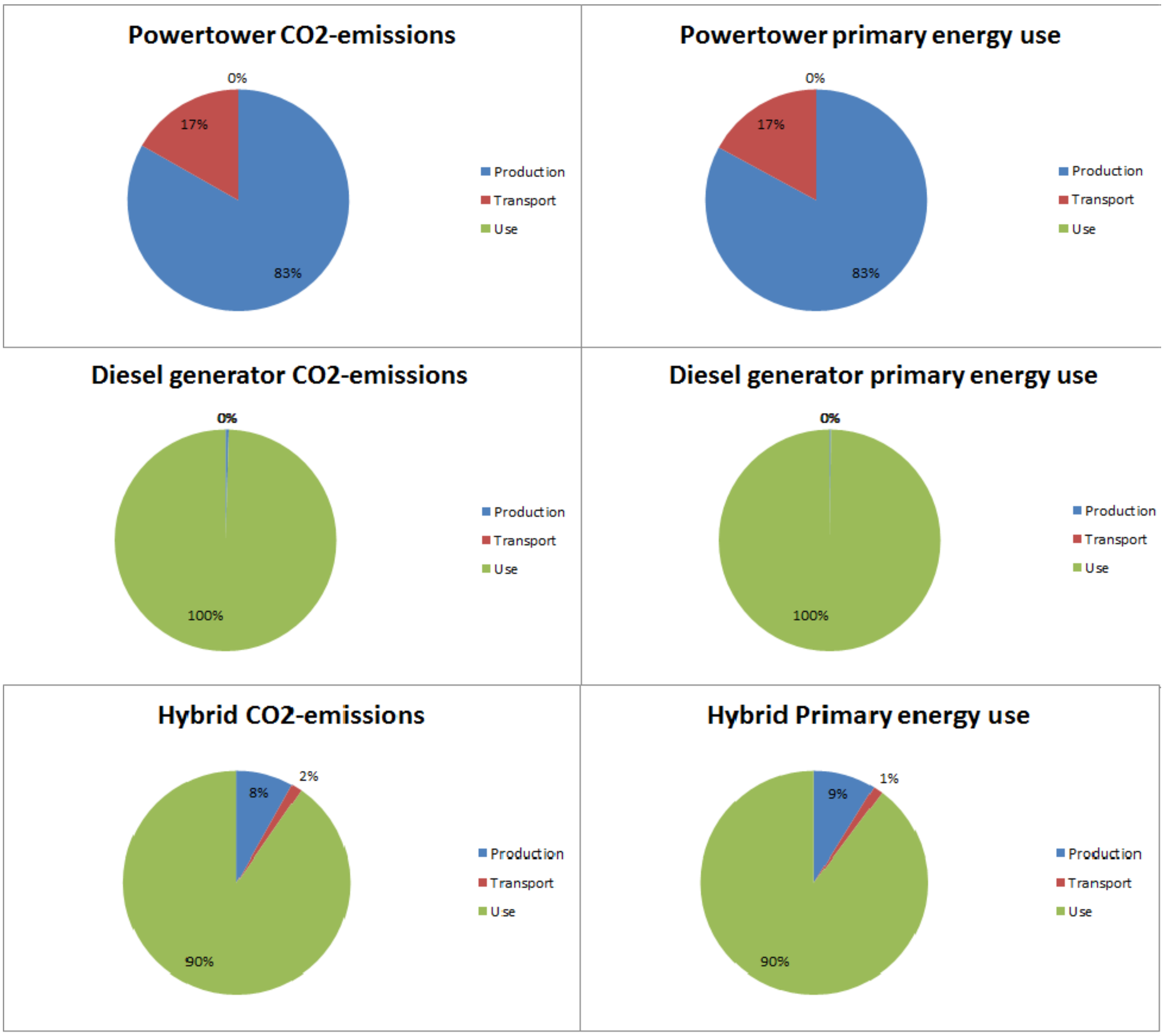

Figure 26. Life cycle emissions of each systems life cycle stage.

Figure 26 above shows that the production phase of the Powertower system contributes the most to the total impact, amounting to more than 80 % of the impact regarding both GWP and primary energy use. The rest of the impact is caused by the transport phase of the life cycle. As can be seen in Figure 26, the components of the Powertower system that have the highest environmental impact is the tower, followed by the concrete and then the transport (in decreasing order). Since the amount of emissions due to transport is highly dependent on the location where the system is to be used (and the Philippines is far away from Sweden) this might be a bit misleading. Therefore, in other cases (concerning other, closer locations) the third most emitting part could instead be the batteries. The component which contributes most to the total emissions is the steel billet that contributes about 85 % of the impact. Therefore the steel billet can be considered the main contributing elementary flow in the Powertower system.

Regarding the diesel generator system, the diesel fuel clearly contributes to the highest amount of environmental impact (amounting to more than 99 % of the total impact) making it the main contributing elementary flow and causing the operational phase to be the dominant phase (as can be seen in Figure 26 above). This also explains the very high contribution of the operational phase of the diesel generator. Regarding the renewable/diesel hybrid, it can be seen in Figure 26 that the use phase of the system is the one causing the highest amount of environmental impact (amounting to 89 % of the total impact). The production phase contributes to 10 % of the impact and the transport phase 1 %.

This shows that the diesel fuel is the main contributor, even in a hybrid system containing 5 Powertowers. As the diesel generator system has about 20 times more environmental impact it is easy to understand how about 90 % of the impact comes from the diesel portion of the hybrid system. This conclusion is in line with that of (Bondesson, 2010), which came to the same conclusion that the diesel generator portion of these systems clearly has the highest environmental impact.

4.4.3 Discussion on the need for further data collection or data quality improvement

This study has some limitations regarding the inventory data completeness and quality. A majority of the components are included in the life cycle inventory phase, with the exclusion of the actual off-grid cabinet and the cables connecting the Powertowers to the off-grid cabinets. This exclusion can be motivated by the 95 % cut-off rule (based on mass). The tower and solar cell portion of the Powertower system can be deemed to be quite accurate to reality as specific LCA data were used. The lead-acid batteries and diesel generator data were not specific to the actual components used in the system, but of a more general nature describing common weight distributions in these components. The data quality of these components is acceptable, but leaves room for improvement.

The composition of the turbine is one of the most speculative, as the manufacturer didn't provide very specific information and assumptions had to be made. The other electrical components are also not that accurate, as they were approximated to have the same material composition as the inverter. Therefore the data quality of the turbine and the other electrical components (excluding the inverter) leaves room for improvement. Surely, the mass has been accounted for, but how this mass is distributed between the composing materials is only speculative. The non-conformity of data sources and their quality might also limit the reliability of the study. Table 17 lists the sources of the different LCI data and an evaluation of the accuracy of the data in relation to the studied system.

Table 17. The sources of the life cycle inventory data of the components in the study (evaluation of accuracy included)

Component	Source	Accuracy
The Dali tower	Anca Stoica	High
The solar cells	(Wild-Scholten, 2012)	High
The batteries	(Bondesson, 2014)	Mid
Inverter	EcoInvent 2.2	High
Other electrical components	Approximation	Mid
The turbine	(Daligault, 2014) + Approximation	Low
The diesel generator	(Bondesson, 2014)	Mid

Regarding end of life treatment, this phase was not included in the main case, but instead studied in one of the sensitivity analyses. In this sensitivity analysis the choice of a 100 year perspective concerning the emissions from the material placed in landfill will lead to an exclusion of emissions from the end of life treatment from the three studied energy supply systems.

4.4.4 Discussion on the choice of sensitivity analyses

This section will discuss some of the methodological choices that have been made in this study. Some important factors of uncertainty affecting the results were identified. These are the geographical conditions, the load profile, the height at which the wind speed is measured, the amount of solar cells that is used, the end-of-life treatment phase and the use of over-production. These factors are described in the following section.

The geographical conditions

The main case of this study was to study the implementation of Powertowers in the Philippines. This choice was made due to the recent activities of InnoVentum in the Philippines (the "Power to the Philippines" project). It is not clear however if the conditions in the Philippines are ideal for the implementation of Powertowers for electricity generation. This is why a geographical sensitivity analysis, with the aim of investigating what other potential locations might be more appropriate for this setup, is performed.

The load profile

The load profile that is used in the main case of this study can be deemed to be quite accurate to that of the Scandinavian village in Tacloban, the Philippines. However, the appliances (and their respective quantities) that have been chosen to constitute the load of one house (inhabiting 10 people) is on the lower end of the standard of living scale. The “higher load sensitivity analysis” intends to perform the same analysis as in the main case, but for an increased load.

The wind speed

When modelling the main case in Tacloban one factor was changed; the height at which the wind speeds were measured. In actuality, the Powertowers that potentially will be mounted in the Scandinavian village will be placed on a hill about 130 meters above sea height. As this is a highly specific condition which will give unreasonably high production it will make the results of the study less comparable to other studies. Instead a height of 30 meters was used, so as to not overestimate the result. In order to account for higher production that the placement of the Powertower system on a hill will lead to, the sensitivity analysis “higher wind turbine production” was performed.

The amount of solar cells

When looking at production at different locations for the Powertower system it might show various ratios of production between the wind turbine and the PV-cells due to different external conditions. The fact that the external conditions differs makes it uncertain that the setup of the main case is the optimal to apply at other locations. Because of this uncertainty a sensitivity analysis is made with 8 PV-cells instead of 6 which is the main case.

End of life treatment

The choice was made to exclude the end of life treatment phase from the main case of this study, making it a cradle-to-gate analysis (including the operational phase). This choice was made due to the uncertainties of the closed-loop recycling model that was intended to be used. In order to make an attempt at performing a cradle-to-grave analysis, a study including end of life treatment was performed in the end-of-life treatment sensitivity analysis instead.

Utilization of over-production

It is clear from the main case of this study that the studied energy supply systems including Powertowers lead to high amount of electricity that is not utilized (over-production). There are many ways to make us of this energy, such as for heating or cooling water, powering mills and more. In order to investigate how the environmental performance is affected if a portion of this “over-produced” energy is utilized, a sensitivity analysis is performed (where 50 % of the electricity is used).

4.4.5 Sensitivity analyses

In order to examine the dependence of the result upon certain factors, a couple of sensitivity analyses will be conducted. The different analyses include the following aspects;

- Localization
- End of life treatment
- Higher wind turbine production
- Different set up (8 solar cells)
- Higher load
- Utilization of 50 % of the over-production

4.4.5.1 Geographical sensitivity analysis

This geographical sensitivity analysis will research how the environmental impact of the Powertower system differs depending upon where in the world it is deployed. All of the locations chosen have humanitarian aid villages present in the area, and the magnitude and variance of the load of these villages are assumed to be the same as the one in Tacloban.

The first step of the geographical sensitivity analysis is calculating the amount of energy that one Powertower can produce under the different local conditions. As no continuous values were available for the other locations studied in this geographical sensitivity analysis, a continuous data-set of actual wind speeds was modified and used instead. The dataset was collected during a year at Kriegers Flak in Denmark. In order to make the dataset applicable to the different locations, the annual average of the location was divided with the annual average of the Danish dataset. This factor was then multiplied with each hourly wind speed value, so that the annual average of the dataset becomes that of the location.

In order to get the hourly wind turbine production each hourly wind speed value was matched to the power curve of the turbine which can be seen in Figure 5. The average insolation values and the annual average wind speeds and the corresponding wind turbine production these calculations are based upon can be found in Appendix C. The results of the individual and combined production of the wind turbine and solar cells of one Powertower in the different locations can be seen in Figure 27 below.

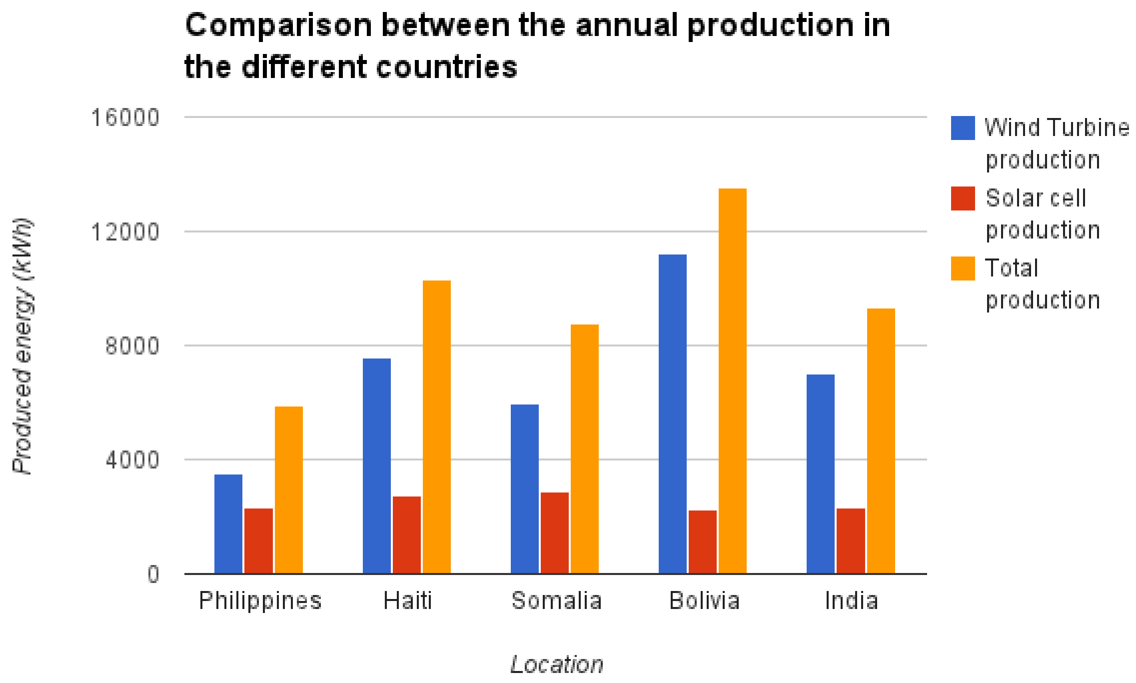

Figure 27. Comparison between the annual production of one Powertower in the different locations

The next step is performing the state of charge simulation to determine what amount of Powertowers are needed to supply the annual load to the village (28.5 MWh) so that the state of charge stays above zero more than 95 % of the time. The amount of Powertowers and the corresponding amount of batteries will be raised until the percentage of time above 0 % SOC crosses the 95 % limit. The results of this simulation can be seen in Table 18.

Table 18. The result of the state of charge simulation

Location	The Philippines	Haiti	Somalia	Bolivia	India
Number of PT's	13	8	9	8	10
Time above 0% SOC	95.3%	95.5%	96.2%	96.8%	96.4%
Nbr of battery deep discharges (below 40 % SOC)	129	135	145	89	107
Yearly over-production (in MWh)	44.4	54.3	50.6	79.7	65.0

Since the numbers of Powertower are in uneven 3's the amount of off-grid cabinets and their respective components will vary between the different locations. These quantities are illustrated in Table 19.

Table 19. The amount of off-grid cabinets and their respective components in the different locations

	Off-grid cabinets	Batteries	MPPT	Inverter	Solar charge controller	Wind charge controller
Philippines	4	32	13	4	4	13
Haiti	3	24	8	3	3	8
Somalia	3	24	9	3	3	9
Bolivia	3	24	8	3	3	8
India	3	24	10	3	3	10

The transportation impact for the different locations can be seen below in Table 20

Table 20. The total transport emissions of the two (fully dimensioned) energy supply systems

	Transport emissions of Powertowers		Transport emissions of Diesel generator	
Location	Total CO2-eqv (Mg)	Total Energy (GJ)	Total CO2-eqv (kg)	Total Energy (MJ)
Philippines	12.1	153	20.3	260
Haiti	4.18	508	22.4	287
Somalia	7.64	967	50.4	646
Bolivia	5.65	713	30.8	394
India	6.69	843	4.10	52.6

Results

Figure 28 and Figure 29 shows the results of the geographical sensitivity analysis. It can be seen that the main case in the Philippines has the highest amount of emissions and therefore is the worst alternative (because of the low renewable resources found here compared to the other locations). The best location is Haiti, followed by Bolivia, Somalia and India.

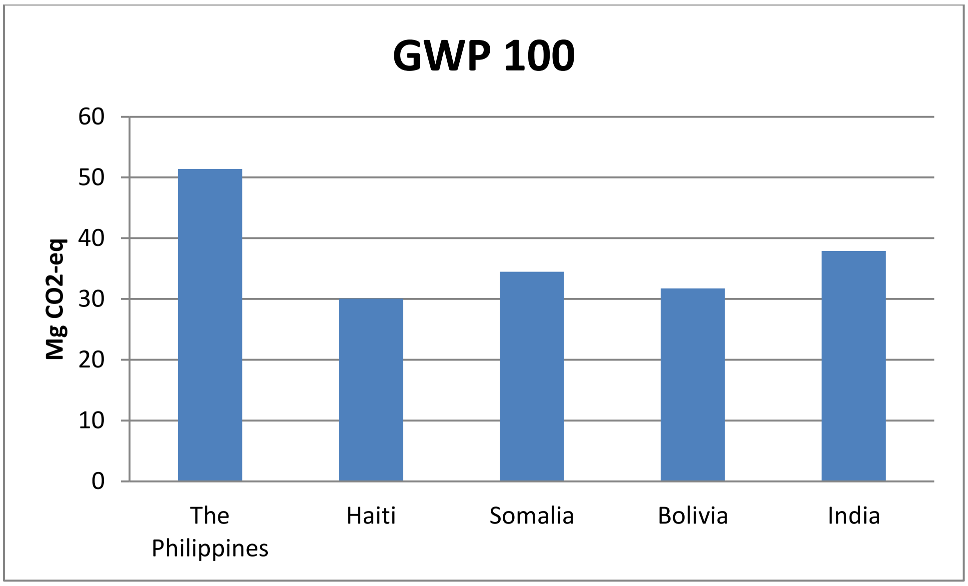

Figure 28. Global warming potential for each location.

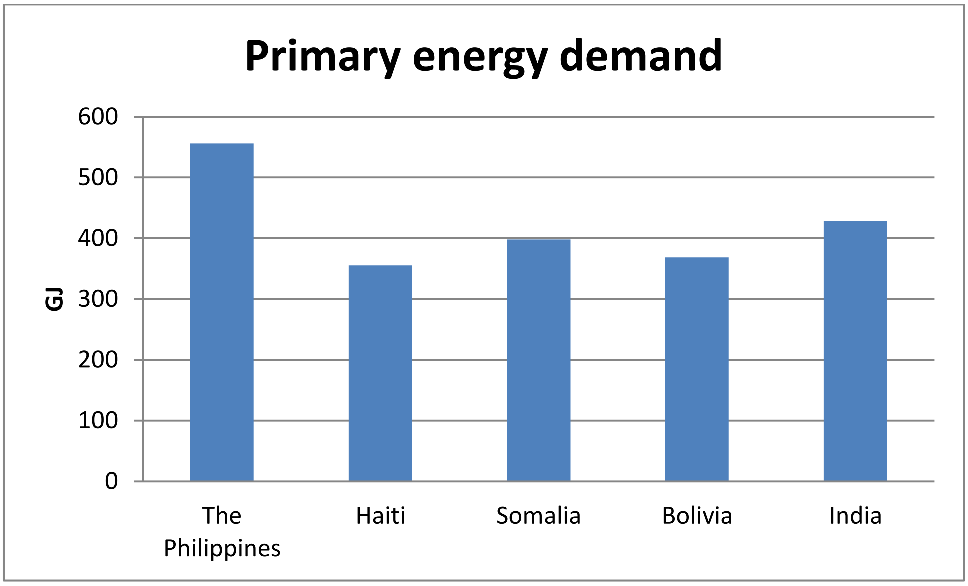

Figure 29. Primary energy demand for each location.

The results regarding the other three environmental impact categories are very similar to each other as they all are relative to the amount of Powertowers that were needed for meeting the load of the humanitarian aid village. The results are also slightly affected by the difference in impact from the transportation of the energy supply systems. The two localizations with the lowest amount of impact therefore were Haiti and Bolivia, followed by Somalia, India and the Philippines. The results regarding the other environmental impact categories for the geographical sensitivity analysis are presented in appendix F.

4.4.5.2 End-of-life treatment sensitivity analysis

In the main case no recycling is being accounted for, making the study a cradle-to-gate analysis. This sensitivity analysis intends to take the recycling of materials into account, in order to make the study into a cradle-to-grave analysis. The recycling of materials will lead to a lower total environmental impact of the product system. There are different ways of modelling the recycling of materials. The two main methods are closed- and open-loop recycling (The Institute for Environment and Sustainibility, 2010).

In this sensitivity analysis, a modified version of the simple closed-loop recycling is used in order to account for some of the reduced environmental impact. Closed-loop recycling means that the recycled material is assumed to not be downgraded in quality during the recycling process, and can therefore be replacing virgin material within the product system, hence creating a closed-loop system. Open-loop recycling means that the properties of the recycled material are assumed to be downgraded (or changed) to such an extent that it cannot be directly replaced by virgin material within the product system. The recycled material instead goes into another product system, creating an open-loop recycling (The Institute for Environment and Sustainibility, 2010).

The portions of materials that are not recycled (by closed-loop recycling) are assumed to be landfilled. A 100-year perspective is assumed for the landfilled material and it is assumed to be no emissions from the landfilled material during this period. This is of course not very realistic, as the landfilled material will be completely released to the environment seen from a long enough time-perspective, but these assumptions are made anyway in order to simplify calculations.

The location of the recycling facility was assumed to be in Europe and the location of the landfill was assumed to be in the Philippines. The material that is to be recycled is shipped by container ship to Europe (equal distance as the transport to the Philippines) and thereafter are transported 250 km by truck, which is an estimate of the average distance to a recycling facility in Europe (EeBGuide, 2012). The material that is to be landfilled is assumed to be transported 250 km by truck to a landfill. The environmental impact of the transport of the materials that are to be recycled or landfilled is then subtracted from the environmental benefit that the recycling of material bring about.

The materials that are to be recycled in this sensitivity analysis (and their respective recycling rates) can be seen in Table 21. These are some of the major constituting materials of the different energy supply systems. As can be seen not all recyclable materials were included here. Some materials were excluded as their recycling rates were not as easy to find as for the materials in Table 21.

Table 21. Recycling rates of some common materials found in the energy supply systems

Material	Recycling rates	Source
Steel	0,8	(Sundqvist, 1999)
Aluminium	0,6	(Sundqvist, 1999)
Copper	0,5	(Sundqvist, 1999)
Lead	1	(Bondesson, 2014)
Plastics	0	(Bondesson, 2014)
Wood	0	(The City of Calgary, 2014)
Silicone plates	0,7	(Davidsson, 2014)
Other electrical components	0,3	Assumption
Concrete	0	(The City of Calgary, 2014)

The respective quantities of recycled material within the product systems that the recycling rates stated in Table 21 give rise to can be found in Appendix I.

Results

Table 22 shows the emissions and the reductions compared to the main case of the study in % of both GWP-100 and primary energy use. It can be seen that the Powertower system has the highest amount of reduction, about 25 % for both the studied impact categories. Since the end of life treatment only takes the materials found in Table 21 (where diesel fuel obviously is not included) the most material intensive energy supply system, the Powertower system will be most affected by the recycling of materials. The diesel generator system is barely affected by the recycling of materials (0.2 % reduction), as the materials involved in the diesel generator has such a minor importance to the overall results when compared to the diesel fuel. The hybrid system has a slightly higher reduction of 2 %, which further shows what big portion of the environmental impact that the diesel generator stands for in the hybrid, as the 25 % decrease in the environmental impact of the Powertower doesn't amount to more than a reduction of 2 %.

Table 22. Emissions of CO2-eq/kWh and primary energy use/kWh (and reductions in % compared to the main case of the study) for the sensitivity analysis including end-of-life treatment.

Energy supply system	g CO2-eq/kWh	Reduction in % (GWP-100)	Primary energy use kWh/kWh	Reduction in % (Primary energy use)
Diesel generator	1864	0.2	6.9	0.6
PowerTower used electricity	67	24.6	0.3	23.6
Power Tower use of 50 % over production	38	24.6	0.1	23.6
Hybrid	537	2.1	2.0	2.1
Hybrid use of 50 % overproduction	468	2.1	1.8	2.1

4.4.5.3 Higher wind turbine production sensitivity analysis

This sensitivity analysis intends to simulate the actual characteristics of the humanitarian aid village in Tacloban, where the Powertowers are intended to be placed on a hill that is estimated to be about 130 meters above sea level (compared to the 30 meters where the wind data for the main case were collected from). By increasing the height at which the annual wind average is gathered a higher wind turbine production will be achieved. In this sense, the main case includes a bit of an underestimation in terms of the amount of available wind resources in Tacloban, and this sensitivity analysis is therefore an attempt to make the analysis more accurate. The results of this sensitivity analysis will be compared to the results of the main case to see what difference the increased wind turbine production might cause in terms of environmental impact. The wind speed at a certain height can be converted by using the wind profile power law (WebMET, 2014) which is seen below;

$$U_x = U_r * ({}^{Z_x}/_{Z_r})^{\alpha}$$

In the wind profile power law the r denotes the reference height at which the wind speed is measured and x denotes the height to which you want to convert the wind speed data. The exponent, α, is an empirically derived coefficient that mainly is dependent upon the surface roughness and the stability of the atmosphere. In this sensitivity analysis a standard value of 0.147 (neutral stability) is used. By using the wind profile power law each hourly wind speed value is converted. This gives a higher total wind power production of 5.47 MWh (compared to 3.54 MWh for the main case). By running the state of charge simulation with this increased wind turbine production, a Powertower system consisting of 12 Powertowers will be used (instead of 13 in the main case).

Results

The results of the higher wind turbine sensitivity analysis can be seen in Table 23 below. In short the sensitivity analysis leads to a reduction of about 6 % in environmental impact regarding GWP and 3 % regarding primary energy use. The higher wind production scenario led to a higher annual wind production of 5.47 MWh (compared to 3.54 MWh for the main case) which equals an increase of about 35 %. This is about 2 MWh more energy produced per Powertower. In that sense it is quite surprising that this scenario only needed 1 less Powertower to meet the load. This probably has to do with the seasonal variation of the wind resource which has two low points around June and October. During these low points the SOC drops below the 0 % limit for long periods of time, and not even the general increase in wind turbine production that this sensitivity analysis brings about can help sustain the SOC above 0 % during these periods. It can be argued that this criterion for dimensioning the system (the SOC should be above 0 % 95 % of the time) matches poorly with the wind speed variation in the Philippines, as an increase of 35 % in production can’t reduce the amount of needed Powertowers more than 1.

Table 23. Comparison of global warming potential and primary energy per used kWh by the village.

Impact category	Main case	Higher wind production
g CO2-eq/kWh	89	84
kWh/kWh	0.33	0.32

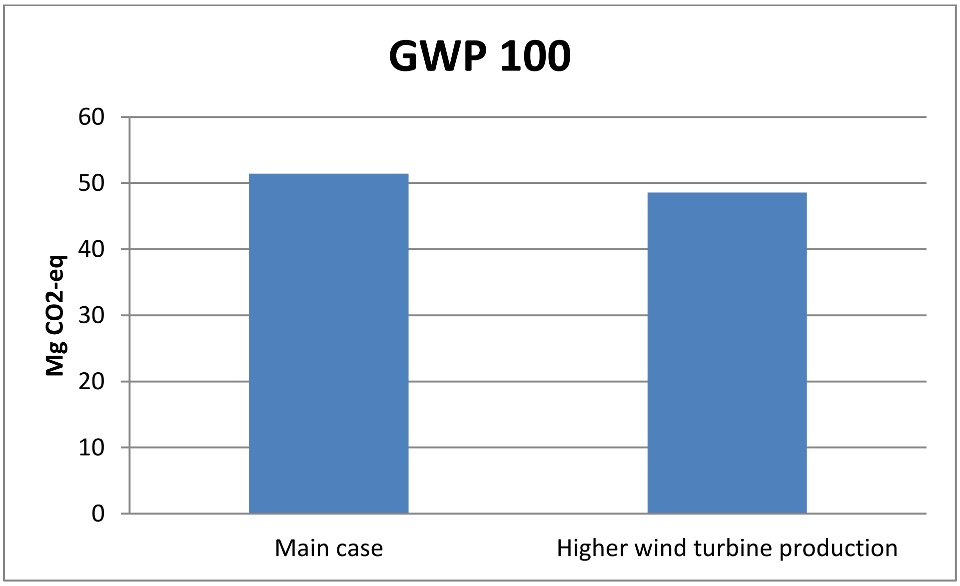

Figure 30. Global warming potential comparison between the main case and higher wind turbine production.

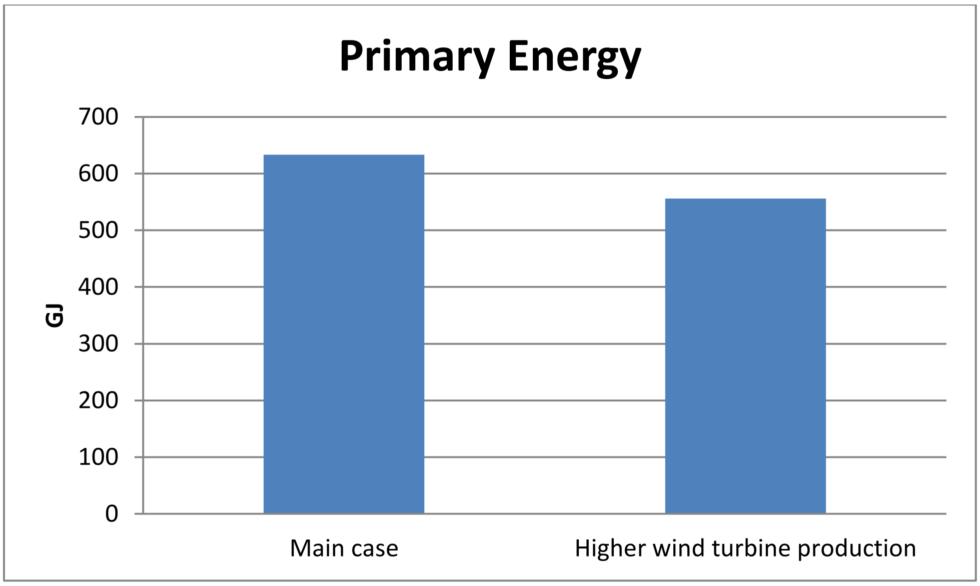

Figure 31.Copmarison of the primary energy consumed between the main case and higher wind production.

4.4.5.4 Different setup of Dali Powertower (8 solar panels) sensitivity analysis

The Dali Powertower comes in various different setups with varying types of wind turbines and amounts of solar cells (6 or 8). In this study, the HY-3000 IV Lite turbine is set as the wind turbine. In the main case, the setup with 6 solar panels is used. This sensitivity analysis intends to compare what difference in results there might be when instead using the setup with 8 solar panels, which will amount to a 33 % higher solar power production. This 33 % increase simply stems from the increase from 6 to 8 solar panels (8/6=1.33).

A state of charge simulation was run which concluded that a lower number of Powertowers was needed, 10 instead of 13. The battery tank was increased by 1 battery (to 30 kWh) in order to get the appropriate percentage of time that the SOC is over 0 without increasing the amount of Powertowers.

Results

As can be seen in Table 24, the setup with the solar panels emits about 17 % less GWP and uses 21 % less primary energy. This is due to the higher production of the Powertower setup containing 8 solar panels which creates a lower required number of Powertowers, resulting in a lower total environmental impact. This setup can therefore be deemed to be superior to the one used in the main case as the increase in solar cells decreases both the amount of Powertowers and the environmental impact about 20 %.

Table 24. Comparison of global warming potential and primary energy per used kWh by the village.

Impact category	Main case	8 solar panels
g CO2-eq/kWh	89	74
kWh/kWh	0.33	0.26

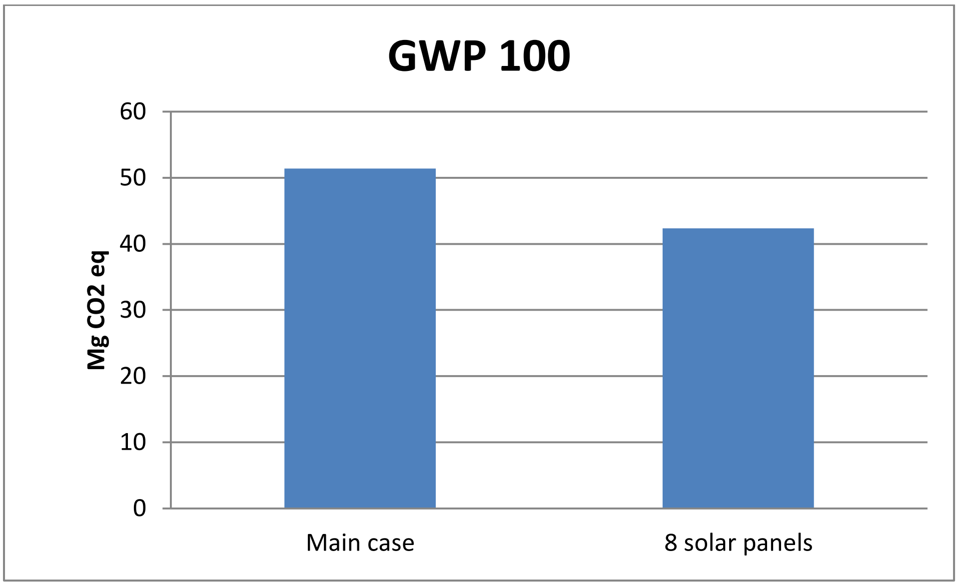

Figure 32. Global warming potential comparison between the main case and the 8 solar panels case.

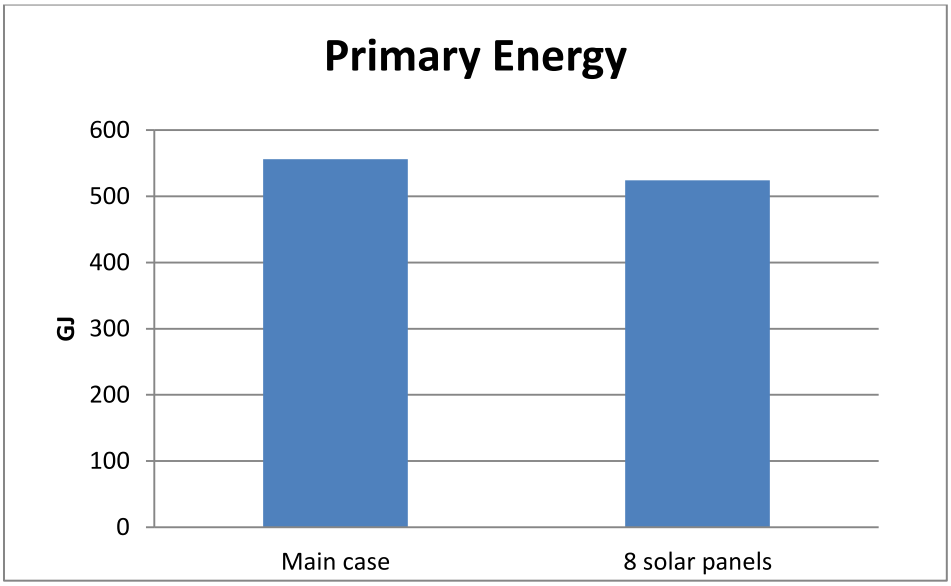

Figure 33. Comparison of the primary energy consumed between the main case and the 8 solar panel case

4.4.5.5 Higher load sensitivity analysis

This sensitivity analysis intends to simulate how the environmental performance of the Powertower system changes when a higher load is supplied. The same analysis as in the main case will be performed but with a different load profile, which will affect the state of charge simulation. This higher load has the aim of reflecting a higher standard of living than that of the Scandinavian village for an increased load. The appliances (and their respective quantities) that each household are assumed to use is found in Table 25.

Table 25. The appliances and their respective quantities (per household) used in the higher load scenario

Appliance	fridge	fan	lamps	cellphone	Tv	Neon type light
Quantity	1	3	12	2	1	6
Load (in Watts)	29	50	8	5	60	28

This amounts to an annual load of 49.0 MWh for the village (instead of 28.5 MWh for the main case). The daily load profile looks as in Figure 34 below.

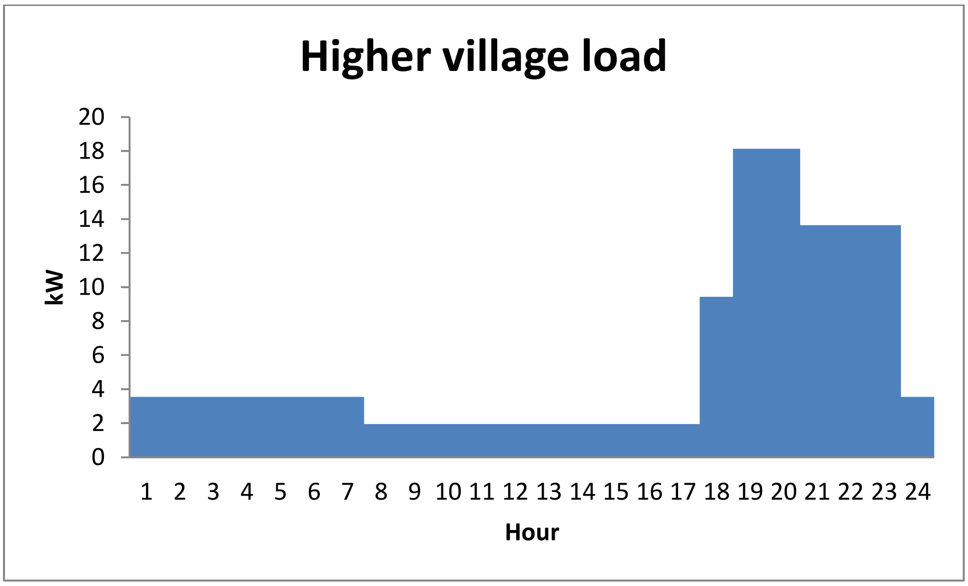

Figure 34. The higher load case displayed.

A state of charge simulation was run which concluded that 28 Powertowers (with a battery tank with a storage capacity of 90 kWh) were needed in order to properly supply the village with the higher load.

To supply the village with proper amount electricity with a diesel generator system are three diesel generators needed of the same capacity as the one in the main case. The diesel consumption is calculated in the same way as in the main case and results in 27 000 liters a year.

Results

As can be seen in Figure 35 and Figure 37 the higher load scenario leads to about a higher amount of environmental impact per kWh for the Powertower- system than the main case. This is also true for the diesel generator system which can be seen in Figure 36 and Figure 38. The difference for the power tower system can be related to the higher amount of over production that a larger system (dimensioned for a higher load) leads to. In the case of the diesel generator system, the difference of environmental impact can be related to the lower efficiency of the diesel generator when running at a higher capacity, and also the higher number of diesel generators required.

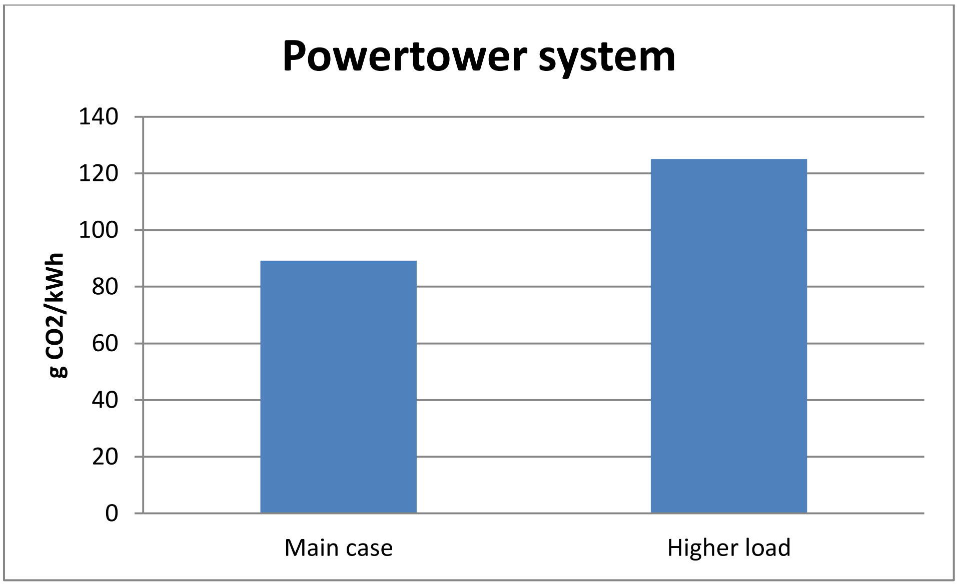

Figure 35. Comparison of emissions of CO2-eq/kWh for the Powertower between higher load sensitivity analysis and main case.

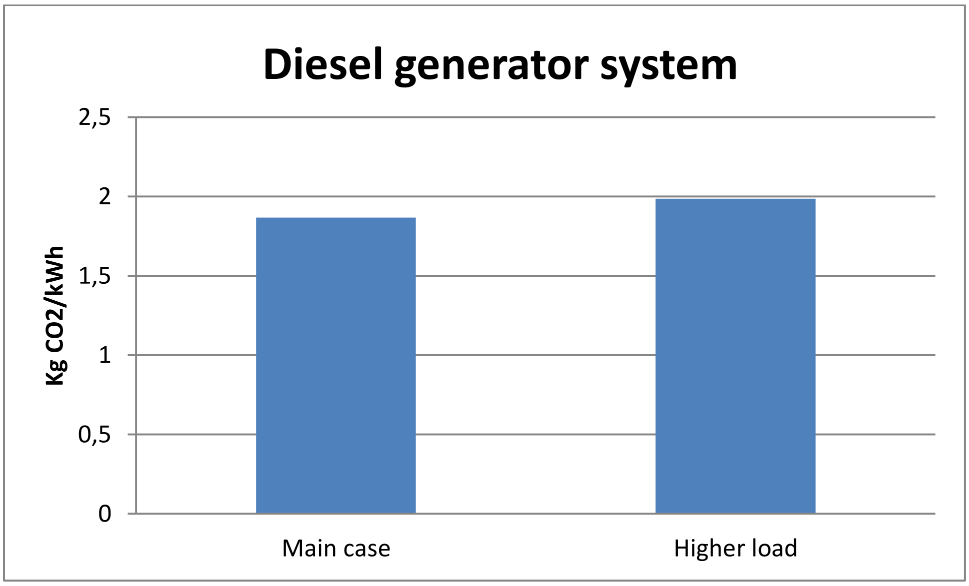

Figure 36. Comparison of emissions of CO2-eq/kWh for the diesel generator system between higher load sensitivity analysis and main case.

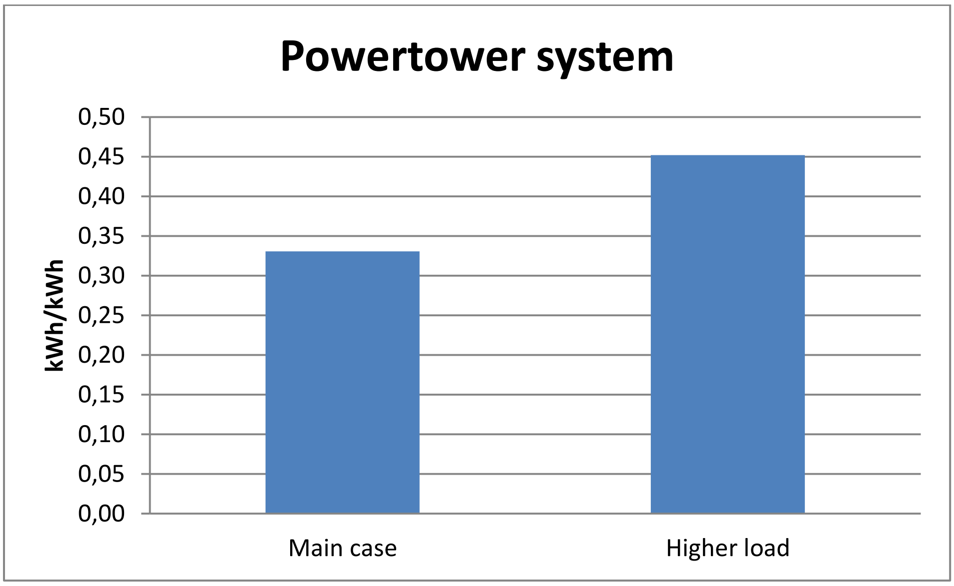

Figure 37. Comparison of use of primary energy per used kWh for the Powertower between higher load sensitivity analysis and main case.

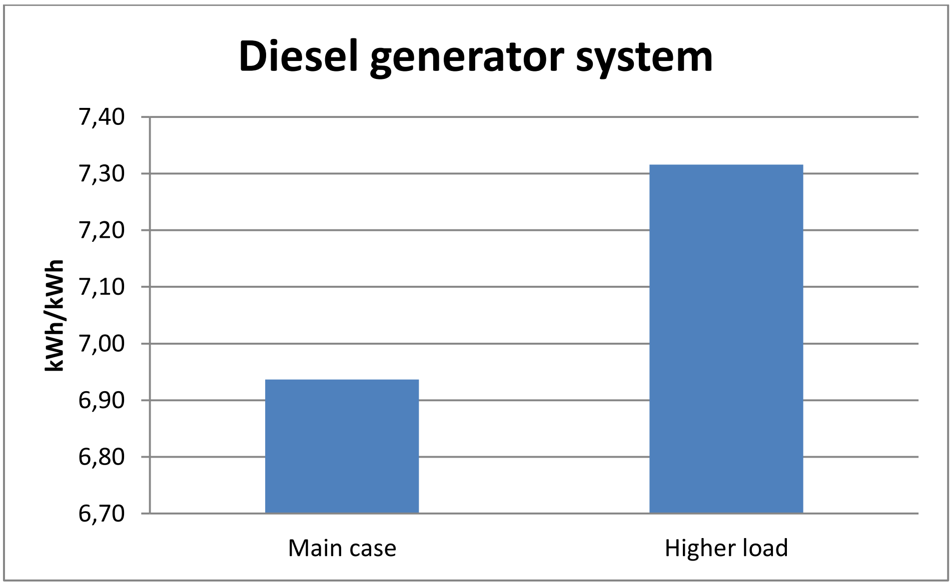

Figure 38. Comparison of use of primary energy per used kWh for the diesel generator system between higher load sensitivity analysis and main case.

4.4.5.6 Utilization of 50% of the over-production sensitivity analysis

Renewable energy solutions often give rise to over-production of energy that may or may not be utilized. This sensitivity analysis intends to simulate how the emissions will change if 50 % of the energy that is not used (the over-production) can be utilized. Since this increases the amount of used energy, the emissions per kWh will be lower. This analysis will only consider the Powertower and renewable/diesel-hybrid system since these are the only systems that bring about over-production.

Results

When comparing the emissions of the Powertower system it can be seen in Figure 39 and Figure 40 that the GWP is decreased by 44 % and the primary energy use is decreased by 43 % when 50 % of the over-production is utilized. The emissions and primary energy use of the hybrid system are decreased by 13 % when 50 % of the over-production is utilized. This decrease in environmental impact is related to a decrease in the number of Powertowers in the Powertower system and a decreased need for diesel fuel in the hybrid system.

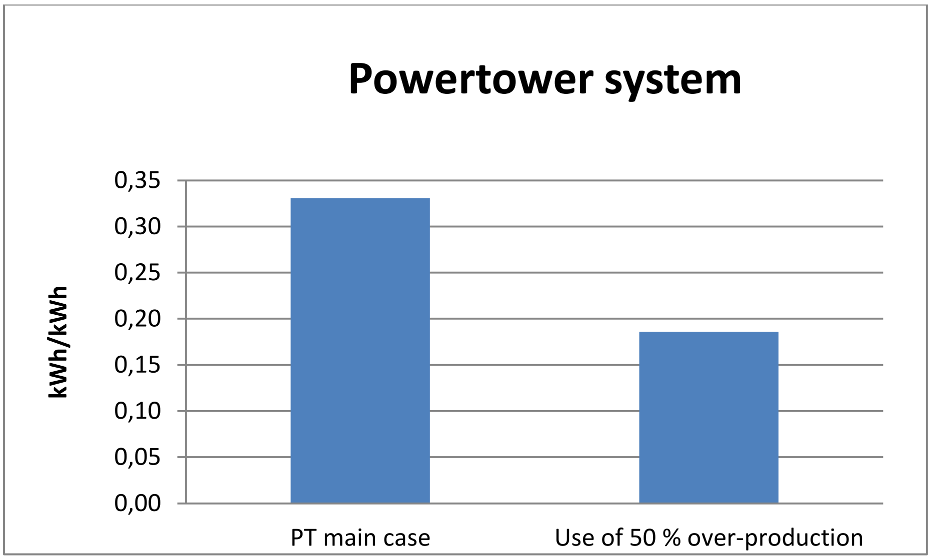

Figure 39. The results from the over-production sensitivity analysis regarding the GWP of the PT system

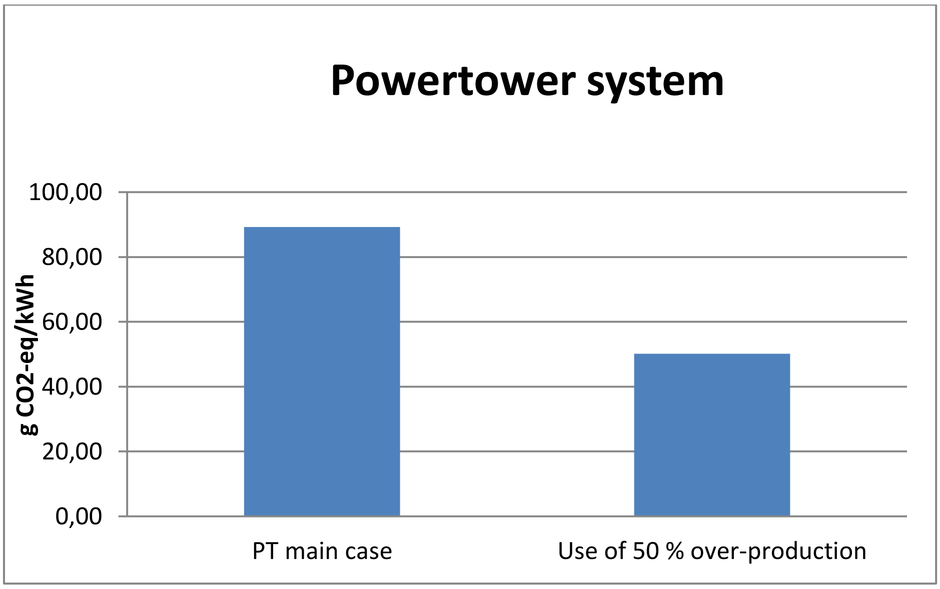

Figure 40. The results from the over-production sensitivity analysis regarding the primary energy use of the PT system

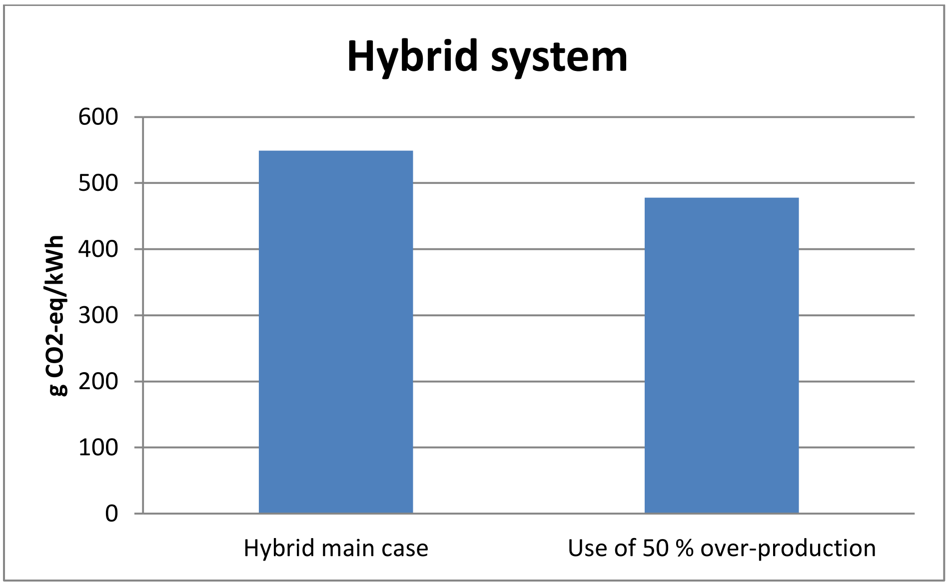

Figure 41. The results from the over-production sensitivity analysis regarding the GWP of the hybrid system

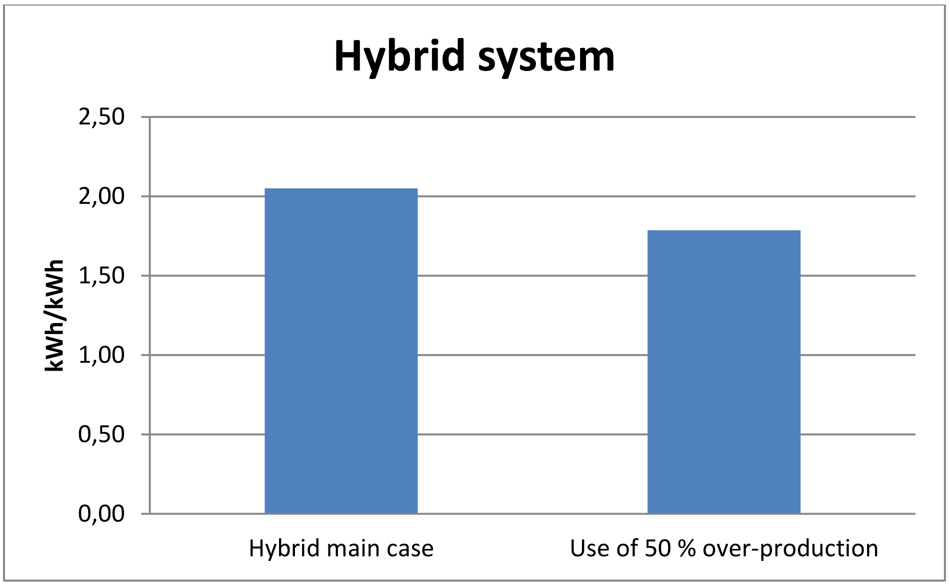

Figure 42. The results from the over-production sensitivity analysis regarding the primary energy use of the hybrid system

5 Economic analysis

5.1 Description of method and assumptions used in the economic analysis

This section intends to describe the procedure of how the costs of the different energy supply systems are calculated. In order to make a fair comparison between the different systems the equivalent annual cost per kWh is calculated for each system. The input values for the energy systems are shown in Table 26 and Table 27.

Table 26.Input values for the Powertower system for the economic analysis.

Powertower system	Cost per unit [USD]	Quantity	Life length [years]
Powertower (InnoVentum, 2014b)	22 000	13	20
Battery (Off Grid Europe, 2014)	300	32	5

The life-span of the battery tank for the Power Tower system is assumed to be 5 years which means that it has to be replaced with new batteries every fifth year. With a life span of 20 years for the system the replacements will result in a total of 4 setups of the battery tank (3 replacements). The cost for each battery tank is assumed to occur at the same time as the initial investment of the Powertowers; therefore it is included in the investment cost.

Table 27. Input values of the diesel generator system for the economic analysis.

Diesel generator system	Cost per unit [USD]	Quantity	Life length [years]
Diesel generator (AMP, 2014)	10 800	3	7
Diesel (Globalpetrolprices.com, 2014)	0.96/liter	12 700 l /year	-

The diesel generator is assumed to have a life-span of 7 years which means that a total of 3 diesel generators are needed during the 20 year period of this study. As for the Powertower case, the costs of all the diesel generators are included in the initial investment.

Table 28. Input data for the renewable/diesel hybrid

Renewable/diesel hybrid system	Cost per unit [USD]	Quantity	Life length [years]
Powertower (InnoVentum, 2014b)	22 000	5	20
Diesel generator (AMP, 2014)	10 800	3	7
Battery (Off Grid Europe, 2014)	300	16	5
Diesel (Globalpetrolprices.com, 2014)	0.96/liter	4 800 l/year	-

In the economic analysis for the renewable/diesel hybrid the life span of the system itself, the diesel generator and the battery tanks are assumed to be the same as for the other systems. The costs of the Powertowers and the diesel generators are included in the initial investment cost.

The basic formula for the equivalent annual cost (EAC) per kWh is;

$$\mathrm{EAC} = \frac{\mathrm{NPV} * \mathrm{k}}{\mathrm{E}}$$

Where NPV is the net present value which is described further down
k is the factor of annuity which is also described further down
E is the electricity produced

The basic formula for the net present value (NPV) is;

$$NPV = \sum_{t=0}^{t} \frac{R_t}{(1+i)^t}$$

Where t is the time of the cost
R_t is the cost at the time
I is the discount rate

$$k = \frac{i}{1-(1+i)^{-n}}$$

Where n is the economic life length of the system

The discount rate is varied between 3 %, 8 % and 13 % to see how the cost varies due to different investors required rate of return. The maintenance cost for each system is neglected. The cost of the consumed diesel is calculated with the equation of net present value divided by the economic life length of the systems which is 20 years.

In order to get the results in the unit USD/kWh the yearly cost of the energy supply systems are divided by the yearly amount of used energy (no over-production included). The total amount of used energy will be the load of the village during a year, which is 28.5 MWh (or 570 MWh during the whole 20-year life cycle). Table 29 shows the amount of energy that the two systems produce during their life cycles. The values differ because of the over-production that the systems utilizing Powertowers give rise to.

Table 29. The electricity produced during the life cycle of each system.

	Powertower	Diesel generator	Renewable/diesel hybrid
Production	1390 MWh	570 MWh	738 MWh

Three different scenarios are created for the Powertower and the hybrid system where 0, 50 and 100 % of the over-produced electricity is utilized (Scenario 1, 2 and 3 respectively). For scenario 3 this means that 1 390 MWh is utilized (instead of the 570 MWh utilized in scenario 1). The three scenarios are created with the aim of comparing the differences that comes from making use of the over-production of electricity compared to not making any use of it.

Scenario 2 coincides with the sensitivity analysis “Utilization of 50 % of the over-production” which is described in chapter 7.1.6. Two other sensitivity analyses will also be studied from an economical perspective, the geographical sensitivity analysis and the higher load sensitivity analysis. For the diesel generator and hybrid system two scenarios are created with the aim of taking the uncertainties of the future increase of diesel price into account. Both scenarios of the diesel generator system include inflation, but one scenario also includes a yearly increase of the diesel price by 2 % (Scenario B).

5.2 Results of the economic analysis

Table 30 shows the result of the economic analysis, as described in chapter 5.1 Description of method and assumptions used in the economic analysis. The box below describes the conditions for the systems that are used in the economic analysis.

1 – No utilization of overproduced electricity

2 – 50 % of the over-produced electricity is used

3 – 100 % of the over-produced electricity is used

A – The cost of diesel increase by 2 % per year

B – Flat rate (No increase in diesel cost)

Table 30. The cost of electricity for the three different power supply systems expressed as USD/kWh.

Discount rate	3%	8%	13%
PT 1	0.75	1.08	1.45
PT 2	0.42	0.61	0.81
PT 3	0.31	0.44	0.59
Diesel A	0.60	0.63	0.67
Diesel B	0.50	0.53	0.57
Hybrid A1	0.56	0.73	0.90
Hybrid B1	0.53	0.69	0.87
Hybrid A2	0.49	0.63	0.79
Hybrid B2	0.46	0.60	0.75
Hybrid A3	0.44	0.56	0.70
Hybrid B3	0.41	0.53	0.67

As can be seen in Table 30 it seems to be important to take care of as much electricity as possible to be able to keep the cost of electricity low. Since the amount of over-production is large for the Powertower system the cost is less than half when taking care of 100 % over-production compared to when not.

5.2.1 Geographical sensitivity analysis

The input values and results of the economic analysis of the geographic sensitivity analysis can be seen in Table 31.

Table 31. The results from the geographical economic analysis.

	PT:s	Investment cost [USD]	Yearly electricity demand [MWh]	Discount rate 3% [USD/kWh]	Discount rate 8% [USD/kWh]	Discount rate 13% [USD/kWh]
Haiti	8	206100	28.5	0.47	0.68	0.91
Somalia	9	228300	28.5	0.52	0.76	1.01
Bolivia	8	206100	28.5	0.47	0.68	0.91
India	10	250500	28.5	0.57	0.83	1.11

5.2.2 Higher load sensitivity analysis

The input values and results of the economic analysis of the geographic sensitivity analysis can be seen in Table 32 and Table 33.

Table 32. The input for the higher load economic analysis.

	PT:s	Battery tanks	Cost [USD]	Produced electricity per year [MWh]	Yearly electricity demand [MWh]
No use of over production	28	9.33	710235	176	49.0
Use of 50 % of over production	28	9.33	710235	176	113

Table 33. The results for the higher load economic analysis.

	Discount rate 3% [USD/kWh]	Discount rate 8% [USD/kWh]	Discount rate 13% [USD/kWh]
No use of over production	0.95	1.37	1.83
Use of 50 % of over production	0.41	0.59	0.79

As can be seen in Table 33 it seems to be important to take care of as much electricity as possible to be able to keep the cost of electricity low. Since the amount of over production for the higher load sensitivity analysis is very large the cost is less than half when taking care of 50 % over production compared to when not.

6 Discussion

Discussion regarding what alternative is the best for powering the humanitarian aid village

The life cycle assessment showed that the best alternative regarding environmental performance is the Powertower system, followed by the hybrid system and lastly the diesel generator system. The Powertower system had about 21 times lower environmental impact (both regarding global warming potential and primary energy demand) compared to the diesel generator system. When compared to the hybrid system, the Powertower system has about 6 times lower global warming potential and about 2 times lower primary energy use.

Regarding the three other environmental impact categories the results differed a lot from the result regarding global warming potential and primary energy use. Regarding eutrophication the diesel generator system had the lowest impact (with 600 kg NOx-equivalents emitted). The hybrid system had about 4 times higher emissions while the Powertower system had about 33 times higher emissions. Regarding acidification the hybrid system had the lowest amount of impact (with 680 kg SO2-equivalents emitted). The diesel generator system had about 3.5 times higher acidification potential while the Powertower system had about 6 times higher. Regarding the photochemical oxidation potential the diesel generator- and the hybrid system had the lowest impact, with 60 and 80 kg C2H4-equivalents emitted respectively. The Powertower system had the highest amount of emissions (about 12 times higher than the diesel generator system).

The results of this study regarding the environmental impact of the Powertower system came to the conclusion that it emits 35 g CO2-eq/kWh (if all energy is utilized). In order to put this result into some sort of context, it needs to be compared to relevant LCA-sources. The results of the PV panels and the wind power will be weighed according to the percentage of the total energy that they contribute in the main case of this study, namely 40 % for PV and 60 % for wind power.

A study collecting and harmonizing data from 13 studies of silicone PV-systems (Hsu, et al., 2012) came to the conclusion that the median environmental impact is 45 gCO2-eq / kWh (for a lifetime of 30 years and an assumed annual production of 1700 kWh/m2/year). These assumptions are for PV panels with both higher production and lifetime than that of the solar panels in the main case of this study, but either way it's a good enough study to compare with due to the quality and quantity of the used studies. A LCA study investigating the environmental impact of a steel 2.5 kW turbine (with storage included) came to the result that the wind power system emits 42 gCO2-eq/kWh (Lenzen & Munksgaard, 2002).

By weighing these results according to the percentages stated above, a GWP potential of 43.2 gCO2-eq/kWh is achieved, which is about 23 % higher than for the Powertower system. One source of error is the lack of LCA studies investigating the environmental impact of small-scale wind turbines that were found. Anyway, the results of this basic analysis show that the environmental performance of the Powertower system is slightly better than similar technologies for energy production. This is probably due to the implementation of the wooden tower which reduces the environmental impact that the Powertower system has compared to its steel counterparts.

Another factor making the comparison uneven is the amount of batteries included in the results. The Powertower system has a large number of batteries, while the number of batteries used in the LCA of the wind turbine is unknown. This discrepancy will cause unfairness in the comparison, probably not in favor of the Powertower system. This difference might negate some of the lower environmental impact that the wooden tower may achieve when compared to a steel tower.

Regarding the results of the economic analysis, it is important to note one thing; the way the analysis of the main case is set up will actually disfavor the systems using the Powertower solution. This is due to over-production resulting from dimensioning the energy supply systems to be able to supply the load of the humanitarian aid village. If instead the energy supply systems where used purely for power production (where all the energy is utilized) the cost of the electricity from the Powertowers will be lowest at all discount rates, except for 13 % discount rate were diesel B is slightly cheaper, as can be seen in Table 30. This is the cost of electricity that should be considered as the “real price”, unaffected by the assumptions made in this study. In this comparison it can be seen that the electricity from the Powertower system is the cheapest (about 0.1 USD/kWh cheaper than the hybrid B option which also utilizes all the energy produced).

However, the results change a bit when the economic analysis is performed according to the main case of this study (where the energy supply systems are dimensioned to supply the load of the village) which can be seen in Table 30. The Powertower system is still the system producing the cheapest electricity, costing 0.42 USD/kWh at 3 % discount-rate (the alternative with 50 % use of over-production). The Powertower system is however closely followed by the Hybrid system (with flat-rate and 50 % use of over-production) which costs 0.46 USD/kWh.

The use, or non-use of the over-production is an important factor for the Powertower system, but less important for the hybrid system. If no over-production is utilized the energy cost of the Powertower system goes up to 0.75 USD/kWh. Even if the economically worst circumstances are chosen for the hybrid, A1, are chosen (2 % increase in diesel price and no use of over-production) the hybrid system is still a relatively cheap alternative at 3 % interest-rate, costing 0.56 USD/kWh. Therefore, if no over-production is utilized, the hybrid system produces the cheapest electricity.

When the discount-rate is increased to 8 % the flat-rate diesel system produces the cheapest energy at 0.53 USD/kWh. At this discount-rate the Diesel B system is closely followed by both PT 2, Diesel A and hybrid A2 and hybrid B2 (which all costs about 0.1 USD more per kWh than the cheapest alternative). When the discount-rate is further increased to 13 % the flat rate diesel system still produces the electricity at the clearly lowest cost of 0.57 USD/kWh, and it increases the leap to its closest competitors.

This trend of the diesel generator system becoming cheaper as the discount-rate gets higher is due to the low capital cost of the system. As the discount-rate gets higher, the alternatives with high capital costs (such as the alternatives incorporating Powertowers) become much more expensive. The diesel generator is characterized by low capital cost but high operational cost (mainly related to the purchase of diesel fuel). As the discount-rate gets higher, these operational costs have less and less relative importance to the total costs. So it’s easy to understand that the economic analysis is highly dependent upon what parameters are chosen for the calculation. What discount-rate is chosen depends upon who the operator of the energy supply system is, and what their required rate of return is.

For a humanitarian aid village run by a non-profit organization the required rate of return will be lower than for profit-driven company, why a 3 % discount-rate can be assumed. If one were to decide which energy supply system is the most suitable for the humanitarian aid village in the Philippines, a third factor also has to be taken into account; the energy security of the system. Even if the Powertower system is dimensioned to be able support the load of the village, it's possible that the supply won't meet the demand during a string of windless and cloudy days. The alternatives also incorporating a diesel generator (the renewable/diesel hybrid system) will be able to ensure the energy security of the system while still providing partially "green energy", why these alternatives can be deemed to have an edge compared to the pure Powertower system.

Taking all the above factors into account, the renewable/diesel hybrid system is deemed to be the best alternative for the humanitarian aid village in the Philippines as it can provide cheap energy with high energy security at a relatively low environmental impact. Therefore, the "Power to the Philippines" project can be deemed to be of interest to the humanitarian aid villages, as long as the energy load of the humanitarian aid village isn't solely met by Powertowers. A hybridization of Powertowers with the existing diesel generators can help lower the carbon footprint of the existing energy system, while simultaneously lowering the cost of electricity (at the 3 % discount-rate since no energy is to be sold).

Comparing the results of the economic analysis

The Ren21 global status report (Ren21, 2014) states some typical energy costs of renewable power generation, stated as levelized cost of energy (LCOE). Small-scale wind power (ranging from 0.1 to 3 kW capacity) costs 0.15-0.35 USD/kWh and solar PV (rooftop mounted, non OECD country) costs 0.28-0.55 USD/kWh. If one were to compare these prices to a hybrid between the two energy sources, such as the Powertower, one possible way could be to multiply the prices with the percentages out of the total production of the Powertower that the PV and wind portions constitute. In the case of the production in the Philippines, the solar panels contribute approximately 40 % of the total production, while the wind power constitutes approximately 60 %. Since the price per kWh are stated in a range, three different prices are to be calculated; a low, mid and a high estimate (where the mid estimate is the price in the middle of the lowest and highest price).

This calculation produces a hybrid cost per kWh of 20.1 (low), 31.5 (mid) and 42.9 US¢/kWh (high). These costs are to be compared with the costs of the power generated by the Powertower, that are 0.31 (3%), 0.45 (8%) and 0.59 (13%) USD/kWh. It can be seen that the electricity generated by the Power tower (with 3 % discount-rate) is more or less in line with the mid-price. If comparing the cost of the Power generated at 8 % discount-rate this is more or less in line with the high price (as stated in the REN21 report), and the 13 % discount-rate price is even more expensive (outside of the range). Since the premises of the calculation of the prices stated in the REN21 report are unknown, it is not known how accurate this comparison is, but it however hints that the power generated by the Powertower system is quite expensive. The Philippine electricity price is 0.22 USD/kWh (KPMG, 2013) which is more or less equal to the low price estimate of the Powertower system, but about half of the high estimate.

Choice of wind energy calculation method

The dataset of the daily wind speeds used in the main case of this study is has both positive and negative aspects to it. The dataset is accurate in terms of the seasonal variation in wind speed, and also in terms of the total amount of wind resource that is available. Some sources of error are the location of the weather station (Naga city) and the conversion from daily average values into hourly values. Despite these sources of error the dataset is deemed to be quite accurate to that of Tacloban.

A certain year's wind profile is unique and therefore uncertainties occurs when predicting the electricity generated from the wind turbine for a typical year. Since the electricity production has a cubical relationship with the wind speed the amount of electricity generated is extremely sensitive to the wind speed. In order to perform a realistic dimensioning of the renewable energy system (including a state of charge analysis) hourly data is generally preferred. As there was a lack of hourly data of the wind speeds in the geographical sensitivity analysis a special approach was therefore undertaken in order to generate hourly data for the other locations. The calculation of the produced electricity from the wind turbine was based on wind speed data gathered during a year in another location, but scaled to the average wind speed of the investigated locations.

Since the wind profile was gathered from Kriegers Flak, the seasonal weather variations will be equal to that of the location in Denmark and not to the investigated locations. The amount of electricity generated over a year will not be affected though, only when the electricity is generated. This may affect the results of the state of charge analysis and indirectly also affect the dimensioning of the PT-systems at the locations in ways that can have big impacts on the final results. It is not probable that the wind profile used looks like the actual wind profile for each location. For example the wind profile may have longer or shorter periods of time with low wind speeds which will impact the discharge rate of the battery. In defense of using the wind profile from Kriegers Flak, it is a method allowing for a quite realistic calculation of the state of charge of the battery tank (and the dimensioning of the Power Tower system following that calculation).

One source of error of the geographical sensitivity analysis is the difference in wind speed data sets. The geographical sensitivity analysis showed that the Philippine case had the lowest annual production per Powertower. The annual production is highly linked to the amount of wind energy that is produced. The main case used site-specific data which can be assumed to quite accurate to "reality", but the 4 other locations used the modified hourly data series from Kriegers Flak. A comparison between the 4 other location is defendable since they used the same type of dataset, but the comparison between the main case and these other locations is a bit skewed because they didn't use the same type of datasets. The difference in seasonal variance of wind energy resource between the two datasets may give a competitive advantage in a state of charge simulation to the type of dataset that is most suitable for sustaining a SOC without deep discharges.

The state of charge simulation and the subsequent dimensioning is highly dependent on the variation of the wind data. The minimum criterion for a "successful" dimensioning is that the state of charge stays above 0 more than 95 % of the time. The data from Kriegers flak has its lowest wind speeds in the period of June to October, which of course will translate to the production of the studied locations. This is a long period with low production, which is not necessarily common for the wind pattern of other locations, where the months of low production might be more scattered over the year, rather than strung together. A long consequent period of low production will generally lead to lower state of charge levels, which coupled with the criteria of a state of charge above zero 95 % of the time, might mean that the choice of wind data sets will lead to an over-dimensioning of the Powertower system.

Energy security of the three systems.

The state of charge simulation allows for a dimensioning of the renewable energy system where the predicted energy security can be controlled. It's important to note that this prediction is just that, a prediction. Of course, every year will vary regarding both the quantity and the temporal distribution of the load and renewable energy resources available to the Powertower system. When comparing the energy security of the Powertower system to the diesel generator system, the diesel generator has some advantages. If the diesel generator system is properly sized and run correctly, the diesel generator will be able to provide energy with a close-to-perfect energy security. Also, the diesel generator system will over-produce much less than the Powertower system.

The renewable/diesel hybrid system is an interesting option to its both constituents individually. The hybrid can increase the energy security without leading to excessive over-dimensioning of the amount of Powertowers, as the diesel generator could “fill up the holes” when the renewable energy production falters. This renewable/diesel hybrid is especially relevant if the user can’t tolerate lack of electricity for longer periods of time, such as a hospital. Even if the system is correctly sized in relation to the load, invariably there will come a string of “bad” days, causing the load to not be met. In these cases a diesel generator would be able to ensure the energy security of the system.

Ways to make use of the over-production

In every purely renewable off-grid energy supply system, there will be over-production of energy due to the variability of the renewable energy sources. The wind and the sun doesn’t exactly follow the energy use patterns of the renewable energy consumers, and in order to make sure that the load is met at a high level, a system dimensioned for over-production is necessary. One way to solve this problem is to increase the battery tank, but this method can be quite expensive and increase the environmental impact of the system a lot. Another way to tackle this predicament would of course be to instead vary the energy use patterns according to the variations of the renewable energy sources, so called load management. There are many different strategies for load management.

One proposed strategy for load management is to incorporate smart meters that can guide the energy use patterns of the user by telling them when energy is the cheapest (when the supply is the highest and the demand is the lowest). This of course requires that the location in question has a variable energy price, which is not yet true for the majority of the world today. If done properly though, this could lead to a system that doesn’t have to be dimensioned for less over-production. This type of load management reduces the flexibility of use for the energy consumer, but will simultaneously result in other benefits. Since the energy supply system can be dimensioned for less over-production, it will lead to a reduction in both the cost and environmental impact of the system. A good predictor for the success of the load management is the amount of “manual” actions that are needed by the user. The less manual action that is needed, the more successful the load management (Nylén, 2011).

The energy that stems from the over-production of energy doesn’t have to be considered as wasted energy. There are several ways to make use of the energy that is produced when the load is met and the battery-tank is full. One common way to make use of the energy is to either heat or cool water. Another possible use of the over-produced energy is powering a mill that continuously provides flour to the community. This is especially viable in communities centered around agriculture.

History of rural electrification in the Philippines

In 1960 the government of the Philippines introduced total electrification policy which intended to electrify the nations' whole population. A national agency called Electrification Administration, EA, was established to implement the electrification. The first 9 years the EA had established 217 smaller systems, with a capacity lower than 500 kW, but because of technical and financial problems many of the systems were forced to shut down. This led to that EA was replaced by a new agency called National Electrification Administration, NEA. At this point 18 % of the population had access to electricity.

In a second wave of implementing the electrification strategy 36 rural electric cooperatives (RECs) were established, with the help of loans from the NEA. The regional electricity cooperatives buy electricity from larger plants (generally diesel plants) which they in turn distribute to their consumers (Grewal et al, 2006). Each REC was planned to provide 100 000 people with electricity. The RECs were controlled by the NEA but managed by the local communities due to the cooperative approach. The RECs tariffs were to cover the operation costs and the repayment of the loan to the NEA.

The strategy led to a rapid expansion thanks to financial help from the government, international banks and donor agencies but this led to major problems. Questionable political actions coupled with tariffs set too low by the RECs for a long period of time led to poor maintenance of the electrical systems. Since the tariffs were kept to low were the RECs unable to pay for their loans to the NEA which ultimately led to the bankruptcy of the NEA in 1989.

The situation forced the Philippine government and World Bank to intervene. They investigated the financial conditions of the RECs and it showed that only 18.8 % were viable and as many as 60.7 % needed immediate financial help or were beyond rescue. The intervention from the government and the World Bank forced the NEA to reconstruct their way of running the RECs with the aim of making them more viable. Despite the reconstruction the financial and maintenance problems are still present and a clear solution is yet to surface (World bank, 2002).

Different strategies for rural electrification

A rural area is defined as a geographic area outside of cities and towns. The population in the rural areas are generally poorer and less educated than people living in urban areas. Rural areas generally have a lower population density than urban areas, lower electrification rate and a lower energy demand potential (National Geographic, 2014). Because of these factors it is seldom economically viable to extend the national electrical grid to these areas. There are several benefits that come along with rural electrification and the services it enables. Electricity enables basic services like for example lighting, possibilities for tele-communication (such as access to the internet) and cheaper irrigation which can increase farm productivity.

All of these services that electricity can provide help drive the socio-economic development of the area. Rural electrification has been found to improve both living standard and quality of life of the people affected by it (World bank, 2002). Regarding the economic benefits of rural electrification in the Philippines, a study attempting to quantify these benefits for a typical household into monetary terms (World bank, 2002) came to the conclusions that Table 34 illustrates;

Table 34. An estimation of the economic benefit of rural electrification. (World bank, 2002)

Benefit category	Benefit value (USD/month) per consumer	Consumer type
Less expensive and expanded use of lighting	36.75	Household
Less expensive and expanded use of radio and television	19.6	Household
Improved returns on education and wage income	37.07	Wage earner
Timesavings for household chores	24.5	Household
Improved productivity of home business	34.00 (current business) ; 75.00 (new business)	Business

As grid-extension generally is not economically viable in rural areas, other strategies has to be undertaken in order to enable the people living in these areas to take part of the aforementioned benefits of rural electrification. According to the mini-grid policy tool-kit (Franz, 2014) there are three main ways of providing electricity in rural areas; national grid-extension, mini-grids and stand-alone system. These three strategies can be divided into centralized (grid-extension) and decentralized strategies (mini-grids and stand-alone systems). Decentralized systems (such as mini-grids) generally don't provide the same amount of energy as is possible through grid extension. Which strategy to apply is highly dependent on the characteristics of the area in question.

Stand-alone systems are small electricity generation systems (such as diesel generators or photovoltaic systems) directly connected to the end-user without any network for distributing the electricity. Stand-alone systems are small in terms of the energy output (and corresponding loads) that they can supply. Mini-grids are larger than stand-alone systems regarding the amount of energy they can produce and the amount of energy consumers it can supply. They also include a network for distributing the electricity within the mini-grid. A mini-grid can be defined as follows;

"Mini-grids involve small-scale electricity generation (10 kW to 10MW) which serves a limited number of consumers via a distribution grid that can operate in isolation from national electricity transmission networks." (Franz, 2014)

The most common energy source for mini-grids in the world today are diesel generators. Hybridization has been found to be a good method for developing and improving mini-grids and it has huge potential. There are high quantities of mini-grids (and stand-alone systems) spread around developing countries, mainly fueled by diesel. Hybridization means coupling these diesel mini-grids with renewable technologies such as hydro, solar, biomass or wind energy. Coupling diesel and renewable technologies in this fashion can help reduce cost and environmental impact, while improving energy security of the mini-grid (Franz, 2014).

Mini-grids versus grid-extension
Developing the national electricity grid is an expensive, long term process. Grid extension to the areas that lie closest to the existing grid will be the least expensive. The cost effectiveness of the different projects has to be taken into account when deciding upon a strategy for rural electrification. Several factors have to be taken into consideration when making a decision regarding grid extension. These can be factors such as the distance to the centralized grid, the population size and density, and socio-economic factors such as the energy demand potential of the area. In areas with low population density and urbanization rate, the option of grid extension is most likely not the most cost-efficient option for providing access to electricity for the population. Spatial analysis using GIS can be used when analyzing the cost-effectiveness of different projects (Franz, 2014).

The question whether it's best to invest money in a centralized or decentralized strategy is complicated and the answer is not an either or. Grid extension and decentralized electrification projects can be seen to complement each other since they both fulfill the same purpose; a higher rate of public electrification. One important factor to take into consideration when planning decentralized electrification projects is the possibility to incorporate the mini-grids into the national electricity grid in the future. If this possibility is accounted for, in the long run both the centralized and decentralized strategy can be seen as contributing to the process of grid-extension. In the shorter time perspective the strategy of building mini-grids is more effective in providing rural electrification as mini-grids can be deployed much quicker than the grid can be extended.

The economy of mini-grids
Financing is a necessary part of introducing a mini-grid. Like all other business the operation of a mini-grid must be economically attractive and the price of electricity should be somewhere around the electricity price of the grid. Therefore it is important when setting up a mini-grid for a municipality to have an understanding of how the energy demand is at the moment and how it will develop over time. The future energy demand can be difficult to foresee if the municipality is not used to use electricity.

The fixed costs of a mini-grid stem from generation and distribution of electricity while the variable costs stem from maintenance, operation and management. For general grids the income comes from connection fees, electricity sales and grants or subsidies and it is usually the same for mini-grids but for a mini-grid it is even more important to have an accurate prediction of the energy demand and match it with the energy supply.

A mini-grid which is entirely based on renewable energy sources have high fixed costs and its energy supply is more insecure than for example a diesel based mini-grid. A renewable energy based mini-grid also needs a costly storage system to make it viable. The aforementioned hybridization between fossil based and renewable energy sources can counter these negative aspects of a mini-grid entirely based on renewable energy as it can help counter the high fixed costs and the low energy security.

As was previously mentioned, the possibility to incorporate the mini-grid into the "big grid" is important. In the case of absorption of this sort, it is important that the mini-grid operator is properly compensated. If no legislation regarding this exists there will be huge economic insecurities in creating and operating mini-grids, which probably will result in less mini-grids, and therefore less rural electrification.

7 Conclusions

- The Powertower system has the lowest environmental impact of the three studied energy supply systems studied in the main case, both regarding global warming potential (89 gCO2/kWh) and primary energy use (0.33 kWh/kWh).
- The diesel generator system has about 21 times higher environmental impact compared to the Powertower system. The hybrid system has about 6 times higher global warming potential and twice the amount of primary energy use compared to the Powertower system
- If all the produced energy is utilized the environmental impact of the Powertower-system goes down to 35 gCO2/kWh. When comparing this number to that of LCAs studying similar systems it is found that the Powertower system has about 20 % lower GWP emissions.
- The hybrid system is deemed to be the most economically viable system at the 3 % discount-rate as it can produce relatively cheap electricity even if the worst circumstances are considered (2 % yearly increase in diesel price and no use of over-production).
- The alternatives incorporating diesel generators are able to provide energy with high energy security compared to the pure Powertower system. This is due to the intermittency of renewable resources and the possibility to regulate the diesel generator according to the load.
- The hybrid is deemed to be the most suitable energy supply system for the humanitarian aid village as it can provide cheap electricity with high energy security and relatively low environmental impact.
- The “Power to the Philippines” project can be deemed to be of interest to the humanitarian aid villages, as long as the energy load of the humanitarian aid village isn’t solely met by Powertowers. A hybridization of Powertowers with the existing diesel generators can help lower the carbon footprint of the existing energy system, while simultaneously lowering the cost of electricity (at the 3 % discount-rate since no energy is to be sold).
- As the discount-rate increases the diesel generator system becomes cheaper while the Powertower system simultaneously becomes more expensive. This trend is due to the low fixed cost and the high operational costs related to the diesel generator system, and the high fixed costs and low operational costs of the Powertower system. As the discount-rate increases the alternatives with low fixed costs will be favored.
- When comparing the cost of electricity of the Powertower system is more or less in the middle range if compared (and weighed) to the typical energy costs as stated in the global status report of Ren21 (Ren21, 2014).
- The differences in wind data series for the other locations in the geographical sensitivity analysis are a major source of error. Site-specific data would have been preferred but were hard to find.
- Mini-grids involve small-scale electricity generation (10 kW - 10 MW) and serve a limited amount of customers through its distribution network (that’s separate from the national grid)
- Rural electrification has been found to improve both living standard and quality of life of the people affected by it. Grid-extension is often not economically viable in rural areas, where the creation of mini-grids can be a viable alternative. If the mini-grid are designed to be able to connect to the “big grid” when it comes, both strategies for rural electrification (grid-

extension and mini-grids) can be seen to fulfill the same purpose – a higher rate of public electrification.

- Hybridization of existing diesel generators with renewable technologies is a viable method for creating and improving mini-grids, and it has huge potential.

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Appendix A – Solar energy calculations

The amount of electricity produced from the solar panels is calculated by gathering daily measures of insolation on the horizontal surface and diffuse insolation from the years 2001 to 2004 from a website owned by NASA (NASA, 2014). From these measures an average insolation value for each day of the year, later summed up to each month, were calculated.

The average monthly insolation values, G, are then put into the following equation to calculate the electricity generated the solar panels.

$$E = A * r * G * PR$$

Table 35. Input values for electricity production of solar panels.

	Value
Area, A (m^2)	10.02
Efficiency, r	0.75
Yield, PR	0.15

Table 36. Insolation per month for Tacloban, Philipipnes.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Insolation, kWh	142	150	186	215	195	175	178	179	184	172	148	140

Table 37. The results of the calculation of electricity production of the sola panels.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Production, kWh	161	169	210	242	219	197	200	202	207	194	167	158

Appendix B – Wind energy calculations

The complete formula for converting the wind speed into the turbine power output is found below;

$$P = ½ * \rho * A * v3 * Cp * Ke \qquad 14$$

Where

P - Turbine power output

ρ - The density of air

A - The rotor swept area

v - The wind speed

C_p - The power coefficient

K_e - Rayleigh probability density function

Here follows a section with a more in depth description of the different parameters and how the values used for calculation of the turbine power output, P, were achieved.

Rayleigh probability density function, Ke

As the available wind data is given as average wind speed, a Weibull factor was used to spread out the wind distribution according to a Weibull (k = 2) curve. The mean wind speed doesn't accurately depict the way the wind blows, most of the time the wind blows more or less than the mean wind. Since the turbine power output formula is very dependent on the wind speed (since it is raised to the power of 3), this aspect has to be accounted for. This is what the Rayleigh probability density functions accounts for. K_e= 6 / π = 1,909

The density of air, ρ

ρ = 1,225 kg/m^3

The rotor swept area, A

A Dali Powertower with the Lite configuration has a rotor diameter of 3 meters (= a radius of 1,5 meters) giving a rotor swept area of;

A = π * r^2 = 7,068 m^2

The power coefficient, Cp

The power coefficient, Cp, specifies how large portion of the wind's energy that the wind turbine can absorb, Cp = Pturbine/Pwind. The maximal theoretical limit of this absorption is 16/27 (=0,593), and it is called the Betz limit. In reality, the how close the power coefficient gets to the Betz limit varies with the wind speed and from turbine to turbine. A good estimate of the Cp over time is;

Cp = 20 %

The wind speed, v

The monthly wind speed in Tacloban can be seen in Table 38.

Table 38. Monthly average wind speeds over the year in Tacloban (source: NASA)

J	F	M	A	M	J	J	A	S	O	N	D	Annual average
9.09	8.26	7.64	6.09	4.59	5.24	5.29	6.8	5.31	5.72	7.25	8.69	6.66

Then, all average wind speed values were put into the turbine power output formula to get the produced electricity (in kWh). The result can be seen below in Figure 43. The electricity produced by the wind turbine of one Powertower during the year.

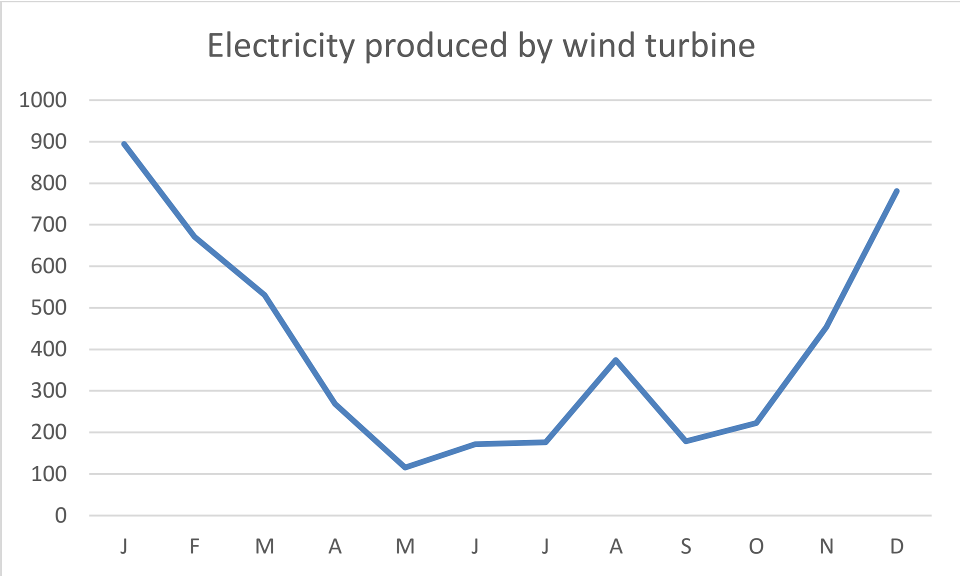

Figure 43. The electricity produced by the wind turbine of one Powertower during the year

Appendix C – Geographical sensitivity analysis

Table 39. The annual wind speed average and wind turbine production of the different locations

Location	Annual wind speed average (m/s)	Annual wind turbine production (kWh)
Haiti	6.37	7585
Somalia	5.63	5942
Bolivia	8.42	11253
India	6.16	7052

Table 40. The average monthly insolation over the year for the 5 different locations (given in kWh/m2/day)

	J	F	M	A	M	J	J	A	S	O	N	D
The Philippines	142.47	149.71	186.27	214.99	194.50	175.12	177.61	179.38	183.72	171.89	148.09	139.72
Haiti	176.31	180.54	213.07	211.95	224.67	237.56	235.52	236.00	201.26	190.46	171.37	167.00
Somalia	230.17	222.04	250.38	207.72	213.71	186.85	196.04	201.97	211.50	206.02	192.91	202.55
Bolivia	205.34	169.09	171.90	150.67	127.11	121.77	136.43	168.67	187.06	199.79	194.07	181.50
India	107.68	114.08	167.52	180.87	234.27	230.08	227.66	206.43	185.56	168.65	126.03	86.67

Appendix D – Transport calculations

Table 41. A compilation of all the different transports involved in the Powertower systems' life cycles

Component	Origin of transport	Destination of transport	Transport type	Length (km)	Weight (kg) / PT	Weight (kg) / 10 PT	CO2-eqv [kg]	Energy (MJ)
Steel billet for foundation	Quebec, Canada	Halifax, Canada	Truck w/ trailer 28-34 ton	1016	242	2420	201.6	70.41
Steel billet for foundation	Halifax, Canada	Malmö, Sweden	Container ship	5509	242	2420	400.9	5140
Steel billet for bolts/washer/nuts	Tranås, Sweden	Malmö, Sweden	Truck w/ trailer 28-34 ton	245	80	800	16.07	236.4
Pine-log	Scanian woods	Varberg, Sweden	Truck w/ trailer 28-34 ton	150	1590	15900	195.6	2877
Impregnated wood	Varberg, Sweden	Malmö, Sweden	Truck w/ trailer 28-34 ton	205	1073.14	10731.4	180.4	2654
Metal parts	Prenzlau, Germany	Malmö, Sweden	Truck w/ trailer 28-34 ton	445	100	1000	36.49	536.8
Solar cells	Glava, Sweden	Malmö, Sweden	Truck w/ trailer 28-34 ton	511.38	114	1140	47.8	703.3
Turbine	Guangdong, China	Malmö, Sweden	Container ship	18900	70	700	425.1	5450
Wind charge controller	Guangdong, China	Malmö, Sweden	Container ship	18900	16	160		
MPPT	Heiligenberg, Germany*	Malmö, Sweden	Truck w/ trailer 28-34 ton	1157.51	1.81	18.13	1.518	22.33
Inverter	Sion, Switzerland*	Malmö, Sweden	Truck w/ trailer 28-34 ton	1416.66	7.67	76.67	8.907	131
Solar charge controller	Watford, UK*	Malmö, Sweden	Truck w/ trailer 28-34 ton	1337	0.42	4.2	0.46	6.77
Battery	Büdingen, Germany*	Malmö, Sweden	Truck w/ trailer 28-34 ton	839.76	82.67	826.67	50.88	748.5
Non-assembled PT	Malmö, Sweden	Tacloban, the Philippines	Container ship	18834	1550	17746	10050	128900
Non-assembled PT	Malmö, Sweden	Port-au-prince, Haiti	Container ship	8533	1550	10934	2805	35960
Non-assembled PT	Malmö, Sweden	Merca, Somalia	Container ship	11688	1550	12291	6235	79940
Non-assembled PT	Malmö, Sweden	Arica, Chile	Container ship	13343	1550	10934	4386	56230
Non-assembled PT	Malmö, Sweden	Mumbai, India	Container ship	12484	1550	13657	5127	65730

Appendix E – Main case results - Other environmental impact categories

E.1 Eutrophication

Figure 45 shows the comparison of the Power Tower and the diesel generator's effects regarding eutrophication emissions.

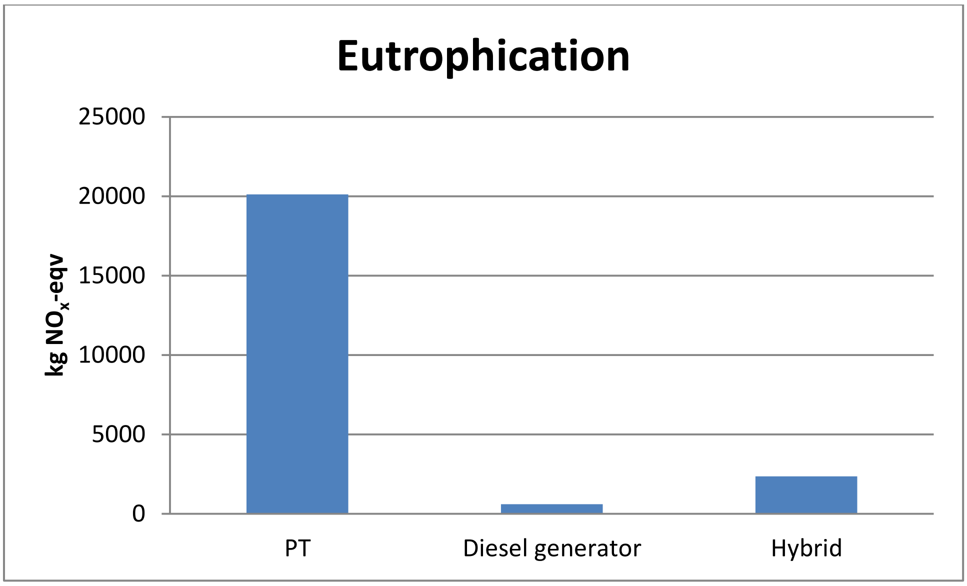

Figure 44. The results from the main case of the study regarding the eutrophication impact

E.2 Acidification

Figure 45 shows the comparison of the Power Tower and the diesel generator's effects regarding acidification emissions.

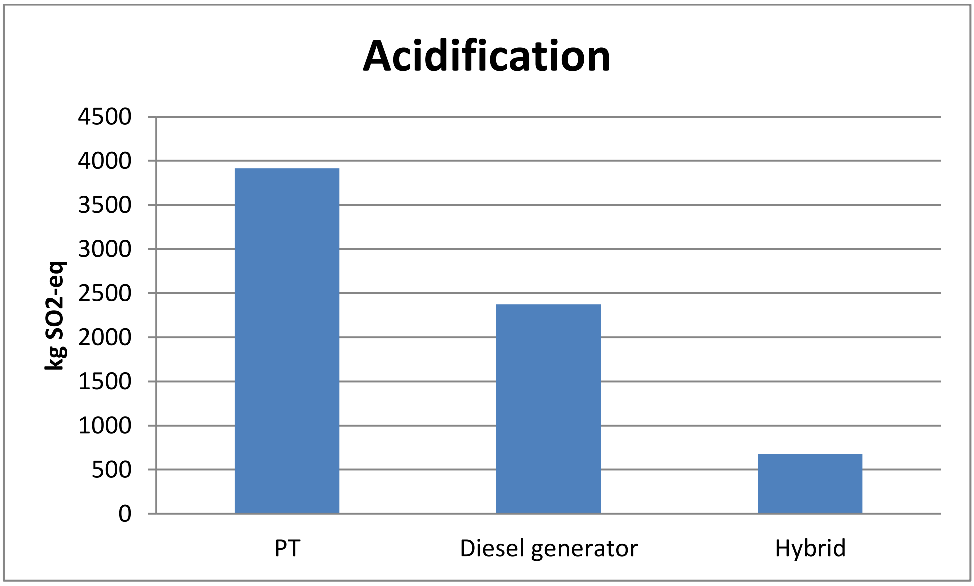

Figure 45. The results from the main case of the study regarding the acidiphication impact

Figure 45 shows that the acidification effect is the highest for the Powertower system, about 31 % higher than for diesel generator system and about 6 times higher than the renewable/diesel hybrid system.

E.3 Photochemical oxidation

Figure 46 shows the comparison of the Power Tower and the diesel generator's effects regarding photochemical oxidation emissions.

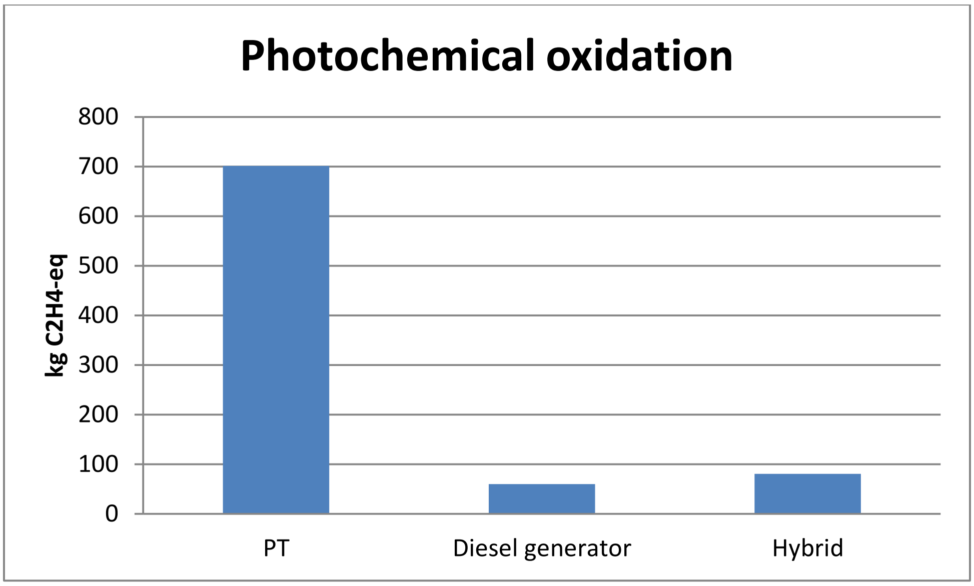

Figure 46. The results from the main case of the study regarding the photochemical oxidation impact

The effects on photochemical oxidation is about 12 times higher for the Power Tower than the diesel generator system and the renewable/diesel hybrid system. This is mainly because of the Power Tower's solar panels.

Appendix F – Geographical sensitivity analysis – Other environmental impact categories

F.1 Eutrophication

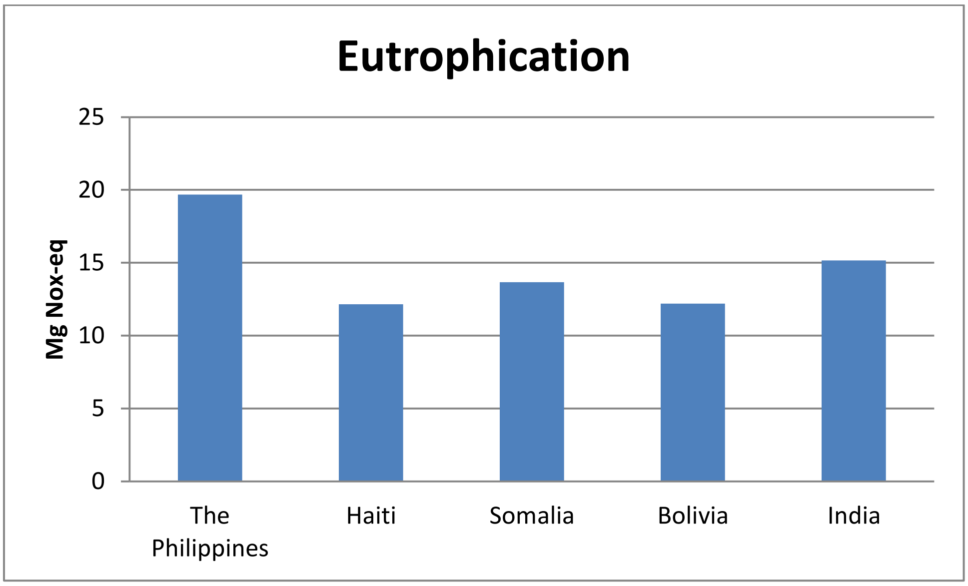

Figure 47. The results from the geographical sensitivity analysis regarding the eutrophication impact

F.2Acidification

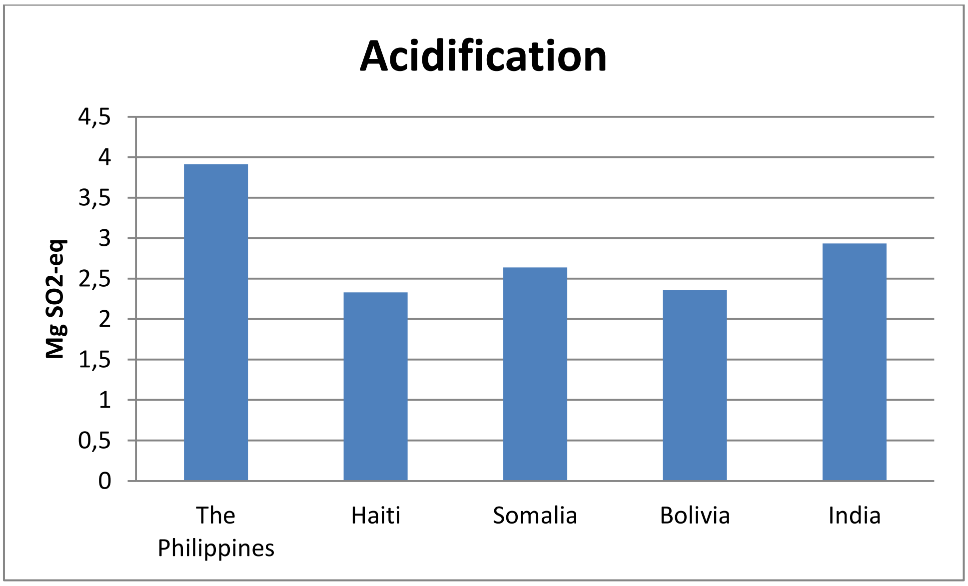

Figure 48. The results from the geographical sensitivity analysis regarding the acidification impact

F.3 Photochemical oxidation

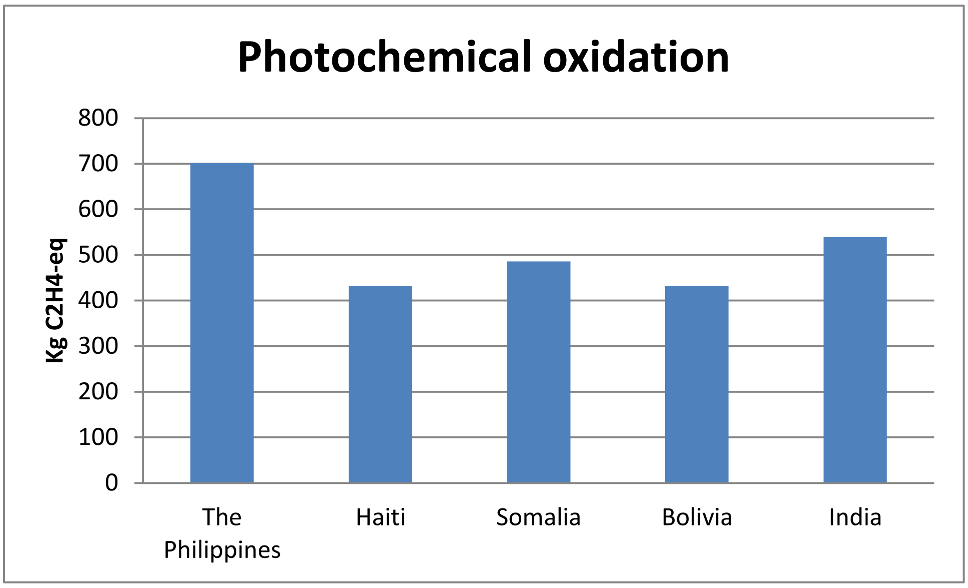

Figure 49. The results from the geographical sensitivity analysis regarding the photochemical oxidation impact

Appendix G – Economical analysis

In this appendix are the input values for the economic analysis presented.

G.1 Powertower equivalent annual cost

Table 42. The values of the calculations of equivalent annual cost for the Powertower.

Powertower			
Investment cost [USD]	326567		
Economic life [years]	20		
Used electricity 20 years [kWh]	28470		
Use of 50% over-production [kWh]	50635		
Use of 100% over-production [kWh]	69500		
Discount rate	3%	8%	13%
k	0.067	0.10	0.14
NPV [USD]	$21,311	$30,798	$41,140
Used electricity 20 years [USD/kWh]	$0.75	$1.08	$1.45
Use of 50% over-production [USD/kWh]	$0.42	$0.61	$0.81
Use of 100% over-production [USD/kWh]	$0.31	$0.44	$0.59

G.2 Diesel generator equivalent annual cost

Table 43. Diesel cost per liter and consumption of the diesel generator.

Litres Diesel per year	12700
Diesel price/litre	0.96

Table 44. The yearly diesel cost with 2 % increase of diesel price for the diesel generator.

A 2% inc		Yearly diesel cost [USD]
y1	1	12366.66
y2	2	12613.99
y3	3	12866.27
y4	4	13123.60
y5	5	13386.07
y6	6	13653.79
y7	7	13926.87
y8	8	14205.40
y9	9	14489.51
y10	10	14779.30
y11	11	15074.89
y12	12	15376.38
y13	13	15683.91
y14	14	15997.59
y15	15	16317.54
y16	16	16643.89
y17	17	16976.77
y18	18	17316.31

y19	19	17662.63
y20	20	18015.89
Total		300477.26

Table 45. The values of the calculations of equivalent annual cost for the diesel generator.

Investment cost [USD]	32400		
Diesel cost flat rate B [USD/year]	12124		
Discount rate	0.03	0.08	0.13
k	0.067	0.10	0.14
NPV flat rate	$14,239	$15,180	$16,206
[USD/kWh]	$0.50	$0.53	$0.57
NPV 2 % inc	$17,126	$18,047	$19,055
[USD/kWh]	$0.60	$0.63	$0.67

G.3 Renewable/diesel hybrid equivalent annual cost

Table 46. Diesel cost per liter and consumption of the renewable/diesel hybrid.

Litres Diesel per year	4780
Diesel price/litre	0.96

Table 47. The yearly diesel cost with 2 % increase of diesel price for the renewable/diesel hybrid.

5,2		Yearly diesel cost [USD]
y1	1	4670.80
y2	2	4764.22
y3	3	4859.50
y4	4	4956.69
y5	5	5055.83
y6	6	5156.94
y7	7	5260.08
y8	8	5365.28
y9	9	5472.59
y10	10	5582.04
y11	11	5693.68
y12	12	5807.56
y13	13	5923.71
y14	14	6042.18
y15	15	6163.02
y16	16	6286.28
y17	17	6412.01
y18	18	6540.25
y19	19	6671.06
y20	20	6804.48

Table 48. The values of the calculations of equivalent annual cost for the renewable/diesel hybrid.

Hybrid			
Investment cost	159433		
Diesel cost flat rate [USD/year]	4579		
Used electricity 20 years [kWh]	28470.00		
Use of 50% over-production [kWh]	32688		
Use of 100% over-production [kWh]	36897		
Discount rate	3%	8%	13%
k	0.067	0.10	0.14
NPV flat rate	$14,984	$19,615	$24,664
Used electricity 20 years [USD/kWh]	$0.53	$0.69	$0.87
Use of 50% over-production [USD/kWh]	$0.46	$0.60	$0.75
Use of 100% over-production [USD/kWh]	$0.41	$0.53	$0.67
NPV 2 % inc	$16,074	$20,698	$25,740

Used electricity 20 years [USD/kWh]	$0.56	$0.73	$0.90
Use of 50% over-production [USD/kWh]	$0.49	$0.63	$0.79
Use of 100% over-production [USD/kWh]	$0.44	$0.56	$0.70

Appendix H – Dimensioning the renewable/diesel hybrid

The comparison showed that the best choice, environmental aspects regarded, was to have 5 Power Towers and a battery tank capacity of 19.2 kWh (2 tanks). As this setup will not fully meet the load, the diesel generator will need to combust 4 780 liters annually in order to cover the remaining electricity demand.

Table 49. The resulting emissions of CO2-eqper used kWh of different setups of the renewable/diesel hybrid dimensioning.

g CO2-eq/used kWh

Battery tank/PT	0	1	2	3	4	5
1	1169	1158	1162	1166	1170	1174
2	1070	1025	1008	1005	1010	1016
3	937	869	839	834	838	844
4	810	720	690	688	693	699
5	684	584	562	564	569	574

Table 50. The resulting demand of primary energy per used kWh for different setups of the renewable/diesel hybrid dimensioning.

kWh/used kWh

Battery tank/PT	0	1	2	3	4	5
1	4.32	4.29	4.31	4.33	4.35	4.37
2	3.96	3.80	3.74	3.74	3.76	3.79
3	3.47	3.22	3.12	3.11	3.13	3.16
4	3.00	2.67	2.57	2.57	2.59	2.62
5	2.53	2.17	2.10	2.11	2.14	2.16

Table 49 and Table 50 shows that the set up including 5 Powertowers and 2 battery tanks (19.6 kWh) is the one with lowest environmental impact, therefore it was chosen as the renewable/diesel hybrid set up.

Appendix I – End-of-life treatment sensitivity analysis

The amount of material recycled is shown in Table 51. The amount of recycled materials

Table 51. The amount of recycled materials.

	Powertower		Hybrid		Dieselgenerator	
	Total mass [kg]	Recycled mass [kg]	Total mass [kg]	Recycled mass [kg]	Total mass [kg]	Recycled mass [kg]
Steel	5783	4626	2628	2102	404	323
Aluminum	358	215	380	228	242	145
Copper	188	94	221	111	34	17
Lead	2428	2404	902	893	0	0
Plastics	31	0	79	0	67	0
Wood	20670	0	7950	0	0	0
Kiselplattor	78	55	30	21	0	0
Electrical components	45	14	17	5	0	0
Concrete	90870	0	34950	0	0	0