Comparative LCA model on renewable power solutions for off-grid radio base stations

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Abstract

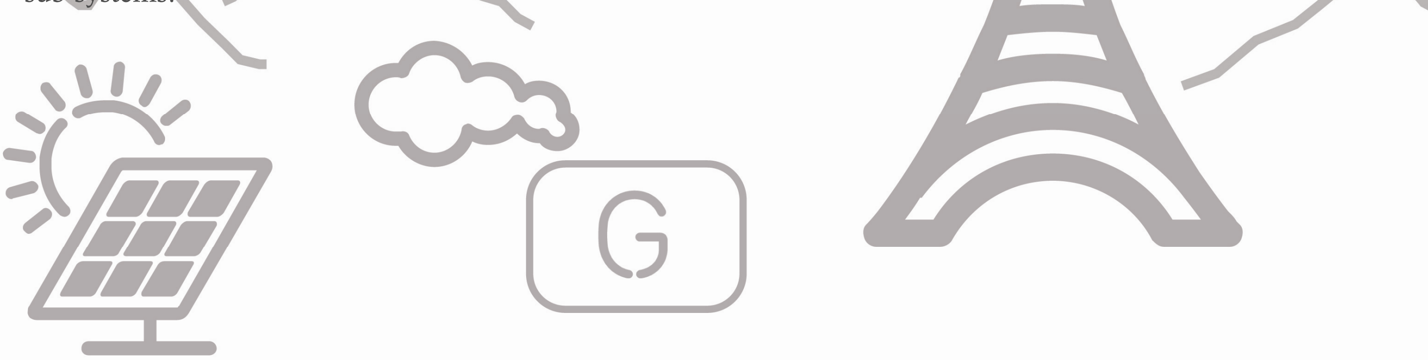
Globally, there are approximately 900 000 telecommunication radio base station sites (RBS-sites) located in areas without access to the electrical grid. Traditionally, these sites are powered by diesel generators, consuming large amounts of fossil diesel fuel. Diesel combustion is connected both to environmental impacts and high economical expenses for the mobile operators. As the mobile network expansion is increasingly located in off-grid areas of developing countries, the search for renewable power alternatives has been intensified.

This Master thesis presents results from a life cycle assessment (LCA) of photovoltaic and wind turbine hybrid power configurations for off-grid RBS-sites. The LCA covers environmental impacts from all life cycle activities of the hybrid system: from raw material extraction, manufacturing, and transportation, to on-site usage, and disposal.

To enable assessment of variable hybrid configurations, four scalable sub-models were constructed: one diesel sub-model including the generator and yearly diesel consumption, one back-up battery sub-model, one PV module sub-model and one wind turbine sub-model. Included in the sub-models were required site equipment; e.g. foundations for generators, PV modules and battery banks, power converters, fuel tanks and possible housings. The number of generators, liters of fuel consumed per year, number of battery cells, square meters of PV module and number of wind turbines were set as variables. Hereby RBS-sites with different capacities and availability of renewable source could be modeled.

A hybrid configuration including 21 square meters photovoltaic modules, one wind turbine, a storage of 36 (12 V) batteries and one generator back-up consuming 1500 liters of diesel fuel per year was evaluated. The hybrid site represents between 11 and 16 percent of the different environmental impact potentials, global warming potential specifically representing 13 percent, caused by a corresponding traditional diesel site consuming 20000 liters of fuel per year. The most important parameters influencing the environmental performance of the renewable hybrid site following the diesel fuel production and combustion are the production energy mix and energy intensive processes including the up-stream silicon and lead processing.

The thesis confirmed great environmental benefits of using wind and solar power at RBS-sites. The additional gain of applying wind power when feasible to decrease the PV module area or battery capacity required was also demonstrated. The great importance of manufacturing location and electricity mix should encourage Ericsson to map supplier manufacturing locations, searching possibilities to decrease the environmental impacts from the manufacturing phase of the different sub-systems.



Sammanfattning

Idag finns det omkring 5 miljoner radiobasstationer i det i det globala telekomnätet, varav 900000 är belägna i områden utan tillgång till elektricitet. Traditionellt drivs dessa stationer av dieselgeneratorer som konsumerar stora mängder diesel. Dieselförbränningen bidrar både till lokala och globala miljöeffekter samt höga driftkostnader för mobiloperatörerna. Expansionen av mobilnätet sker i allt större utsträckning i områden i utvecklingsländer utan elförsörjning, vilket har ökat intresset för alternativa kraftkällor.

Inom examensarbetet har ett redskap för jämförande livscykelanalys (LCA) av förnyelsebara kraft-hybridlösningar för radiobasstationer utvecklats. Hybriderna kombinerar solceller och vindturbiner med dieselförbränning och batterier.

Genom att använda LCA inkluderas miljöeffekter från alla steg i hybridsystemets livscykel; från utvinning av råmaterial och tillverkning av sub-system, transport, användning på RBS-siten till den slutliga avvecklingen.

För att kunna utvärdera olika hybridkonfigurationer skapades 4 olika delmodeller: en delmodell för dieselförbränning innefattande generator och dieselkonsumption, en batteri-delmodell, en PV-delmodell samt en vindturbin-delmodell. Delmodellerna inkluderar även nödvändiga komponenter som betonggrund till generatorer, PV-modulerna och batteribanken. Antal dieselgeneratorer, battericeller, vindturbiner samt PV-moduler och liter dieselkonsumption kan varieras för att simulera en specifik anläggning.

En hybridlösning med 21 m^2 solceller, en vindturbin, 36 stycken (12V) battericeller och en dieselgenerator som konsumerar 1500 liter diesel per år analyserades. Hybridlösningen ger upphov till miljöeffekter motsvarande mellan 11 och 16 procent, global uppvärmning motsvarande 13 procent, av miljöeffekterna orsakade av en traditionell dieselkonfiguration som konsumerar omkring 20000 liter diesel per år. Betydelsefulla parametrar som påverkar miljöeffekterna från hybridlösningen förutom produktion och förbränning av diesel är vilken elektricitetsmix som används vid tillverkning av de olika komponenterna och energiintensiva processer som kisel- och blyframställning.

Resultaten tydliggör de stora minskningar av miljöeffekterna som en övergång från dieselförbränning till sol- och vindkraft på RBS-anläggningar kan ge. Den relativa förbättringen av att installera vindturbiner för att minimera mängden sol- och battericeller har även visats. Betydelsen av produktionsplats och elektricitetsmix för den totala miljöpåverkan bör motivera Ericsson att kartlägga och välja tillverkare som innebär ett litet bidrag till de totala miljöeffekterna.

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Many people have contributed to the understanding of the studied system and the broad data collection. Especially I would like to address Kristian Liljebäck and Patrik Ström for guiding me through the jungle of information within Ericsson and for helping me to define the surrounding environment of the studied system. Others that contributed to the work of data collection were: Tom Linusson, Anna-Maria Varga, Sebastian, Schaplitz, Lars Humla.

The methodology of life cycle assessment is a life long learning processes. Thank you Craig Donovan, Jens Malmodin and once again my two supervisors for helping me approach it.

For the final work of the report completion, I am grateful for the time spent, advice and corrections provided by Nina Lövehagen at Ericsson Research, Kosta Wallin at KTH, my close friend Maria Udén and my partner Gunne Ekelin.

Stockholm, March 2010

Anna Bondesson

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1 Terminology

AC / DC current – Alternating/Direct current

Alternative power system/alternative electricity supply system – Alternative renewable energy solutions

Background/Upstream system – System supporting the observed technical system but not a part of it e.g. electricity and fuel production, transportation infrastructure etc.

BOS - Balance of system (components)

Category indicator – Quantifiable representation of an impact category

Elementary flows – Flows between the technical system studied and the natural environment

Embodied energy – Total energy required for manufacturing a system, from raw material extraction to finalization of the system.

BNET/BUGS – Ericsson Business Unit Networks and Business Unit Global Services respectively

EPBT – Energy Pay-Back Time

Generator – An engine and an electrical generator; correctly called an engine-generator set or a gen-set but in this context the engine is taken for granted and the unit is called generator

GHG – Green House Gas

Hybrid system – Here a combination of power sources, including renewable sources

Impact category – Class representing environmental aspects of concern, to which life cycle inventory can be assigned

Intermediate flows - Internal flows between unit processes

Inventory data – Mass and energy flows between the technical system observed and the surrounding environment or between different activities within the technical system observed

kWh – kilo Watt hours (electric energy content)

LCA – Life cycle Assessment

Off-grid – Location not connected to the central electricity grid

Process unit– The most detailed process studied, for which input and output flows are mapped

PV –Photovoltaic

RBS-site – Telecommunication site including one or many radio base station (RBS) and other supporting systems such as transmission equipment, power backup systems, tower, cooling etc

Renewable-hybrid – A power solution combining different renewable power solutions

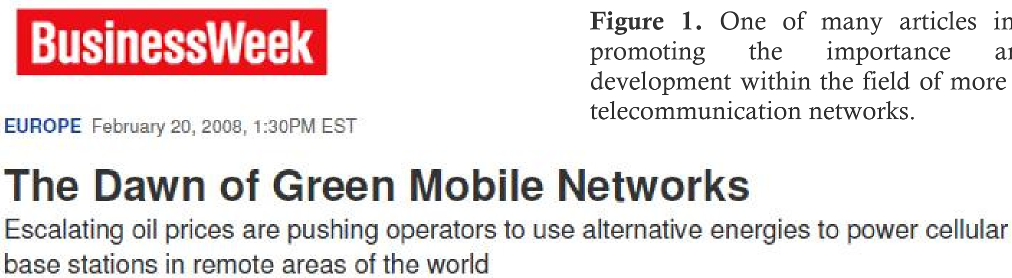
Total cost of ownership – Total investment and operational cost

2 Introduction

There are approximately 5 million radio base station sites (RBS-sites) in the global telecommunication network, with the number growing every year as the network expands (Ericsson internal, Lindkvist and Fager, 2009). Currently approximately 900 000 of these RBS-sites are located in areas where central electricity grid connections are unavailable (Alcatel-Lucent, 2009b) and the population targeted by the mobile network expansion is increasingly located in off-grid areas of developing countries. Around 75000 new off-grid sites are estimated to be installed each year in developing countries through 2012 (GSMA, n.d.). Extending the electricity grid to distant locations is linked to enormous costs and lead-times of years. Hence, the traditional way to power all off-grid applications including RBS-sites is by continuously driven diesel generators, consuming large amounts of diesel fuel. Diesel combustion is not only connected to local, regional and global environmental impacts but also to high economical expenses for the mobile operators. One solution to promote more sustainable mobile networks is the employment of alternative power solutions (Boccaletti et al., 2007, GSMA, n.d.).

Alternative power solutions are not commonly used at telecommunication sites. However the public climate change debate, increased corporate social responsibility, expensive maintenance and higher diesel fuel prices have increased the interest for small scale alternative electrification solutions for off-grid RBS-sites (exemplified in Figure 1[1]). In 2007, 1500 so-called green-sites had been installed and 10000 were planned within the 800 GSMA member operators. Especially in developing countries, where there are vast rural areas without access to any electricity grid, the importance and potential of photovoltaic (PV) solar power and other renewable energy sources has been argued (Boyle, 2004). Available renewable electrification systems are mainly based on wind and/or solar PV power but configurations with stored hydrogen and fuel cells, bio-fuels and small scale hydro power are under investigation and trials (Boccaletti et al., 2007). Successful stand-alone systems are usually hybrids, combining different renewable power techniques, battery banks and diesel back-ups to secure the power supply. GSMA predicts that in 2012 up to 50 percent of all new off-grid RBS-sites in the developing world will be powered by renewable energy.

Ericsson currently offers a PV solar powered RBS-site and has an interest in mapping other alternative power systems that are applicable to off-grid RBS-sites with their comparative environmental impacts.


BusinessWeek

EUROPE February 20, 2008, 1:30PM EST

The Dawn of Green Mobile Networks

Escalating oil prices are pushing operators to use alternative energies to power cellular base stations in remote areas of the world

Figure 1. One of many articles in the press promoting the importance and rapid development within the field of more sustainable telecommunication networks.

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[1] *http://www.reuters.com/article/pressRelease/idUS126747+16-Mar-2009+BW20090316*

2.1 Background

Mobile telecommunication networks are built up by fixed RBS-sites that receive and transmit radio signals and provide local access to the network. When possible the RBS-site is connected to the local AC electrical grid. On off-grid sites, when a connection to the electricity grid is not economically feasible, the traditional power solution is to use two diesel generators. The generators are operated alternately by a control system and are normally connected to a back-up battery bank. Figure 2[2] illustrates a general off-grid diesel powered RBS-site.

A diesel generator system requires continuous diesel fuel supply and regular maintenance (Hashimoto et al., 2004). High operational costs, fuel losses due to theft and increased environmental concerns have intensified the research and deployment of alternative energy solutions for different off-grid appliances including RBS-sites.

Figure 2. General off-grid diesel RBS-site.

Renewable energy can be defined as continuous currents of energy in the natural environment. The main source of renewable energy is solar radiation that can be used directly. However, solar radiation also creates wind, waves and the hydrological cycles and nurses the growth of bio energy (Boyle, 2004).

The high reliability demands on RBS-sites increase the size of any possible renewable power facility. Recent improvements of RBS-sites concerning energy optimization has opened the door for the use of alternative energy sources (Alcatel-Lucent, 2009a). Commercially available alternative power solutions for RBS-sites only include PV modules and wind turbine solutions, however there is research and site specific trials on other alternative sources and storages like bio-fuels, small-scale hydro power and fuel cells (GSMA, n.d.).

Successful renewable systems are often hybrids combining different renewable technologies, currently wind turbines and PV modules. Most renewable sites rely on extended battery banks and normally also employ a diesel back-up. The concept of using hybrid renewable power systems at RBS-sites is illustrated in Figure 3.

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[2] *http://upload.wikimedia.org/wikipedia/commons/e/eb/CellPhoneTower_OR.jpg*

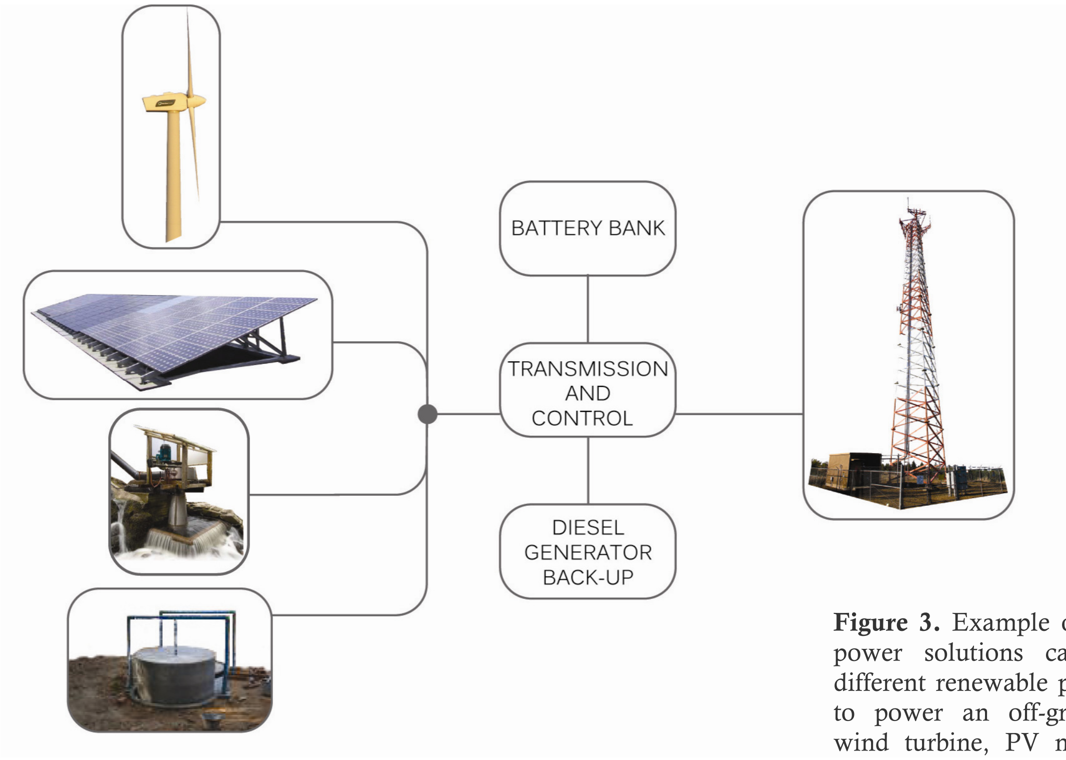


Figure 3. Example of how hybrid power solutions can consist of different renewable power sources, to power an off-grid site. Here wind turbine, PV modules, pico-hydro and bio fuels.

Ericsson has recently developed a battery diesel hybrid power solution where one diesel generator is replaced with an extended battery bank. This decreases the diesel consumption by around 50 percent compared to a traditional diesel site. Ericsson's product catalogue also includes a PV power site solution. Some RBS-sites in networks managed by Ericsson are driven by wind turbines provided by local suppliers but currently Ericsson does not provide any wind power solution.

Life cycle assessments (LCAs) are used to map the total environmental footprint of products or services and there are several previous studies on different fossil and renewable power solutions. Most of these LCA studies have been performed on large scale power plants and are simplified, focusing mainly on the carbon dioxide emissions and climate change (Gagnon et al, 2002). Generally the environmental impacts of combustion engines arise in the fuel production and combustion phase of the life cycle. By comparison, renewable energy systems such as wind and solar power cause no emissions during operation and the manufacturing of the equipment becomes the dominant phase of the environmental life cycle (Khan et al., 2004).

2.2 Terms of reference

This Master thesis was based on a project defined by Ericsson Research and undertaken at the division for EMF Safety and Sustainability located in Stockholm, Sweden during 20 weeks between the beginning of September 2009 and the end of February 2010.

The terms of reference requested an environmental comparison based on an LCA approach between renewable power solutions for off-grid RBS-sites. The evaluation should be used as a basis for further research within the area of EMF Safety and Sustainability and at the Business Unit Networks (BNET) and Business Unit Global Services (BUGS) to promote alternative energy systems towards their customers (e.g. network operators).

2.3 Aim and objectives

The aim of this Master thesis is to develop a model to compare the environmental performance of selected renewable electricity supplies for off-grid RBS-sites based on previously performed LCAs. The research questions to be answered are; "*What different renewable power solutions for off-grid RBS-sites are available?*", "*In what life cycle stage and for which components of the selected systems do the major environmental impacts occur?*", and "*What is the relative scale of environmental impacts between the selected renewable systems?*".

As a secondary aim, a simplified tool with variable parameters to evaluate specific RBS-sites should be developed. This simplified tool should be possible to use by a second party and be developed in a standard software.

The objectives include:

- to complete a baseline study mapping existing and near future renewable power solutions suitable for off-grid RBS-sites.
- to select systems (renewable power solutions) to include in the LCA.
- to perform an LCA of selected systems; including the collection and organization of environmental data and building of a model (using the specified LCA software GaBi (PE & LBP, 2008)).
- to evaluate the developed LCA model.

2.4 Scope and delimitations

The assessment only covers alternative power sources. Hence, solutions decreasing energy consumption (e.g. energy management, green shelter solutions) or alternative cooling systems (e.g. thermal cooling instead of air conditioning) are not included in the baseline study neither are improved fossil fuel power systems.

Based on the baseline study, alternative power systems to be included in the comparative LCA evaluation should be chosen according to the criteria presented in section 5.1. The scope and delimitations of the LCA can be found in section 6.

The simplified evaluation tool should be developed as a trial version for further evaluation and user adoption. The trial tool should be based on main user requirements and developed with a suitable user interface.

2.5 Overall methodology and report structure

The thesis project was divided in three phases as illustrated by the outline in Figure 4.

In phase one, a literature study was performed and a selection of power systems to evaluate in the LCA was made. The literature study followed the methodology of Kihlén and Lantz (2005) and covered two areas; the framework and methodology of Life cycle Assessment (LCA) and state-of-the-art on renewable power solutions suitable to power off-grid RBS-sites. Internal documentation provided information on power alternatives considered by Ericsson and an external literature study mapped the global status of renewable electricity solutions for RBS-sites or comparable off-grid applications and background to LCA methodology.

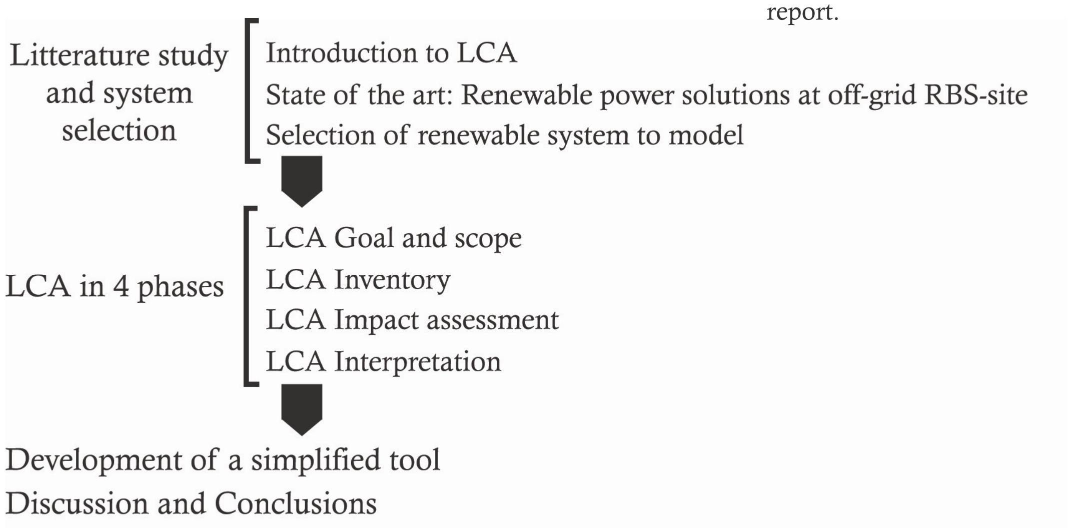
Based on the baseline study and set criteria defined in section 5.1, alternative power systems were selected for evaluation.

In phase two, a comparative LCA was performed on the selected power systems using a methodology according to Bauman and Tillman (2004). Methodical choices for the LCA are reported in section 6 and the characteristics of the software in section 6.2.8 and in section 9. The practical modeling and evaluation was performed in the LCA software GaBi (PE & LBP, 2008).

The required installation capacity of renewable power facility and battery storage is dependent on the site characteristics and availability of renewable resources. To be able to compare different hybrid configurations, the LCA used mass and volume as a reference for the different selected systems. Hence, the RBS capacity requirements and intermittency of renewable energy supply sets the amount of wind turbines, solar cells, etc. needed. To illustrate the environmental impact from the different systems, two site configurations were evaluated and compared to a traditional diesel site.

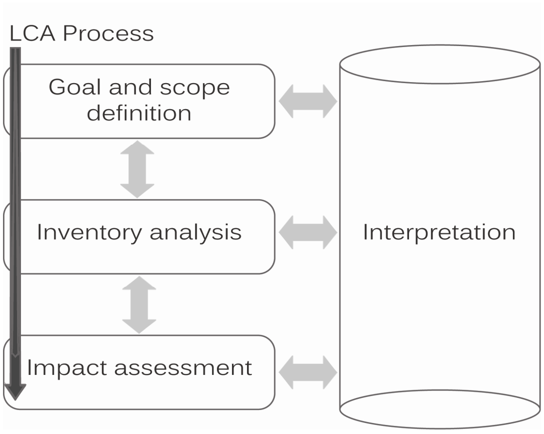
In phase three, the LCA results were exported from GaBi and summarized into a simplified environmental evaluation tool. Criteria on the simplified tool were set based on requirements from the project owner (Ericsson Research EMF Safety and Sustainability) and through discussions with employees at BUGS, being the user target group.

Figure 4. Outline of the report.



Life cycle assessment is a systematic framework to analyze the environmental impact of products, systems or services on a life cycle basis, from the raw material extraction (the cradle), processing and manufacturing (the gate) to use and disposal (the grave). The aim should be a transparent assessment where the depth and details are allowed to vary with the goal and scope (Varun et al., 2008).

The methodology and standardization of procedures for life cycle assessments has developed greatly in recent years. Future developments include application and implementation focused processes for existing methodologies and an extension of the framework to include economical and social concerns (Hunkeler and Rebitzer, 2005).



By definition an LCA includes 4 phases as illustrated in Figure 5; definition of goal and scope, inventory analysis, impact assessment and interpretation, where the results from the other three phases are summarized and evaluated (ISO 14040:2006).

Figure 5. Schematic illustration of the working phases of an LCA assessment. Translation of illustration from Baumann and Tillman (2004).

3.1 Goal and scope definition

In the goal and scope phase the purpose of the project, usually given by the project description from a commissioner, should be formulated into a detailed goal and scope description. The description should include application of the study, reason for carrying it out and planned audience, methodology and requirements on the results. In reality a life cycle assessment is an iterative process, hence the scope will change throughout the working process, however considering and making most choices in the beginning is an advantage.

A core feature of an LCA is the construction of a flow-chart or inventory model where the technical system is illustrated as a set of process units, intermediary product flows linking them together and entry/exit flows in connection to the natural system. A system boundary defines which process units should be considered as part of the technical system and which should fall outside (Cavallaro et al., 2006). Deciding on which data to collect and showing where impacts could occur is the backbone of the whole LCA (Baumann and Tillman, 2004). The choice of which environmental impacts (climate change, acidification etc.) to assess and hereby which inventory data (CO_2 and SO_2 emissions etc.) to search for is defined in the goal and scope definition. A functional unit is also defined to be used as a reference flow to which all other flows included in the model are later related.

3.2 Life cycle inventory analysis (LCI)

In the life cycle inventory analysis, input and output flows from/to the technical system are analyzed, for example, environmental data on mass and energy for all activities included within the system boundary are collected (Kato et al., 1997). The smallest process for which input and output data are quantified is called a process unit. Considered environmental flows are use of resources and releases to air, water or land (ISO 14040:2006). In addition, assumptions are stated and calculations to connect the inventory data to the selected functional unit are made.

3.3 Life cycle impact assessment (LCIA)

While the aim of the inventory process is to model human activities, the impact assessment focuses on the potential impacts these activities have on the natural environment (Baumann and Tillman, 2004). The inventory data is converted into indicators assigned to specific impact categories (Cavallaro et al., 2006).

The impact assessment includes some mandatory activities, e.g. classification and characterization, but also optional elements to clarify the results including normalization, sorting and ranking or weighting of the indicators based on value-choices (ISO 14044:2006).

3.4 Life cycle interpretation

In this continuous phase, results from the LCI and LCIA are summarized and discussed (ISO 14040:2006). The focus should be on identifying significant issues, evaluating the completeness, sensitivity and consistency of the results and providing conclusions and possible recommendations on improvements (ISO 14044:2006).

3.5 Delimitations and critical review of LCA methodology

The most critical aspect of using LCA methodology is that the results are highly dependent on the availability of data and that the study is performed through an iterative process using a series of approximations and dynamic specifications of data. Cavallaro and Ciraolo (2006) add critique on the unreliable scientific verification within databanks and the working process of adopting second hand data to a specific system assessed. They stress the importance of a constant revision of calculations and assumptions to decrease the uncertainties connected to the practitioner.

A general solution is to use standardized methodologies ensuring that studies are conducted in similar ways, based on similar basic assumptions and criteria and use common mass units for input and output data (Fleck and Huot, 2009).

A methodological limitation suggested by Ciroth and Becker (2006) is the absence of validation and assurance that the model mimics the real system. Currently, LCA studies are more questioned in terms of methodology and comparison to other models, rather than on how well the results represent reality. To follow the modeling rules becomes more important than the result for the practitioner. The LCA model should be validated through comparison to reality and improvements should be made if necessary.

In addition to the methodological limitations there are complications concerning data sources. Most LCAs depend on data with questionable reliability from producers and fail to present the underlying process data because of confidentiality (Ayres, 1995).

4 Renewable power at off-grid RBS-site

This section contains a summary of the pre-study found in Appendix A. The study covers available renewable power solution and storage alternatives for off-grid electrification and a review of previously performed environmental analysis on different renewable power systems.

The GSMA foundation (GSMA Developing Found, 2007) considers solar PV power to be the most suitable renewable power source for off-grid network sites, followed by wind turbines, pico-hydro, and bio fuel power all illustrated in Figure 6[3]. The advantages with PV modules are the abundant resource supply, the modular design and low operational costs. Within the member operators of the GSMA association nearly 1500[4] PV sites have been installed globally, representing the main part of installed sites utilizing renewable resources. Another growing technique to utilize solar radiation at off-grid sites is solar thermal-engine systems based on parabolic-dish concentrators, the most common being different dish-Stirling designs (Boyle, 2004). To obtain the high temperatures needed, a dish-Stirling system has to be located in direct solar radiation, as diffuse radiation is not enough.

Only 6 wind powered sites and 42 hybrid sites combining PV modules and wind turbines are currently reported within the member operators of GSMA[5]. Wind power has a very low operational cost, is theft resistant, has a lower initial cost than solar power, and is reliable. The wind tower and RBS antenna tower can be combined if dimensioned for it (Boccaletti and Santini, 2007). The variations in wind speed is considered to be the limiting factor, restricting wind powered sites to locations with abundant wind resources like coastal and mountain areas. Thereby, making this solution less suitable for the average RBS-sites than solar power (GSMA Developing Found, 2007).

Hydro power is a mature technology for rural electrification but is highly site-specific (Gagnon et al, 2002). In the case of RBS-site powering the focus lies on pico-hydro facilities, being a hydro power plant harvesting the power of streams and rivers to produce up to 5 kW of electricity (Maher et al, 2002). There is no commercial best-practice solution and it is difficult to determine how many small-scale hydro power plants are installed globally.

The pre-study revealed that at least three RBS-site trials using bio fuels as a power source for radio base stations have been installed[6]. The two main sources of bio energy for small-scale electrification are bio diesel from oily seeds like soya beans, sunflowers etc. or biogas from digested wastes that can be used in traditional diesel or combustion engines driving electrical generators (Boyle, 2004). Negative environmental and social impacts are raised due to the extensive farm and forest land required, the usage of fertilizers and pesticide and risks of decreasing biodiversity (Boyle, 2004).

One of the main problems when applying alternative power is meeting the generated and required power capacities. Traditionally lead-acid batteries are used as storage at RBS-site and will be used for this assessment, but currently other solutions are investigated e.g. chemical fuel for combustion or feeding of fuel cells and different mechanical storages (Bitterlin, 2005).

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[3] *http://www.convergedigest.com/images/articles/ericsson-solar.jpg , http://www.flexenclosure.com/, www.ericsson.com and http://www.arun.gov.uk/images/eh/Small_Hydro_Station.jpg*
[4] *1447 according to http://www.wirelessintelligence.com/green-power/*
[5] *http://www.wirelessintelligence.com/green-power/*
[6] *http://www.wirelessintelligence.com/green-power/*

Around 10 trials using fuel cells as back-up at RBS-sites have been made globally[7] and fuel cells are considered as a promising future storage, but currently have no commercial applications within telecom. A fuel cell uses a reversed electrolysis to convert, for example hydrogen and oxygen fuel into DC electricity (Boyle, 2004). Currently, the hydrogen fuel is mainly produced centrally from natural gas and cannot be considered a renewable storage solution (Bitterlin, 2005). The pre-study also found several research projects on using fuel cells as a power source in combination with renewable power systems and on-site hydrogen production (Boccaletti and Santini, 2007, Boyle, 2004).

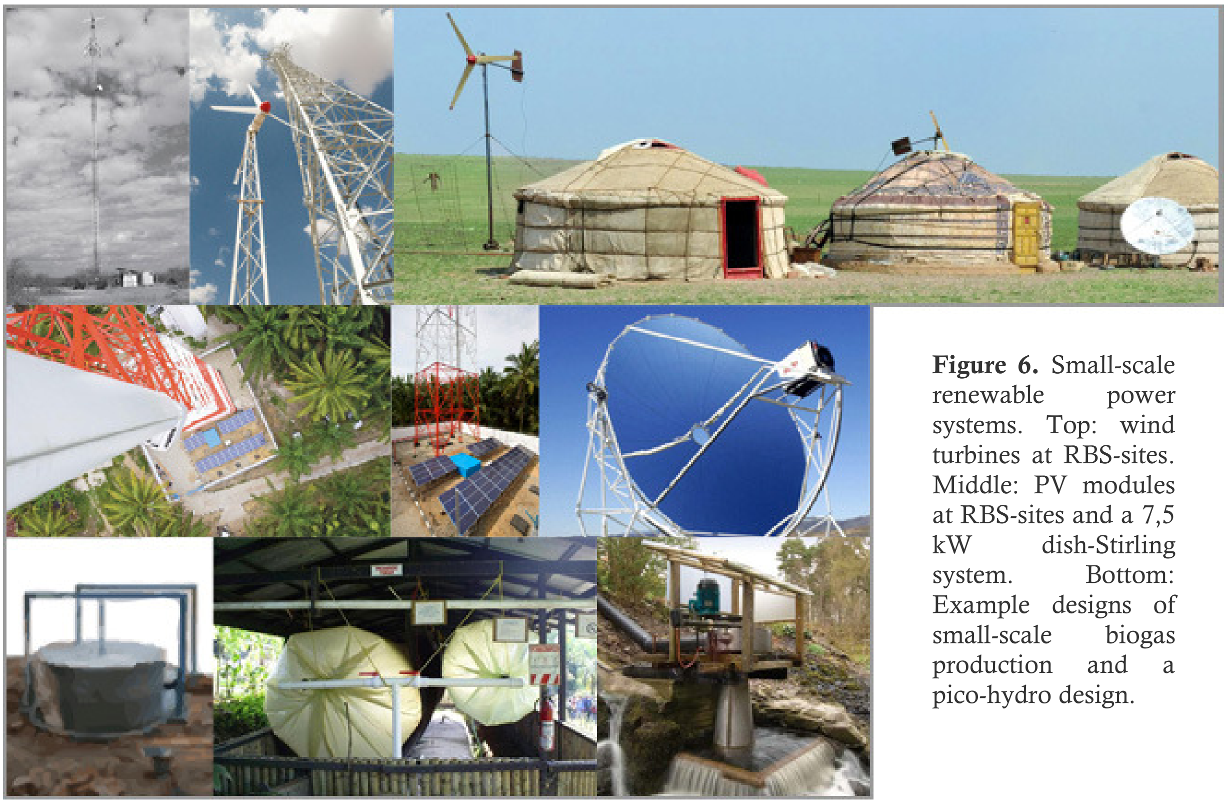

Figure 6. Small-scale renewable power systems. Top: wind turbines at RBS-sites. Middle: PV modules at RBS-sites and a 7,5 kW dish-Stirling system. Bottom: Example designs of small-scale biogas production and a pico-hydro design.

[7] *http://www.wirelessintelligence.com/green-power/*

5 Selection of renewable system to evaluate

In this section, the criteria used to select alternative power systems, the selected systems and the motivation for selection are presented.

5.1 Selection criteria and evaluation

Criteria for the alternative power systems based on suitability at RBS-sites, technological maturity and an evaluation of the power solutions are presented in Table 1.

Table 1. Selection criteria and evaluation of the alternative power systems.

The power supply system must:	PV	Dish-stirling	Wind turbine	Pico-hydro	Bio fuels	Fuel-cell
- supply power independently, e.g. must be the main power source.	x	x	x	x	x	
- be possible to order from a supplier as an application.	x	x	x			x
- be assembled by standard components applicable to different sites.	x	x	x	(x)		x
- be possible to install without community agreement or involvement.	x	x	x			x
- be independent of a local 24*7 employee work load, only be dependent on service	x	x	x			x
- be considered to have a feasible investment cost.	x		x	x	x	
- agree with the values that Ericsson has set for their ethical standpoint.	x	x	x			x

5.2 Selected power supply systems

Solar PV modules and wind turbines will be evaluated further in the LCA. They are already applied at telecommunication sites and meet the criteria in Table 1. Further more they are commercially applied as off-grid electrification (Boyle, 2004) and expected to have an increased usage in the future (Boccaletti et al., 2007).

Bio-fuels such as biogas and bio diesel are promising but will not be included in this comparative assessment because of the many uncertainties regarding the social sustainability and production capacity.

Pico-hydro power is widely used for rural electrification in the same capacity range as RBS-sites (as described in Appendix A). The solution was discarded because of the absence of a standard system solution, the unspecified installation process depending on social aspects and community involvement, and insufficient experience on commercial usage or previous uses in telecommunications.

The concentrating dish-Stirling system was discarded because of the fact that the telecom industry has not shown this solution any interest as an alternative. In addition, a study comparing different solar-dish solutions combined with Stirling engines or PV cells in 2005 (Firak) concluded that combinations with PV cells has higher efficiency, lower maintenance requirements and investment costs than the dish-Stirling solution. The suitability for these systems must be further investigated.

The only alternative for hydrogen fuel cells to be considered as a renewable power supply system is if combined with on-site hydrogen fuel production. Since this technology is still premature and not proven, fuel cells are not evaluated as a power source.

5.3 Storage and back-up alternatives

To provide storage and back-up the PV/wind turbine hybrid will be combined with a lead-acid battery bank and a diesel generator. In the future other storage alternatives might be developed, though currently renewable systems are dependant on batteries to store energy. Different lead-acid battery designs are those commonly used. Previous work shows that liquid fossil fuels and diesel generators dominated the role as a stand-by system due to the low volume requirements compared to, for example, hydrogen for fuel cells, flywheels, compressed air and lead-acid batteries (Bitterlin, 2005).

The only storage solution besides batteries that was uncovered by the pre-study to be used at off-grid applications similar to RBS-sites was fuel cells on trials. The trials were located at high cost sites, using an external fuel supply. Economical expenses of hydrogen production, supply and storage are often mentioned as barriers to an extended usage of hydrogen as a fuel for fuel cells (Briguglio et al., 2009). Hence fuel cells are too expensive for the developing market. It is obvious that there are still technical issues to be solved before systems combining renewable energies and fuel cells could be operational. A study by Khan et al. (2004) states difficulties for integrated wind turbine and fuel cell systems, e.g. wind turbines provide varying output capacities while the electrolysis requires a stable voltage.

6 LCA Goal and scope

This section defines the purpose, scope, methodology, context and limitations of the LCA to be performed. Furthermore the targeted audience and applicability of the result, type of LCA, definition of functional unit, system characteristics and boundaries, data requirements as well as a critical review of the methodology chosen is reported.

6.1 Goal

The reason for carrying out this study is to evaluate the environmental impacts caused by alternative power solutions for RBS-sites. The power solutions include PV modules, wind turbines and diesel generator power systems in individual or hybrid configurations with a back-up of lead-acid batteries.

The study should enlighten the question: *"Which life cycle stage and system components within a PV/wind/diesel/battery hybrid-power system influence the environmental performance and what is the comparative scale of environmental impacts between a renewable power hybrid and a traditional diesel site".*

This thesis aims at creating a generic evaluation of renewable power that can be applied to any RBS-site. The thesis should provide an indication of which configurations are connected to the least/greatest environmental impacts.

The deliverables of the study will be a comparative simulation model developed in the LCA software program GaBi (PE & LBP, 2008), a trial version of a simplified evaluation model, including user instructions, possible to use without any specific software knowledge and a project report.

6.1.1 Target audience and applicability of the study

The model developed in GaBi and results from this study will be used internally at Ericsson Research EMF Safety and Sustainability as a base for further research. The simplified model and conclusions will provide internal education and sales support to the business units.

6.2 Scope

As a framework a comparative accounting LCA methodology, according to Baumann and Tillman (2004), was used.

Four sub-systems were modeled and compared in different configurations; a PV sub-system, a wind sub-system, a diesel sub-system and a battery sub-system. Because of the comparative approach only the process units and impacts that differ between the different sub-systems are included in the inventory and analysis. The different sub-systems are made technically comparable through providing the LCA results as a function of needed capacity, for example, per amount of PV module, number of wind turbines, diesel generators, diesel fuel consumption and battery capacity. The sub-system results are scalable and can be applied for specific pre-dimensioned power system configurations.

The different sub-systems compared are assumed to have vital impacts in different stages of their life cycles; hence the system boundary will include the whole life cycle using a cradle-to-grave approach. By using accumulated data from previously conducted LCAs on wind turbines, PV modules, diesel combustion systems and lead-acid batteries as main data sources, the depth of LCA analysis is restricted.

The scope only covers biophysical impacts and not social or economical aspects.

This study presents a status-quo LCA (for the year 2009) hence, does not consider further reductions of environmental impacts due to technical improvements of the PV cells, batteries, generator or wind turbine themselves or of the background system e.g. electricity production and transportation means.

6.2.1 System definition

All off-grid RBS-sites can be divided into the following main parts: power source, storage, electrical transmission including controllers and the RBS units requiring electricity.

The hybrid-power source that will be evaluated include four different sub-systems; a PV sub-system and wind sub-system being the renewable energy generators, a diesel back-up sub-system and a battery storage sub-system, illustrated in Figure 7. By varying the amount of PV modules, number of wind turbines, battery capacity and diesel fuel required, RBS-sites with different capacity requirements and access to renewable energy can be evaluated. As an example a traditional diesel site is configured of two diesel generators, a minor battery bank and specified diesel consumption. By eliminating the PV and wind sub-systems the traditional diesel site can be evaluated. Similarly a pure PV-driven site can be evaluated by eliminating the wind turbine and diesel generator sub-systems. The life-time of the sub-systems will vary for different configurations as described in section 7.

No specification on the surrounding RBS-site and transmission is set but currently at Ericsson only RBS-sites requiring less than 1 kW power should be considered for solar power, the main reason being that the business case will be hard to justify for large solar installations. These sites are usually main-remote sites, that is configurations where the transceiving radio units are placed in the tower close to the antenna, decreasing energy losses. The new generation of traditional macro base stations will have low enough power demand to make solar a viable option for these as well. For sites with larger daily energy demands wind power or combinations of solar and wind (and a back-up generator) will provide the lowest total cost of ownership (Ericsson employee 3, 22 Jan 2010).

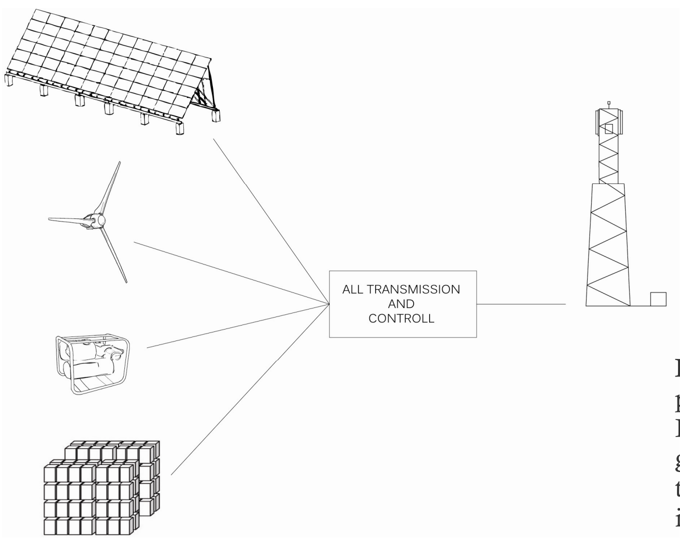

Figure 7. Illustration of the hybrid power system assessed; including PV modules, wind turbine, diesel generator and battery bank, and the surrounding environment including the RBS-site and transmission.

6.2.2 System boundaries

The system boundary states which unit processes that should be a part of the studied system (ISO 14040:2006) such as the sub-systems and components that are included in the LCA as illustrated in Figure 8. Because of the comparative character of the assessment the RBS-site is not included but only described as surrounding environment and as a reference capacity indicator. The function of the sub-systems assessed is to supply the RBS with sufficient electrical power. An RBS-site generally requires both AC and DC power and all power sources require input/output controls governed by the control system (Salas and Olias, 2000). Hence, common transmission and control equipment is not included in the LCA. PV modules produce and batteries require DC power while the wind turbine and diesel generator produce AC power (Ericsson employee 1, personal communication 17 Oct. 2009). Hence, the only transmission equipment included in this assessment is the rectifiers (transforming AC to DC power) required by the wind and diesel sub-systems.

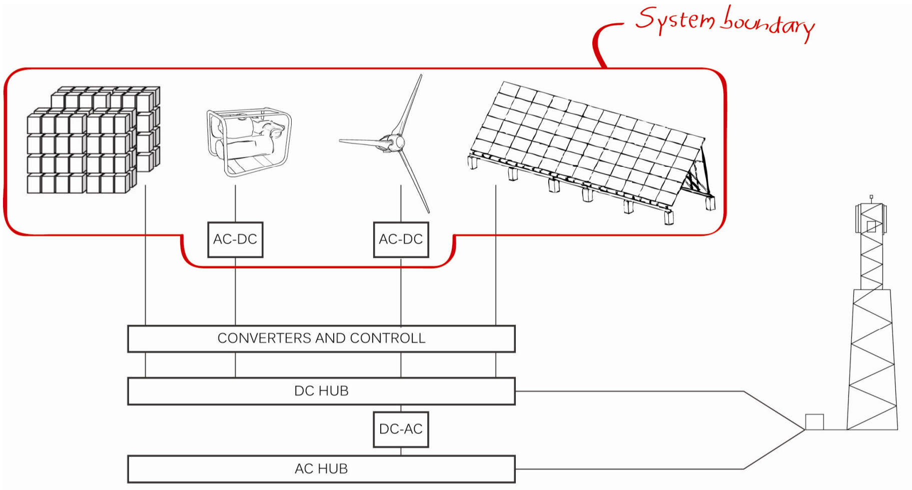

Figure 8. Overall technical system boundary for the LCA assessment. The battery storage, diesel generator main power or back-up solution and the renewable power systems of wind turbines and PV modules are included. In addition rectifiers transforming AC power from the generators to DC power are also included. The RBS-site, common transmission and control systems are left outside of the system boundary.

In this cradle-to-grave life cycle assessment the manufacturing of power facility and diesel fuel, transportation, installation, operation and end-of-life decommissioning are included. The manufacturing stage also includes upstream data on raw material extraction and processing.

To delimit the thesis the developing world is set as geographical reference. Data on transportation, usage and end-of-life treatment is collected from this geographical area.

Flows and process units not included or considered negligible are reported in Table 2.

Table 2. Life cycle activities not included in the LCA assessment for the different sub-systems.

Processes not included or only partly included in the assessment:
The manufacture, maintenance and decommissioning of capital equipment, e.g lightning and heating of production facilities, personnel and the component development work are not included due to limiting project time for data collection.
The transportation within the decommissioning phase was considered to be handled in different stages, combined with transportation of other goods and difficult to map since the location is unspecified.
The cooling system of the battery banks within the pre-fabricated shelter from Ericsson is not included.
Problems on sites and additional maintenance that accure due to vandalism and theft, including theft of copper wire and diesel, is difficult to estimate and is hence excluded.
All transportation activities require access to roads, other infrastructure and a vehicle in need of regular maintenance, which was not included in the assessment.
The loading and reloading transportation activities are not included.
Processes considered negligible in the assessment:
Boxes and other shipping material are not included.
The required maintenance of the different sub-systems is not included since it is performed simultaneously as the refueling at the diesel site and seldomly at the renewable sites.
The transportation and use of electrical tools and possible other machines for installation of the sub-system facilities are neglected.

6.2.3 Sub-system definition

The four sub-systems were defined according to how diesel generators, back-up batteries, PV modules and wind turbines are applied to and integrated at off-grid RBS-sites.

6.2.3.1 Diesel sub-system

Considered components of the diesel sub-system are illustrated in Figure 9. A 10 kW diesel generator from the supplier AJ Power (AJ Power, product specification, 2009) and rectifier from ABB (ABB Automation, product specification, 2009) was used as references to provide data. A traditional diesel fueled off-grid RBS-site needs refueling around every 10th day.

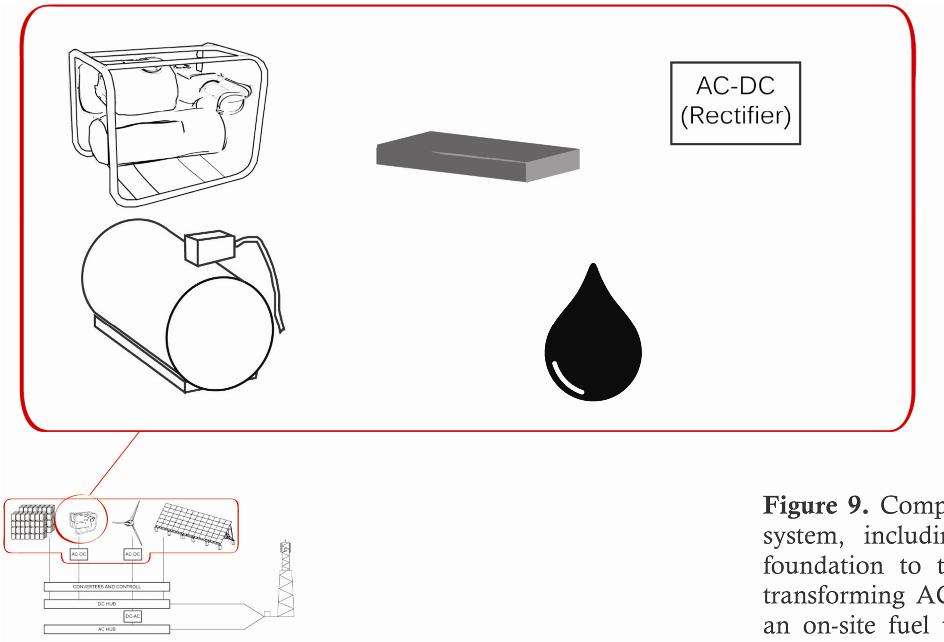

Figure 9. Components of the diesel sub-system, including; a generator, on-site foundation to the generator, a rectifier transforming AC voltage to DC voltage, an on-site fuel tank, the diesel fuel and possible transportation fuel tanks.

6.2.3.2 Battery sub-system

Components included in the battery sub-system are shown in Figure 10. The assessment is based on a Compact Power lead-acid battery model from Oerlikon (Ericsson internal, P. Bergmark, 2001).

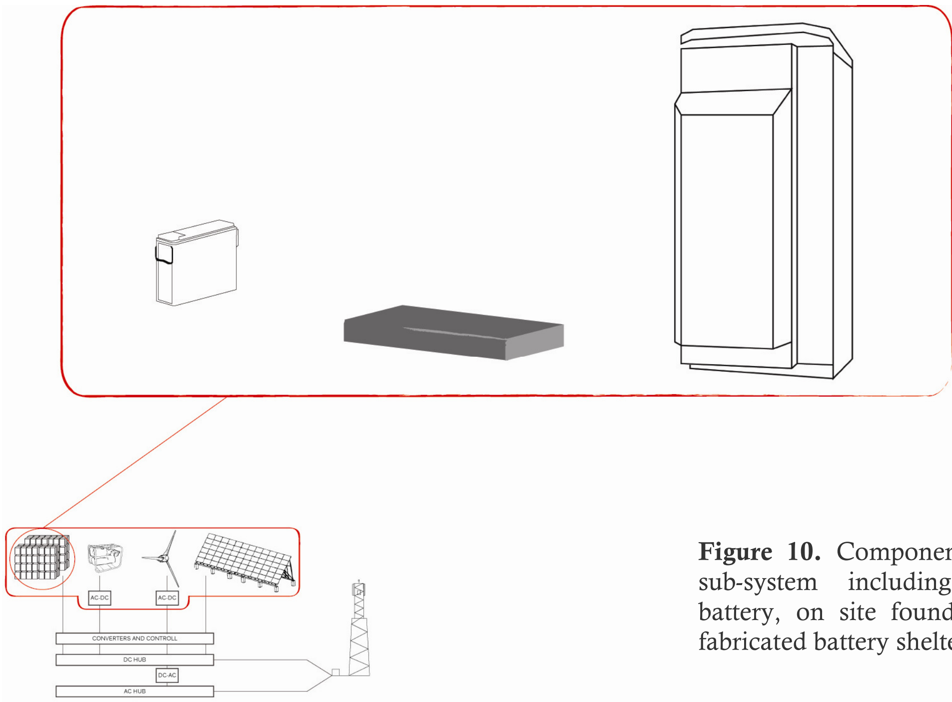

Figure 10. Components of the battery sub-system including; the lead-acid battery, on site foundation and a pre-fabricated battery shelter from Ericsson.

The different power sub-systems (PV, wind turbine and diesel generators) require battery designs with different capacity, also providing different life-times. For example the renewable hybrid solutions demand batteries which can handle cyclic charges and discharges and a photovoltaic source generates power more slowly than a wind turbine requiring batteries with higher load responsiveness (Ericsson employee 1, 17 October 2009). This assessment assumes general lead-acid batteries, only varying the life-time required by the different sub-systems.

6.2.3.3 PV sub-system

The PV sub-system is mainly based on the Sun-site found in the product catalogue of Ericsson, applying solar panels from BP Solar (BP Solar, 2007a). The components included in the sub-system are illustrated in Figure 11.

The basic limitations for any PV facility applied to this study are that it is built of multi-crystalline silicon PV cells framed in aluminum and is mounted on the ground using a concrete foundation and an aluminum supporting structure.

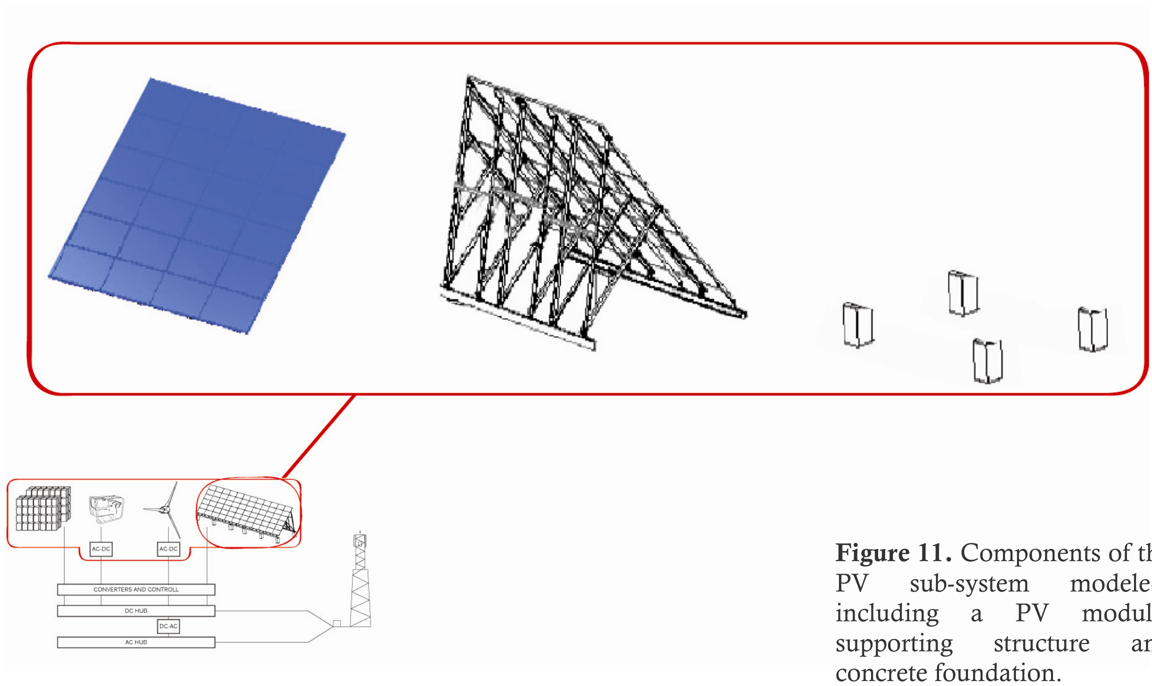

Figure 11. Components of the PV sub-system modeled; including a PV module, supporting structure and concrete foundation.

6.2.3.4 Wind sub-system

The wind sub-system includes a wind turbine and a rectifier, as illustrated in Figure 12. Ericsson does not specify any wind turbine in their product catalogue hence the assessment is based on a horizontal wind turbine from Bergey (Product specification Excel-R, n.d.). The main components of a wind turbine are the rotor, rotor blades and nacelle including the generator. Generally, LCA studies include a tower construction. For economically feasible application to RBS-sites the turbine will be mounted in the existing antenna tower, hereby the tower is excluded from the assessment.

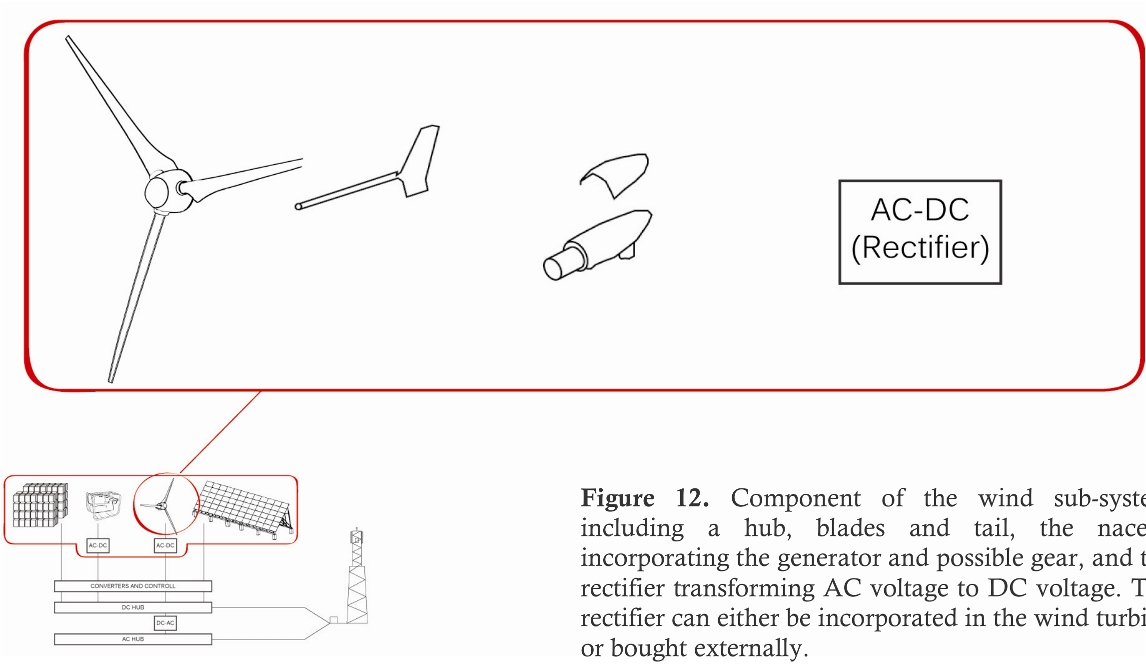

Figure 12. Component of the wind sub-system including a hub, blades and tail, the nacelle incorporating the generator and possible gear, and the rectifier transforming AC voltage to DC voltage. The rectifier can either be incorporated in the wind turbine or bought externally.

6.2.4 Functional unit definition

The amount of energy produced (kWh) is adopted as functional unit for most LCAs of renewable power production (Gagnon et al, 2002) but for this assessment the capacity is not constant. One functional unit for each of the sub-systems was set:

- one square meter of PV module (weight 13 kg) for the PV sub-system.
- one wind turbine for the wind sub-system.
- 42 kilograms or one 12 V cell for the battery sub-system.
- one generator and one liter of diesel consumed for the diesel sub-system.

Each system is scalable and different specific configurations can be analyzed.

6.2.5 Data requirements, quality and delimitations

Data for the life cycle activities were initially searched in previous LCI and LCIA reports and articles. Differences between previous assessments and the actual system used at RBS-sites were searched and modifications were made using supplier data and internal Ericsson information. The technological coherence was secured by using internal Ericsson information to set demands on capacity and size of the systems and restricting the data collection to coherent LCA studies.

Renewable energy technologies are rapidly developing, hence the data time-frame was set to 10 years (1999 to 2009). An exception was made for the lead-acid batteries; where a data time-frame between 1990 and 2009 was considered.

Since it is an accounting assessment, average data was used according to Bauman and Tillman (2004) when possible. When not available, supplier or site specific data were used. Limitations on data quality and completeness are reported in Table 3.

Table 3 Data quality and completeness limitations.

Limitations on data quality:	
	The manufacturing data comprises a problem because of the high level of the study, leading to compromises in geographical differentials and limits. As an example there is no local steel production in Africa (Pusca and Ekblom, 2008), hence the steel reinforcement in the foundation originates from different parts of the world which is not mapped.
	The diesel production is assumed to be located in the local African market but the standard database process uses European diesel production.
Limitations on data completeness:	
	Output emission data for activities is seldom reported in previous LCAs, hence the emissions are restricted to the predefined process emissions. Emissions occuring in the specific product manufacturing process units are likely missed.
	Ancillary material inputs that have been reported by previous studies are included, however there are no security that these cover all ancillary requirements.
	The hybrid solution requires a special type of battery, requiring a built-in cooling system (Minde, 2009) which was not included.
	The differences between the control systems, additional converters, cables, monitoring systems, climate systems, etc. connected to the different sub-systems were neglected based on previous studies concluding that the electrical components are negligible. The only components required by parts of the sub-systems and hence included are the AC-DC convertes of the wind turbine and diesel generator.
	The rectifier is given a different life time in the diesel and wind sub-system because of model limitations.
	Any hybrid system requires a more advanced control system than a regular diesel site, however, the extra electronics are considered negligible.

6.2.6 Methods for inventory analysis

Three different steps were performed within the inventory analysis following the methodology of Bauman and Tillman (2004); detailed flow-charts for each sub-systems were created, data was collected and documented; and environmental loads, such as, resource use and emissions connected to the functional units of each sub-system were calculated. The sub-system flow-charts include all life cycle activities (process units) for identified components and related mass and energy flows, as illustrated by an example in Figure 13.

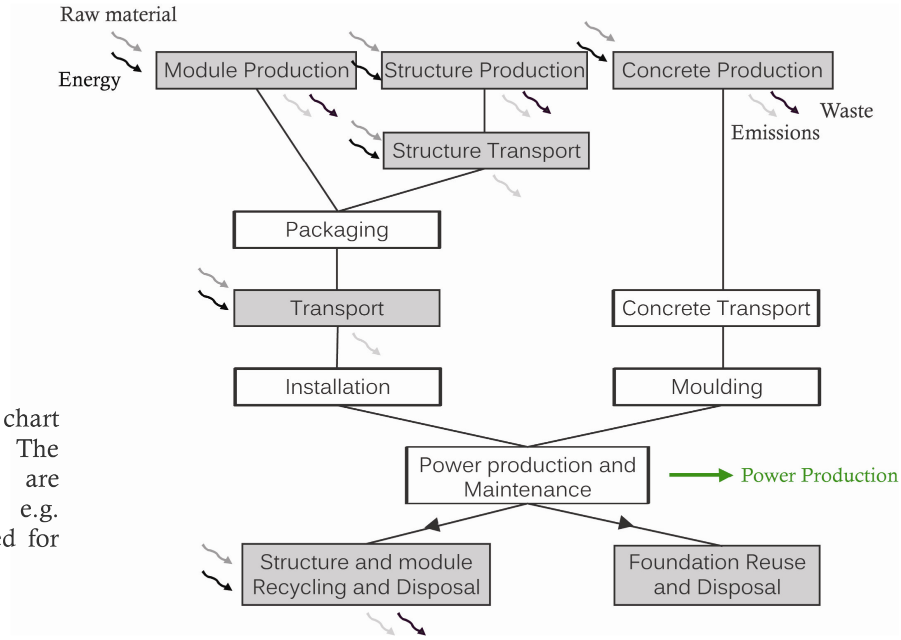

Figure 13. Example flow chart for the PV sub-system. The highlighted activities are included in the model, e.g. inventory data are collected for them.

Both descriptive data, to gain better understanding of the technological system to model, and numerical data for building the GaBi model were collected in an iterative process. The numerical data was collected based on a free translation of the methodology suggested by Bauman and Tillman (2004) where information is searched for each process unit, as illustrated in Figure 14. Initially data was searched from previously performed LCA reports without limitations. As important parameters were found they were searched actively in different reports and included in the inventory. Extended important data to include, such as, ancillary materials waste and minor components were searched throughout the data inventory.

The numerical and associated descriptive data was collected during the period of 7th of September 2009 to 1st of February 2010. Main inventory data for the manufacturing comes from reference LCA studies and supplier data sheets; transport, installation and usage data from internal Ericsson sources, and the end-of-life treatment data from extended literature studies, supplier information and internal Ericsson sources. Additional expert consultancy on battery types and usage and generator manufacturing were used.

Because mainly secondary and aggregated data were used, most allocation decisions were already taken. In accordance with Baumann and Tillman (2004) an allocation principle of partitioning was chosen when necessary. As an example, allocation on mass was applied for the transportation process units and for the aggregated data on silicon purification.

Validation of the inventory data was made through comparison with other sources according to Bauman and Tillman (2004).

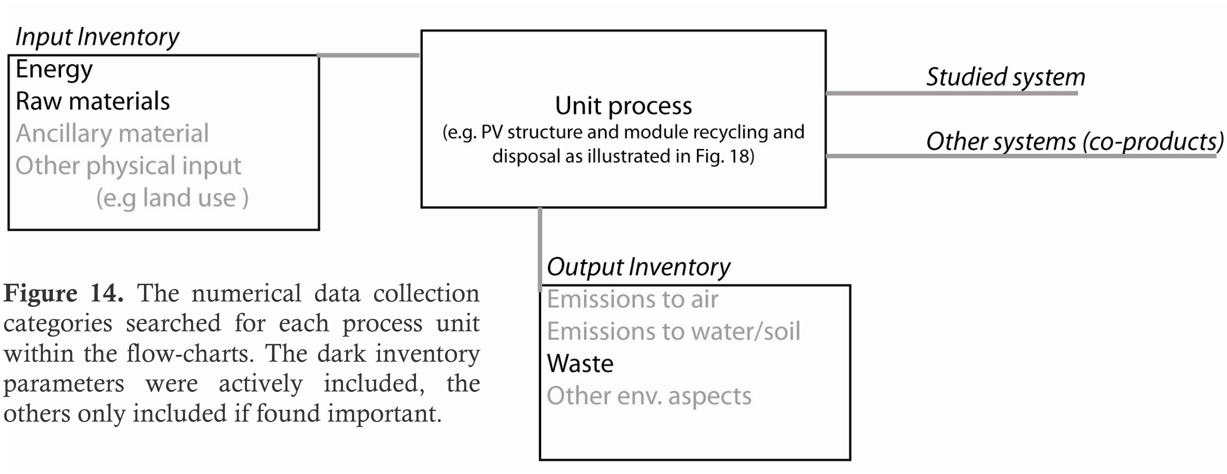

Figure 14. The numerical data collection categories searched for each process unit within the flow-charts. The dark inventory parameters were actively included, the others only included if found important.

6.2.7 Methods for impact assessment (LCIA)

Only the mandatory phases of the life cycle impact assessment, hence the impact category definition, classification and characterisation were included in this study. A ready-made characterisation model, created by the Institute of Environmental Sciences (CML) at the University of Leiden in the Netherlands, was used. The CML methodology is problem-oriented e.g. focuses on the midpoint of the cause-effect chain rather than on environmental damages e.g. end-points of the cause-effect chain (Guinée et al, 2004). The impact category selection was made from the CML 2001 database baseline categories (including depletion of abiotic resources, impact of land use, climate change, stratospheric ozone depletion, human toxicity, ecotoxicity, photo oxidant formation, acidification and eutrophication). Criteria for which impact categories to use include the prominence in the public discussion, characteristic as a global or big scale impact and the availability of comprehensive data. Toxicity was excluded both because it is a local phenomenon and because of uncertainties in the pre-defined impact categories for toxicity (CML 2001). According to the Montreal protocol the ozone layer has not grown thinner since 1998[8] hence ozone depletion can be considered to be under control. The photochemical ozone creation is considered a local impact and hence excluded. The chosen impacts were abiotic resource depletion, acidification, eutrophication and global warming. Impact categories mapping process electricity usage and primary energy consumption were added to the selected CML categories.

The classification or assigning of different inventory parameters (resource requirements, NO_X emissions, etc.) to the different impact categories was managed through the default CML classification (2001) in GaBi.

In the characterization step the different inventory parameters classified to one impact category are assigned a category indicator (equivalency factor) and added to a sum illustrating the total impact from that category (Baumann and Tillman, 2004). For instance, the carbon dioxide, methane and nitrous oxides are assigned a carbon dioxide equivalent each and summarized into a total global warming potential (kg CO_2 equivalent). Again, the equivalent factors were set by default in the software.

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[8] *http://www.epa.gov/Ozone/downloads/MP20_FactSheet.pdf*

Table 4 summarizes the selected impact categories, related inventory parameters and category indicators.

Table 4 Selected impact categories, related input inventory parameters and category indicators.

Impact Category	Type of impact	Reference measure	Inventory parameters
Baseline categories (CML)			
Abiotic Resource Depletion		kg Sb eq.	Resource consumption.
Acidification Potential	Regional impacts on lakes, forests and materials.	kg SO_2 eq.	*SO2;* sulfur dioxide from coal or oil combustion, smelters, processing of natural gas. *NOX ;* nitrogen oxides from transportation and other combustion. *NH3;* ammonia from animal manure and agricultural soils. *HCL;* combustion of fuels, refuse incineration, smelting of metal scrap, retardant treated materials.
Global Warming Potential	Affecting forest and agricultural productivity and effecting the climate cycles and occurance of extreme events.	kg CO_2 eq.	*CO2;* carbon dioxide from combustion of fossil fuel, trees and solid waste, destruction of forests and also as a result of other chemical reactions (e.g., manufacture of cement). *CH4;* methane from livestock, paddy fields, landfill sites, exraction, transportation and distribution of natural gas, extraction of oil and coal. *N2O;* nitrous oxides from agricultural soils, animal manure, sewage treatment, combustion of fossil fuel, acid productions. Fluorinated gases from different industrial processes and sometimes used as substitutes for ozone-depleting substances.
Eutrophication Potential	Local and regional impacts on terrestrial and aquatic ecosystems.	kg PO_4 eq.	*NOX;* nitrogen oxides from transportation and combustion of fossil fuel and solid waste and from agricultural and industrial activities. *NH3;* ammonia from animal manure and agricultural soils.
Additional categories			
Process Electricity use		MJ	Electricity with unspecified primary energy source.
Energy resource depletion		MJ	Primary energy requirement as net calorific value.

A data quality check was managed through two methods; comparison with other sources according to Bauman and Tillman (2004) and a sensitivity analysis (reported in section 9.4.1).

6.2.8 Software

The calculations were performed using the LCA modeling and evaluation software GaBi (PE & LBP, 2008). This software is built on a modular system of organizing processes and flows in planes as illustrated in Figure 15[9], to create a mimic of the real life cycle activities. The software allows analyzing input and output balances of the whole lifecycle, separate planes (e.g. the manufacturing phase) down to individual processes. In addition it incorporates a databank with pre-fabricated industrial processes and flows simplifying the modeling process.

[9] *PE & LBP, 2008. GaBi Manual, Introduction to GaBi 4. Software-System and Databases for Life cycle Engineering. PE International and the Chair of Building Physics, University of Stuttgart.*

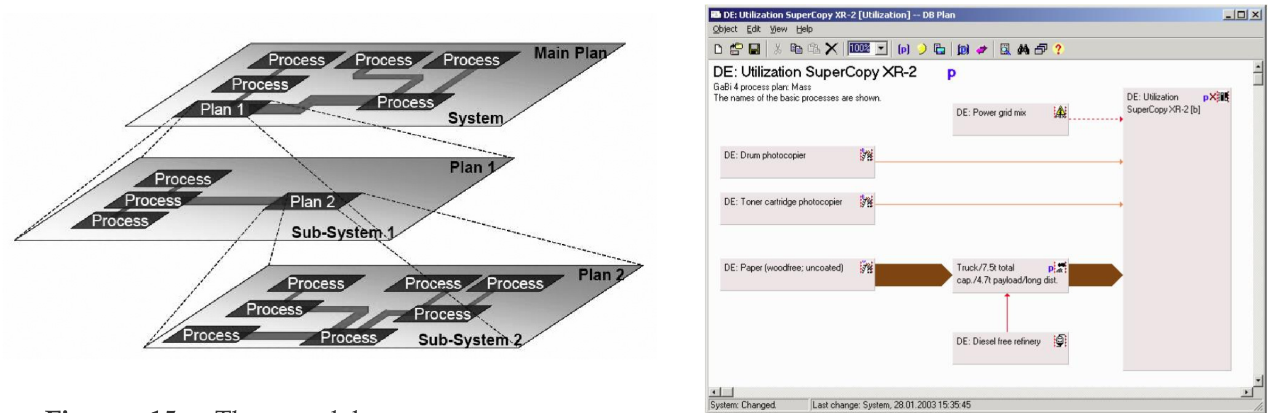

Figure 15. The modular structure of GaBi in theory and practice.

6.2.9 Interpretation case configurations

To analyze the LCIA results three different site configurations were assessed; a traditional diesel site, a PV/wind/diesel hybrid site and a fully driven PV site. The different site configurations were normalized against the corresponding traditional diesel site; resulting in a percentage for the environmental performance compared to the reference diesel system.

The traditional diesel power solution used as a reference comprises two diesel generators working alternately, using a battery back up of four (12 V) batteries and consuming 20000 liters of diesel per year.

The analyzed renewable diesel hybrid uses 21 square meters of PV panels, one wind turbine, 36 (12 V) batteries and one generator and consumes 1500 liters of diesel fuel per year. The analyzed PV site requires 51 square meters of PV modules and 58 (12 V) batteries.

Currently, Ericsson promotes a hybrid solution where one of the diesel generators has been substituted for an extended battery bank. This diesel battery hybrid was also evaluated, assumed to use 24 (12 V) battery cells and consumes 12000 liters of diesel fuel per year. Refueling is required every 20th day compared to every 10th day for a traditional diesel site (Ericsson internal, N. Gimple, 2009).

There must always be a diesel back-up at a wind powered site because of the fact that it is not possible to dimension the battery-bank for the high RBS-site security and possible weeks without wind. This is why no such case configuration was evaluated.

6.2.10 Study-wide assumptions, simplifications and limitations

This study focuses on off-grid solutions in the developing world, leaving sites connected to the electrical grid and sites in the developed markets outside of the assessment. It will not provide any general conclusion on which sub-system configuration is the ultimate one, but a model to assess pre-defined configurations.

The contribution to the environmental impact by individual processes within the life cycle phases will not be analyzed since aggregated data is used. Requirements for extracting and processing raw materials are included in the manufacturing stage and hence no conclusion on the importance of raw material manufacturing versus final component and product manufacturing requirements will be provided.

6.2.11 Critical review procedure

A continuous review process aiming to evaluate taken decisions was undertaken through midpoint meetings (Workshop, 7th Dec. 2009, Supervisor meeting, 25th Nov. 2009) and a review on the final report was conducted by Ericsson and KTH.

7 LCA Inventory (LCI)

The inventory is presented for the four different sub-systems; the PV, wind, battery back-up and diesel generator and fuel sub-system. Flow-charts for the sub-systems are provided in Appendix B. The inventory for the applied electricity mixes, transportation, recycling processes and common component inventory data are covered in section 7.5.

7.1 Diesel sub-system

The sub-model of the diesel generator was based on a previous LCA study of an off-grid hybrid wind diesel system powering a rural home (Fleck and Huot, 2009) and a diesel generator model (DA3-AJ18) from the supplier AJ power. The reference study only analyses energy requirements and carbon dioxide emissions and modifications were made concerning generator weight, addition of generator housing, production location and transportation specifications. The rectifier sub-model was based on a previous LCA provided by ABB (ABB Automation, external product declaration n.d., 2009).

A generator life cycle of 10 years is generally assumed in previous LCA studies while the generators at RBS-sites are expected to be replaced after 12 000 hours of running. Hence a generator is assumed to be replaced after 3 years at a traditional diesel site, after 7 years on a battery hybrid site and after 10 years if combined with PV generators or a wind turbine (workshop, 7th Dec. 2009). The rectifier has a life-time of 10 years independently of site configuration (Ericsson internal, N. Gimple, 2009).

AJ Power has their full production and assembly in Northern Ireland. The diesel fuel production was assumed to take place locally in the developing market. Material and energy requirements for the production of the diesel sub-system are given in Table 5.

A traditional diesel site consumes between 15000 and 22000 liters of fuel per year, while a battery hybrid site requires 50 percent of that and the fuel consumption at a renewable-hybrid site varies with the configuration and available renewable energy. In the model the fuel consumption was made variable. Emissions connected to the combustion were modeled using an average of pre-modeled GaBi processes for a diesel truck (Euro 4) combustion engine.

AJ Power does not have any recycling program (Calvert, P., email communication 4th Dec. 2009) but the included materials are assumed to be independently recycled because of the high market price on metals.

7.2 Battery sub-system

The lead-acid battery model was provided by a previous LCA study including the manufacturing and recycling of a two volt (2V) battery cell performed at Ericsson (Donovan, 2009). This model was in turn based on another Ericsson analysis of the manufacturing of a lead-acid battery from the supplier Oerlikon (Bergmark and Andrae, 2001) and an external study on the environmental issues connected to recycling of lead-acid batteries (Salmone et al., 2005). Modifications to this model were made through transportation specifications and adding a battery shelter solution and a foundation.

The batteries life-time varies with the different site configurations; assumed to be 5 years on renewable hybrid sites, 5 years on diesel battery hybrid sites and 3 years on traditional diesel sites (Ericsson internal, N. Gimple, 2009, Workshop, 7th Dec. 2009).

Material and energy requirements for the production of the battery system is given in Appendix C (available upon request from the project owner Ericsson Research EMF Safety and Sustainability) and more information could be found in the reference LCA study.

The processes for recycling of batteries are well developed, for further information on these processes and environmental concerns connected to battery recycling see Salmone et al. (2005). No take-back of batteries occur because of restrictive border legislations but there are lead smelting plants worldwide (Karlsson, personal communication 30th Nov 2009); hence the location of the end-of-life activities was set to the local market.

7.3 PV sub-system

The data collection was based on a previously performed study on a conventional poly-crystalline silicon photovoltaic system (Battisti and Corrado, 2003), a summarizing LCA review on poly-crystalline PV cells (Jungbluth, 2003) and PV modules from BP solar (BP Solar, 2007a). Modifications have been made to include a ground foundation and additional aluminum structure, a representative manufacturing power mix, transportation distance to installation site and processes for the end-of-life treatment.

The PV sub-system is considered to have a life-time of 20 years (Workshop, 7th Dec. 2009) mainly restricted by the UV-ray deterioration of the capsulation resin or failure of connections (Doi et al., 2001). BP Solar module manufacturing sites are located in China and India and are not dedicated to specific export areas. China was assumed as the manufacturing location.

A photovoltaic module consists of many electrically connected solar cells, placed between glass and tedlar sheets and usually framed by an aluminum frame. In the reference study five different module manufacturing processes are considered; silicon purification, casting, ingot cutting into wafers, cell manufacturing and module assembling. For more information on the manufacturing techniques, energy and resource requirements and environmental aspects see Battisti and Corrado (2005). A pre-made GaBi process for metallurgical silicon production was incorporated and the subsequent manufacturing steps were modeled and added. The production of the supporting structure is not located at the PV module production facility in China, but in France. The main materials and energy requirements used to produce the PV sub-system are given in Table 5.

According to BP Solar they use their distribution network to collect used solar panels. The aluminum frames are dismantled and recycled while the other materials are recycled if possible otherwise handled according to legal regulations (BP Solar, 2007b). In accordance with previous studies (García-Valverde et al., 2009), the modules are assumed to be land-filled after removing the aluminum frames. PV modules are normally considered to be safe for landfills because the photovoltaic material is generally enclosed in glass or plastic and mostly insoluble[10].

[10] *US Department of energy, http://www1.eere.energy.gov/solar/panel_disposal.html , 17th Nov 2009.*

7.4 Wind sub-system

The wind sub-model is based on two previous LCA studies (Fleck and Huot, 2009, Kemmoku, 2002). Modifications regarding the turbine weight and exclusion of tower or building mounting were made to the reference studies based on a reference turbine from the manufacturer Bergey rated at 7,5 kW (product specification Excel-R, n.d.a.[11]). A review made by Lenzen and Munksgaard (2002) was used as a verification reference. The rectifier sub-model is based on the same inventory as in the diesel sub-system, e.g. based on a previous LCA report provided by ABB (ABB Automation, n.d.).

A small-scale wind turbine consists of a rotor and rotor blades normally made in fiber reinforced plastic and nacelle incorporating the generator and possible gear. The Bergey wind turbine has a life-time of 30 years (Bergey, n.d.b) and the separate rectifier is assumed to have the same life-time for this sub-system.

The small-scale wind turbines from Bergey are produced in Beijing (Workshop, 7th Dec. 2009). The main energy and material requirements for the components of the wind sub-system manufacturing are given in Table 5.

In the end-of-life phase the plastics of the wind turbine are incinerated because of the technical problems with separation of different materials (Lenzen and Munksgaard, 2002). Included metals are assumed to be recycled according to the general recycling rates given in section 7.5.3.

[11] *n.d.a. and n.d.b represents two unknown documentation dates for documents from the same source.*

Table 5. Inventory data for the production of the sub-systems.

Diesel system manufacturing (functional unit of 10 kVA generator)	Value	Source
Weight of generator (kg)	500	Work shop, 7th dec. 2009
Process energy/generator (kWh)	50	Calvert, P., email communication 4th dec. 2009
Material (kg/generator incl. housing)		
Aluminum	180	Fleckand Huot, 2009
Copper	25	Fleckand Huot, 2010
Steel	300	Fleckand Huot, 2011
Plastic	50	Fleckand Huot, 2012
Converter (nr of 1 kWh units)	2	
Foundation		
Volume (m^3/generator)	0,40	Work shop, 7th december 2009
Weight (kg/generator)	1030	LCA of Building Frame Structures, 1996
Fuel		
Process energy/kg diesel (kWh)	1	Pre made Gabi process.
PV system (functional unit of 1 sqm PV)	**Value**	**Source**
Module	13	Battisti and Corrado, 2005
Weight of general modul (kg/sqm PV)		
Process energy/module (kWh)	990	Battisti and Corrado, 2005
Material (kg/module)		
Silicone	3,0	Kemmoku et al., 2002; Battisti and Corrado, 2005; Jungbluth et al, 2004
Copper	0,35	Kemmoku et al., 2002
Insulating material	1,7	Kemmoku et al., 2002
Glass	8,6	Kemmoku et al., 2002
Aluminum	1,3	Battisti and Corrado, 2005
Polyethylene	0,00012	Jungbluth et al, 2004
Hydrochloric acid	0,27	Jungbluth et al, 2004
Structure		
Process energy (kWh/kg Al structure)	10,3	Kannan et al., 2006
Process energy (kWh/sqm PV)	240	Kannan et al., 2006
Material		
Aluminum (kg/kg PV module)	1,8	Kannan et al., 2006
Aluminum (kg/sqm PV)	23	Kannan et al., 2006
Foundation		
Volume (m^3/sqm PV)	0,080	Work shop, 7th december 2009
Weight (kg/sqm PV)	210	LCA of Building Frame Structures, 1996
Wind system (functional unit of one 7,5 kWh turbine)	**Value**	**Main source**
Total weight of turbine (kg)	600	BWC EXCEL Shipping doc, 2007 and Installation manual, 2007
Process energy/turbine (kWh)	3400	Fleck and Huot, 2009; Kemmoku et al., 2002
Material/turbine		Ancona and McVeight, n.d., Fleck and Huot, 2009; Kemmoku et al., 2002
Rotor (25 % of turbine weight)		
Blade (50 % of rotor weight)		
epoxy (kg/kg blade)	0,41	-
glass fibre (kg/kg blade)	0,64	-
steel sheet (kg/kg blade)	0,050	-
Nose cone (29 % of rotor weight)		
glass fibre (kg/kg nose cone)	0,60	-
polyester (kg/kg nose cone)	0,40	-
Hub (21 % of rotor weight)		
Aluminum (kg/kg hub)	0,050	-
steel sheet (kg/kg hub)	1,0	-
Nascelle (75 % of turbine weight)		-
Generator (33 % of nascelle weight)		
Copper (kg/kg generator)	0,35	-
Steel (kg/kg generator)	0,65	-
Gear (33 % of nascelle weight)		
Steel (kg/kg gear)	1,0	-
Frame and machinery (33 % of nascelle weight)		
Aluminum (kg/kg frame and machinery)	0,38	-
Copper (kg/kg frame and machinery)	0,10	-
glass fibre (kg/kg frame and machinery)	0,040	-
Steel (kg/kg frame and machinery)	0,48	-
Converter (nr of 1 kWh units)	2,0	

7.5 Common inventory

The common inventory for activities shared by all or some of the sub-systems includes electricity production, transportation, recycling and production of concrete and rectifiers.

7.5.1 Electricity

A Chinese electricity mix was used for the production of most of the different system components except for the generator using a British electricity mix, the PV system structure being produced in France and the locally-produced diesel fuel and foundation using an African electricity mix. A world average energy mix was used for the converter manufacturing, since the location of production was not traced. All energy mix compositions are documented in Table 1 in Appendix D.

7.5.2 Transportation

Many of the unit processes studied in the different systems include transportation of materials and components from manufacturing to installation site. A general assumption is that sea freight accounts for 90 percent and freight trucks or pick-up trucks for 10 percent of the transportation. Distances for transportation of the sub-systems were estimated with Google Maps[12] and are given in Table 2 in Appendix D. The transportation from the site to the recycling plant is not included because of data uncertainties, the components often being handled by a second part before being recycled. For the diesel fuel, only the local transportation was considered, assuming a distance of 250 km.

The local truck transportation was modeled as truck (Euro 2) with an capacity of up to 7,5 ton and 3,3 ton payload (traveling on country side roads 80 percent of the time and in the city 20 percent of the time). The sea freight was modeled with a tanker carrying 10000 to 300000 ton.

7.5.3 Recycling

Locations for recycling plants vary for different metals, hence a world average electricity mix was considered for all end-of-life treatment including recycling. Global average recycling rates or rates for the developing world were used according to Table 6. The amount of material recovered from the recycling depends on the efficiency of the processes, for example, the efficiency of the lead recovery from the battery recycling is approximately 40 percent (Salmone et al., 2005).

Table 6. Recycling rates applied for the end-of-life treatment of all sub-systems.[13]

Recycling rates	Percent	Source
Steel	80	Wendin, personal communication 14 Dec. 2009
Reinforcement steel	0	Work shop, 7th Dec. 2009
Aluminum	60	EAA official homepage, 21st Feb. 2010
Copper	50	World copper factbook, 21st Feb. 2010
Plastics	0	Assumption
Lead	100	From previsus study

[12] *Online service found at http://maps.google.com/*

[13] *EAA official homepage; http://www.eaa.net/en/about-aluminium/production-process/recycled-aluminium/ and Copper world Factbook; http://www.icsg.org/.*

7.5.4 Concrete foundation

All the different systems (solar panels, wind turbine, batteries and the generator) require site foundations, generally being a concrete foundation. In this study ready-mixed concrete molded on site is assumed. Foundation production inventory data is given in Table 3 in Appendix D, the size of the foundation varied for each sub-system. An LCA of building frame materials (LCA of Building Frame Structures, 1996) was used as a data source.

The emissions from the on-site excavation, construction and casting of the foundation are considered to be negligible. In the end-of-life phase the concrete is assumed to be crushed and reused as filler in other constructions (LCA of Building Frame Structures, 1996). The transportation and churching process required is allocated to the construction using the reused concrete as valued material.

7.5.5 Rectifier

The manufacturing requirements for the rectifiers used within the diesel and wind sub-system are provided in Table 4 in Appendix D.

8 LCA Impact assessment (LCIA)

In the life cycle impact assessment (LCIA) the impacts on the environment from the resource consumption and emissions mapped in the inventory analysis are described (Baumann and Tillman, 2004). As described in the LCIA methodology this assessment is based on the CML problem-oriented approach and CML defined impact categories, category indicators and characterisation model.

8.1 General allocation procedure

One problem in classification is if the LCI parameters are assigned to more than one impact category causing double-counting (Baumann and Tillman, 2004); e.g. nitrogen oxides cause both acidification, eutrophication and photo-oxidant formation and sulphur dioxide cause human health effects and acidification. If the impacts are caused in series independent of each other this multiple assignment is correct but if they are parallel processes the parameters should be allocated to each impact category. In this study no allocation between impact categories was considered because of the serial character or minor allocation problematic between the impact categories analyzed.

8.2 Definition of impact categories

In this section a short description of the chosen impact categories is presented. Selection criteria for these impact categories can be found in the goal and scope definition, in section 6.2.7.

8.2.1 Abiotic resource depletion

Abiotic resource depletion potential (ADP) is a measure of the use of non-living natural resources e.g. crude oil, minerals, etc. The extraction rate and remaining reserves are considered and compared to the reference of Antimony metal depletion creating a reference unit of kilograms Antimony equivalent (kg Sb eq.) (Guinée et al., 2004).

8.2.2 Global warming

Climate change is according to Guinée et al. (2004) defined as the impact on the atmospheres heat radiation absorption, having secondary impacts on the ecosystem and human health. Most of the emissions considered enhance the absorption of radiation causing a rise in the earth's surface temperature, referred to as the "greenhouse effect" and are called by the common name greenhouse gases (GHGs). The characterisation model is defined by the Intergovernmental Panel on Climate Change (IPCC) and describes the global warming potential over 100 years. Any emission of a GHG to the air is measured by the carbon dioxide equivalency factor (kg CO_2 eq.).

8.2.3 Acidification

Acidification arises from emissions of acidifying pollutants, mainly being sulphur dioxide (SO_2), nitrogen oxides (NO_X) and ammonia (NH_4). When the pollutants reach the atmosphere they react with water causing "acid rain" that affects living organisms, ecosystems and construction materials. Visible secondary effects include fish mortality, forest decline and crumbling of building materials. The acidification potential for every acidifying emission to the air is given the reference unit of kilogram sulphur dioxide equivalent (kg SO_2 eq.). The characterization model is based on the RAINS10 model for the deposition of acidifying substances developed at the International Institute for Applied Systems Analysis (IIASA).

8.2.4 Eutrophication

The eutrophication potential incorporates all discharge of nutrients, the most important being nitrogen (N) and phosphorus (P), which cause an undesirable shift in the ecosystem. Apparent effects are unacceptable nutrition concentrations in drinking waters or decreased oxygen levels in aquatic systems due to increased biomass production and decomposition. The eutrophication potential for all related emissions to air, water and soil is measured by a phosphate equivalent (kg PO_4 eq.) (Donovan, 2009).

8.2.5 Primary energy and electricity requirements

The primary energy consumption (MJ), measured in net calorific value, were used as the primary comparative indicator for the energy requirements. Since the manufacturing phase includes much up-stream data for raw material extraction and processing, the modeled manufacturing electricity demand (MJ) is not complete. Therefore the electricity demand was mainly used to detect electricity intensive activities and possible relation to other impact categories.

8.3 Classification and characterization

In the classification process the inventory data was coupled to the different impact categories and in the characterization calculations the indicators were weighted and summarized to a reference indicator representing the full scale of each impact category (Guinée et al, 2004, ISO 14040:2006). In this assessment these processes were defined by the CML methodology and indicators aggregated in the pre-defined CML 2001 characterization database.

8.4 Normalization

The resulting impacts for each configuration were normalized against the impacts caused by corresponding traditional diesel site for the different categories to provide comparative results, related to the present state.

9 LCA modeling and calculation procedure

To create a GaBi model imitating the reality of a hybrid system four different sub-models were created and coupled in a hybrid configuration; one sub-model resembling the life cycle of the PV sub-system, one of the wind sub-system, one of the battery sub-system and one of the diesel sub-system. The four sub-systems were given different functional units that could be scaled in the main hybrid model according to Figure 16.

The PV sub-system was calculated per square meter PV module, the wind system per wind turbine, the batteries per 7 kilograms or 2 V cell and the diesel system per number of diesel generators and liters of diesel consumed. The demands of the different functional units were calculated for 30 years representing the longest life-time of the sub-systems, being the life-time of the wind sub-system.

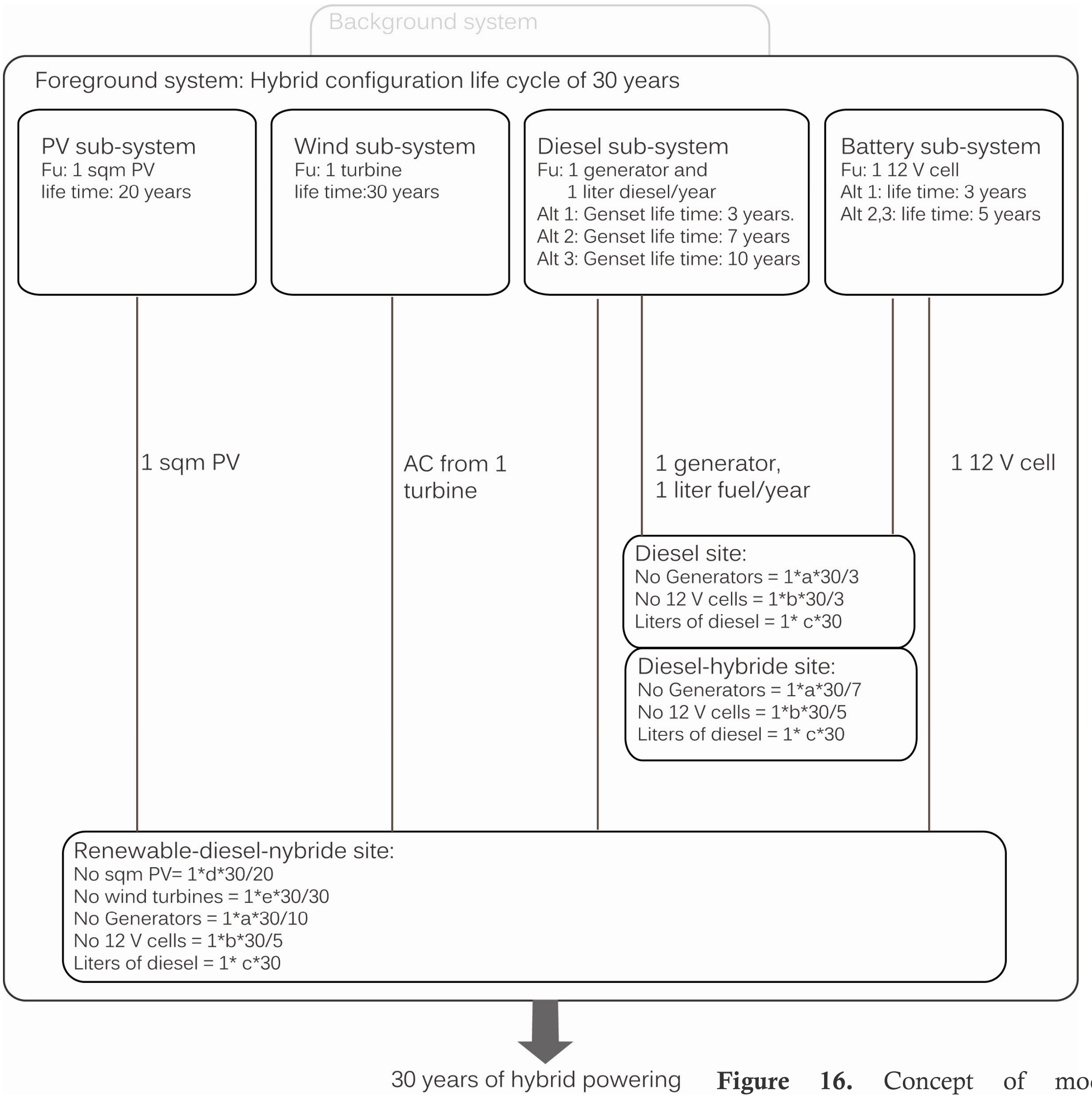

Figure 16. Concept of modeling including the scaling factors for the different sub-models. The different factors are defined accordingly: a = no of generators at the site, b = no of 12 V cells required and c = fuel consumption per year.

Figure 17 shows the resulting structure of the GaBi model including the sub-models. The modular structure makes it possible to analyze the whole model, by sub-model or individual processes.

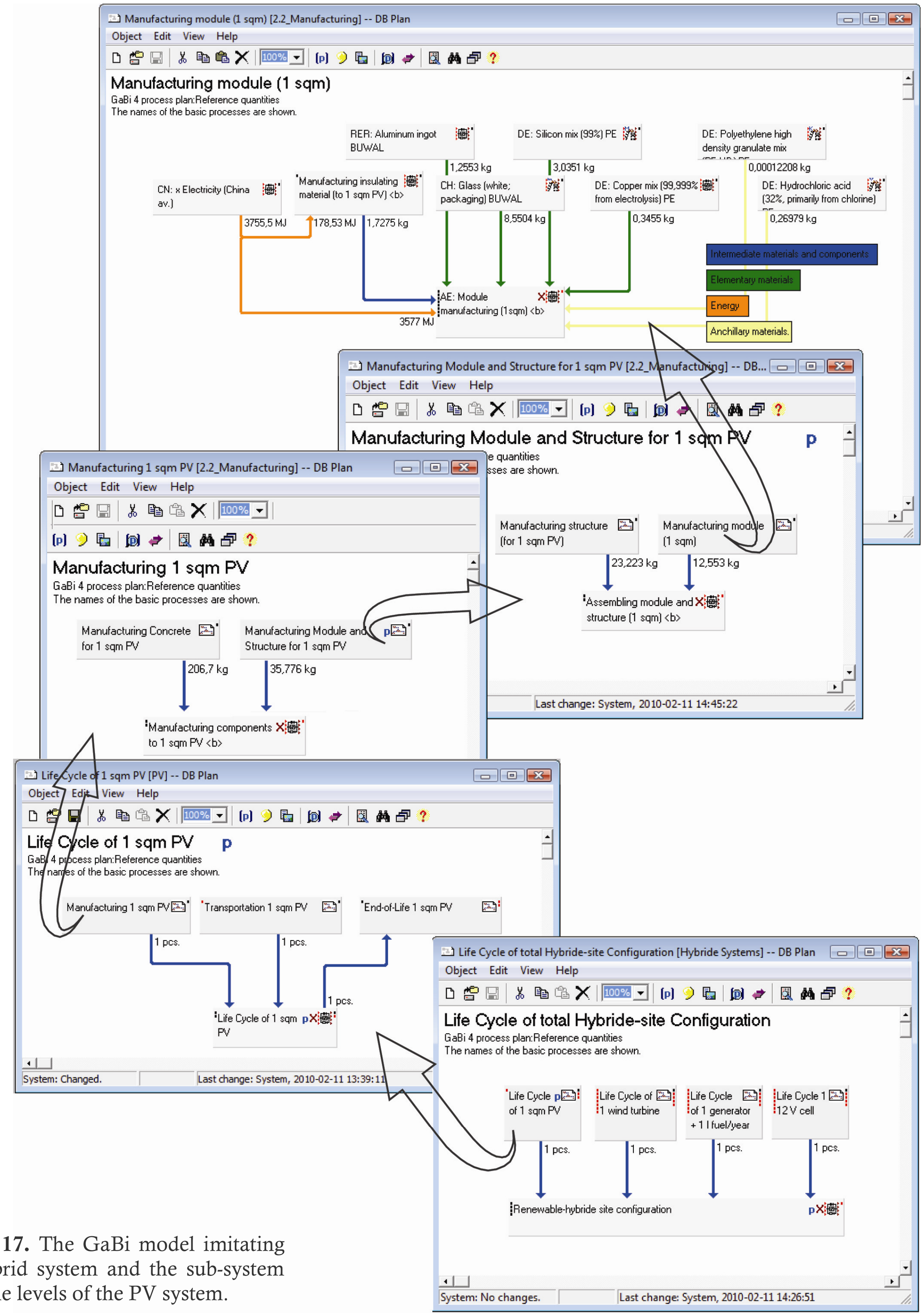

Figure 17. The GaBi model imitating the hybrid system and the sub-system life cycle levels of the PV system.

10 LCA Impact assessment results

For the comparative evaluation three typical case configurations (designed through advisory by Ericsson employee 3, 22 Jan 2010) were analyzed by looking at the different impact categories; one traditional diesel site, one hybrid configuration using PV modules, a wind turbine, diesel fuel back-up and battery storage and one hundred percent driven PV site. The case configurations are described in section 6.2.9. A more detailed analysis of essential components and life cycle phases for each sub-system are provided in Appendix E. The specific numeric values for the impact categories are not evaluated since the aim is a comparative evaluation. Numeric values can be found in Appendix F.

10.1 Traditional diesel site

The diesel fuel cycle corresponds to over 95 percent of the resource usage and impact-related emissions of the configuration. The number of generators required throughout the life-time of the system (the two generators are replaced ten times in 30 years summing up to 20 generators) present a notable contribution to the different impact categories through the generator manufacturing. The batteries could be considered negligible because of the low capacity required, representing below 1 percent for all impact categories and life cycle phases. The fuel transportation corresponds to around 4 percent of the impact categories.

Within the traditional diesel site, the diesel fuel production contributes to 98 and 91 percent of the electricity and the primary energy demand, respectively and it uses over 90 percent of the abiotic resources. Manufacturing of generators and transportation of fuel correspond to between 3 and 5 percent of the energy demand and resource depletion.

About 95 percent of the global warming potential originates from the diesel fuel life cycle, the combustion phase representing 74 percent, the diesel manufacturing 18 percent and the transportation 3 percent. Manufacturing of the generator has a notable contribution to the global warming potential with 3 percent. The battery bank life cycle has a negligible environmental impact.

The diesel fuel life cycle represents around 96 percent of the acidification and eutrophication potential; the main activity being the combustion (73 and 82 percent respectively), followed by diesel manufacturing (18 and 10 percent respectively) and transportation represented by the local diesel truck transportation (5 percent for both impact categories). The manufacturing of the generators has a similar acidification potential as transportation of diesel.

10.2 Diesel battery hybrid site

In the diesel battery hybrid life cycle the fuel still corresponds to the main environmental impacts however now the batteries correspond to more impact than the engine; 5 percent of the acidification potential (engine 1 percent), 3 percent of the resource depletion (engine 1 percent), 2 percent of the eutrophication (engine 1 percent); 2,5 percent of the global warming (engine 1,4 percent) and 2,8 percent of the net calorific energy usage (engine 1,5 percent).

When normalized the diesel battery hybrid site has impacts of about 60 percent of a traditional diesel site considering the different impact categories analyzed (Figure 18).

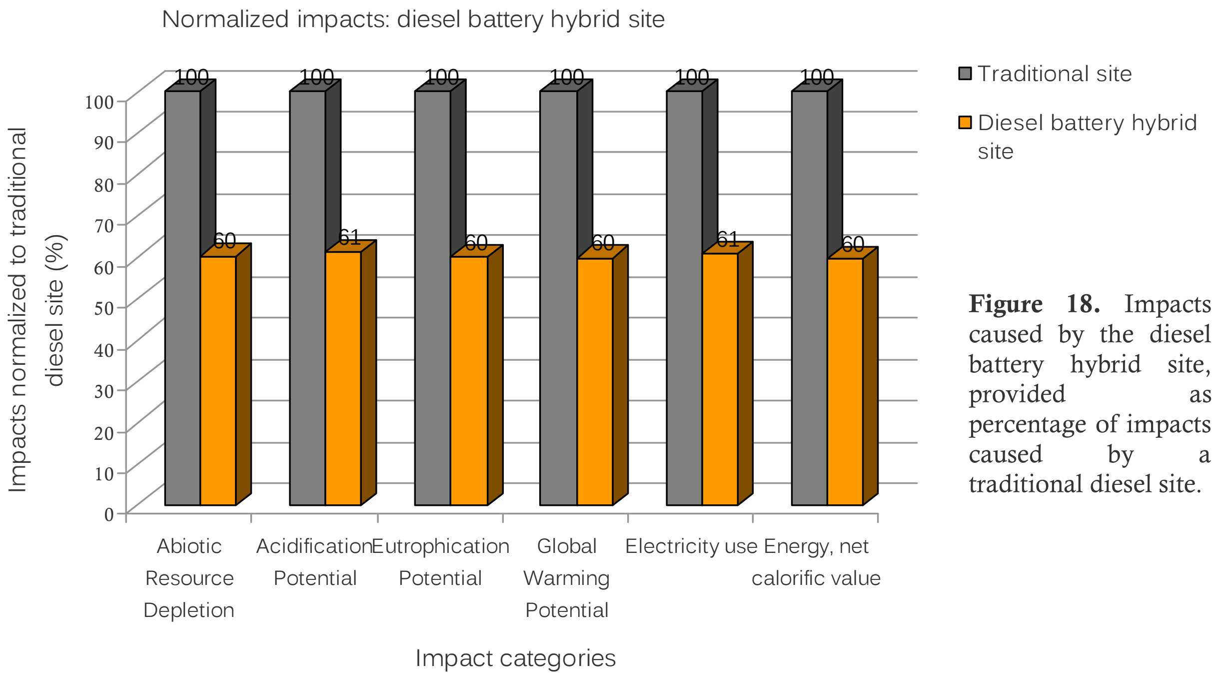

Figure 18. Impacts caused by the diesel battery hybrid site, provided as percentage of impacts caused by a traditional diesel site.

10.3 Diesel renewable hybrid site

The renewable hybrid configuration is connected to environmental impacts of between 11 and 16 percent compared to a traditional diesel site, as illustrated in Figure 19. If compared to a diesel battery hybrid site the corresponding impact is around 19 to 27 percent. Figure 20 and 21 describes the life cycle phases and the sub-systems relative contribution to the total site configuration impacts. As can be seen, the diesel fuel dominates the resource consumption and emissions also for this site configuration.

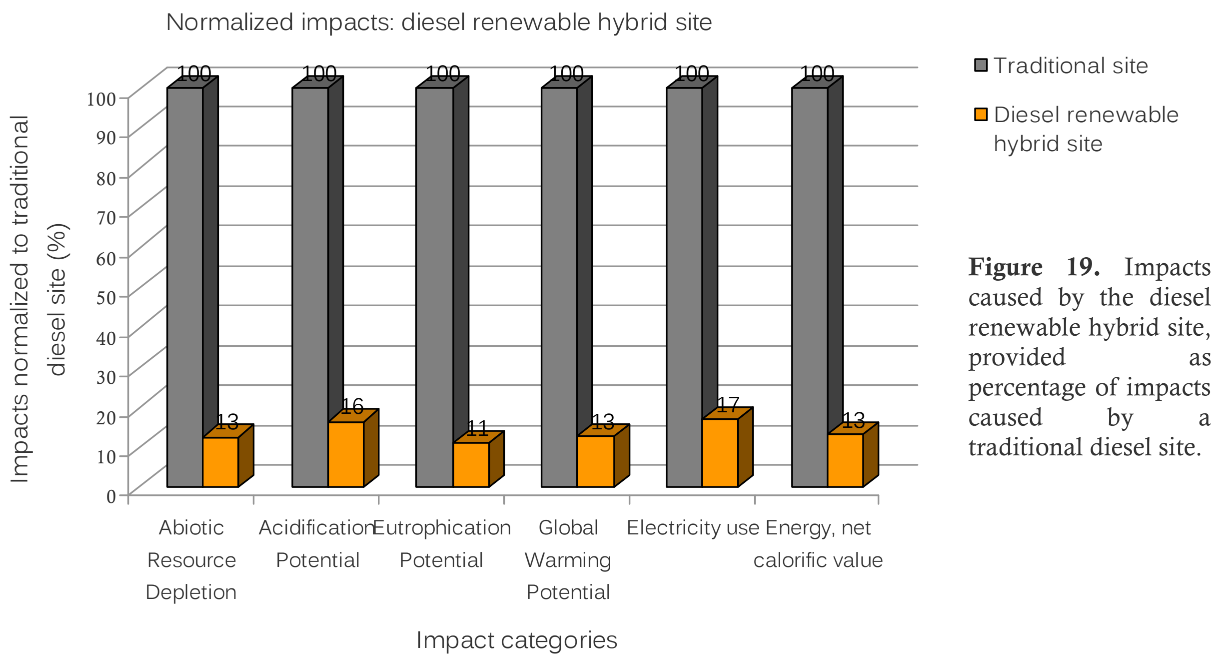

Figure 19. Impacts caused by the diesel renewable hybrid site, provided as percentage of impacts caused by a traditional diesel site.

The main primary energy usage phase is the manufacturing. Fuel production consumes 52 percent of the life cycle primary energy, while the other sub-system components consume 42 percent together. Of this the PV sub-system manufacturing stands for 19 percent (corresponding to the manufacturing electricity requirement representing 37 percent of the total hybrid configuration electricity usage) and the battery sub-system for 19 percent (of which 16 is used for manufacturing, 2 for transportation and 1 percent in the recycling process). Transportation of the battery and fuel uses 8 percent of the primary energy together.

The diesel renewable hybrid site configuration uses 13 percent of the abiotic resources compared to the traditional diesel site; the diesel generator and fuel consuming 61 percent, followed by the batteries using 22 percent, the PV system using 14 percent and the wind turbine using 2 percent.

The renewable diesel hybrid site causes 13 percent of the GHG emissions compared to the traditional diesel site. 62 percent of this global warming potential origins from the diesel sub-system life cycle. The PV life cycle represented by the manufacturing phase causes 18 percent, the battery manufacturing and transportation cause 17 percent together and the wind system manufacturing 3 percent of the global warming potential.

The acidification potential has decreased with 84 percent compared to the traditional diesel system because of the decreased usage of diesel. In the sub-systems of the renewable diesel hybrid the fuel and generator cause 47 percent of the acidification potential, the battery sub-system 28 percent, PV sub-system 22 percent and wind sub-system 2 percent. Critical activities are the combustion, PV and battery system manufacturing and the diesel fuel production.

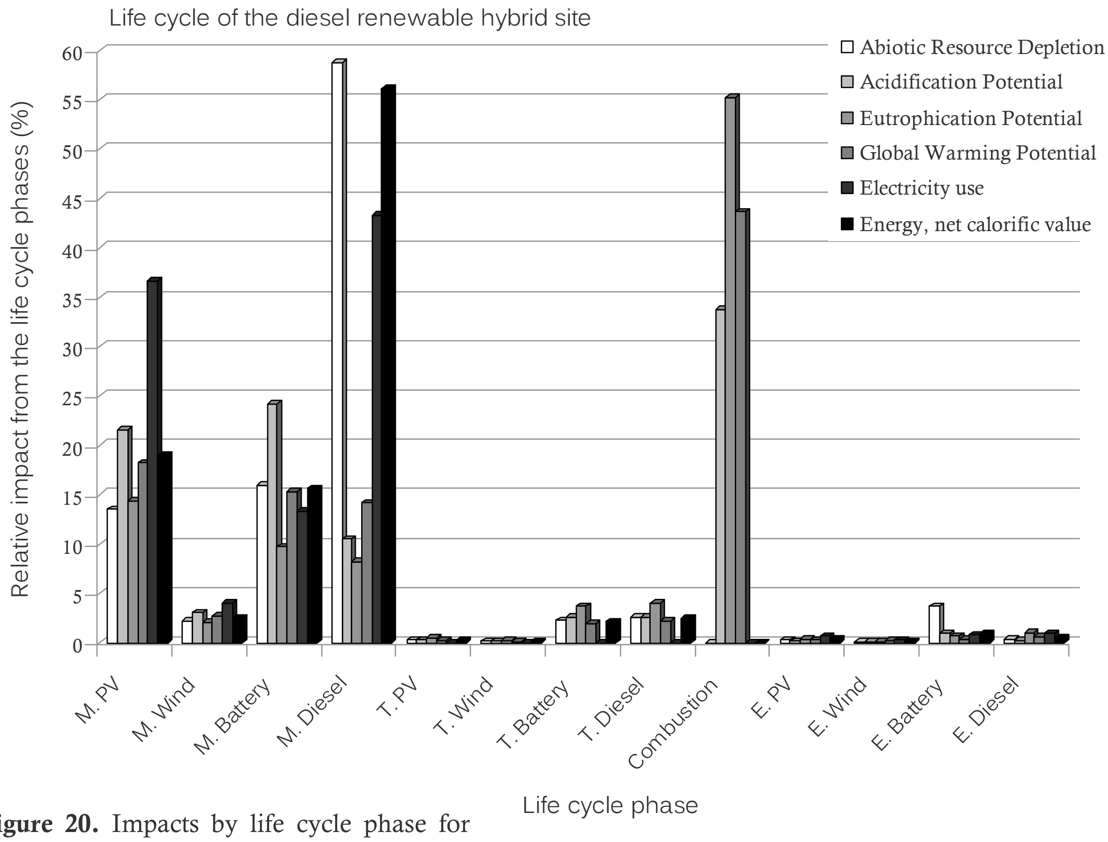

Figure 20. Impacts by life cycle phase for the diesel renewable hybrid site. M. = manufacturing phase, T. = transportation phase, and E. = end-of-life phase.

The renewable diesel hybrid causes 11 percent of the eutrophication potential compared to the traditional diesel site. Important activities include the combustion (55 percent), PV sub-system manufacturing (14 percent), battery sub-system manufacturing (10 percent) and fuel production (7 percent). Transporting the batteries and fuel; and manufacturing the generators and wind turbine provide emissions below 5 percent.

On the hybrid site the battery and PV sub-systems have similar impacts but the battery system use more abiotic resources and has a higher acidification potential. The electricity mix and up-stream lead processing dominates both the resource requirements and emissions of the battery sub-system. The silicon processing followed by the aluminum requirements for the structure dominates the PV sub-system impacts. Transportation and end-of-life treatment have a higher contribution in the battery life cycle than in the PV sub-system life cycle. In the PV sub-system, transportation contributes to below 3 percent and the end-of-life stage with between 1 to 2 percent while, the transportation of batteries corresponds to as much as 26 percent for some impacts and the end-of-life recycling up to 17 percent of the batteries life cycle.

The generators seem to have a higher influence than expected on RBS-sites because of the short life-time. Still the influence is minor (up to 4 percent on traditional or diesel battery hybrid sites) except for sites with low diesel consumption. Resource sinks within the generator manufacturing are the aluminum processing and generator facility energy requirements.

Also the transport has a higher influence than expected, the diesel fuel transportation distance being of high influence and requiring further investigation.

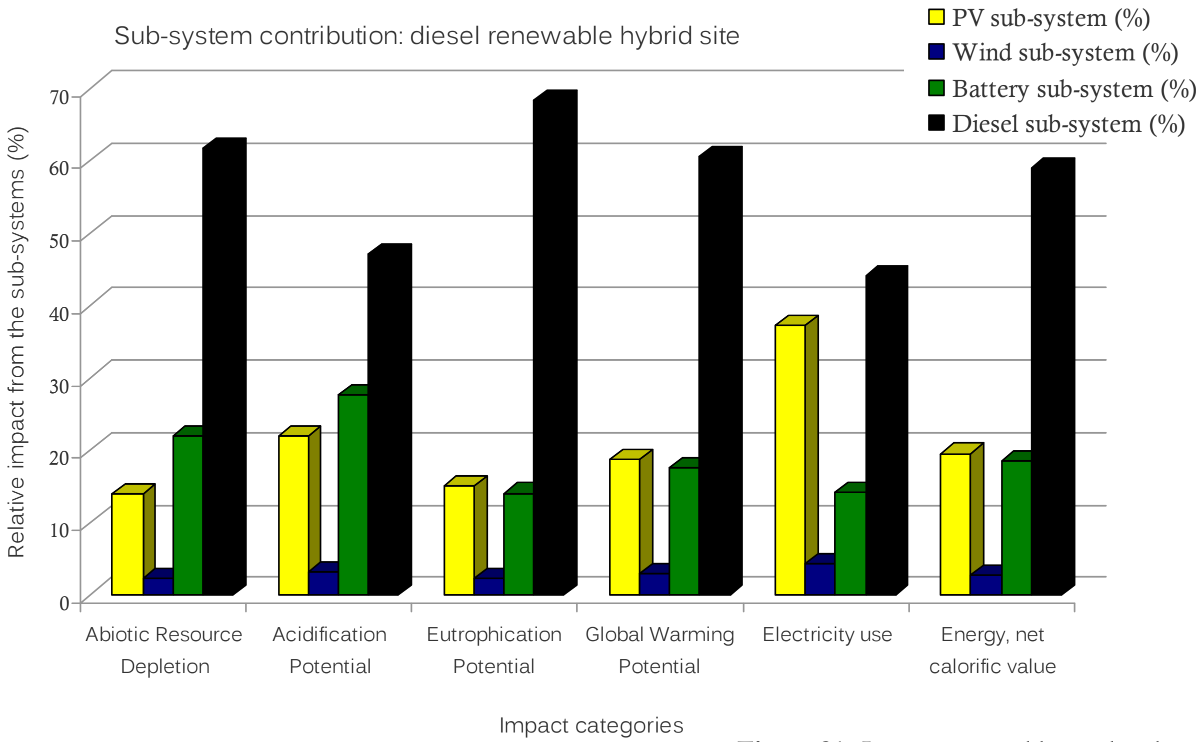

Figure 21. Impacts caused by each sub-system within the diesel renewable hybrid, presented as percentage of total impact caused by the diesel renewable hybrid site.

The environmental impacts connected to the wind tower are normally dominant in environmental assessments of wind power. This assessment only includes the turbine, making the impact of the wind sub-system comparable to that of the diesel generator and therefore of minor influence. The wind turbine impacts mainly depend on the aluminum and glass-fiber requirements.

Generally it can be concluded that the concrete foundations, converters in the wind and generator sub-systems and shelters for the battery sub-system give a minor contribution to the different impacts analyzed (in the scale of up to 5 percent).

10.4 PV site

The PV site uses around 10 percent of the resources used by the traditional diesel site and causes between 7 and 16 percent of the evaluated emissions. The PV site consumes much electricity, corresponding to almost 20 percent of the electricity consumption of the traditional diesel site. For this configuration the PV sub-system has higher requirements and environmental effects than the battery sub-system when it comes to all the impact categories except the abiotic resource depletion (Figure 22).

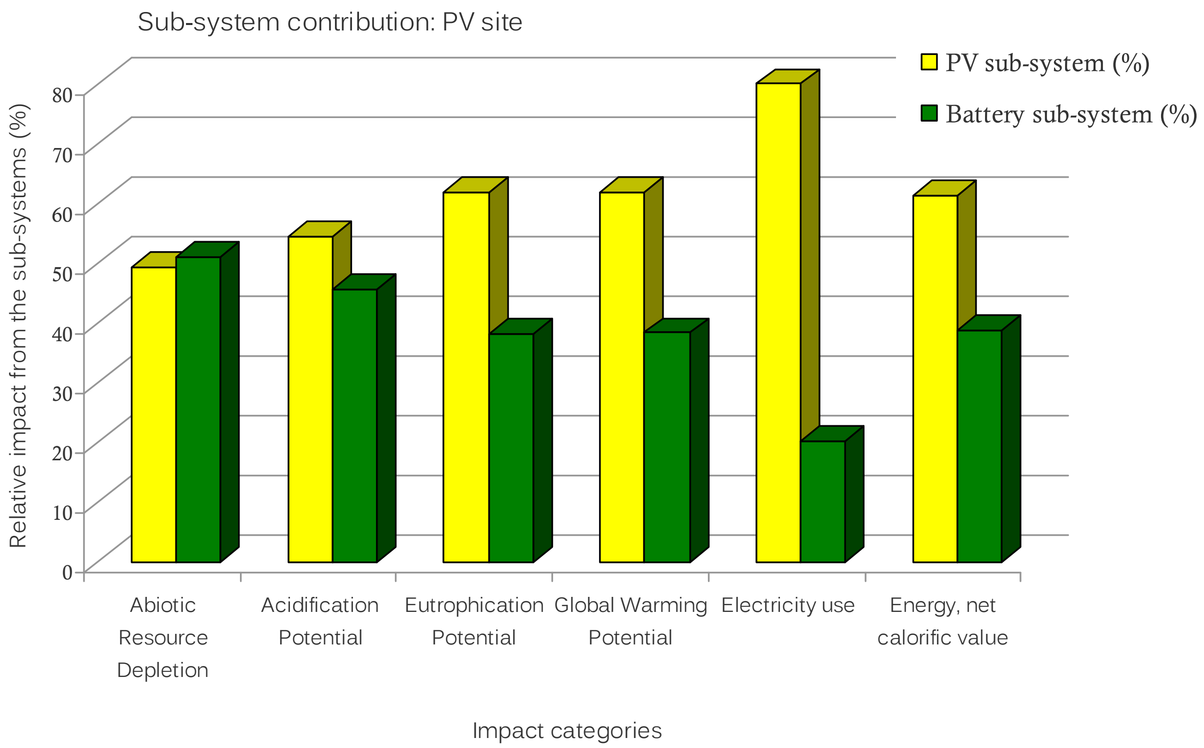

Figure 22. Impacts caused by the PV and battery sub-systems within the PV site, presented as percentage of total impact caused by the PV **site.**

11 LCA Interpretation

This section includes discussions on the LCA process, methodological choices and results but also a robustness analysis of the model and summary and interpretation of the results.

11.1 LCA complications

Performing a general LCA on a product or service group without any specific case (as with the performed analysis) results in many uncertainties. For example impacts are depending on and vary greatly with geographical location (Gagnon et al, 2002). García-Valverde (2009) and Pehnt (2005) state that especially when it comes to environmental analysis of renewable energies, no general conclusion can be drawn and the LCA can only provide information on typical systems.

Uncertainties in the electricity production remain even though the location is specified; corresponding to the question "Where does the electricity actually come from?". A line of action in this assessment was to map the electricity use as one impact category, hence making it easier to compare the different systems separated from their background electricity mix.

11.2 Methodological choices

Many LCA studies comparing renewable power systems use a functional unit of capacity e.g. provided kWh. The different systems will fulfill the capacity with different security, where a minimum that all alternatives must fulfill is normally set. This results in over-dimensioned systems and higher environmental impacts. In this analysis a functional unit of mass or number of sub-system facility is used. Hereby, the problem with the differences in power security is avoided.

The most correct methodology for this high level, general assessment would be to use average data from different previous assessments to receive a more comprehensive evaluation. Time limited the data collection to a few data sources. The fact that decisions on which extended inventory to include and detailed allocations are already taken within the second hand data collected is another source of model uncertainty.

11.3 Inventory

Generally the problem with using second-hand data should be stated. For instance there are important environmental impacts, like process NO_X emissions from wafer etching (Jungbluth et al., 2004), which are not reported in any of the previous inventory reports, and hence not included in the inventory of this assessment. Neither, are possible environmental impacts from specific materials placed in landfill investigated, but a common process for commercial waste is utilized. In addition some PV modules can be categorized as hazardous waste[14] which was not considered in this assessment.

The local transportation is probably underestimated since military escorts are required for most deliveries (Workshop, 7th Dec. 2009).

[14] *US Department of energy, http://www1.eere.energy.gov/solar/panel_disposal.html , 17th Nov. 2009.*

The diesel generator, PV sub-system and battery system are all probably overestimated concerning the concrete foundation; a new foundation is assumed every time the generator, module or battery bank is exchanged. This should be negligible considering the final normalized ratios. As an example the foundation only represents up to 9 percent of the impact potentials of the generator sub-system representing below 4 percent of the diesel sub-system. Similarly, the rectifier was assigned a life-time of 30 years in the wind sub-system, considered an underestimation.

For the wind turbine manufacturing process the aggregated data on production energy included the energy for raw material extraction, this was accounted for by applying other study results to the ratio between raw material extraction and production facility energy requirements.

The energy requirements for production of the different sub-systems vary significantly between different LCA studies. Generally, the uncertainties are greatest for PV modules and least for wind and diesel combustion system (Gagnon et al, 2002).

11.4 Sensitivity and uncertainty analysis

The data quality analysis aims at investigating how data and model uncertainties affect the result, thus it maps the robustness and accuracy of the result. A sensitivity analysis was performed where different scenarios were constructed by varying important process parameters and the impacts on the results were mapped.

The analysis was based on the base case of 21 square meter PV module, one wind turbine, 36 12 V batteries, one generator and a diesel consumption of 1500 liter per year (evaluated in section 10.3). For each scenario one parameter within the base case was varied independently according to Salmone et al. (2005), keeping all other parameters constant to map the deviation from the base case. An overview of the different scenarios is given in Table 7. Assumptions and motivations are given in more detail in Appendix G.

The sensitivity variations are given as deviation from the base case, providing an uncertainty range of the comparative ratios. For scenario 2, 3, 4, 6.1, 7, 8.1, and 9.1 the model can be considered robust, the normalized ratio varying with below 1 percent in most cases. Exceptions include scenario 4 decreasing the normalized ratio for acidification with 2 percent and scenario 6.1 raising the normalized ratio for acidification with 3 percent and the potential for eutrophication, global warming and primary energy consumption with 2 percent. The contribution from the different sub-systems does not change for most of these scenarios. Considering a maximized usage of recycled material in the manufacturing phase, maximized electricity requirement for Silicon processing or maximized electricity requirement for the battery manufacturing are exceptions that shift the main sub-system contribution. The variations connected to an increased usage of recycled materials in manufacturing mainly depend on the decreased lead usage. Also when increasing the end-of-life recycling (according to Scenario 3) the PV sub-system contribution increases significantly because of the added Silicon recycling, however the total effect on the resulting ratio is below 0,5 percent.

Table 7. Sensitivity and uncertainty scenarios.

Scenario 1: The manufacturing and end-of-life electricity mix is exchanged for electricity from hydro power.
Scenario 2: The manufacturing and end-of-life electricity production is exchanged for a Chinese electricity mix.
Scenario 3: Raising the end-of-life recycling rates of metals to 100 percent.
Scenario 4: Raising the usage of recycled material in the manufacturing phase, from zero up to between 35 and 90 percent for the different materials.
Scenario 5: Lowering the system life-time to 10 years without allocation of the reuse/continued use of the system or system components.
Scenario 6.1 Maximising the energy requirements within the Silicone refining process (7200 MJ/sqm), according to Alsema (2000), considering poly-crystalline cells.
Scenario 6.2: Maximising the energy requirements within the Silicone refining process, considering mono-crystalline cells.
Scenario 7: Minimising the energy requirements within the Silicone refining process (2400 MJ/sqm), according to Alsema (2000).
Scenario 8.1: Doubling the energy requirements for the wind turbine manufacturing processes.
Scenario 8.2: Multiplying the energy requirements in the wind turbine manufacturing with a factor ten.
Scenario 9.1: Raising the electricity requirements for the battery manufacturing processes (up to 14 kWh/2 V cell).
Scenario 9.2: Simulating vanadium battery production through decreasing the electricity requirements for the battery manufacturing (down to 4,23 kWh/2 V cell).

A summary of the variations from the base case normalized ratio for all scenarios are presented in Table 8. Detailed graphs including variations from the normalized ratio and sub-system contribution of all the sensitivity scenarios are presented in Appendix H.

The electricity mix importance and future possible improvements is shown by Scenario 1, using electricity produced from hydro power for all process units, decreasing the normalized ratio with between 2 and 5 percent. The influence of the energy intensive processes decrease, hence the PV sub-system contribution decreases with between 10 and 17 percent for the different impact categories. That the normalized ratio does not decrease more illustrates how important it is to think about the whole life cycle activities including raw material extraction and processing.

The importance of the assumed technical life-time for the system is shown by Scenario 5 increasing the normalized ratio between the renewable-hybrid and traditional diesel site with between 2 and 5 percent (8 percent considering the electricity ratio). The assumed life-times for the different systems vary noticeably between previous studies. As an example previous LCA studies (García-Valverde, 2009, Fleck and Huot, 2009) attribute batteries a life-time of 10 years and most reviewed reports attribute generators with a life-time of 10 years which is not the actual technical life-time on a RBS-site. The life-time of modules is expected to rise from 25 years in 2010 to 30 years in 2030 (Pehnt, 2006). This attributes to a high level of uncertainty.

Mono-crystalline cells have a considerably higher refining energy demand than poly-crystalline cells, increasing the normalized ratio with between 4 to 10 percent for the different impact categories.

The sensitivity analysis results show that the contribution from the wind system can be considered negligible to the resulting ratio; doubling or increasing the electricity requirements ten times still only increases the ratio with less than 2 percent as shown in Table 8.

Increasing or decreasing the battery manufacturing electricity requirements has minor effects, below 1 percent variations from the base case if considering lead-acid batteries. For an assumed usage of Vandium batteries the ratio decreases with about 1,4 percent.

Table 8. Variations of the normalized ratio of the base case for all sensitivity scenarios.

Scenario Impact categories	1	2	3	4	5	6.1	6.2	7	8.1	8.2	9.1	9.2
Abiotic Resource Depletion	-2	0	0	-1	2	4	4	0	0	1	0	0
Acidification Potential	-5	1	0	-2	5	10	10	-1	1	3	0	-1
Eutrophication Potential	-2	0	0	0	2	5	5	0	0	1	0	0
Global Warming Potential	-3	0	0	-1	3	6	6	-1	0	2	0	0
Electricity use	0	0	1	0	8	17	17	-2	1	5	1	-1
Energy, net calorific value	-3	0	0	-1	3	6	6	-1	0	2	0	0

The sensitivity analysis does not report the deviation from the numerical results but from the normalized comparative ratios. The variation from the numerical results is in the range of up to 7 percent compared to the range of 1 percent when analyzing the deviation from the normalized ratio. The reasons to provide deviations from the normalized results are the usability of the results.

11.5 Comparison to previous LCA results

According to ISO (14044:2006) an assessment can be performed to map deviations from expected or normal results. A measure often reported in LCA studies is the carbon dioxide equivalent per kilogram, hence values for the different sub-systems on this was calculated, as summarized in Table 9, to provide a possibility to compare the results with previous studies. Note that the sub-systems include both the main functional component and other required components e.g. foundations, shelters and converters, hence the values presented are higher than for a single PV module, battery, wind turbine or diesel generator.

Table 9. Carbon dioxide equivalents (kg CO_2 eq.) for the sub-systems.

Sub-System	kg CO_2 eq./kg main component of the sub-system	kg CO_2 eq./functional unit and year of service
Diesel		
Generator	8 kg CO_2 eq./kg generator	400 kg CO_2 eq./generator and year of service
Fuel	4,1 kg CO_2 eq./kg diesel	3,45 kg CO_2 eq./liter diesel
Battery	5,4 kg CO_2 eq./kg battery bank	45 kg CO_2 eq./12 V cell and year of service
PV	130 kg CO_2 eq./kg PV array	85 kg CO_2 eq./sqm PV and year of service
Wind	14 kg CO_2 eq./kg wind turbine	300 kg CO_2 eq./turbine and year of service

Further analyzing the diesel sub-system the manufacturing of diesel fuel corresponds to 0,77 kg CO_2/kg diesel, the fuel transportation 0,14 kg CO_2/km and tonnage and combustion 3,2 kg CO_2/kg diesel. Similarly Fleck and Huot (2009) and Kemmoku et al. (2002) conclude that the combustion phase stands for about 90 percent of energy input and CO_2 emissions. In most studies the generator is considered negligible; but in the case of RBS-site powering, the contribution could not be neglected because of the short technical life-time of the generators. The transportation varies much with different studies and must be evaluated for every specific case.

Garcia-Valverde et al. (2009) provide a study on mono-crystalline PV modules and batteries included in an off-grid power system. This study states a similar allocation of energy requirement to the batteries as to the PV modules and the higher material requirement for the batteries than for the PV modules. The difference between the model created and this previous study is the relatively high energy demand for manufacturing the batteries, even though the battery life-time is set to ten years. Alsema (2000) (assuming a PV cell system consisting of aluminum framed PV modules on a ground mounted supporting structure in steel) settled a ratio between the different components in accordance with this study.

In coherence with the conclusions from this LCA evaluation, a previous LCA study on carbon dioxide emissions (Rydh, 1998) show that the main activity in the life cycle of lead-acid batteries is the lead mining and production.

For the wind system it is difficult to find a reference study that describes the environmental impacts caused by the turbine alone, the tower or building attachment almost always being included and the dominant contributor.

11.6 Summarizing the results

For a traditional diesel site the fuel life cycle corresponds to over 95 percent of the different environmental impacts and for the diesel battery hybrid site the fuel is still the main contributor; standing for over 50 percent of all the environmental impacts. Any hybrid site decreasing the fuel consumption will therefore contribute to a reduced environmental impact.

The diesel renewable hybrid site analyzed corresponds to a decrease of environmental impacts of around 11 to 16 percent compared to the corresponding diesel site and around 19 to 28 percent if compared to a diesel battery hybrid site. The relative scale between the PV and wind sub-system analyzed, states an environmental impact similar for one wind turbine and around three square meters of PV modules.

A comparison between the diesel battery site and the renewable hybrid site shows that the PV module area has to be increased to 300-500 square meters or the battery bank has to be increased to 400-800 (12V) battery cells to equalize the different impact categories from the diesel battery hybrid site.

The manufacturing phase is the major life cycle phase of all the sub-systems, excluding the emissions from combustion of the diesel fuel. The transportation phase corresponds to between 2 and 25 percent of the different impacts for the sub-systems; influencing the battery sub-system the most, followed by the wind and diesel sub-systems and least for the PV sub-system. The end-of-life treatment has a varying influence for the different sub-systems being higher for the wind and battery sub-systems (around 6 percent) and lower for the PV sub-system (around 1 percent). If the whole diesel sub-system is considered, the end-of-life treatment of the generator is negligible.

11.7 Identification of main parameters

The most important parameters influencing the results of the comparative evaluation of any hybrid site configuration include:

- the diesel consumption; decreasing the diesel consumption will improve the environmental performance compared to a traditional diesel site with around 5 percent per every thousand liters (varying between the different categories and actual decrease in diesel).

- the energy production mix and energy intensive processes including the silicon and lead processing.

    - The silicon requirements have a high influence but not in terms of input metallurgical silicon but because of the high processing energy requirements. This activity is the second most important single activity after diesel production and combustion for the analyzed renewable-hybrid site.

    - The third most important activity is the combined lead processing and battery manufacturing.

    - The aluminum material represents a high allocation of the electricity demand if components in the different sub-systems are summed.

12 Simplified evaluation (MS Excel) model

The aim of the tool is to compare the environmental performance of an RBS hybrid power system. The tool should be able to assist in deciding on power alternatives to consider for unique RBS-sites. The target user group is Ericsson employees "Solution architects", belonging primarily to BUGS.

12.1 Stakeholder criteria

The criteria set by the project owner, Ericsson Research EMF Safety and Sustainability, were that the simplified tool must be based on scientific data and extended to more impacts than simply carbon dioxide emissions.

The environmental parameters that are mostly discussed in the internal business units and in the relationship with the customers are possible energy reductions and sometimes also carbon dioxide emissions. BUGS had a wish to build up local know-how with help from the tool and hereby add customer value to compete with local solutions, through providing information on environmental benefits. The business units at Ericsson consider extended environmental information as added value.

BUGS and BNET set a request that the tool should be combined with other tools on costs and energy optimization, which was not possible within this project's boundaries.

12.2 Features

Five different input parameters will be variable based on different site dimensioning options: PV module area (m^2), number of wind turbines (No), number of 2 V battery cells required (No of 12 V cells), number of diesel generators (no generators), and liters of diesel to be consumed per year (Liters/year)

Given output parameters from the tool are electricity requirements, energy resource requirements, material resource requirements, global warming potential, acidification potential and eutrophication potential.

The tool was developed in the software MS Excel and the outputs are presented numerically and in comparative graphs, as illustrated in Figure 23.

12.3 Comments on simplified model

Problems when transferring the analytical model from a more complex software (GaBi) to a less complex one (Excel) include that the variable parameters are made constant. This effect was minimized by exporting the data from GaBi for different alternatives where necessary e.g. three datasets for the diesel generator and two for the battery cells were exported and assigned different life-times depending on site (traditional diesel site, a diesel battery hybrid site or a renewable hybrid site). Still some parameters are not possible to vary in the simplified model e.g. the transportation distances and local energy mix which cannot be varied between different sites.

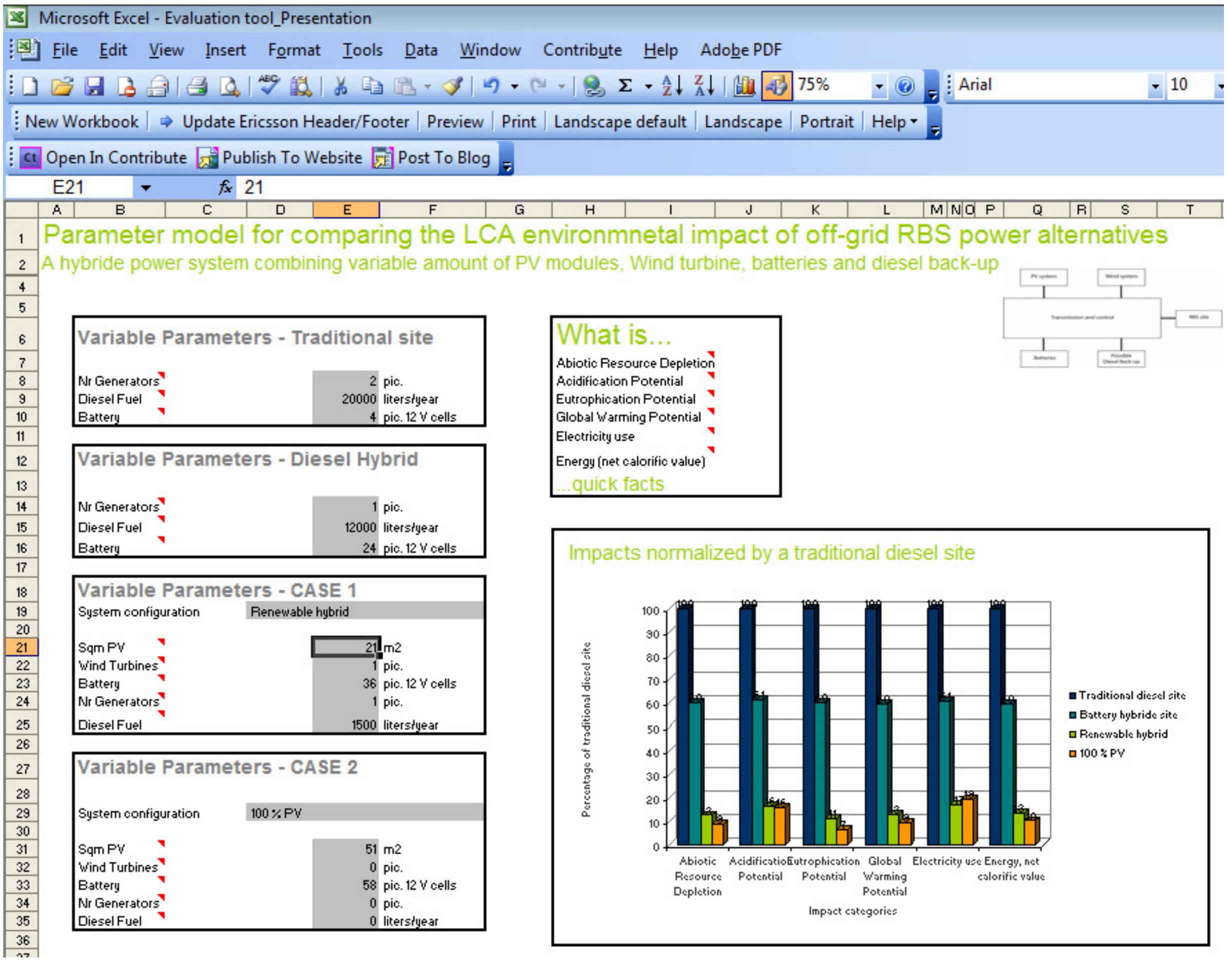

Figure 23. Simplified tool developed in Microsoft Excel. Parameters for a traditional diesel site, a diesel battery hybrid site and two diesel renewable sites are possible to vary to the left. The resulting impacts are calculated and provided as percentage of impacts caused by the traditional diesel site in the graph to the right. Short definitions of the impact categories presented in the graph are given in pop-up windows on the top of the page.

13 Discussion

13.1 System selection

The overall conclusion from previous studies was that it is impossible to create a general best practice solution for off-grid electrification and that site-specific characteristics determine which renewable resource to use, especially if a hybrid of two or more systems is required to provide the needed capacity. Available or possible renewable power solutions for off grid RBS-sites have been mapped showing an existing usage of PV modules and a growing usage of PV and wind hybrids. Potential and feasibility for small-scale hydro power, different bio fuels and solar concentrator solutions must be further investigated. Currently lead-acid batteries dominate as the storage solution, but fuel cells and other battery designs are being discussed for future use in the telecom market.

The mapped renewable hybrid power solutions should also be considered for urban areas of developing countries where the grid connection is unreliable. In East Africa, for example, there is a power outage, on average, once a week (GSMA, n.d.).

13.2 Gains of the thesis work

The conclusions and discussions from this work will be useful as a knowledge enhancer at Ericsson Research, however will also be useful for other Ericsson employees wanting to gain more understanding of the power alternatives available. The assumed environmental benefits from using renewable power sources have been confirmed and its scale further investigated, showing great environmental benefits from using wind and PV power at RBS-sites. The relative scale between applying a wind or a PV facility has also been provided, showing the gain of applying wind power when feasible to decrease the PV module area or battery capacity required.

13.3 Possible future improvements and work

Uncertainties in suitability and limited project time restricted the LCA to comparing PV and wind turbine solutions. Another approach would be to perform a more simplified LCA, including all possible renewable power solutions (PV cells, wind turbine, dish-Stirling, pico-hydro, bio fuels and fuel cells). However, uncertainty because of the low level of understanding of the different technical systems, generalization of the systems and approximations of immature systems would then be greater.

To assure the accuracy of the model, a deeper completeness and consistency check should be performed focusing on the accuracy of the end-of-life treatment, ancillary materials in the production, the raw-material up-stream consistency and intermediary material transportation influence.

Data on different manufacturing locations for possible suppliers of the sub-system solutions should be mapped to find possibilities to decrease the environmental impacts from the manufacturing phase of any of the different sub-systems.

The layout of the simplified model should be developed and the function evaluated by possible users.

13.3.1 Missing dynamic approach

For this assessment a status-quo LCA approach was used, hence future developments of the system and the background system were not considered (Pehnt, 2005). A more dynamic view should include an investigation of how fast possible improvements of the sub-system and the background system will be accessible.

As an example, manufacturing electricity requirements of crystalline PV modules are assumed to be reduced with up to 85 percent in the near future (Pacca et al., 2007) mainly through developments of a lower quality solar grade silicon feedstock purified directly from metallurgical silicon (Sarti and Einhouse, 2002). However the developments of electricity mixes will lead to the highest decrease of impacts. As an illustration; the future electricity mix is assumed to decrease the carbon dioxide emissions from PV module production with around 20 percent, meanwhile wafer losses are considered to be reduced from 25 percent to negligible losses in 2030 still only having a minor improvement effect due to the already optimized process (Pehnt, 2006).

Other discovered future improvements of the systems include the usage of other types of batteries and increased PV module life-time and decreased amount of square meters required (through increased module efficiency). A comparison between lead-acid and so called Vandium batteries has shown an improvement in life cycle environmental impacts for the vanadium batteries (Rydh, 1998).

In the future the diesel battery hybrid site should be the standard configuration of diesel sites and should be used as a reference for similar assessments.

13.3.2 Extended impacts

The LCA was restricted to few impact categories. It would be interesting to cover also depletion of valuable resources e.g. iron ore. Other excluded impacts that could be considered for future work are the noise pollution, visual impacts and land requirements. Land requirements could gain critical importance in the future when wind and solar power solutions and bio-fuel farmlands require vast areas. Also, indirect land losses due to for example change of climate should be considered (Gagnon et al, 2002). These factors are important since RBS-sites are often located near villages (Ericsson internal Marie Minde, 2009). For example, the visual impacts of wind turbines are widely discussed and there is improvement work concerning reducing the night time generator noise pollution with diesel battery hybrid solutions (Ericsson internal, N. Gimple, 2009).

Complementing investigations on social and economical aspects should be performed to be able to compare sustainable indicators for the different systems.

14 Conclusions

It is possible to significantly decrease the environmental impacts of off-grid radio base station power systems by utilizing PV modules and wind turbines. The diesel/PV/wind turbine hybrid site evaluated, represents around one sixth of the environmental impact potentials caused by corresponding traditional diesel sites, the global warming potential specifically corresponding to 13 percent.

Generally when configuring hybrid sites, wind turbines corresponds to the least environmental impacts: the environmental impacts for one wind turbine equals that of 3.5 square meters of PV module and 6.4 12V battery cells.

The most important parameters influencing the environmental performance of the renewable hybrid site following the diesel fuel production and combustion are the production electricity mix and electricity intensive processes including up-stream silicon and lead processing and battery production in declining order.

Ericsson should promote PV/wind power on their sites and map PV module, wind turbine and battery supplier manufacturing locations to decrease the environmental impacts connected to RBS-site powering.

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15.5 Software

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15.6 List of Tables

15.7 List of Figures

16 Appendixes

Appendix A – Baseline review of available renewable power solutions for off-grid sites

A.1. Renewable small-scale electrification alternatives

Here a summary of the baseline review of available renewable electrification solutions for off-grid RBS-site is presented. The maturity of the solutions and current usage at, and visions for, RBS-site applications are reviewed.

The need for power storage is vital when discussing alternative energy systems. Hence, a minor search for alternative back-up and storage solutions as alternative to battery banks and diesel generator back-up is also presented.

A.1.1 Solar

Solar radiation can be used as an electricity source through different technologies, either it can be concentrated by reflectors providing heat in "solar thermal-electric" power stations or it can be converted directly into electricity within solar photovoltaic (PV) modules. Combinations using concentrators to focus the solar radiation onto photovoltaic cells are also available and increase the photovoltaic efficiency.

A.1.1.1 Photovoltaic modules

Generally the different photovoltaic technologies can be divided into crystalline silicon cells (mono- and poly-crystalline), thin film (using amorphous silicon or alternative materials) and third generation technologies (based on nanotechnology). The commonly used PV cells are mono-crystalline, poly-crystalline and amorphous silicon PV modules (Sherwani et al., 2009). These PV cells are made almost entirely from Silicon which is the second most abundant element in the earth´s crust. Solar radiation is directly converted into DC electricity by semi conducting materials in the PV modules. One PV cell produces only around 1,5 W which is why many cells are grouped and connected into modules. In turn these modules are mounted together in arrays with the number of modules widely varying depending on the specific capacity required (Boyle, 2004).

Much progress in increasing the efficiency and reducing the cost of PV cells has been made in the last decades, but still PV systems have a high initial cost and cost reductions are foreseen to continue (Boyle, 2004).

Both small scale and large PV power plants are now becoming widely used. Applications are especially increasing for remote areas in developing countries, where telecommunication sites are among the most common applications (Boyle, 2004). The GSMA foundation (GSMA Developing Found, 2007) considers solar power to be the most suitable renewable power source for off-grid network sites. This because of the abundant resource supply, modular design, scalability of the modules and low operational costs. Within the member operators of GSMA nearly 1500[15] PV sites have been installed globally, representing the majority of installed sites utilizing renewable sources.

A.1.1.1.2 Solar-dish

Different solar thermal-engine systems can be used to produce electricity from solar radiation. Solar collectors produce high temperatures that drive thermal engines connected to electrical generators. There are different designs available but the most common way to concentrate the radiation is to use a parabolic mirror reflecting the radiation to its focus point (Boyle, 2004).

A growing use of solar thermal-engine systems at small-scale off-grid sites based on a parabolic-dish concentrator system has been observed. Commercially available solutions are different dish-Stirling models with a typical capacity of between 5 and 25 kW (Boccaletti and Santini, 2007). The same main techniques are delivered in complete solutions, as illustrated in Figure A1[16].

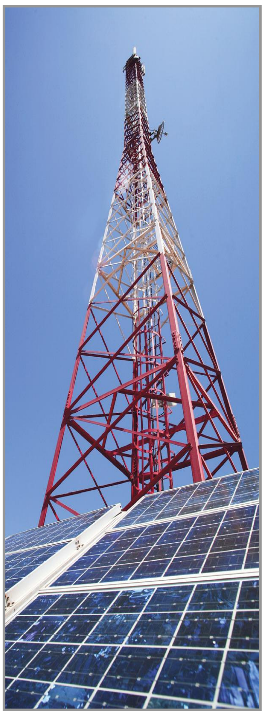


Figure A1. General design of a a) photovoltaic module, here powering a RBS-site b) a dish-Stirling system from Cleanergy.

[15] *1447 according to http://www.wirelessintelligence.com/green-power/*

[16] *http://www.convergedigest.com/images/articles/ericsson-solar.jpg and http://www.cleanergyindustries.com/img/concept_stirling.jpg*

Technically the size of solar dish-Stirling systems make them ideal for powering RBS-sites (Boccaletti et al., 2007) but to obtain the high temperatures needed, the system has to be located where there is a high availability of direct solar radiation, since diffuse radiation is not enough. The economic feasibility of solar concentrators depends on the availability of commercial power turbines and the scale of the order on the mirror glass. The optimum size is thought to be around 150-200 MW (Boyle, 2004).

Hybrids where PV cells are placed in the solar concentrator focus decreases the required amount of PV cell by a factor up to one thousand (Firak, 2005, ETSI, 2009), being a promising future solution.

A.1.2 Wind turbines

Small-scale wind turbines have been manufactured since the 1930s to provide electricity to remote communities and to charge batteries for boats and caravans. Recently they have also been applied to power remote telecommunication masts. Small-scale wind turbines are expensive if calculated per kilowatt hour and are only economically competitive in areas far away from the electrical grid (Boyle, 2004).

Available wind turbines have a wide capacity range between tens of watts up to 5 megawatts (Boyle, 2004) and can provide both AC and DC output power (ETSI, 2009). Horizontal wind turbines with two or three turbine blades are the most common turbines produced today (Boyle, 2004).

The GSMA foundation considers wind power to be the second most viable power solution for network sites after solar power (ETSI, 2009). So far only 6 wind powered sites and 42 hybrid sites combining PV modules and wind turbines have been reported within the member operators of GSMA[17]. Wind turbines have a very low operational cost, lower initial cost than solar PV power, high reliability, and are theft resistant. In addition, on RBS-sites the wind tower can be used to mount the antennas if dimensioned for it (Boccaletti and Santini, 2007), as illustrated in Figure A2[18].

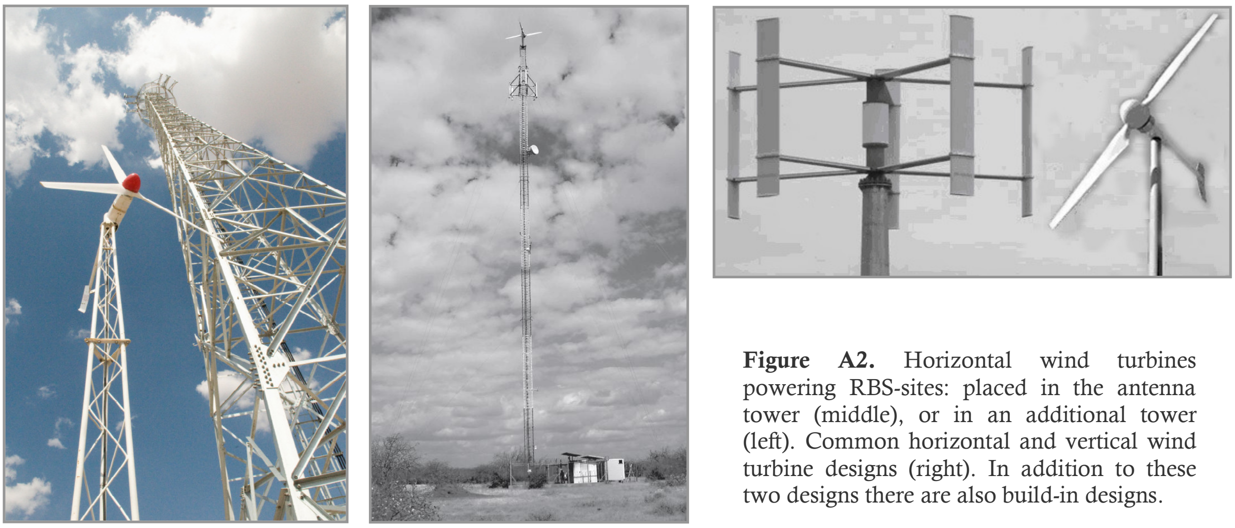


Figure A2. Horizontal wind turbines powering RBS-sites: placed in the antenna tower (middle), or in an additional tower (left). Common horizontal and vertical wind turbine designs (right). In addition to these two designs there are also build-in designs.

[17] *http://www.wirelessintelligence.com/green-power/*
[18] *http://www.flexenclosure.com/ and www.ericsson.com*

Variations in wind speed restrict wind-powered RBS-sites to locations with abundant wind resources like coastal and mountain areas, making this solution less suitable for the average RBS-sites than PV power (GSMA Developing Found, 2007).

Possible environmental impacts associated with the usage of small-scale wind towers are mechanical and aerodynamic noise, electromagnetic interference, possible impacts on flora and fauna and visual impacts like sunlight flicker (Boyle, 2004).

A.1.3 Small-scale hydro plants

Pico-hydro facilities, being hydro power plant harvesting the power of streams and rivers to producing up to 5 kW electricity (Maher et al, 2002), are most suitable for RBS-site power.

Hydro power is a mature technology for rural electrification. Hydro power is highly site-specific and most systems are private owned, located in remote areas or in countries with low reliability of data (Gagnon et al, 2002). Therefore, there are no commercial best-practice solutions and it is difficult to determine how many small-scale hydro power plants are installed globally. Figure A3[19] provides one example small-scale design. A theoretical case of a basic pico-hydro plant powering an RBS-site is described in a white paper by Motorola. This example was based on an off-grid village electrification projects implemented in Kenya, by The Micro Hydro Centre at Nottingham Trent University. The main components required to build a typical small-scale hydro facility is a weir, a penstock, a turbine, an induction generator and a tailrace to carry the water back to the river (Motorola White Paper, 2007).

Figure A3. Example of a small-scale hydro facility design.

[19] *http://www.arun.gov.uk/images/eh/Small_Hydro_Station.jpg*

According to the GSMA foundation (GSMA Developing Found, 2007) pico-hydro is the third most viable power solution for future off-grid network sites. These sites would have a very low initial cost, low operational cost, high reliability, and theft resistance (ETSI, 2009). The drawback with pico-hydro as with all hydro power solutions is that it is highly site-specific and restricted by the availability of water flow resources (Gagnon et al, 2002). Recently there have been improvements in standardization of components and development of off-shelf systems for small-scale hydro power systems (Boyle, 2004).

A.1.4 Biofuels

The two main sources of bio energy are purpose grown energy crops and biodegradable wastes from human activities. Bio diesel is produced from oily seeds like soya beans, sunflowers, etc. and wastes are digested into biogas. These fuels can be used in traditional diesel or combustion engines driving electrical generators (Boyle, 2004). Also previously discussed Stirling-engines could be used; the ability to use varying heat sources makes Stirling-engines suitable for hybrid configurations e.g. utilizing heat both from the sun and biofuel combustion (Boyle, 2004).

The pre-study revealed that at least three trial sites using biofuels as a power source for radio base stations have been installed[20]. In the study "Green Power for Mobile" conducted by the GSMA Developing Found (n.d.), bio diesel is considered to be the forth most viable power generation alternative after solar, wind and small-scale hydro power.

Usage of biofuels leads to a decrease in amount of atmospheric emissions through capture of carbon dioxide when planting trees and a decrease in naturally produced methane during combustion. Negative environmental and social impacts are also raised due to the extensive farm and forest land use affecting food crop production and the carbon dioxide capturing forestry. Where 40 acres of PV modules or 100 acres of wind farms are required; an area of between 300 and 1000 acres will be required for growing energy crops. There is also a discussion on the impacts of fertilizer and pesticide requirements, risks of decreasing biodiversity and possible positive features of sewage land treatment (Boyle, 2004).

A.2 Storage alternatives

One of the main problems when applying alternative power is meeting the generated and required power capacities. On an RBS-site the required load is constant but the intermittency of the renewable source is still an uncertainty, requiring a sufficient storage alternative.

Traditionally, lead-acid batteries are used at RBS-site, however other forms are currently being investigated e.g. chemical fuel for combustion or feeding of fuel cells and different mechanical storages (Bitterlin, 2005).

[20] http://www.wirelessintelligence.com/green-power/

A.2.1 Batteries

On traditional diesel sites batteries have only been used as back–up, but in systems with renewable resources batteries have received an additional role as storage. Extended storage capacity is required to bridge the gap between the available resource and the required capacity. The currently most used battery types at RBS-sites are recombination Valve Regulated Lead-acid (VRLA) batteries available as free liquid electrolyte, absorbing glass mat (AGM) or gelled electrolyte type (Bitterlin, 2005). Lead-acid batteries is one of the more economical options for storing renewable energy at off-grid sites but there are many other alternatives. An analysis of different lead-acid batteries, or any comparison to other battery types, will not be performed within this study; see ETSI (2009) for a complementing review.

A.2.2 Hydrogen production, storage and fuel cells

A fuel cell is in principle a battery that uses a reversed electrolysis to convert for example hydrogen and oxygen fuel into DC electricity. The only by-products from this process are water and an almost negligible amount of pollutants (Boyle, 2004). There are different types of fuel cells. The Proton Exchange Membrane Fuel Cell (PEMFC) is considered the most promising for telecommunication base station (Motorola White Paper, 2007). The PEMFC has an important role as future back-up power system; requiring little maintenance in back-up mode, having high performance in varying climates and being scalable to meet run-time requirements by increasing the fuel storage or adding a hydrogen generating unit. Fuel cell capacities normally range between 50 W and 250 kW (ETSI, 2009).

Currently, the hydrogen fuel is mainly produced centrally from natural gas (methane) with the by-product carbon dioxide, requiring additional transportation to the site and a vast storage volume (Bitterlin, 2005). The costs and logistics connected to the fuel supply and the limited life-time of the fuel cell stack (around 2000 hours in practice) are observed complications with hydrogen fuel cell systems. The hydrogen fuel can be stored as liquid, gas or solid hydride, the most common being as compressed hydrogen gas (ETSI, 2009).

The pre-study also found several concepts of using fuel cells as a primary or secondary power source in combination with renewable power systems and on-site-hydrogen-production. Boccaletti et al. (2007) and Wells and Scott (1993) describe a fuel cell system producing hydrogen on site, on a grid-connected telecommunication site, replacing the back-up batteries. Renewable hydrogen can also be produced through gasification of biomass or thermal dissociation of water using e.g. concentrating solar collectors. The operational costs are very high for theses systems and the creation of heat and hydrogen gas waste are some areas that need improvement.

Fuel cells have been tested as a back up solution at around 13 RBS-sites globally, but still have no commercial applications.[21] These fuel cells were feed by centrally produced hydrogen.

A.2.3 Alternative storage solutions

There are a number of alternative energy storages, some would have to be modified in accordance to size and capacity requirements for a RBS-site; and their performance and suitability will vary (Schainker, n.d.).

[21] *http://www.wirelessintelligence.com/green-power/*

Flywheel storage is based on an electric engine that spins a flywheel when excess energy is available. The flywheel then regularly takes over and powers the alternator producing electricity. Small flywheels up to 1 kW for 3 hours are commercially available and widely used. The storage capacity is proportional to the square of the wheel speed; hence current developments are focused on material usage enabling higher wheel speed while reducing the facility size, weight and costs (Schainker, n.d.).

Compressed air storages compress air into underground reservoirs or surface vessel and pipe systems. When energy is required, the air is heated and run through an expansion turbine that drives an electrical generator. The air is heated through combustion with various fuels. The fuel requirements are about one third of that of traditional combustion systems. Currently there are only large scale facilities in operation but air could be stored in pressurized tanks for smaller systems (ETSI, 2009).

Pumped hydroelectric storage is the only alternative storage technology that is widespread. However, it must store large capacities to be economically feasible. The storage consists of two water basins at different levels and a pump driven by excessive energy that transfers water to the higher elevation reservoir.

Superconducting magnetic energy storages feed DC current into an electromagnetic coil of superconducting wire. While the superconducting material is kept at a temperature corresponding to its superconductive properties the power is stored. Again, this storage solution only exists in large scale applications (Schainker, 2004, ETSI, 2009).

For peak power applications super capacitors that store electricity as an electric field between two electrodes can be applied but their specific energy (e.g. kWh per kg or liter) is about ten times lower than that for batteries (ETSI, 2009).

A.3 Previous LCA results of renewable energy electrification alternatives

Different energy pay back ratios and energy balances, describing the ratio between the energy produced by a power facility during its life-time; and the required energy to construct, maintain and dispose the facility are often reported. Generally, previous studies on renewable energies promote the high performance of hydro and wind power (Uchiyama, 2006, Gagnon et al., 2002). The energy balance ratios for big scale power plants varies greatly between different studies but places the different solutions in similar order relative to one another; the energy pay back ratio for small-scale hydro power rates highest, followed in descending order by wind and PV power (Uchiyama, 2006, Dragu et al., n.d.). In a study by Gagnon et al (2002) run-of-river hydro power also has the highest performance compared to wind and PV power when it comes to greenhouse gas emissions.[22] Dragu et al. adds an energy payback ratio for solar thermal power between that of hydro and wind power. Varun et al (2009) adds a ratio of greenhouse gas emissions for solar thermal and biomass power production between that of wind and PV power production. According to Gagnon et al. (2002) fuel cells feed with hydrogen from gas reforming and biomass plants using specially grown bio crops, have an energy pay back ratio lower than all the others. However according to Uchiyama (2006) small scale bio fuel plants have to be assessed individually because of the differences in technology, construction and fuel supply availability.

[22] The size of plant was not considered in this study, but presents environmental impacts that can be generally expected.

In a study by Pehnt (2006) the comparative environmental life cycle impacts connected to small-scale run-of-river facilities using concrete weirs, 3 kW poly-crystalline PV cells, large onshore wind farms and solar- thermal-parabolic-trough power facilities were compared (all the facilities were assumed to be produced in Germany). The usage of finite energy resources, greenhouse gas effect and acidification potential was much lower for the renewable alternatives than the average German electricity mix (from the year 2010), with the PV facility having substantially higher values than the other alternatives. Surprisingly the PV, wind and solar thermal facilities consumed more finite resources for example iron ore and bauxite per kWh produced than the German electricity mix and the hydro power plant consumed almost as much. The high specific resource requirements depend on the PV module mounting, high aluminum content in the solar collectors and high steel consumption in the solar collector structure and wind turbine tower (Pehnt, 2006).

The direct land requirements for the different alternative energy systems are difficult to map but biomass usage requires substantially more direct land than the other alternatives if based on planting crops, wind power generally requires more direct land than PV modules and run-of-river is considered to have negligible land requirements (Gagnon et al, 2002).

A.3.1 Diesel generator versus renewable energy system usage

A number of LCA studies looks at the environmental impacts of using diesel generators or renewable alternatives for rural small-scale electrification using an electricity and CO_2 emission life cycle approach. Fleck and Huot (2009) shows that using small-scale wind turbines in combination with battery banks result in large CO_2 emission reductions, the wind system contributing to below ten percent of the green house gas emissions caused by the diesel system.

Kemmoku et al. (2002) performs an LCA study of a PV/wind turbine/diesel generator/battery system generally showing that the PV components represent a higher amount of the manufacturing energy requirements than the other system components. The CO_2 emission from the manufacturing phase of this system configuration decrease with increased ratio of wind generation per PV generation. The PV module manufacturing energy being about 3 times that of the wind turbine system and the CO_2 emissions being about 4 times that of the wind turbine system. The CO_2 emissions during the manufacturing phase increase with up to 15 times when applying the PV module/wind turbine/diesel generator/battery system compared to that of the single diesel generator system, but the emissions from the operation phase and hence from the total life cycle will decrease. The study also analyzes the relationship between the renewable energy supply ratio (solar/wind) and the CO_2 emissions. When the renewable energy ratio is below 20 percent it is preferred to only use wind power facilities, when the ratio exceeds 30 percent solar PV power should be introduced and when the ratio exceeds 50 percent equal amount of PV and wind turbine generations should be applied.

An interesting conclusion from the Kemmoku et al. (2002) study is that when the ratio between renewable and fossil power supply is less than 60 percent; the reductions in CO_2 emissions decrease as the amount of renewable energy increases. No decreases in CO_2 emissions can be seen when the renewable energy supply ratio exceeds 60 percent. The total amount of CO_2 emissions at a renewable energy ratio of 50 percent is around 70 percent of the emissions of a solely diesel generation system. Another conclusion is that the total CO_2 emissions increase with increased battery capacity required; the CO_2 emissions from the system operation decreases due to the installation of batteries but the emissions from the battery manufacturing becomes greater than the decrease they contribute to when the renewable energy supply ratio are below 40 percent.

A.3.2 Solar PV

An Ericsson internal comparison between the CO_2 emissions related to a grid-connected site and a specific PV site, the Ericsson *SunSite*, was performed in 2001 and concluded that the CO_2 emissions were similar for these alternatives if the distance to the grid is not too far, but increase much with increased distance. The main CO_2 emissions contributor within the PV solution was the production of the big volume of batteries required and the PV module (Palm et al., 2001).

Analyzing previous results on the life cycle of PV systems, Alsema (2000) concludes that the energy demand in the utilization phase are generally negligible and that there are very little data on recycling or alternative end-of-life treatment. Hence these studies, as most other studies, focus on the manufacturing phase. According to Alsema the manufacturing requirements for poly-crystalline silicon modules vary between 2400 and 7600 MJ/m^2 (and between 5300 and 16500 MJ/m^2 for mono-crystalline silicon) over different studies.

Sherwani et al. (2009) also analyzed previous LCA results to compare energy requirements and green house gas emissions of different types of PV cells and module designs. The energy payback time for mono-crystalline, poly-crystalline and amorphous PV systems lies in the order of 3-16, 2-6 and 2-3 respectively, the green house gas emissions following a similar pattern (Pacca et al., 2007). The main source of the higher energy consumption of mono-crystalline cells is the energy intensive crystallization process (Alsema, 2000).

The variations of results depend on many different factors such as the PV cell type, assumptions of the production stages, placing of module and irradiation, installation design, component efficiency and life-time and electricity mix of the manufacturing country (Sherwani et al., 2009, Alsema, 2000). The most important source of difference in the manufacturing phase was found by Alsema (2000) to be the variations in estimates for silicon purification and crystallization process, assumptions on wafer thickness and wafering losses also having some influence. Most silicon solar cells are made of scrap material from the electronic industry, which makes the allocation of the energy consumption by the electronic wafers and the PV wafers difficult. There are also uncertainties in the actual energy consumption of the purification and crystallinization processes. The estimates of the cell processing and module assembly are more homogeneous between different studies. The high variations and uncertainty range is assumed by Alsema (2000) to affect the uncertainty in the final value by around 40 percent.

Future improvements to reduce the energy requirements and green house gas emissions include making the cells more efficient, less material use through improved wafering and casing technology, and maximizing the use of recycled material (Sherwani et al., 2009). How the silicon feedstock is produced is important within this development; the amount of off-grade silicon is limited and the electronic-grade silicon is expensive, hence silicon purification processes dedicated to the solar cell industry are needed. The development of solar-grade silicon would essentially reduce the energy requirements for the purification process (Alsema, 2000). Alsema assumes an energy requirement of 2600 MJ/m^2 in 2010 but when looking beyond 2010 the production efficiency will be stagnant to around 1 percent as with mature production technologies.

Looking at different components within a 4,2 kW peak roof mounted PV system for rural electrification García-Valverde (2009) states that the batteries, PV modules and structure requires most energy and material, that the aluminum frame requires little of both and that the electrical components are negligible.

Selected more advanced PV cell technologies have also been reviewed, for example by Sherwani et al. (2009) analyzing nano-crystalline dye sensitized (ncDSC) PV solutions and cadmium telluride (CdTe) and CIS (copper, indium and selenium) solar cells.

A.3.3 Wind turbines

Most studies into wind turbines are based on a system including a tower, foundation and a battery bank in addition to the actual wind turbine with the result that the turbine is almost negligible and not reviewed in detail. In a study by Fleck and Huot (2009) of small scale electrification with wind turbines in combination with a battery bank, the battery manufacturing result in around 40 percent of the CO_2 emissions, the manufacturing of the tower to 30 percent and manufacturing of the turbine to around 5 percent.

Kahn et al. (2004) investigate a wind/fuel cell integrated system and conclude that the main CO_2 emissions from the wind turbine come from the manufacturing stage. The transportation and disposal only corresponds to one percent of the global warming potential in this study.

According to a review by Lenzen and Munksgaard (2001) the energy required to manufacture a wind turbine system varies greatly between different studies. The review also states that the material input required at manufacturing has minor variations over a wide range of power ratings. This despite the fact that additional material is required for example to add stiffness to the rotor blades if the wind forces are greater, hence the manufacturing requirements per unit of effect produced decreases with higher turbine capacity. Lenzen and Munksgaard also mapped important variations in energy requirements for manufacturing the turbine components depending on manufacturing location. In this study the manufacturing of a 500 kW wind turbine requires almost double the amount of energy if manufactured in Brazil compared to Germany. The main reasons for this variation are differences in scrap utilization and the energy content in the steel required.

A.3.4 Batteries

Previous LCA work on electrification hybrid systems, including lead-acid batteries shows that the batteries have a significant environmental impact if high storage capacity is required. Life cycle impacts include lead emissions to air and water, SO_2 and NO_X emissions, hazardous waste from the recycling and risk of sulphuric acid leakage. In addition, batteries require air conditioning in order to have a long life (Sára et al., n.d.).

Rydh (1999) concludes that the most important factors concerning the environmental impact of lead-acid batteries are the recovery factor and the re-use rate of secondary lead in manufacturing. Important future improvements include the production of primary-grade metal in secondary smelters and development of batteries with longer life-times. Rydh also proves that there are other battery types than lead-acid batteries with lower environmental impacts per given capacity, in this case the Vandium battery.

The transportation of a large amount of batteries can have a significant effect on the LCA result; according to Fleck and Huot (2009) the transportation contributes to around 20 percent of the life cycle CO_2 emissions when transported 3000 km.

A.3.5 Fuel cells

Most of the previous LCA studies on fuel cells focus on the usage in vehicles and only some data is published on electrolyze hydrogen production and reactant storages (Khan et al., 2004). Most of these studies have concluded that the complications of fuel cell power lie in the hydrogen production (Karlström, 2004). Due to the production of fuel from natural gas, fuel cell systems are considered to emit more greenhouse gases than natural gas turbines (Gagnon et al, 2002). In a system with on-site hydrogen production using renewable energies this natural gas consumption and transportation is eliminated.

Khan et al. (2004) have performed an LCA study mapping green house gas emissions for a wind/fuel cell integrated system; including a tower mounted wind turbine, a proton exchange membrane (PEM) fuel cell, electrolysis of water and hydrogen storage. The study generally shows that the electrolyzer corresponds to the main part of the electricity requirements and global warming potential; the electrolyzer requiring 95 percent, the fuel cell about 4 percent and the wind turbine about 1 percent of the total energy consumption. In the fuel cell life cycle the main part of the global warming potential comes from material production and energy consumption and a minor part from the transportation and disposal phases. Finally, it is concluded that the global warming potential for the integrated wind/fuel cell system studied (using an energy mix of 65 percent hydroelectricity, 5 percent nuclear and 30 percent thermal power) is at least one order lower than using a traditional diesel system for off-grid electrification.

A comparison between a back-up system using an electrolyzer and a PEM fuel cell and a nickel-metal hybrid (Ni-MH) battery system (Grégoire and Germain, n.d.) shows greater environmental impacts from the fuel cell back-up system. The Ni-MH batteries correspond to approximately 70 percent of the electricity requirements and related environmental impacts of the fuel cell system.

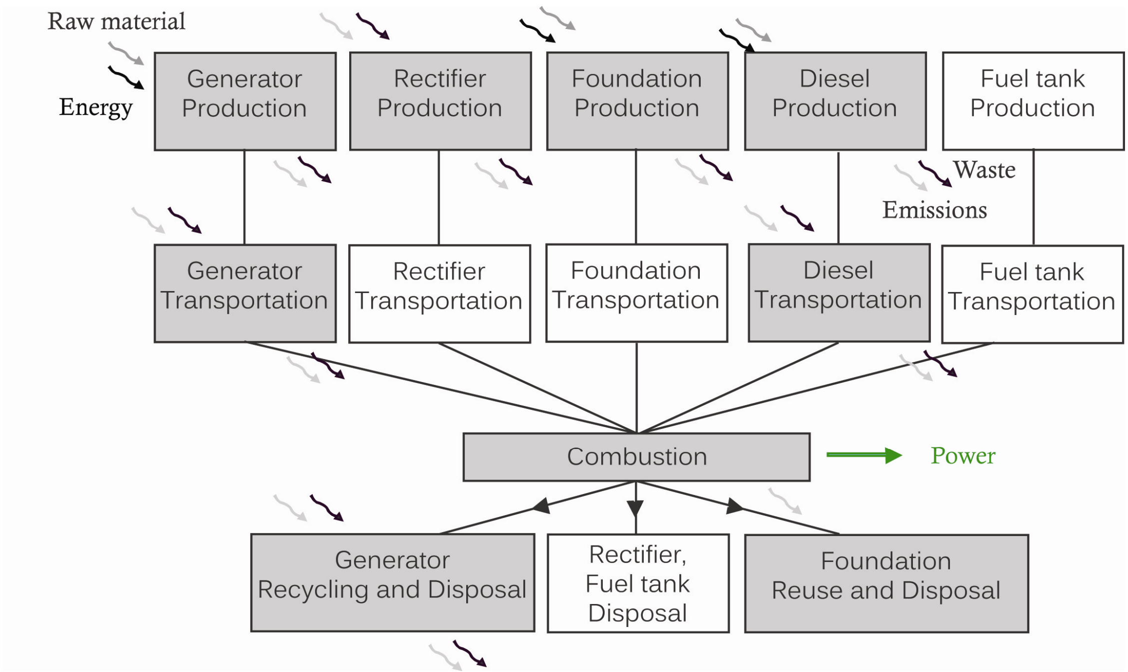
Fuel cells create a great deal of excess heat; hence their environmental performance within a heating cogeneration system is increased (Khan et al., 2004).

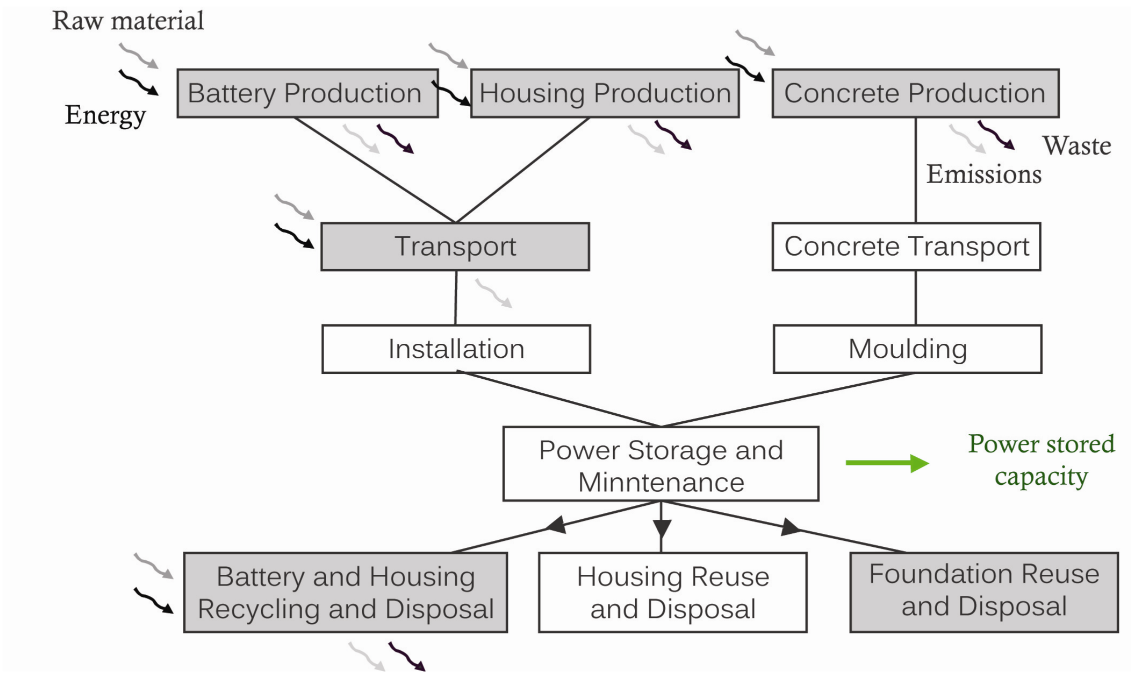
A.3.6 Balance of system components

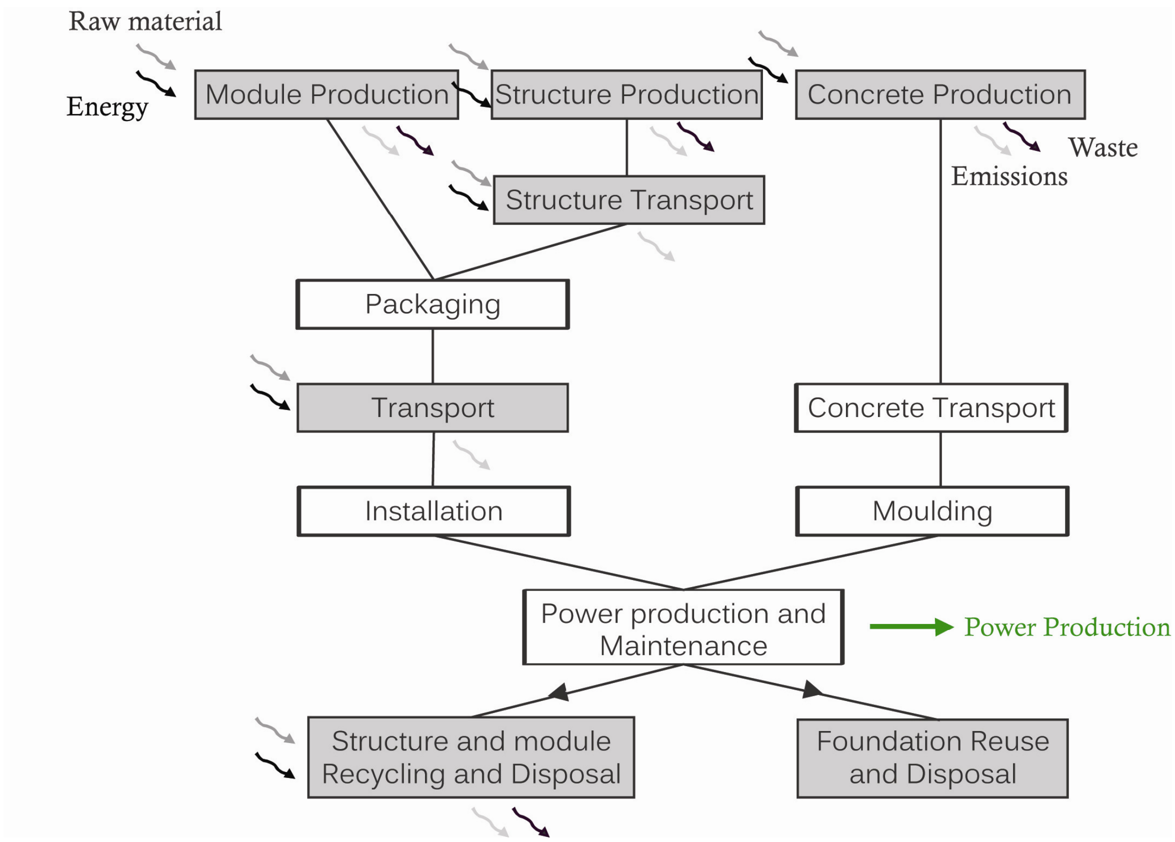
Most previous reports analyze the contribution of the balance of system and different electrical components together, their contribution to impacts being considered negligible. Allen et al. (2007) analyzes a regulator and a rectifier as one unit and concludes that the main emissions from them are heavy metals and carcinogens; however the total emissions are relatively small.

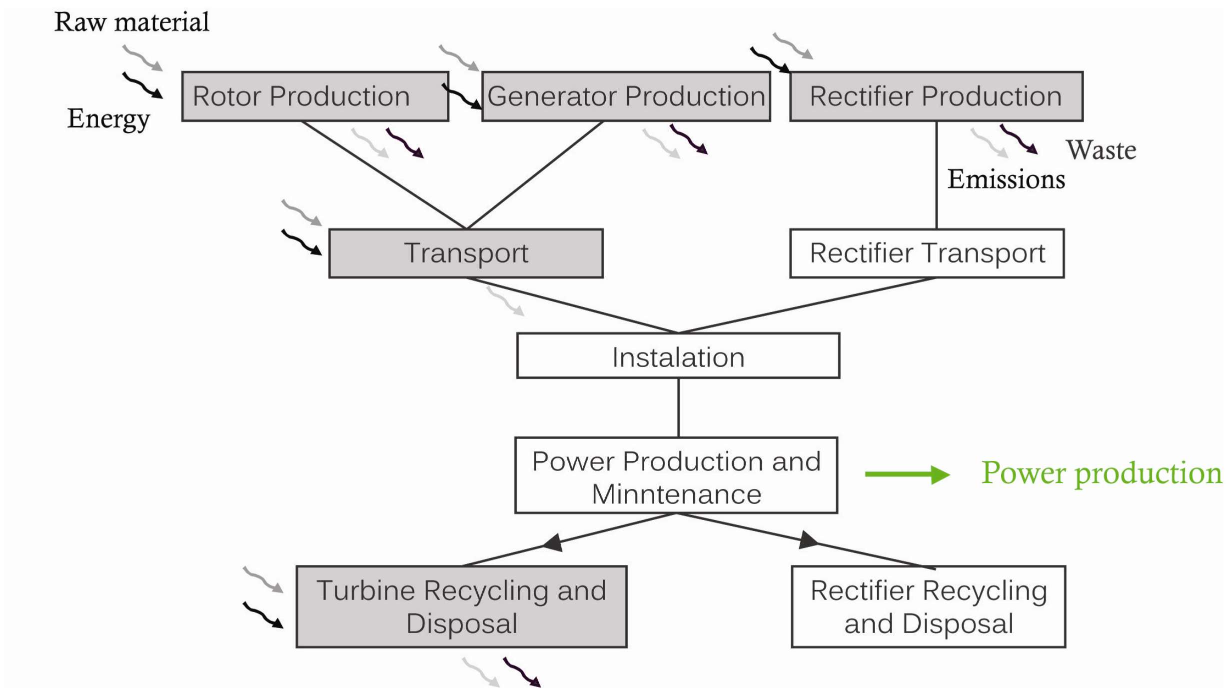
Appendix B – Inventory flow-charts for the sub-systems

The life cycle phases of the diesel, battery, PV and wind sub-system are illustrated in this order below. Phases included in the inventory are highlighted.






Raw material
Energy
Module Production
Structure Production
Concrete Production
Waste
Emissions
Structure Transport
Packaging
Transport
Concrete Transport
Installation
Moulding
Power production and Maintenance
Power Production
Structure and module Recycling and Disposal
Foundation Reuse and Disposal


Raw material
Energy
Rotor Production
Generator Production
Rectifier Production
Waste
Emissions
Transport
Rectifier Transport
Instalation
Power Production and Minntenance
Power production
Turbine Recycling and Disposal
Rectifier Recycling and Disposal

Appendix D – Additional inventory data

Table D1. Composition for the different electricity mixes used.

Electricity mix	Utilities	If based on other pre-fabricated Gabi processes	Main primary energy sources (%)
Chinese	PV module manufacturing Wind turbine manufacturing Batteries manufactueing		80,0 hard coal 20,0 hydro
French	PV structure manufacturing		78 nuclear 12 hydro 4,2 natural gas 3,7 hard coal
British	Generator manufacturing		47 nuclear 31 brown coal 9,0 hard coal 6,3 hydro 3,6 natural gas
African average	Foundation material manufacturing	Electricity oil based Electricity Swedish average Electricity natural gas based Electricity coal based	38 oil based 24 hydro 19 natural gas 19 coal gas
World average	Converter manufacturing End-of-life treatment	0,25 Chinese electricity mix 0,25 EU electricity mix 0,25 Japaneese electricity mix 0,25 US electricity mix	31 hard coal 28 nuclear 20,0 natural gas 9,1 hydro 5,4 gaseous biofuels 3,4 brown coal 2,2 heavy fuel oil

Table D2. Assumed distances for the different transportation process units.

Sub-system	Manufacturing location	Instalation/assembly location	Distance (km)
Diesel system			
Generator	Ireland	Central Rebublic of Africa	9000
Fuel	Central Africa	Central Rebublic of Africa	250
Battery system	Beijing	Central Rebublic of Africa	13000
PV system			
Module	Beijing	France	9300
Structure	France	Central Rebublic of Africa	10000
Wind system	Beijing	Central Rebublic of Africa	13000

Table D3. Inventory of the concrete foundation manufacturing.

Reinforced concrete foundation (kg)	Value	Source
Material (kg/kg foundation)		
Portland cement (K30 and K40)	0,12	LCA building frame materials.
Steel	0,065	LCA building frame materials.
Aggregates	0,00 (natural sand, gravel, stone)	LCA building frame materials.
Water	0,00 (closest community water system)	LCA building frame materials.
Additives	0,00 (negligible)	LCA building frame materials.
Process energy (kWh/kg foundation)	0,0042	LCA building frame materials.

Table D4. Main inventory for the converter manufacturing.

Converter (1 kWh)	Value	Source
Total weight of converter (kg)	8,4	ABB Poroduct specification
Aluminum (kg/converter)	1,6	-
Iron (kg/converter)	5,3	-
Copper (kg/converter)	1,0	-
Sulphuric acid (kg/converter)	0,1	-

Appendix E - Impacts correlated to the life cycle phase

Generally, environmental impacts from renewable power systems and batteries, both resource depletion and emissions, mainly arise in the manufacturing phase. Fossil power systems also consume most resources in the manufacturing of fuels but release most emissions during the usage phase through combustion.

Presented here are the environmental impacts connected to each of the sub-systems of the diesel/battery/PV/wind hybrid power system for RBS-sites.

E.1 Diesel sub-system

The diesel fuel is the dominant component of the diesel sub-system but because the heavy run at RBS-sites, the generators have to be replaced often, providing a notable contribution to the impact categories. The lower the annual fuel consumption, the more influence the generator has on the sub-systems impacts. As an example, if the annual diesel consumption is low (2000 liters per year) the environmental impacts attributed to the generators vary with up to 4 percent depending on different life-times; between 3 to 10 years. If the diesel consumption is halved the generator attribution is raised by up to 9 percent for the short life-time of 3 years.

In Figure E1 the sub-system components relative contributions to the impact categories are presented for an assumed diesel consumption of 20000 liters per year and two generators. The rectifier and foundation is included in the generator model.

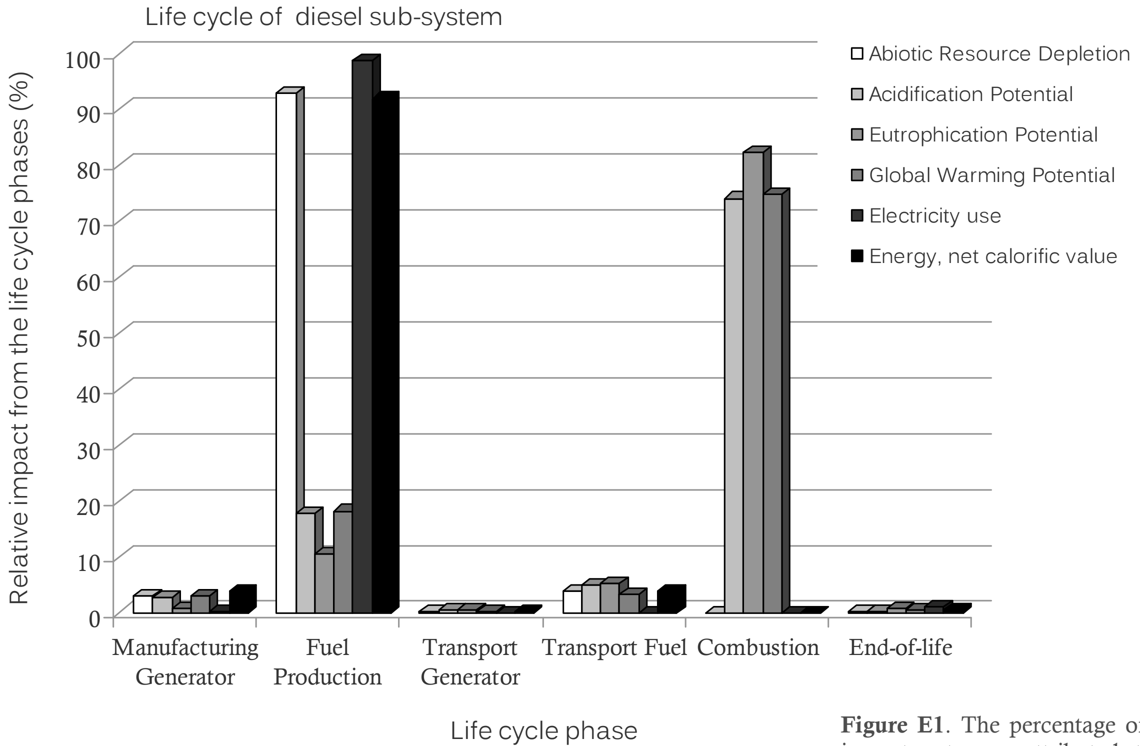


Figure E1. The percentage of each impact category attributed to the different components and life cycle phases of the diesel sub-system.

Manufacturing diesel fuel uses many resources both as crude oil and natural gas but also because of the high electricity requirements. Main activities in the manufacturing of the generators are the up-stream aluminum processing and generator facility electricity usage.

When considered as a part of the diesel system, the concrete foundation and inverter has minor influence (below 0,1 percent) and are considered negligible. If the generator system would be analyzed separately, the concrete foundation should be further evaluated, influencing the generator life cycle with between 3 and 9 percent for the different impact categories.

The usage and transportation activities combust fossil fuel, this cause acidification and eutrophication mainly because of the high amount of sulphur dioxide, ammonia and nitrogen oxide emissions, and global warming mainly because of the carbon dioxide emissions. The fuel transport only includes the local transportation, which still has a notable impact on the different categories (up to 5 percent). Figure 1 also presents emission related impacts attributed to fuel production depending on the extraction and industrial processing.

Recycling of metals within the generator uses a minor part of the life cycle electricity and contributes to minor eutrophic emissions and green house gas emissions (below 1 percent).

E.2 Battery sub-system

To the battery sub-system life cycle impacts (illustrated in Figure 2) the battery bank itself is the main contributor; the housing and foundation contribute with around 6 percent of the different impact categories. Up-stream lead processing and battery facility electricity requirements are the most important activities, followed by the collective effect from the different steel components within the batteries, the foundation and the shelter.

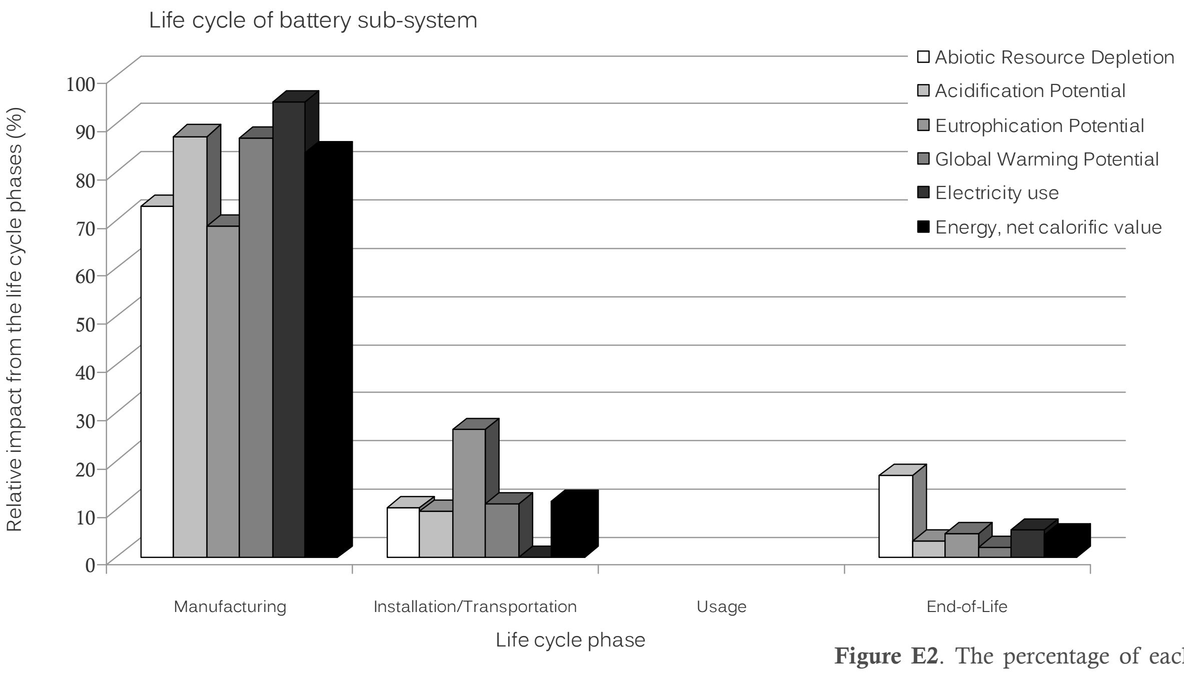


Figure E2. The percentage of each impact category attributed to the different components and life cycle phases of the battery sub-system.

The manufacturing phase consumes 84 percent of the primary energy and 73 percent of the abiotic resources and cause between 70 to 80 percent of the emissions of the battery sub-system life cycle. Main resource sinks are the lead raw material in the batteries and the Chinese electricity mix used for production. The resource consumption of the housing and foundation mainly depend on the amount of steel required and represent 8 and 6 percent respectively. Correspondingly, the manufacturing emissions are attributed to the Chinese electricity mix and processing of lead, followed by different steel components within the housing, foundation and battery bank; and battery bank plastics and glass fibers.

Transporting the batteries influences both the resource requirements and emissions released. The local truck transportation represents around 93 percent of the primary energy requirements of the battery transportation and around 90 percent of the emissions, the ocean sea freight having minor contribution.

The end-of-life phase uses 6 percent of the life cycle electricity requirements, allocated to the battery recycling process. In addition to the electricity production, the battery processing raises the acidification and eutrophication potential; and the direct landfill emissions raise the eutrophication and global warming potentials.

E.3 PV sub-system

The most influential component of the PV sub-system is the PV cell followed by the aluminum structure.

The manufacturing phase of the PV system corresponds to the main life cycle impacts as illustrated in Figure E3. The module manufacturing represents between 70 and 90 percent of different impact potentials. The high influence is mainly attributed to the high electricity requirements in the module manufacturing; including Silicon refining, casting, ingot cutting, cell manufacturing and module assemble. The up-stream metallurgical silicon only represents up to around 2 percent and the aluminum and glass sheet up to 1 percent of this module manufacturing resource requirement and emissions. The aluminum structure and foundation manufacturing corresponds to between 7 and 30 percent and 1 and 3 percent of the different life cycle impact potentials respectively.

The transportation affects the life cycle resource requirements and pollution potentials with up to 3 percent. Approximately 96 percent of these impacts are attributed to the local truck fuel consumption. The ocean freight transportation of the module and the total package correspond to much longer distances but still has minor importance.

The end-of-life phase corresponds to below 2 percent for the different impact categories. Main emission sources are the electricity usage for aluminum recycling and direct landfill emissions.

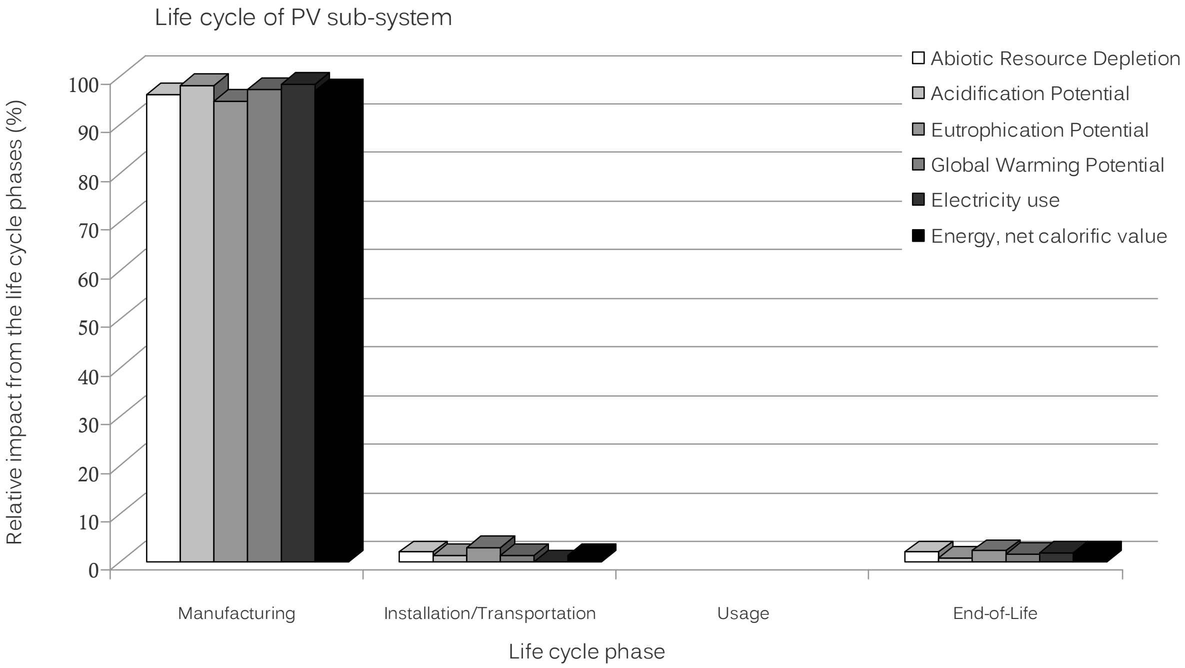


Figure E3. The percentage of each impact category attributed to the different components and life cycle phases of the PV sub-system.

E.4 Wind sub-system

The normalized life cycle impacts of the wind sub-system are illustrated in Figure E4. Main sources of impact are the manufacturing of aluminum and glass fiber components within the wind turbine.

Around 90 percent of the wind sub-system's life cycle impacts originate from manufacturing of the turbine components. For instance around 50 percent of the primary energy is connected to the turbine manufacture and assembling and the remaining to the up-stream material processing. Energy intensive components include aluminum, plastics (glass fiber and epoxy) and copper parts but also the different steel parts are essential because of the high amount required. In manufacturing, the Chinese electricity production is responsible for the main emissions but also aluminum and glass fiber parts are of importance.

The converter resource requirements and emissions are considered negligible (using 0,5 percent of the primary energy and 2,7 percent of the abiotic resources and emitting below 0,5 of the different manufacturing emissions).

The transportation phase consumes around 5 percent of the resources and emits up to 7 percent of the pollutants of the wind sub-system life cycle, the impacts mainly caused in the local diesel truck transportation.

The end-of-life phase corresponds to up to 7 percent of the different impact potentials caused by the wind sub-system. The main primary energy sinks are the recycling of steel and copper and the main emission sources are the electricity production, plastic incineration (which affect the acidification and global warming potential) and direct landfill emissions (which mainly affect the eutrophication potential).

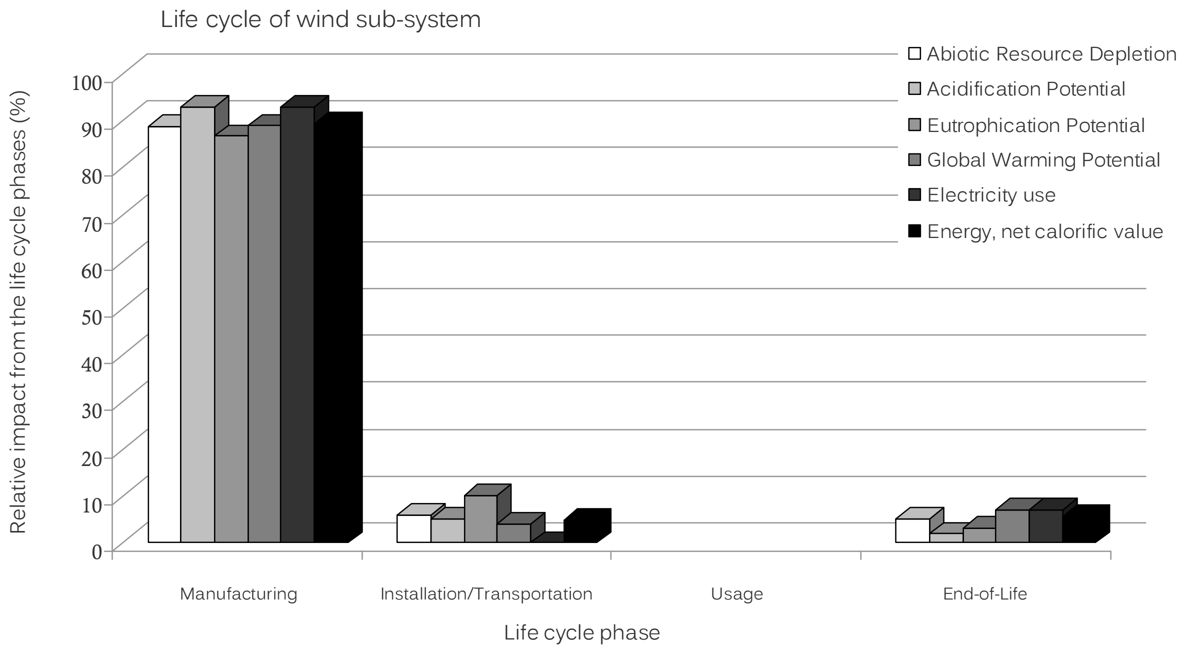


Figure E4. The percentage of each impact category attributed to the different components and life cycle phases of the wind sub-system.

Appendix F – Numeric values for the LCA results related to the different sub-systems.

		For 1 Gen-Set				
Baseline categories (CML)	Manufacturing	Transport/Installation	Usage	Disposal	Tot LC	Unit
Abiotic Resource Depletion	19	1,8		2,0	22	kg Sb eq.
Acidification Potential	15	2,3		1,3	18	kg SO2 eq.
Eutrophication Potential	0,80	0,4		0,72	1,9	kg PO4 eq.
Global Warming Potential	3300	260		570	4100	kg CO2 eq.
Additional categories						
Electricity use	220	0,0		1200	1400	MJ
Energy resource depletion	50050	3700		5700	59000	MJ

		For 1 liter of Diesel				
Baseline categories (CML)	Manufacturing	Transport/Installation	Combustion	Disposal	Tot LC	Unit
Abiotic Resource Depletion	0,020	0,00080	0,0		0,020	kg Sb eq.
Acidification Potential	0,0033	0,00091	0,014		0,018	kg SO2 eq.
Eutrophication Potential	0,00032	0,00016	0,0025		0,0	kg PO4 eq.
Global Warming Potential	0,65	0,12	2,7		3,5	kg CO2 eq.
Additional categories						
Electricity use	3,6	0,0	0,0		3,6	MJ
Energy resource depletion	41	1,7	0,0		43	MJ

		For 1 12V cell				
Baseline categories (CML)	Manufacturing	Transport/Installation	Usage	Disposal	Tot LC	Unit
Abiotic Resource Depletion	1,2	0,17		0,27	1,6	kg Sb eq.
Acidification Potential	2,1	0,22		0,079	2,4	kg SO2 eq.
Eutrophication Potential	0,093	0,036		0,0065	0,14	kg PO4 eq.
Global Warming Potential	200,0	25		4,6	230	kg CO2 eq.
Additional categories						
Electricity use	240	0,0		14	250	MJ
Energy resource depletion	2600	350		140	3070	MJ

		For 1 sqm PV				
Baseline categories (CML)	Manufacturing	Transport/Installation	Usage	Disposal	Tot LC	Unit
Abiotic Resource Depletion	6,9	0,14		0,14	7,2	kg Sb eq.
Acidification Potential	13	0,18		0,086	13	kg SO2 eq.
Eutrophication Potential	0,94	0,030		0,022	0,99	kg PO4 eq.
Global Warming Potential	1600	21		26	1700	kg CO2 eq.
Additional categories						
Electricity use	4400	0		84	4500	MJ
Energy resource depletion	21000	290		410	22000	MJ

		For 1 Turbine				
Baseline categories (CML)	Manufacturing	Transport/Installation	Usage	Disposal	Tot LC	Unit
Abiotic Resource Depletion	34	2,3		2,0	39	kg Sb eq.
Acidification Potential	56	3,0		1,2	60	kg SO2 eq.
Eutrophication Potential	4,2	0,50		0,15	4,9	kg PO4 eq.
Global Warming Potential	7600	350		600,0	8600	kg CO2 eq.
Additional categories						
Electricity use	15000	0,0		1200	16000	MJ
Energy resource depletion	89000	4900		5600	100000,0	MJ

Appendix G – Detailed sensitivity analysis parameter variations

Scenario	Variable	Base case		Alternative scenario
1	Electricty mix	Cinese for		Hydro power
			manufacturing PV modules	
			manufacturing wind turbin	
			manufacturing batteries	
		French for		Hydro power
			manufacturing PV structure	
		British for		Hydro power
			manufacturing generator	
		European		Hydro power
			manufacturing fuel for sea fright and truck tansportation	
		African		Hydro power
			manufacturing concrete	
		World average		Hydro power
			manufacturing converter	
			end-of-life process for batteries, PV, Wind and generator	
		Not defined		Unchanged
			manufacturing diesel for site	
2	Electricity mix			Chinese
3	End-of-life recycling	Glass		
			0%	Data missing
		Aluminum		
			60%	100%
		Steel in foundation		
			0%	100%
		Steel in components		
			80%	100%
		Silicon (1)		
			0%	100%
		Plastics		
			0%	missing
		Copper		
			50%	100%
		Lead		
			all	No increase possible
4	Recycled mat. in manufacturing (2)	Aluminum in generator, PV module, structure, turbine		
			0%	34%
		Lead in batteries (3)		
			0%	80%
		Steel in generator and wind turbine		
			0%	90%
		Cu		
			0%	35%
5	Life-time of system	total system		
			30 years	10 years
		of wind system		
			30 years	10 years
		of PV system		
			20 years	10 years
		of battery system		
			3 and 5 years	3 and 5 years
		of diesel generator		
			3,7 and 10 years	3,7 and 10 years

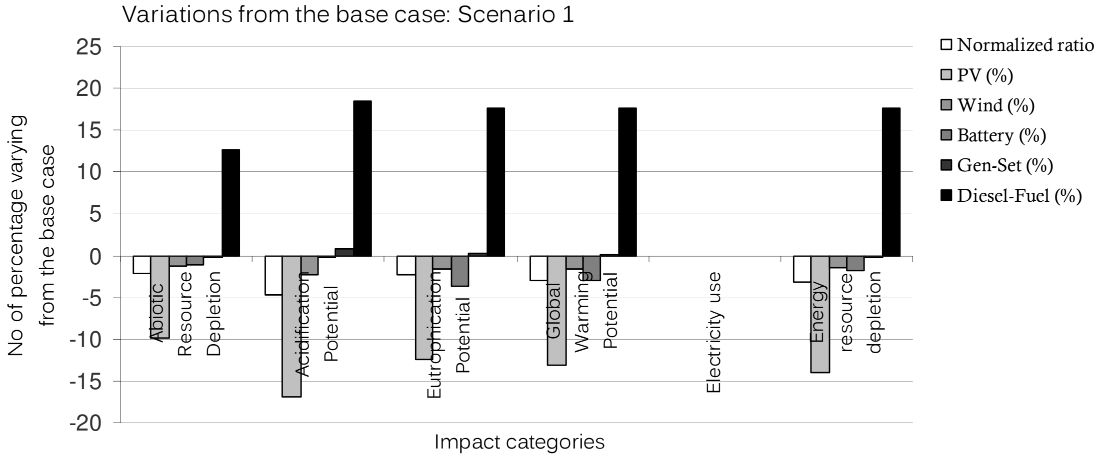
6.1	Silicon refining energy	3577 MJ	7200 MJ
6.2		3577 MJ	16500 MJ
7	Silicon refining energy	3577 MJ	2400 MJ
8.1	Energy in wind manufacturing	3385,6 kWh	8899 kWh
8.2		3385,6 kWh	33856 kWh
9.1	Energy in battery manufacturing	10,59 kWh/2 V cell	14,01 kWh/2 V cell
9.2	Energy in vandium battery manu.	10,59 kWh/2 V cell	4,23 kWh/2 V cell

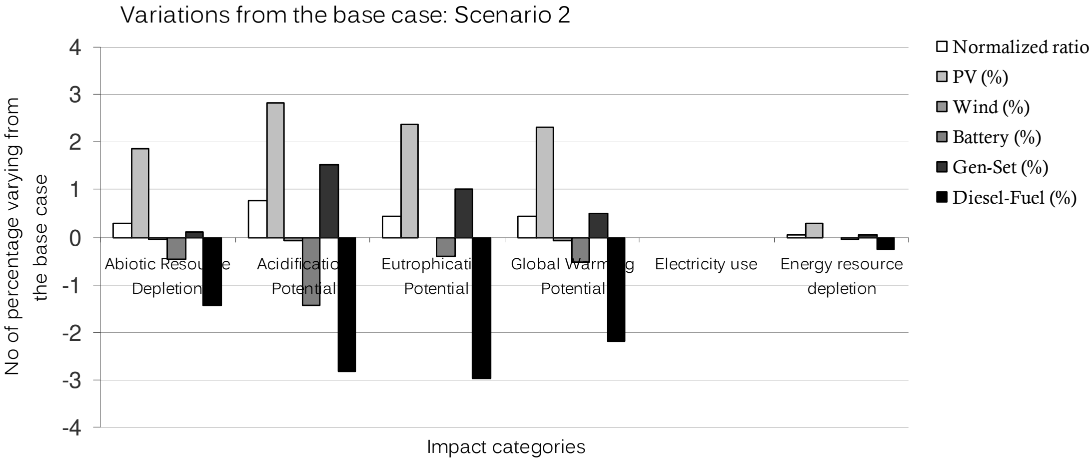
1) Requireing 1/3 of minimum production energy (García-Valverde et al., (2009) stating thatPV module recycling could save up to two thirds of the energy requirements for wafer production and Alsema (2000) reviewing the maximum and minimum energy requiremets).

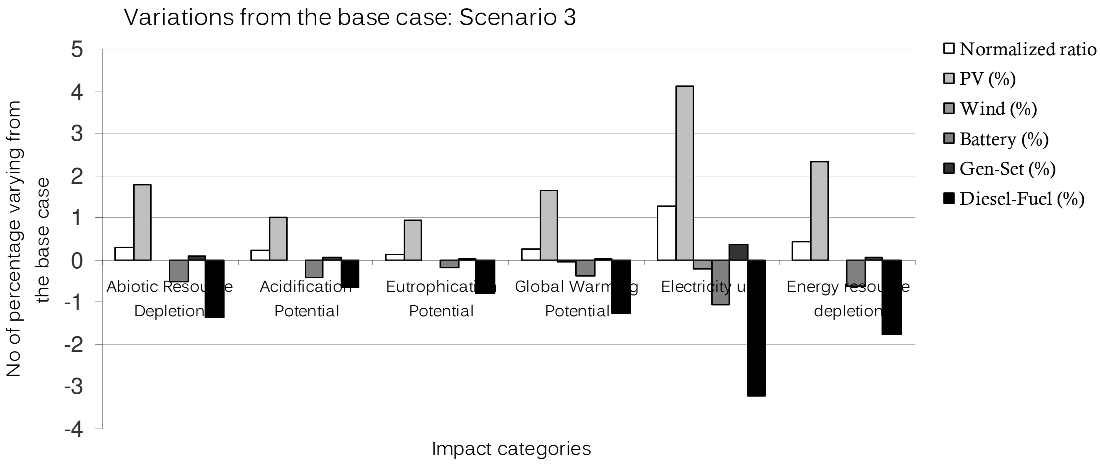
2) Within scenario four the main production metal material requirements were varied between no usage of recycled metals and the global average usage of recycled metals in production (www.world-aluminum.org, www.recycle-steel.org). The choice only to vary the metal input depended on the high cleanness specifications on the glass sheets used for the PV modules, missing data on rates of recycled plastic and acids in manufacturing and the low importance of the metallurgical silicon amount.

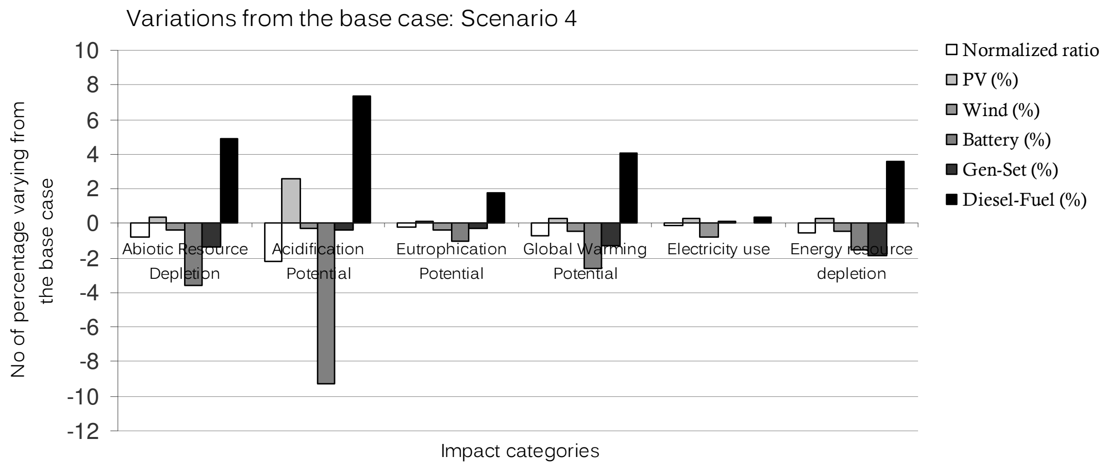
3) In reality the usage of more than 50 to 60 percent of secondary lead can lead to technical complications (Rydh, 1998, Ericsson employee 1, personal communication 2009-11-30), but this high value of recycled lead was used to map the greatest variations from the base case.

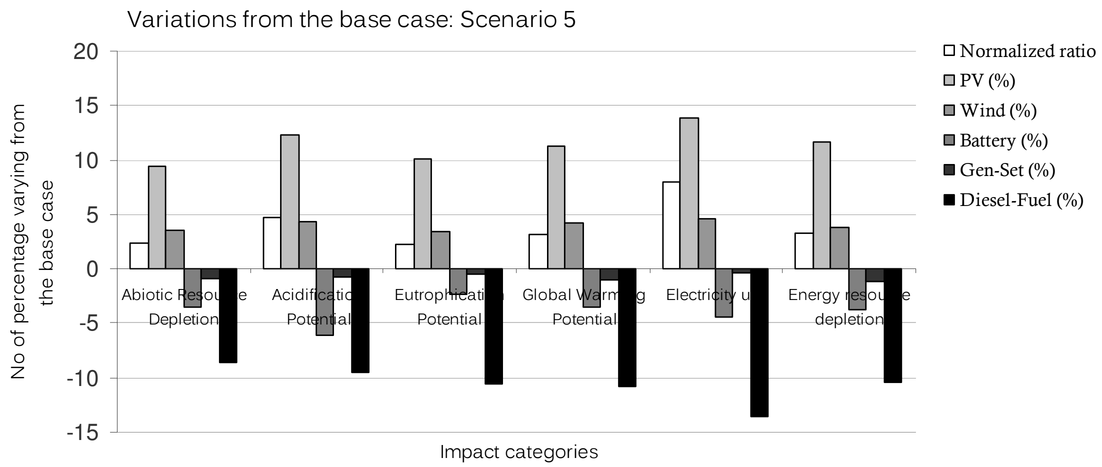
Appendix H – Detailed sensitivity analysis results

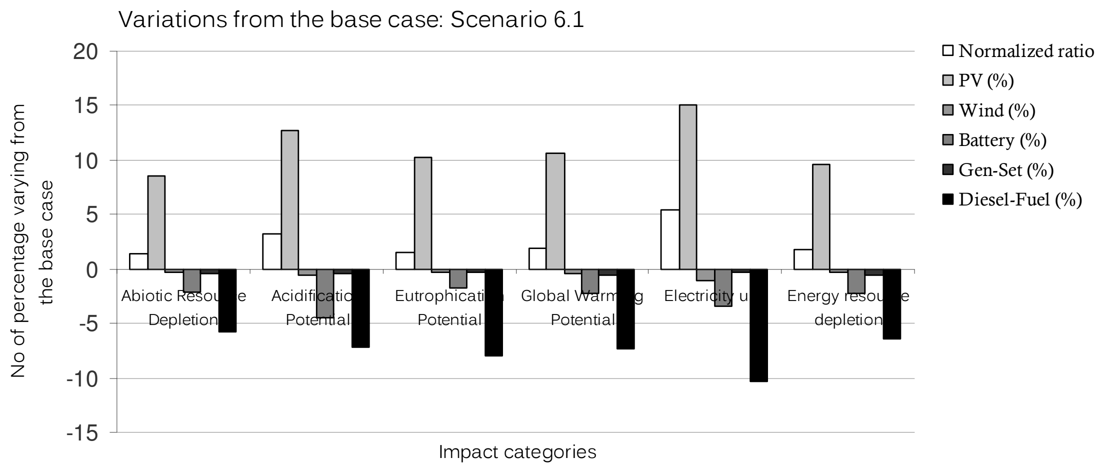


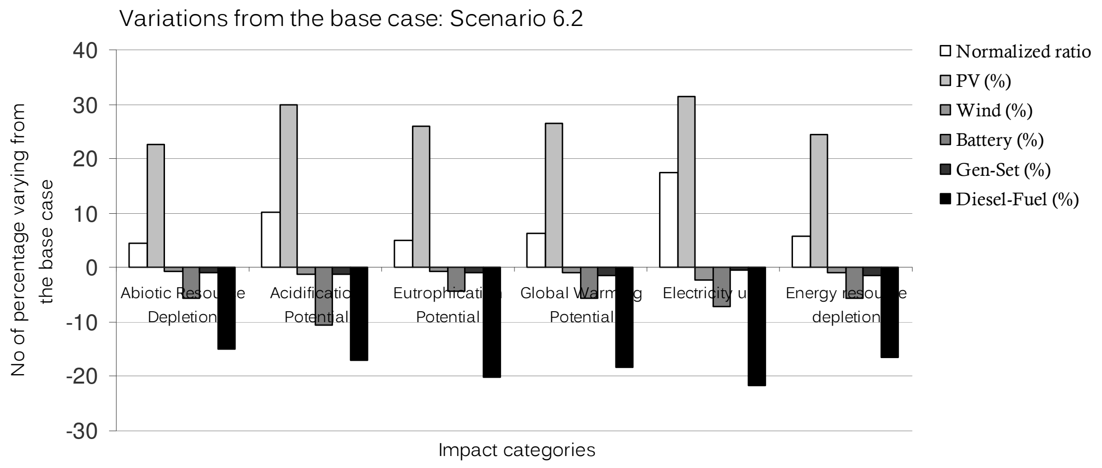




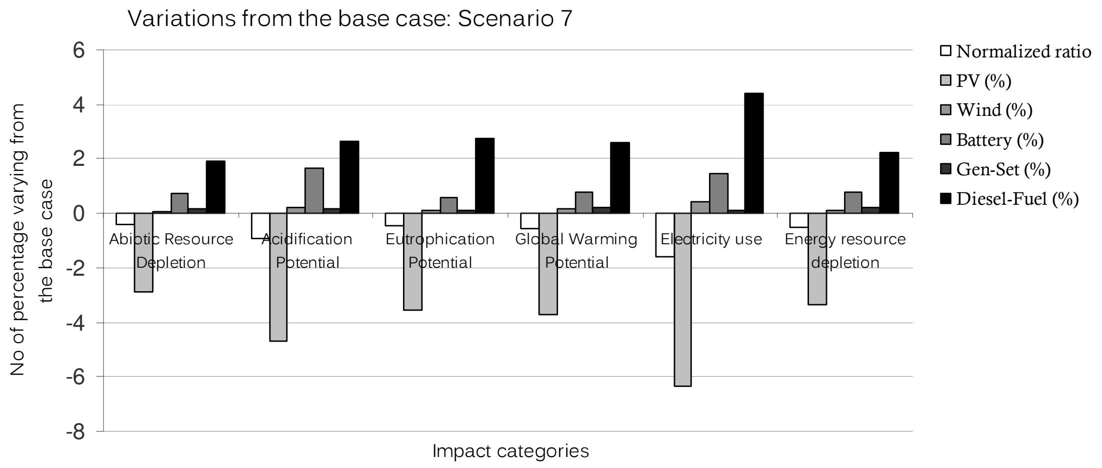

Variations from the base case: Scenario 4
No of percentage varying from the base case
Impact categories
Abiotic Resource Depletion
Acidification Potential
Eutrophication Potential
Global Warming Potential
Electricity use
Energy resource depletion
Normalized ratio
PV (%)
Wind (%)
Battery (%)
Gen-Set (%)
Diesel-Fuel (%)


Variations from the base case: Scenario 5
No of percentage varying from the base case
Impact categories
Normalized ratio
PV (%)
Wind (%)
Battery (%)
Gen-Set (%)
Diesel-Fuel (%)

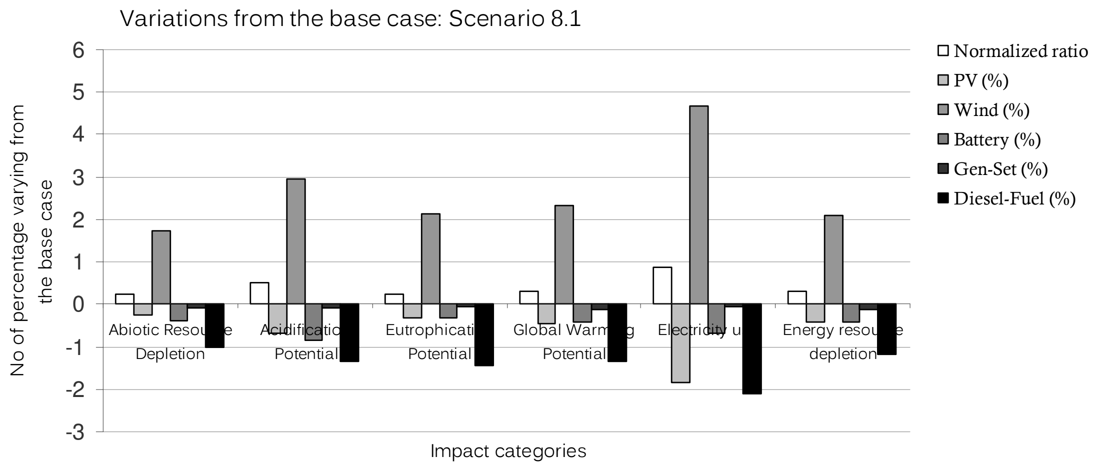

Variations from the base case: Scenario 6.1
No of percentage varying from the base case
Impact categories
Normalized ratio
PV (%)
Wind (%)
Battery (%)
Gen-Set (%)
Diesel-Fuel (%)



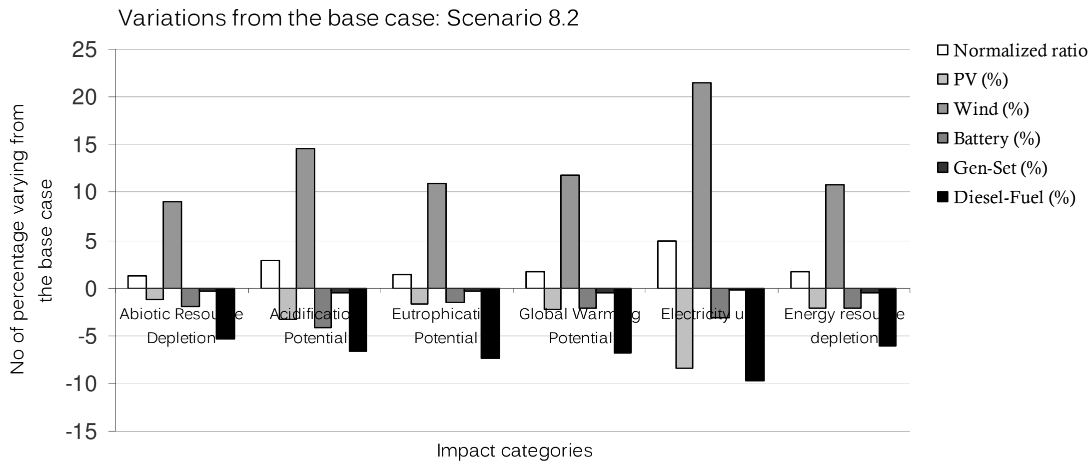
Variations from the base case: Scenario 6.2
No of percentage varying from the base case
Impact categories
Abiotic Resource Depletion
Acidification Potential
Eutrophication Potential
Global Warming Potential
Electricity use
Energy resource depletion
Normalized ratio
PV (%)
Wind (%)
Battery (%)
Gen-Set (%)
Diesel-Fuel (%)

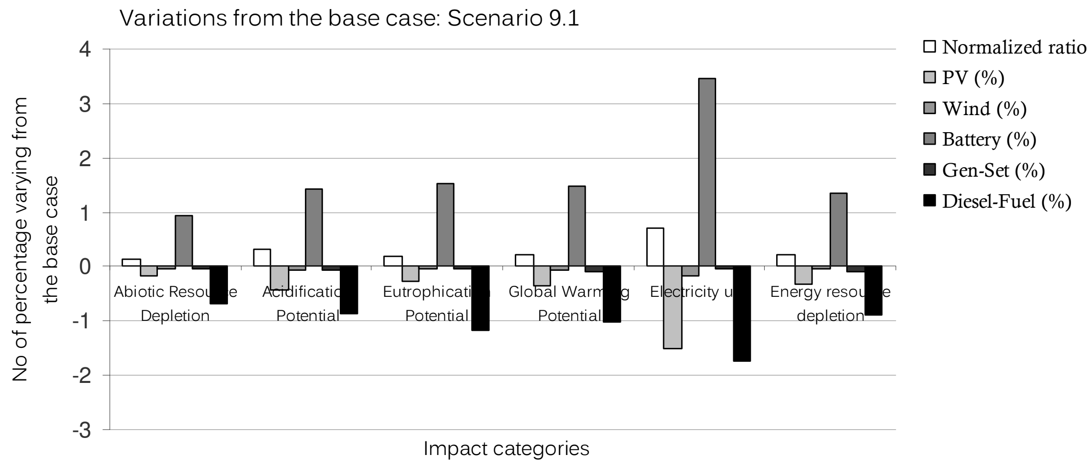


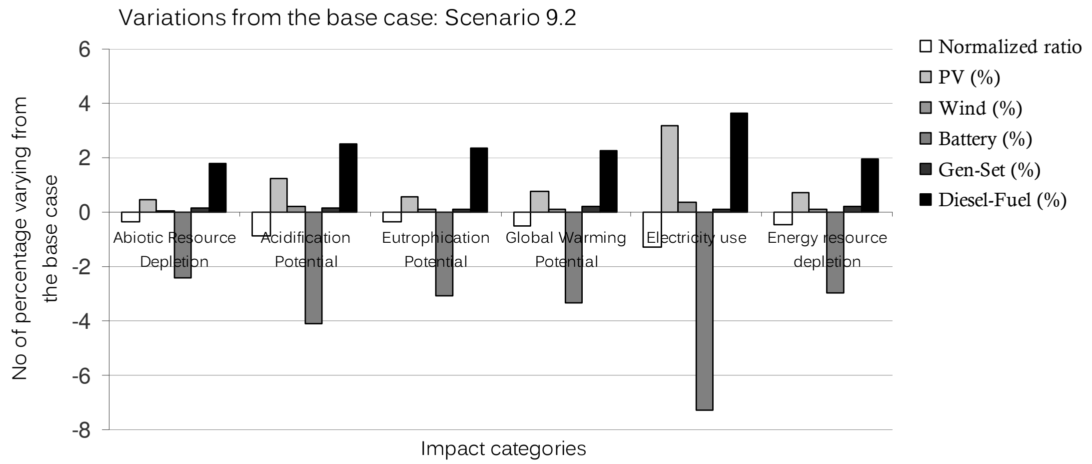
Variations from the base case: Scenario 7
No of percentage varying from the base case
Impact categories
Abiotic Resource Depletion
Acidification Potential
Eutrophication Potential
Global Warming Potential
Electricity use
Energy resource depletion
Normalized ratio
PV (%)
Wind (%)
Battery (%)
Gen-Set (%)
Diesel-Fuel (%)



Variations from the base case: Scenario 8.1
No of percentage varying from the base case
Impact categories
Abiotic Resource Depletion
Acidification Potential
Eutrophication Potential
Global Warming Potential
Electricity use
Energy resource depletion
Normalized ratio
PV (%)
Wind (%)
Battery (%)
Gen-Set (%)
Diesel-Fuel (%)


Variations from the base case: Scenario 8.2
No of percentage varying from the base case
Abiotic Resource Depletion
Acidification Potential
Eutrophication Potential
Global Warming Potential
Electricity use
Energy resource depletion
Impact categories
Normalized ratio
PV (%)
Wind (%)
Battery (%)
Gen-Set (%)
Diesel-Fuel (%)


Variations from the base case: Scenario 9.1
No of percentage varying from the base case
Abiotic Resource Depletion
Acidification Potential
Eutrophication Potential
Global Warming Potential
Electricity use
Energy resource depletion
Impact categories
Normalized ratio
PV (%)
Wind (%)
Battery (%)
Gen-Set (%)
Diesel-Fuel (%)


Variations from the base case: Scenario 9.2
No of percentage varying from the base case
Abiotic Resource Depletion
Acidification Potential
Eutrophication Potential
Global Warming Potential
Electricity use
Energy resource depletion
Impact categories
Normalized ratio
PV (%)
Wind (%)
Battery (%)
Gen-Set (%)
Diesel-Fuel (%)

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