Environmental and economic investigation of telecom site back-up power systems

Master of Science Thesis in Industrial Ecology

CAROLINE ERSTRÖM

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2010
Report No. 2010:17

MASTER'S THESIS 2010:17

Environmental and economic investigation of telecom site back-up power systems

Master of Science Thesis in Industrial Ecology

CAROLINE ERSTRÖM

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2010

Environmental and economic investigation of telecom site power back-up systems
ISSN nr: 1404-8167

Master of Science Thesis in Industrial Ecology
CAROLINE ERSTRÖM

Examensarbete / Institutionen för energi och miljö
Chalmers tekniska högskola 2010:17

Department of Energy and Environment
Division of Environmental Systems Analysis
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: +46 (0)31-772 10 00

Environmental and economic investigation of telecom site back up power systems

CAROLINE ERSTRÖM

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY

Abstract

Diesel generators and lead-acid batteries are currently used as telecom site back-up power in areas where the local electricity grid is not always available. Fuel cell systems are an interesting alternative. In this study, environmental and economic aspects of the following five power back-up systems have been investigated: a diesel generator system, a lead-acid battery system, a fuel cell system with H_2 from steel bottles (produced from central electrolysis), a fuel cell system with on-site electrolysis, and a fuel cell system with on-site reforming of methanol. Calculations have been performed for different combinations of power demands (1.5 kW, 3 kW, 5 kW, 8 kW) and electricity grid availabilities (99.9%, 99%, 95%, 90%, 75%).

The fuel/electricity use is an important factor in the environmental investigation. Based on the four chosen impact categories (abiotic depletion potential, acidification potential, eutrophication potential, and global warming potential), the battery system and the fuel cell system with a reformer have lower potential environmental impact than the diesel system. The two fuel cell systems with H_2 from electrolysis could have better environmental performance than the diesel system if the electricity is based on a significant share of renewable energy. However, it is important to remember that the choice of weighting factors has a significant impact on the ranking of the different power systems.

The battery system is the cheapest for most of the combinations of power demand and grid availability, especially when there is no need for a change of batteries. Fuel cell systems with H_2 bottles or reformer can be a cost-competitive option for smaller power demands and grid availabilities down to 95%, if the site conditions are inappropriate for battery systems and if the investment cost for the fuel cells is lowered.

It is suggested that calculations should be performed for a variety of site locations, in order to eliminate some of the uncertainties in the estimates and to be able to identify sites were fuel cell systems can be used. A study capturing a bigger variety in battery configurations should also be executed.

Acknowledgments

First of all, I have to thank Christer Lindkvist and Leif-Olof Fager at Ericsson for coming up with the idea and for giving me the opportunity to do this master’s thesis. I want to thank all employees at Ericsson who have helped me during my work, especially my supervisor Christer Lindkvist and Anna Bondesson. I also want to thank Mesut Ogur for a valuable cooperation and my academic supervisor Bengt Steen at Chalmers University of Technology.

Finally, I want to thank my family and friends for their eternal support. I also want to thank everyone who offered me a place to stay during my trips to Göteborg.

Göteborg September 2010

Caroline Erström

Table of contents

List of figures

List of tables

1 List of abbreviations

ADP – Abiotic depletion potential

AP – Acidification potential

BoP – Balance of plant

CAPEX – Capital expenditure

CML – Institute of Environmental Sciences, Netherlands

CO_2 – Carbon dioxide

EI – Environmental impact

EP – Eutrophication potential

FC – Fuel cell

g.a. – Grid availability

GWP – Global warming potential

H_2 - Hydrogen

kW – Kilowatt

kWh – Kilowatt-hour

LCA – Life cycle assessment

LCIA – Life cycle impact assessment

MEA – Membrane electrode assembly

MeOH – Methanol

Nm^3 – Normal cubic meter

OPEX – Operational expenditure

PAFC – Phosphoric acid fuel cell

PEM – Polymer electrolyte membrane

PGM – Platinum group metals

PO_4 – Phosphate

pv – Present value

RBS – Radio base station

Sb – Antimony

SLPM – Standard liters per minute

SO_2 – Sulfur dioxide

2 Outline of the report

Section 3 contains an introduction with the purpose to enlighten why the study should be performed.

The aim of the thesis, choice of back-up power systems and methodology are presented in section 4.

Section 5 contains a general description on life cycle assessment and a short description on how to perform present value cost calculations.

The chosen power demands and grid availabilities are presented in section 6 and the components and fuels/electricity needed in each of the five different power systems are presented in section 7.

The results from different steps of the performed life cycle assessment are presented in sections 8-10 and the results of the total cost calculations in section 11.

The results of the environmental and economic investigations are compared in section 12.

Section 13 contains recommendations on subjects for further investigation.

The overall conclusions of the work are stated in section 14.

Section 16 and 17 and contains life cycle inventory data and characterization results for all power systems.

Total cost results for power demands of 1.5 kW, 5 kW, and 8 kW are displayed in sections 18-20.

3 Introduction

Today, there are more than 5 billion subscribers in the telecom industry. The number of users has been increasing exponentially in the last 10 years. Currently, there are approximately 5 million telecom sites, and in order to meet the increasing demand, the number of sites increases every year.

The operation of radio towers requires a constant supply of energy. Thus, it’s easy to build cellular networks in developed areas with a reliable main power grid. However, in developing areas, 1.6 billion people have no access to an electricity grid. In addition, about 1 billion are connected to unreliable grid base stations.

Currently, most of the off-grid and back-up power is supplied by diesel generators. Lead-acid batteries are also used for back-up. From a sustainability perspective, the use of diesel generators is not a good alternative because of the significant amount of environmentally hazardous emissions during operation. The actors in the telecommunications market have started to focus on sustainability issues, trying to find appropriate solutions that are both sustainable and economically feasible. Thus, there is a need to compare the sustainability aspects with investment costs and operation costs for different power supply alternatives on telecommunication site level. Solar power, wind power and fuel cells are mentioned as appropriate sustainable solutions.

This thesis work will be a basis for the communication of sustainability aspects to customers and for the development of new back-up solutions.

4 Aim and scope

4.1 Aim

The main purpose with the thesis is to evaluate power back-up systems on telecommunication sites from a sustainability point of view. The results from the sustainability investigation will be compared with economical aspects in order to find feasible solutions. The thesis aims to answer the question:

Which power back-up systems on a telecommunication site level are appropriate from a sustainability and economical perspective when parameters such as grid availability, reliability and outage time of the local electricity grid are taken into account?

4.2 Scope

The following power solutions for back-up will be investigated:

- Diesel generators
- Lead batteries
- Fuel cell systems
    - H_2 from central electrolysis delivered in steel bottles
    - On-site electrolysis
    - On-site reforming of methanol

The sustainability aspects will be investigated with life cycle assessment (LCA). A time perspective of 5 years will be used in the study. The total calculations will include investments cost of the equipment as well operational costs during a 5-year-period.

Off-grid applications will not be covered in this work. An internal study on environmental performance of off-grid applications has been performed by Anna Bondesson at the division EMF Safety and Sustainability.

5 Methodology

This section provides a general description on life cycle assessment and a short description on how to perform present value cost calculations.

5.1 Life cycle assessment (LCA)

Life cycle assessment is a method used for estimation of potential environmental impact of products, services or systems along the whole life cycle. The life cycle model can according to Baumann & Tillman (2004) be illustrated as in Figure 5.1. The arrows in Figure 5.1 represent flows of material or energy.

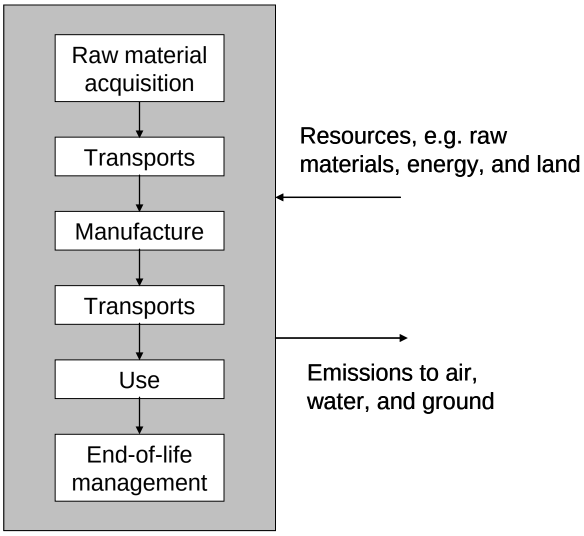

Figure 5.1: An example of life cycle model

The results from a LCA can be used in decision making as well as for learning and communication. Since a LCA maps a whole product system, sub-optimization can be avoided. There is also a possibility to compare the potential environmental performance of different products and systems. The results from a LCA can not be directly connected to a specific site, since the different processes during the life cycle of a product or system usually take place at various locations. Thus, environmental impact cannot be modeled at a very detailed level.

A LCA is conducted in four steps; goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation. The steps are illustrated in Figure 5.2. It is an iterative process, which is indicated with dashed arrows in the figure. A description of the activities in each step is provided in sections 5.1.1-5.1.4. A series of international standards, ISO 14040-14043, have been issued from 1997 onwards and are now a reference for all practitioners of LCA.

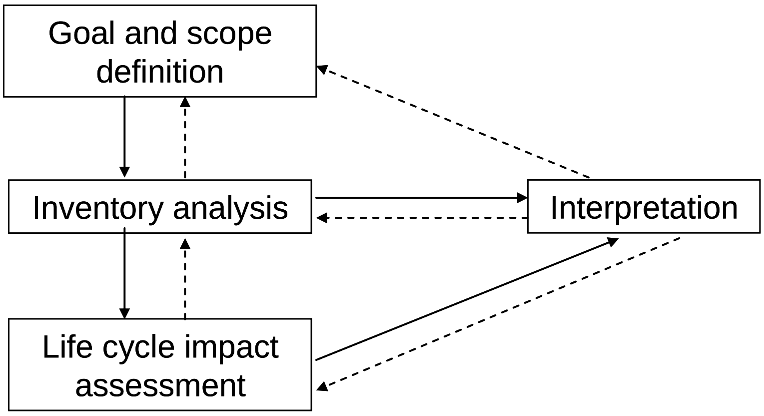

Figure 5.2: Illustration of the LCA procedure

Currently, economical and social aspects are not taken into account during a LCA. One exception is the weighting process, which is described in section 5.1.3. However, it is predicted that the economical and social aspects will be included as the method is developed. Risk assessment is another aspect that is not included in a LCA.

The biggest critique on LCA is connected to the data collection process. The result of the LCA is highly dependent on the availability of data, and finding reliable data can be a very time consuming process. It is common to use data from LCA databases or secondary data from other LCA studies. The validation of data can be obstructed if highly aggregated data is used.

5.1.1 Goal and scope definition

The purpose and intended application of the LCA is stated in the goal definition. It is also important to state which audience the results will be communicated to. It is quite common that the initial purpose of the LCA is vaguely expressed, i.e. “we want to perform an LCA on our product”. It is necessary to determine a specific goal of the study, in order to be able to make methodological choices in the scope definition. The following two questions are good examples of a more specific purpose:

- Which product/system used for a certain application has the best environmental performance?

- Which activities in a product’s life cycle contribute most to the environmental impact of the product?

Once the goal definition is set, methodological choices can be made in accordance with the purpose of the study. Which type of LCA to conduct and selection of products, services or systems to be included in the study are stated in the scope definition. The choice of system boundaries, functional unit, impact categories and method of impact assessment as well as data quality requirements are other important parts of the scope definition.

The purpose of choosing a functional unit is to determine a reference flow to which all flows in the model should be related. For instance, emissions from different phases of the life cycle are expressed in terms of the functional unit. A kWh is an example of an appropriate functional unit when comparing the environmental performance of different power systems. Common environmental impacts considered in LCAs and methods for impact assessments are described in section 5.1.3.

5.1.2 Inventory analysis

The following activities are performed during the inventory analysis:

- Drawing of flow charts
- Data collection
- Relating data to the functional unit

In this step, systems are modelled according to the specifications in the goal and scope definition. A detailed flow chart is constructed in order to show all activities and flows included in the assessment in detail. Only environmentally relevant flows are included, such as use of scarce resources and emissions of hazardous substances to air, water or land. Thus, the mass and energy balances of the flow charts are incomplete. The process of collecting data is started when the important activities and flows have been identified. The data collection is one of the most time consuming steps of the LCA. Finally, when the data is collected, calculations are performed in order to relate the data to the functional unit. LCA software is usually used to keep track of the collected data and to perform the required calculations.

5.1.3 Life cycle impact assessment (LCIA)

In this step, the data from the inventory analysis is transformed from information on emissions and use of resources to information on potential environmental impact. The mandatory phases of the LCIA are illustrated in Figure 5.3.

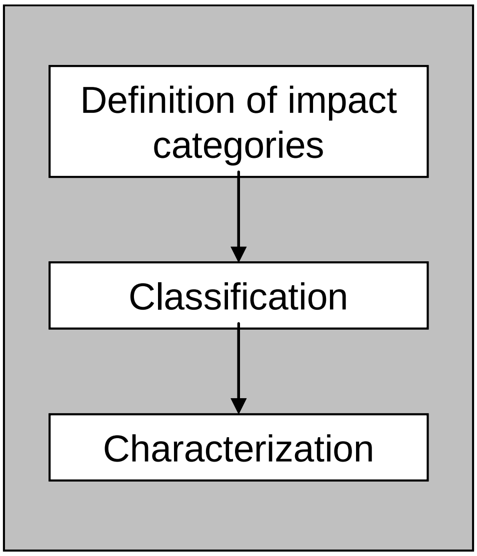

Figure 5.3: Mandatory phases during the life cycle impact assessment.

Impact categories are defined based on models of cause-effect chains and their end-points. Different suggestions on complete sets of impact categories are available in the LCA literature. Abiotic depletion potential, acidification potential, eutrophication potential and global warming potential are impact categories suggested by the

Institute of Environmental Sciences (CML). The mentioned categories only constitute a part of the total set of impact categories in the CML model.

During the classification step, the inventory data is coupled to the defined impact categories. Equivalency factors are defined for all emissions in terms of the reference unit of the impact category. For instance, the reference unit of the global warming potential impact category is kg of CO_2-equivalents and the equivalency factor of 1 kg of methane is 21 kg of CO_2. After the characterization step, all emissions are expressed in terms of the reference unit of the impact category they have been classified in.

Sometimes it is difficult to draw conclusions based on the characterization results. For instance, when comparing two systems a situation might occur where none of the systems has the best environmental performance for all impact categories. At this point, it is possible to perform two extra steps during the life cycle impact assessment; normalization and weighting.

A normalization step has to be performed, since the characterization results for the impact categories differ several orders in magnitude. CML provides normalization factors as well. A normalization factor relates the characterization result for each category to the predicted magnitude of emissions in a region or globally.

In order to aggregate the data into a one-dimensional index, the relative importance of the impact categories has to be determined. The relative importance can be determined in several ways. For instance, formalized and quantitative weighting procedures or expert panels can be used. Values have to be introduced in the process, since the relative importance of the categories can not be determined based only on natural science. Today, only a few sets of weighting factors are provided in literature.

The weighted results are calculated with the formula below:

$$Total\ impact\ = \sum_i weighting\ factor_i \cdot \frac{characterization\ result_i}{normalization\ factor_i}$$

The summation index *i* represents different impact categories.

5.1.4 Interpretation

In this phase, the results from the previous steps are summarized and critically reviewed. For instance, a completeness check of data and/or a sensitivity analysis can be performed. Conclusions and recommendations on improvement of the models are also stated in this step.

5.2 Present value cost calculations

In order to estimate the total costs, future costs should be discounted because of the time value of money. The investment cost I and operational costs (fuel costs (E), maintenance costs (M), and replacement costs (R)) are usually included in total costs.

$$Total\ cost = I + E_{pv} + M_{pv} + R_{pv}$$

The index *pv* denotes present value. The present value is calculated according to the formula below

$$C_{pv} = \frac{C}{(1+i)^t}$$

C is the known cost, *i* is the annual interest rate, *t* represents the number of years from the present year during which the cost occurs, and C_{pv} is the present value cost.

6 Choice of power demands and grid availabilities

The environmental and economic aspects for each of the five chosen systems will be investigated for power demands of 1.5, 3, 5 and 8 kW combined with the grid availabilities presented in Table 6.1. The power range is chosen in order to cover the power demand of a majority of radio base station applications. In addition, the smallest diesel generator on the market has a maximum capacity of 8 kW.

A diesel generator has the highest number of operation hours (12000 h) compared to the other components. With 75% grid availability, the diesel generator has to be replaced after 5 years. This is partly the reason for choosing a 5 year time perspective in this study. The aim to focus on present state of technology is another reason. A rather short time perspective is necessary because of the rapid development of fuel cell technology.

Table 6.1: Number of outage hours per year and grid availability

Grid availability (%)	Outage hours/year
99.9	9
99	88
95	438
90	876
75	2190

The size of the battery banks and the amount of H_2 bottles to be stored on site are dependent on the demanded number of back-up hours for the power system. The intervals of back-up hours for different grid availabilities are presented in Table 6.2. These intervals are collected from the internal report “Fuel cells in RBS applications – a technology study” by Hellmans. In order to simplify the analysis, the systems in the study are designed for the mean amount of back-up hours of the intervals. The exception is the case of 75% grid availability, in which a demand of 12 back-up hours is assumed.

Table 6.2: Common amount of back-up hours for different grid availabilities according to Hellmans and the back-up hours chosen in the study.

Grid availability (%)	Required back-up hours	Back-up hours in this study
99.9	2-4	3
99	4-8	6
95	4-8	6
90	6-12	9
75	>6	12

7 Power systems chosen for investigation

The equipment and fuel/electricity needed for each power system are presented in sections 7.1-7.5. Additional diesel/electricity consumption as a part of regular maintenance is not included in the calculations. Additional components may be required to get a fully functioning system. These components are omitted in the system description since it's assumed that their environmental impact and costs are negligible in comparison with other system components.

7.1 System 1: Diesel generator

The main components needed in the system are a diesel generator, rectifiers (AC from diesel generator to DC for site) and a fuel tank. A generator with 10 kVA capacity and 1400 W rectifiers are used in the calculations. The configuration of the diesel generator includes dummy loads to handle low loads levels without damaging the engine and to increase the fuel efficiency. The life length of all components in the system is at least 5 years. The number of rectifiers needed for each power demand is presented in Table 7.1.

Table 7.1: Number of rectifiers needed in the diesel system for different power demands

Power demand (kW)	Number of rectifiers
1.5	3
3	4
5	5
10	9

7.1.1 Fuel demand

The yearly diesel demand resulting from an assumed generator fuel consumption of 0.5 l/kWh is found in Table 7.2. This fuel consumption corresponds to an energy efficiency of 18%. Since the diesel generator will be used as back-up, the fuel consumption per kWh will be higher than for a generator used in off-grid applications. Rectifier losses (10%) are also included in the fuel consumption.

Table 7.2: Yearly consumption of liters of diesel at different grid availabilities and power demands

	Power demand (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	7	13	22	35
99	66	131	219	350
95	329	657	1095	1752
90	657	1314	2190	3504
75	1643	3285	5475	8760

7.2 System 2: Lead-acid batteries

The components included in the analysis for the battery back-up system are batteries, rectifiers (AC from electricity grid to DC for batteries) and racks. 2*100 Ah@12 V batteries of AGM type and rectifiers with a capacity of 1400 W were used in the calculations. Ten batteries can be placed in a standard rack. The amount of batteries and rectifiers needed was determined with a battery model available at Ericsson

(Brehmer, 2007). The amount of batteries, rectifiers and racks required per power demand and grid availability are presented in Table 7.3-Table 7.5. The assumed life length of the batteries per grid availability is presented in Table 7.3. The rack and the rectifiers are assumed to have a life length of at least 5 years.

Table 7.3: Required number of 24 V batteries for different power demands and grid availabilities

	Power demand (kW)				Battery life length (years)
Grid availability (%)	**1.5**	**3**	**5**	**8**	
99.9	3	6	9	15	7
99	5	10	16	25	7
95	5	10	16	25	5
90	7	15	24	38	3
75	10	19	32	50	2

Table 7.4: Required number of 1400 W rectifiers for different power demands and grid availabilities

	Power demand (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	3	4	6	7
99	3	4	6	9
95	3	4	6	9
90	3	5	8	12
75	3	6	9	14

Table 7.5: Required number of racks for different power demands and grid availabilities

	Power demand (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1	1	1	2
99	1	1	2	3
95	1	1	2	3
90	1	2	3	4
75	1	2	4	5

7.2.1 Electricity demand

With an efficiency of 85%, the amount of kWh needed per year from the electricity grid in order to charge the batteries are presented in Table 7.6.

Table 7.6: Number of required kWh per year from the electricity grid in order for charging of batteries

	Power demand (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	15	31	52	82
99	155	309	515	824
95	773	1546	2576	4122
90	1546	3092	5153	8245
75	3865	7729	12882	20612

7.3 System 3: PEM fuel cell with H_2 from central electrolysis

The fuel cells used in the calculations have the same capacity as the power demand (1.5, 3, 5 and 8 kW). The fuel cell is assumed to be able to operate for 4000 hours. If the hydrogen is produced from electrolysis, then it's pure enough to be used in the fuel cell. Information on the bottles in which the hydrogen is delivered is found in Table 7.7.

Table 7.7: Bottle characteristics

Pressure (bar)	200
Volume (l)	50
Storage capacity (Nm3 H2)	9
Storage capactity (kg H2)	0.8
Bottle weight (kg)	70
Material	Steel

7.3.1 Fuel demand

The required amount of hydrogen bottles per year is calculated based on a fuel cell efficiency of 0.4 and the information in Table 7.7 (see results in Table 7.8). One bottle can supply 10.8 kWh.

Table 7.8: Required amount of H_2 bottles per year

	Power demand			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	2	3	5	7
99	13	25	41	65
95	61	122	204	325
90	122	244	407	650
75	305	610	1016	1625

7.4 System 4: PEM fuel with H_2 from on-site electrolysis

The fuel cells used in the calculations have the same capacity as the power demand (1.5, 3, 5 and 8 kW). The capacity of the electrolyzer is assumed to be 0.3 Nm^3/h (5 SLPM).

7.4.1 Electricity demand

Based on data from product sheets, the electricity consumption is assumed to be 6.7 kWh/Nm^3 (45% efficiency) for the electrolyzer. The yearly consumption of Nm^3 H_2 and electricity for the electrolyzer are presented in Table 7.9 and Table 7.10.

Table 7.9: Required amount of H_2 (Nm^3/year)

	Power demand (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	11	22	37	58
99	110	219	365	585
95	548	1096	1827	2924
90	1096	2193	3655	5848
75	2741	5482	9137	14619

Table 7.10: Amount of kWh per year needed to produce H_2 with on-site electrolysis

	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	73	147	245	392
99	735	1469	2449	3918
95	3673	7346	12244	19590
90	7346	14693	24488	39180
75	18366	36731	61219	97951

7.5 System 5: PEM fuel cell with on-site reforming of methanol

The fuel cells used in the calculations have the same capacity as the power demand (1.5, 3, 5 and 8 kW). A fuel tank is assumed to be available on the site.

7.5.1 Fuel demand

The fuel is a mix of methanol and water (60:40 volumetric ratio). It is assumed that the fuel consumption is 1.1 l/kWh (equivalent to a reformer efficiency of 83%), which results in the yearly methanol/water mix consumption shown in Table 7.11.

Table 7.11: Methanol/water mix consumption (l/year)

	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	14	29	48	77
99	145	289	482	771
95	723	1445	2409	3854
90	1445	2891	4818	7709
75	3614	7227	12045	19272

8 Life cycle assessment: goal and scope definition

The goal and scope definition is the first phase of a life cycle assessment. In this step, choices and specifications are made in order to ensure that the analysis can provide answers to the questions asked by the initiator of the study. The purpose, choice of systems for investigation, functional unit, impact categories, method of impact assessment, system boundaries, limitations of the study and requirements on data are presented in this section.

8.1 Goal

Today, either diesel generators or lead-acid batteries are used as back-up power systems at RBS-sites. The purpose of this study is to compare the environmental impact for PEM fuel cell systems with the environmental performance for the currently used solutions. The work will aim to provide a general analysis resulting in indications on environmental performance of the different systems.

The results of the study will be compared to economic aspects for each investigated system. It should also be used as a base for further research of sustainability aspects connected to back-up power systems and for internal education at Ericsson.

8.2 Scope

8.2.1 Systems chosen for investigation

Five different power back-up systems will be evaluated:

- Diesel generator
- Lead-acid batteries
- PEM fuel cell with centrally produced H_2 via electrolysis, delivered in 200 bar steel bottles
- PEM fuel cell with H_2 supply from on-site electrolysis
- PEM fuel cell with on-site reforming of methanol

8.2.2 Type of LCA

The study aims to evaluate results for the present state of technology. Thus, an accounting LCA is performed. This means that changes in environmental impact resulting from technical improvement for different system components or changes in background systems such as electricity production are not taken into account.

8.2.3 Functional unit

The systems will be compared based on their performance during a time period of 5 years for the different power demands and grid availabilities mentioned in section 6. The results will be a sum of cradle-to-grave impact for the different components in the systems (i.e. diesel generator, fuel cell) and the impact from the fuel/electricity consumption during the 5 year period.

8.2.4 System boundaries

The technical system boundary is illustrated in Figure 8.1. Since this is a comparative study, neither common transmission and control equipment nor the radio base station are included.

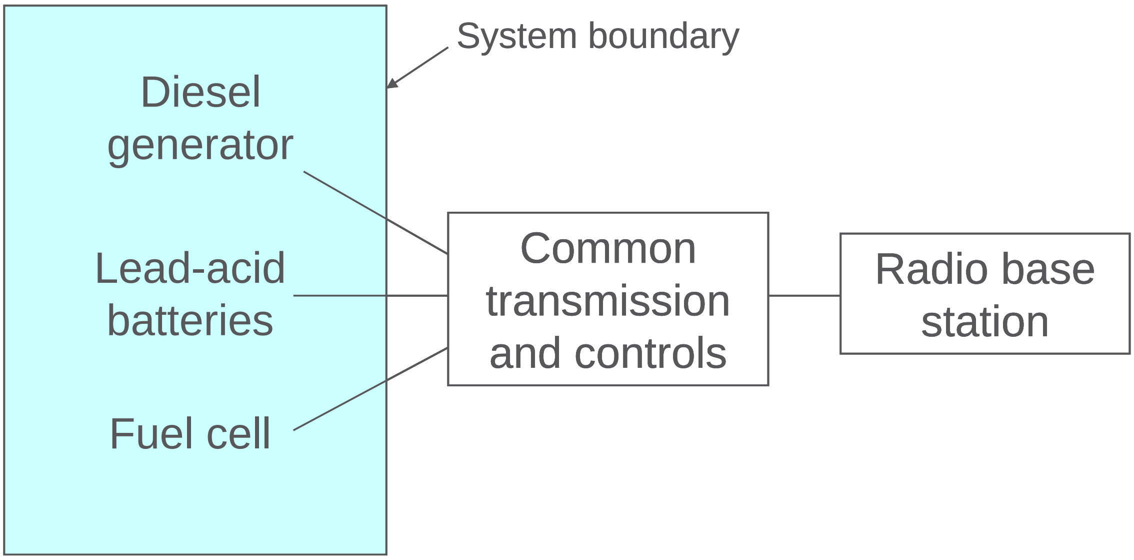

Figure 8.1: Technical system boundary.

It has been assumed that the site is located in Africa or Asia (China excluded), because of the differences in grid availability between and within countries in these regions. As stated before, a time perspective of 5 years has been used in the study.

8.2.5 Choice of impact categories and method of impact assessment

In this study, characterization, normalization and weighting of the inventory data will be performed. The impact categories were chosen from the ready-made characterization model created by the Institute of Environmental Sciences (CML) in the Netherlands. In this study, the impact categories abiotic depletion potential, acidification potential, eutrophication potential and global warming potential have been chosen. The normalization and weighting factors are also pre-made by CML, and are presented in Table 8.1.

Table 8.1: Normalization and weighting factors from CML2001 used in the study.

Normalization factors – CML2001 Europe		Unit
Abiotic depletion potential	$2.02\cdot10^{10}$	kg Sb-equiv./year
Acidification potential	$3.73\cdot10^{10}$	kg SO_2-equiv./year
Eutrophication potential	$1.10\cdot10^{10}$	kg PO_4-equiv./year
Global warming potential	$6.45\cdot10^{12}$	kg CO_2-equiv./year
Weighting factors – CML2001 Central Europe		
Abiotic depletion potential	1.5	
Acidification potential	2	
Eutrophication potential	7	
Global warming potential	10	

8.2.6 Data quality requirements

Average data was sufficient in the assessment, since the purpose of the study was to provide a general overview of the power systems' environmental performance at present state. Part of the inventory data was collected from previously conducted LCAs at Ericsson or publicly available LCA reports from external sources. The rest of the data was found in LCA databases from Eco-invent or PE International.

8.2.7 Software

The life cycle models were constructed using the software GaBi. The modeling can be simplified by using pre-made models of common industrial processes which are available in a database connected to GaBi. GaBi also contains tools for characterization, normalization and weighting of results.

9 Life cycle assessment: inventory analysis

The inventory data for equipment and fuel/electricity is presented in section 9.1 and 9.2. Part of the inventory data and GaBi models originate from previously conducted life cycle assessments at Ericsson. Data originating from LCA databases can not be explicitly presented in the report. Thus, the inventory data will be presented at different levels of detail. The radio base station site is assumed to be localized in Africa or Asia. The average electricity mix in these regions is presented in section 9.3.

9.1 Equipment

The following general assumptions for equipment have been made in the study:

- All equipment is manufactured in Europe.
- The distance between the manufacturing location and the RBS site is 9000 km.
- 90% of the distance is covered by sea and 10% by truck.
- Materials in the equipment are recycled according to the recycling rates in
- Table 9.1.

Table 9.1: Recycling rates for different materials

Material	Recyling rate (%)	Source
Steel	80	Bondesson, 2010
Aluminium	60	Bondesson, 2010
Copper	50	Bondesson, 2010
Plastics	0	Bondesson, 2010
Lead	42	Bondesson, 2010

No assumptions have been made on end-of-life treatment of the fuel cell because of lack of data. However, the recycling process is very important because of the platinum content in the fuel cell.

9.1.1 Diesel generator

The inventory data is collected from previous work at Ericsson. Materials and energy required during the manufacturing process of the generator is presented in Table 9.2.

Table 9.2: Raw material and energy required during generator manufacturing

	Material	Amount	Source
Raw material and manufacturing			
Weight of generator (kg)		500	Bondesson, 2010
Process energy (kWh/generator)		50	Bondesson, 2010
Material (kg/generator incl. housing)			
	Aluminium	180	Bondesson, 2010
	Copper	25	Bondesson, 2010
	Steel	300	Bondesson, 2010
	Plastic	50	Bondesson, 2010

9.1.2 Lead-acid battery

The inventory data for manufacturing and recycling of the lead-acid batteries was collected from a previous LCA study on a 2 V battery cell performed by Ericsson (Donovan, 2009). Donovan's work was based on an internal report on battery manufacturing at the supplier Oerlikon (Bergmark and Andrae, 2001) and an external study on recycling of lead-acid batteries (Salmone et al., 2005). It is assumed that 40% of the lead needed for a battery comes from secondary production, because of the well developed recycling processes of batteries.

9.1.3 Fuel cell

9.1.3.1 Main stack

The amount of materials required to manufacture a 1 kW fuel cell stack is presented in Table 9.3.

Table 9.3: Amount of required materials for manufacturing of 1 kW fuel cell stack

	Weight of MEA and Bipolar Plates for 1 kW stack		
Material	Raw material (kg)	Losses during production (%)	Amount in stack (kg)
PGM	0.00105	4.8	0.001
Nafion	0.089	6.9	0.083
Carbon Paper	0.069	11.7	0.061
Graphite		N/A	3.3
Total weight	3.45		
End-plates (same amount for all fuel cell capacities)			2.52

According to Karakoussis et al, the total amount of energy needed to produce the raw materials is several magnitudes larger than the total energy required during the manufacturing process. Thus, only energy input for the raw materials will be considered in this study.

In 2009, South Africa produced 78% of the world supply of platinum (Johnsson Matthey, 2010). South Africa is chosen as production country in this study, and cradle-to-gate data for primary PGM production from Eco-invent is used in the inventory. Significant amounts of SO_2 are emitted during the production process, which heavily influences the environmental impact for the PGM (Pehnt, 2001).

9.1.3.2 Balance of plant

The additional weight for the balance of plant varies a lot between fuel cell systems from different suppliers. In this study it is assumed that the components in the balance of plant consist of the same share of materials as the diesel generator, with a total weight of 50 kg. Hence, the environmental impact of the balance of plant is equal to a tenth of the environmental impact of the diesel generator.

9.1.4 Electrolyzer

Inventory data has not been available for PEM electrolyzers. It is assumed as a first approximation that the PEM electrolyzer has the same inventory data as a 3 kW fuel cell and a balance of plant of 150 kg. However, the amount of materials in a PEM fuel cell and a PEM electrolyzer varies for PGM and carbon. The PGM loading is lower in the electrolyzer and carbon cannot be used in the electrolyzer because of corrosion hazard. Metal materials are used instead.

9.1.5 Reformer

Assumptions on the inventory data have been done based on information from product sheets from suppliers and a thesis work for a PAFC system which includes a reformer (van Rooijeen, 2006). It is assumed that the inventory data is equivalent to the data for the diesel generator. The efficiency of a reformer is about 70-80 %. In this study an efficiency of 75 % will be used, which means that 1.33 MJ methanol will be used to produce 1 MJ of hydrogen.

9.1.6 Rectifier

A GaBi-model for a 1 kW rectifier made by Ericsson was used. The model is based on data from ABB. The amount of materials in a rectifier is presented in Table 9.4.

Table 9.4: Materials in a 1 kW rectifier (ABB product declaration)

Rectifier 1 kW	Amount of material
Total weight of converter (kg)	8.4
Aluminum (kg/converter)	1.6
Iron (kg/converter)	5.3
Copper (kg/converter)	1.0
Suphuric acid (kg/converter)	0.1

9.2 Fuel

9.2.1 Diesel

A pre-made model from Eco-invent was used to determine the environmental impact of the diesel. Oil extraction, diesel production and combustion in a diesel generator were included in the model.

9.2.2 Central production of H_2, delivered in bottles

The hydrogen is assumed to be produced via electrolysis.1.629 MJ electricity is needed to produce 1 MJ hydrogen (including compression to 200 bar), which is equivalent to 4.88 kWh/Nm3. This corresponds to an energy efficiency of 61%. The electricity model described in section 9.3 was used when assessing the environmental impacts.

9.2.3 Methanol/water mix

About 90% of the methanol production in the world is based on natural gas (Olah, 2005). It is assumed in this study that 1.41 MJ natural gas is needed to produce 1 MJ of methanol, which is approximately equal to an efficiency of 70%.

During steam reforming, methanol and water is needed to form hydrogen. Thus, the fuel used in a reformer is a mix of methanol and water. The methanol and water is assumed to be mixed with a 60:40 volume ratio. Since the energy density is of methanol is 15.9 MJ/liter, the energy density of the fuel mix is 9.5 MJ/liter. The methanol mix is assumed to be transported 500 km.

During the steam reforming reaction, 1 mole of methanol will yield 1 mole of CO_2. If it's assumed that all of the methanol will take part in the reaction, 0.83 kg of CO_2 will be emitted per kWh.

9.3 Electricity

A GaBi model for the average electricity mix in the regions of interest was created based on statistics from the International Energy Agency. If China is excluded from the average statistics for Asia, the electricity mix is rather similar to the average African mix. The main primary energy sources are presented in the table below.

Table 9.5: Electricity mix used in the study.

Primary energy source	%
Coal	43
Natural Gas	28
Hydro	16
Oil	11
Nuclear	2

10 Life cycle assessment: results and interpretation

In the subsection “Total potential environmental impact”, the results for each case are presented. A sensitivity analysis is presented in subsection 10.2 and subsection 10.3 contains a general discussion on the LCA results.

10.1 Total potential environmental impact

The total potential environmental impact is obtained by adding results from the life cycle impact assessment for the separate components and fuels needed for each system described in section 7. The weighted results of all systems are normalized against the weighted result of the diesel system. The total potential environmental impact for each system is presented in Figure 10.1-Figure 10.4. The characterization results for each power system are presented in section 16.

The environmental performance of the equipment can be roughly estimated by looking at the results for all power demands at 99.9% grid availability. The potential impact for the fuel cell is smaller compared to the diesel generator. The combined fuel cell and reformer system performs worse than the diesel generator. This is a consequence of the assumption that the reformer requires the same amount of materials and energy as the diesel generator. The battery system has a significantly higher potential environmental impact than the diesel generator, and this is mainly because of the lead used in the batteries, contributing to the abiotic depletion potential category.

As the amount of back-up hours increases, the fuel/electricity demand becomes a very important factor. For a power demand of 1.5 kW, the fuel/electricity contributes to more than half of the environmental impact for almost all systems after approximately 250-2000 back-up hours. The battery system is the only exception. The biggest environmental impact for a battery system is related to the batteries, not to the electricity used to charge the batteries.

A general trend to be observed in Figure 10.1-Figure 10.4, is that the environmental performance of the two fuel cell systems supplied with H_2 from electrolysis gets worse and worse compared to the diesel system as the number of back-up hours increase. However, the opposite applies for the fuel cell system with a reformer as well as the battery system. The difference for the systems results from variations in environmental impact of the fuels/electricity.

The environmental impact connected to the fuel/electricity needed to provide 1 kWh to the site is presented in Figure 10.5. The biggest differences between the diesel and methanol/water mix are the results for acidification and eutrophication potential. Even though less electricity is used during central electrolysis, the use of H_2 bottles has higher acidification potential and eutrophication potential compared to on-site electrolysis. This is because of the transportation of the bottles. The environmental performance of H_2 produced from electrolysis is very dependent on the electricity mix used in the study. This is discussed in section 10.2.1.

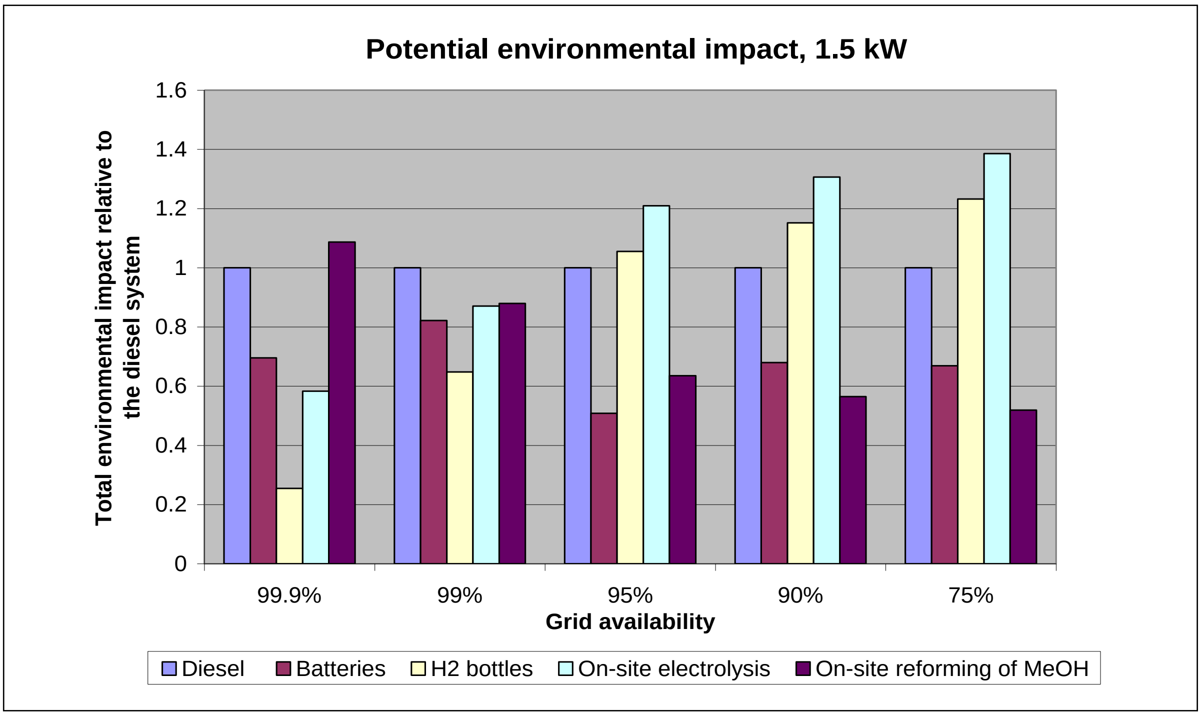

Figure 10.1: Total potential environmental impact for a power demand of 1.5 kW at different grid availabilities.

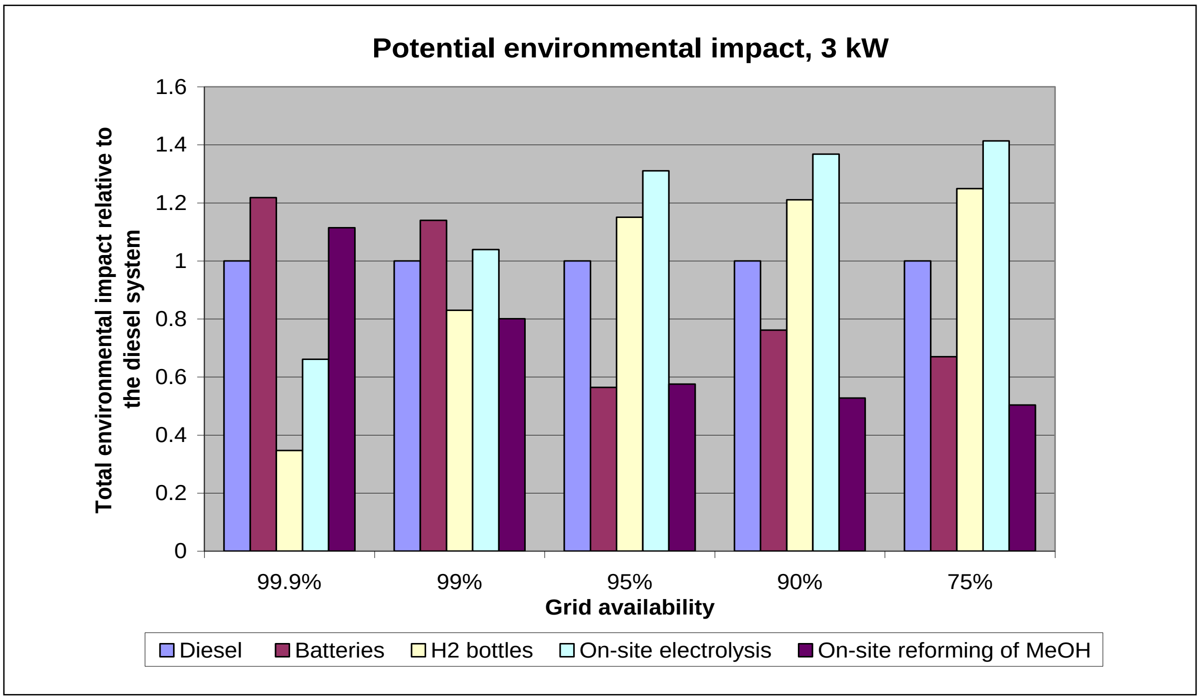

Figure 10.2: Total potential environmental impact for a power demand of 3 kW at different grid availabilities.

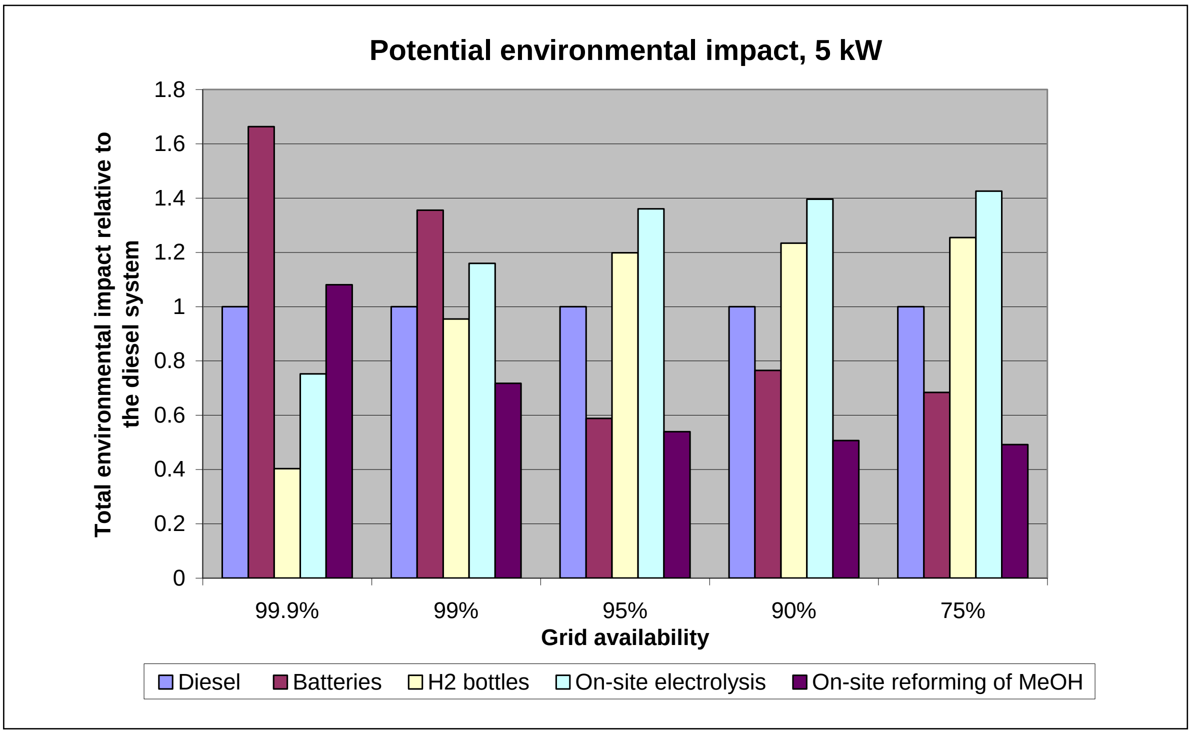

Figure 10.3: Total potential environmental impact for a power demand of 5 kW at different grid availabilities.

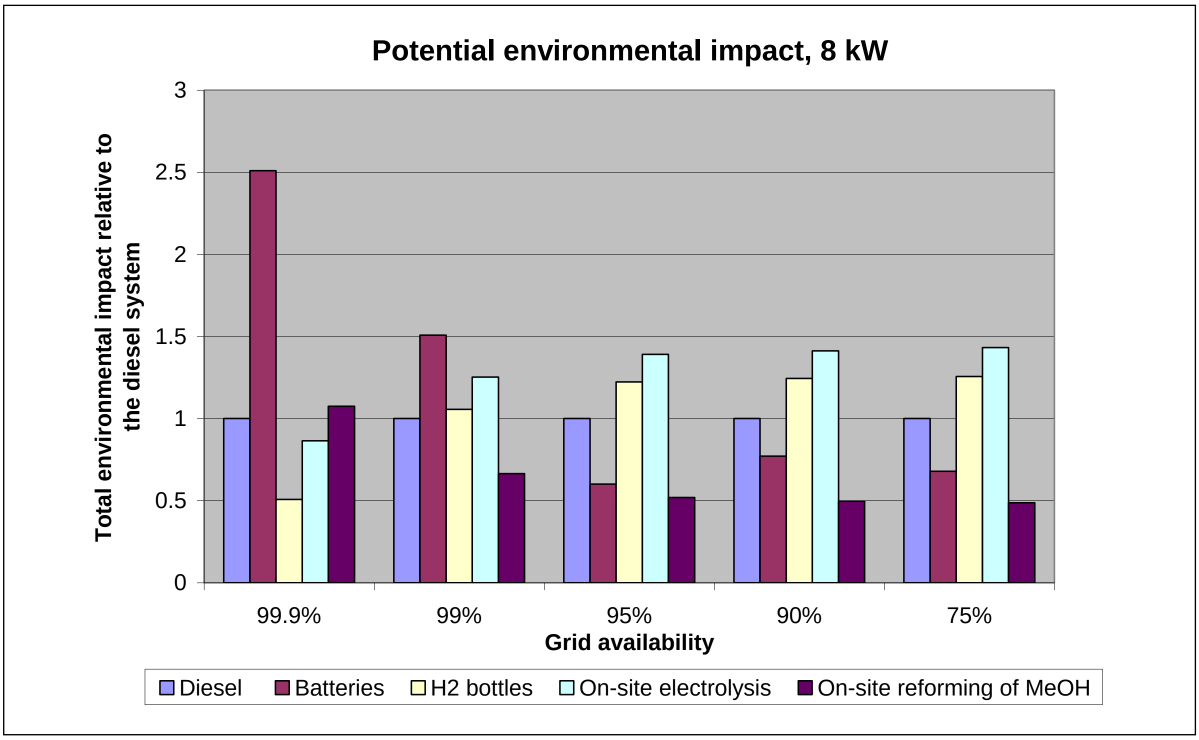

Figure 10.4: Total potential environmental impact for a power demand of 8 kW at different grid availabilities.

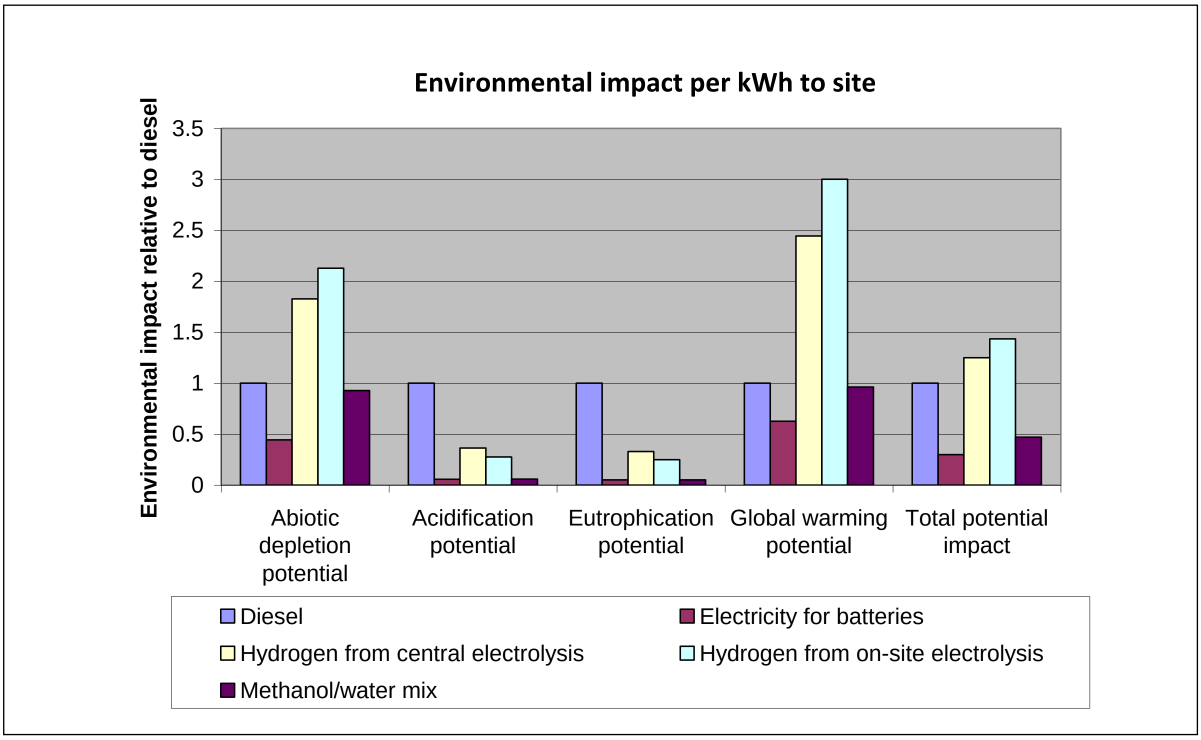

Figure 10.5: Environmental impact for fuel/electricity needed to provide 1 kWh to site

10.2 Sensitivity analysis

In this section, the effect of changing the electricity mix will be illustrated as well as the impact on the results when the life length of the batteries is decreased.

10.2.1 Changing the electricity mix

The choice of electricity mix affects the results for batteries, H_2 from central electrolysis and on-site electrolysis. The on-site electrolysis case will be used as an example when performing calculations with different electricity mixes. The environmental impact per kWh to site for the grid mix described in section 9.3, an average EU-25 electricity mix and a Swedish electricity mix are compared in Figure 10.6. All results are presented relative to the environmental impact per kWh to site for diesel. The primary energy sources used in each mix are presented in Table 10.1.

Table 10.1: Sources of primary energy for different electricity mixes.

Source of primary energy (%)	Mix used in study	EU-25	Sweden
Coal	43	30	1.6
Oil	11	6	2
Natural gas	28	17	0.4
Nuclear	2	32	46
Hydro	16	10	46
Other	0	5	4

As can be seen in Figure 10.6, the results for the different electricity mixes are varying. As concluded in the section Total potential environmental impact, hydrogen produced from the grid mix used in the study will not have a better environmental performance than the diesel. The EU-25 electricity mix has approximately the same weighted environmental impact as the diesel. On-site electrolysis based on Swedish electricity is better than diesel from an environmental point of view because of the high share of hydro- and nuclear power. Based on these results, it's possible to conclude that H_2 produced from on-site electrolysis has potential to have a better environmental performance than the diesel system with an appropriate electricity mix. This conclusion is also valid for battery systems and the fuel cell system with H_2 bottles.

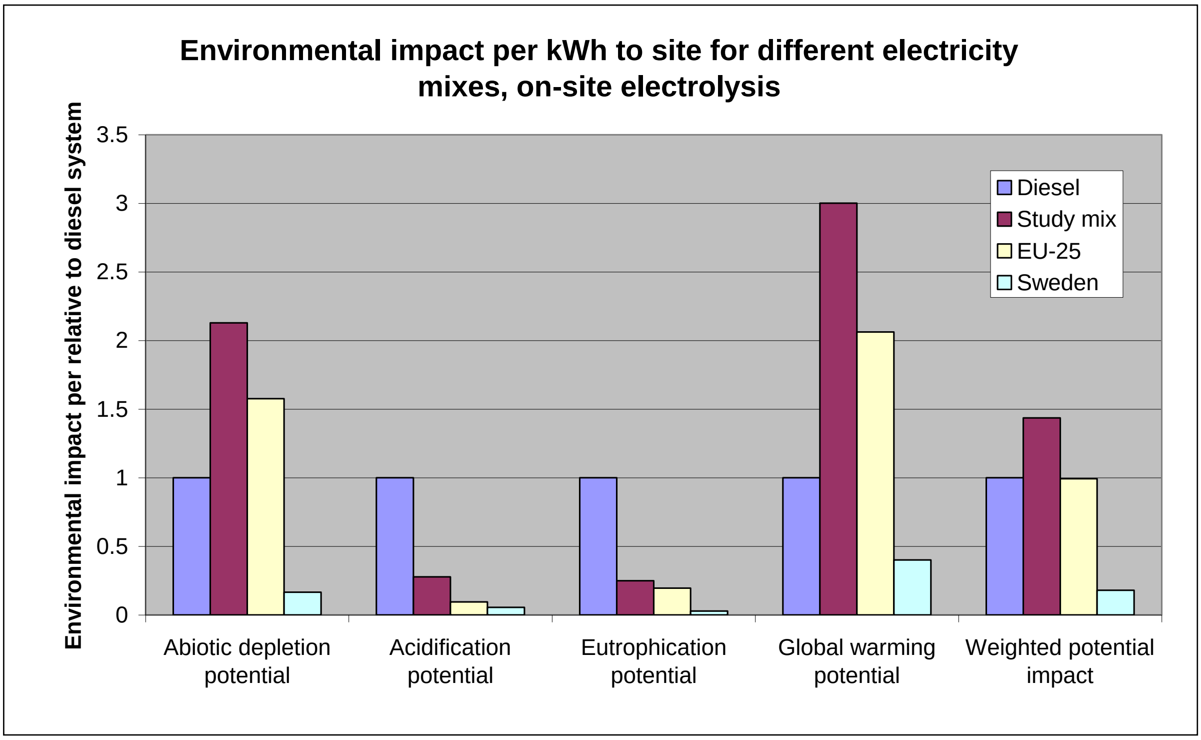

Figure 10.6: Environmental impact per kWh to site for different electricity mixes relative to diesel for on-site electrolysis.

10.2.2 Decreasing life length of batteries

The life length of the batteries for 95% grid availability was previously assumed to be 5 years. As a result of this, the batteries are never replaced during the investigated time period. This can be a bit misleading, since the life length of other components (i.e. the diesel generator) is longer and can still be used after a 5-year-period. New calculations have been performed for the battery system under the assumption that the batteries have to be replaced once during 5 years of operation. A comparison of the results with and without battery replacement is displayed in Figure 10.7. In the previous calculations, the battery system had an environmental impact corresponding to approximately 60% of the impact of the diesel system. The difference between the systems is decreased when the batteries are changed, but the battery system still has a better environmental performance than the diesel system.

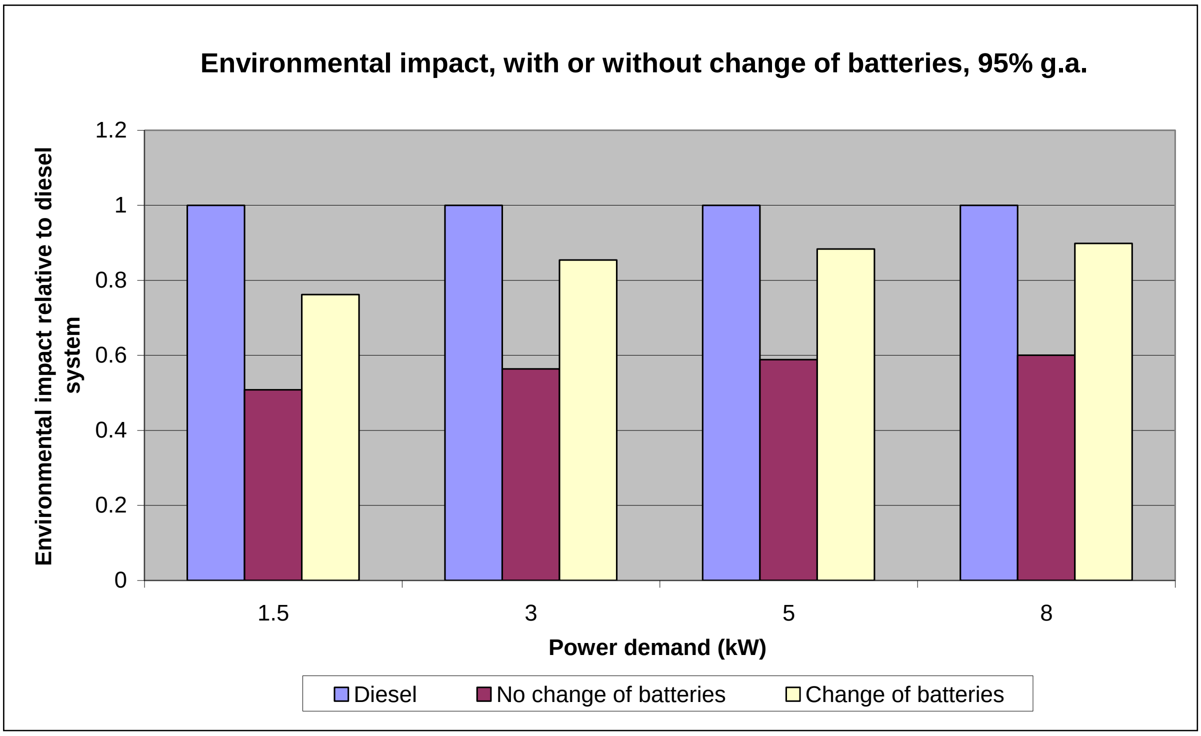

Figure 10.7: Comparison of environmental impact with or without battery change at 95% grid availability.

10.3 Discussion on LCA results

According to the results mentioned in the previous section, fuel and electricity contributes to the biggest share of the total environmental impact. An extension of the time period of investigation would have a rather small impact on the presented results. Batteries and fuel cells would have to be replaced for lower grid availabilities, but the results in section 10.2.2 imply that this wouldn't affect the overall conclusion.

Finding reliable inventory data for a PEM fuel cell and a PEM electrolyzer is a difficult task because of the immaturity of the technology. However, the uncertainties in the gathered fuel cell and electrolyzer data probably have a small impact on the results. In fact, availability of data is a crucial issue when performing a LCA. The results of the LCA will only be as good as the collected inventory data used in the calculations. Collection of data can be obstructed because of confidentiality issues. In this study, secondary data has been used from other LCA studies or from LCA databases. This results in difficulties when validating the collected data. The validation process is complex for data with a high level of aggregation.

The weighting factors used in this study are constructed by a group of experts. However, there is no report stating on which principles the choice of weighting factors is based. The choice of weighting factors is of significant importance when ranking the systems. For instance, if the impact category abiotic resource depletion would have a higher rating, the potential environmental impact of the battery system would be higher because of the lead used in the system.

The aim of the life cycle assessment has been to compare the five different systems based on current technology state. It is important to keep in mind that the system technologies have reached different levels of maturity. For instance, it is not possible to conclude from this study that fuel cell systems provided with H_2 from electrolysis has no potential to have better environmental performance than the diesel or battery systems. With appropriate changes in the electricity production, H_2 from electrolysis would have a better environmental performance and should be regarded as a potential fuel supply path in the long-tem.

For some systems, external heating or cooling will be necessary. For instance, batteries can be placed in special cooling cabinets. This has not been included in this study, but might have a significant impact on the results. However, it is difficult to determine unless calculations are performed on a specific system.

The results of this study can be applicable on other regions if the electricity mix at the location of the site is changed in the calculations.

An end-of-life process for the fuel cell has not been included in the study because of lack of data. Since platinum group metals are scarce resources, recycling of fuel cells will be necessary. For more information on PGM resources or recycling of fuel cells the reader is referred to Råde (2000) and Handley (2004).

It is also important to remember that only four impact categories were chosen in this study. Conclusions on the environmental performance for each system are only based on the results for these four categories, and they might change if additional categories are included. For instance, it would be interesting to see how an impact category on toxicity would affect the environmental performance of the battery system.

Life cycle assessment is a rather new methodology. Thus, it is still possible to make substantial improvements of the methodology. For instance, the currently available impact categories and weighting factors are very focused on European conditions. Some important factors, such as land use, are currently difficult to quantify.

11 Calculations of total cost

This section contains calculations of total costs and the results will be compared with the environmental performance in section 12. The collected price data and cost assumptions are presented in section 11.1. The results are displayed and discussed in section 11.2 and 11.3, respectively.

11.1 Cost data

The cost data is estimated based on information from suppliers and literature. No cost data can be linked to a specific supplier or product. An interest of 5% has been used to convert the costs to present values.

11.1.1 Equipment costs

The estimated costs for equipment are presented in Table 11.1. The diesel generator and the fuel cell require regular maintenance. The maintenance cost is assumed to be €300/visit for both power systems and the number of required maintenance visits is displayed in Table 11.2. Costs for disposal of used equipment have not been included in the total cost calculations.

Table 11.1: Estimated equipment costs.

Equipment	Investment cost
Diesel generator, 10 kVA	€7200
12 V lead-acid battery, 100 Ah	€160
Battery rack	€230
1400 kW rectifier	€120
Fuel cell (X is fuel cell capacity in kW)	€(1300X+3700)
Reformer	50% of fuel cell cost
Electrolyzer, 0.3 Nm^3/h	€45000*

*)The cost function based on capacity for a PEM electrolyzer is €(43000Y+32000), where Y is electrolyzer capacity in Nm^3/h.

Table 11.2: Required maintenance visits for the diesel generator and the fuel cell

Grid availability (%)	Diesel generator	Fuel cell
99.9	1 visit per year	1 visit every second year
99	1 visit per year	1 visit every second year
95	1 visit per year	1 visit every second year
90	2 visits per year	1 visit per year
75	4 visits per year	2 visits per year

11.1.2 Fuel costs

The estimated costs for fuel and electricity are presented in Table 11.3. Transportation costs have to be taken into account for diesel, methanol/water mix and the H_2 bottles. It is assumed that the site is located at a normal delivery distance for the fuel suppliers. Unless information on the transport costs of fuel has been retrieved from suppliers, it has been assumed that the fuel cost including transport is twice the retail price. The transportation costs for diesel, methanol/water mix and H_2 bottles are included in the cost data presented in Table 11.3.

Table 11.3: Estimated costs for fuel/electricity

Fuel/electricity	Cost	Fuel consumption per kWh to site	Cost per kWh to site
Diesel	€1.5/l	0.5 l	€0.75
Methanol/water mix	€1.23/l	1.1 l	€1.35
Hydrogen	€8.7/Nm^3	9 Nm^3	€78*
Electricity for charging of batteries	€0.14/kWh	1.18 kWh$_{el}$	€0.16
Electricity for on-site electrolysis	€0.14/kWh	5.59 kWh$_{el}$	€0.78

*)Excluding bottle rental

In the fuel cell case with H_2 bottles, costs for bottle rental have to be included in the total cost. The assumed number of bottles to be rented for each combination of power demand and grid availability is presented in Table 11.4. Five years rental of one steel bottle is assumed to cost €420.

Table 11.4: Assumed number of rented H_2 bottles for each combination of power demand and grid availability

	Power demand (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1	2	2	3
99	3	4	5	7
95	7	9	12	15
90	9	13	17	21
75	15	21	27	34

11.2 Results

The total costs for all combinations of grid availabilities and power demands for each case are displayed in Figure 11.5. Cells marked with grey represent the cheapest solution out of all five different systems. The battery system is the cheapest for most combinations of power demands and grid availabilities. In order to display and discuss the contribution of different costs to the total cost, cost calculations for a power demand of 3 kW are presented in section 11.2.1. The equivalent diagrams for a power demand of 1.5 kW, 5 kW, and 8 kW are placed in sections 18-20.

Table 11.5: Total costs for all systems and combinations of power demands and grid availabilities

Diesel generator system	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	9419	9733	10063	11233
99	9822	10540	11407	13383
95	11614	14124	17381	22941
90	15218	19968	26211	36251
75	24665	36135	51339	74819

Lead-acid battery system	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1523	2576	3752	5968
99	2227	3984	6431	9987
95	2620	4771	7743	12086
90	9407	19813	31786	50129
75	27453	52466	88289	137965

Fuel cell with H2 bottles	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	7208	9879	13115	18036
99	11958	18537	27169	40328
95	30697	55107	88031	136074
90	54057	100982	163107	254918
75	133061	249289	403182	633178

Fuel cell with on-site electrolysis	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	49969	51911	54499	58381
99	50390	52752	55902	60626
95	52260	56492	62135	85984
90	55443	62013	86157	116220
75	89298	123245	145944	224607

Fuel cell with on-site reforming	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	8936	11859	15755	21601
99	9664	13314	18182	25483
95	12899	19784	28964	42735
90	17787	28716	43288	65145
75	41375	67875	103209	156209

11.2.1 Total costs for a power demand of 3 kW

The total costs for a power demand of 3 kW at different grid availabilities are displayed in Figure 11.1-Figure 11.5. The different types of costs (i.e. investment cost, fuel cost) contributing to the total cost are also displayed in the diagrams. For a power demand of 3 kW, a battery system will be the cheapest solution, as long as the batteries do not have to be changed. If the site conditions are not appropriate for batteries, then the fuel cell systems with H_2 bottles or reformer can be cost-competitive alternatives to the diesel generator system for good grid availabilities. However, when the grid availability is down to 90%, the fuel cell systems will not be able to compete with the diesel system because of the difference in maximum amount of operation hours. On-site electrolysis is currently not an option for any power demand, because of the high investment cost of PEM electrolyzers.

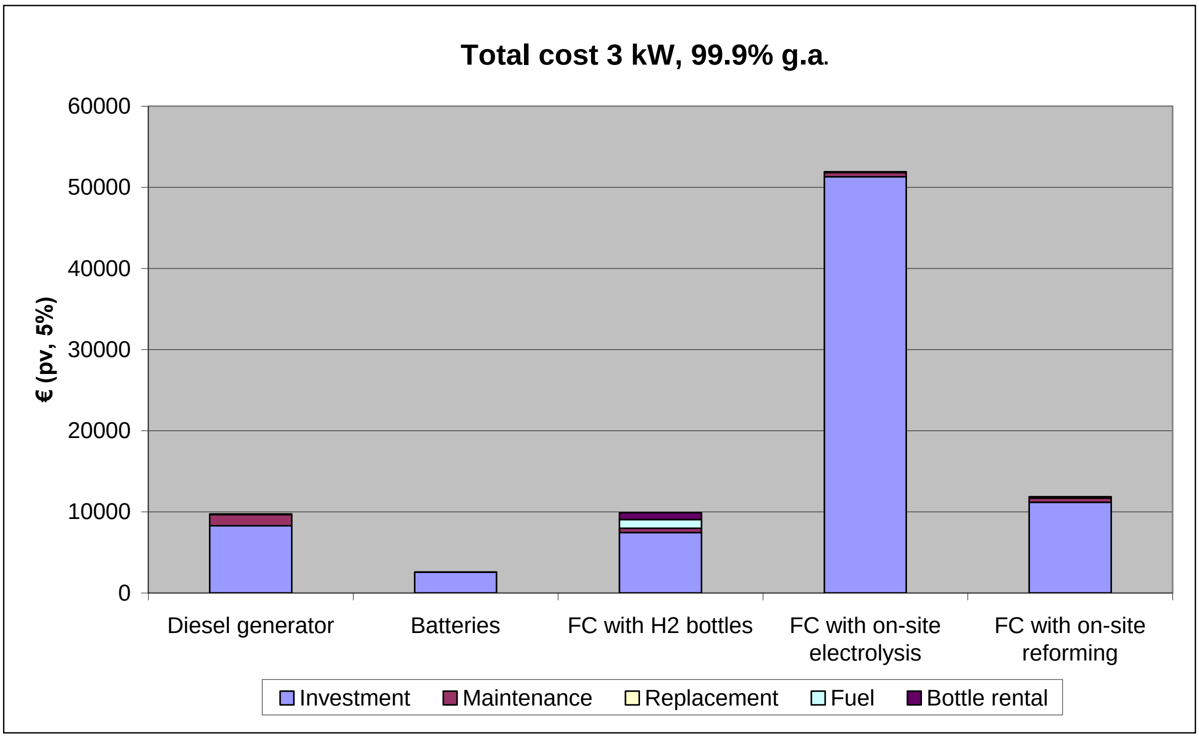

Figure 11.1: Total costs for each power system with a power demand of 3 kW and 99.9% grid availability

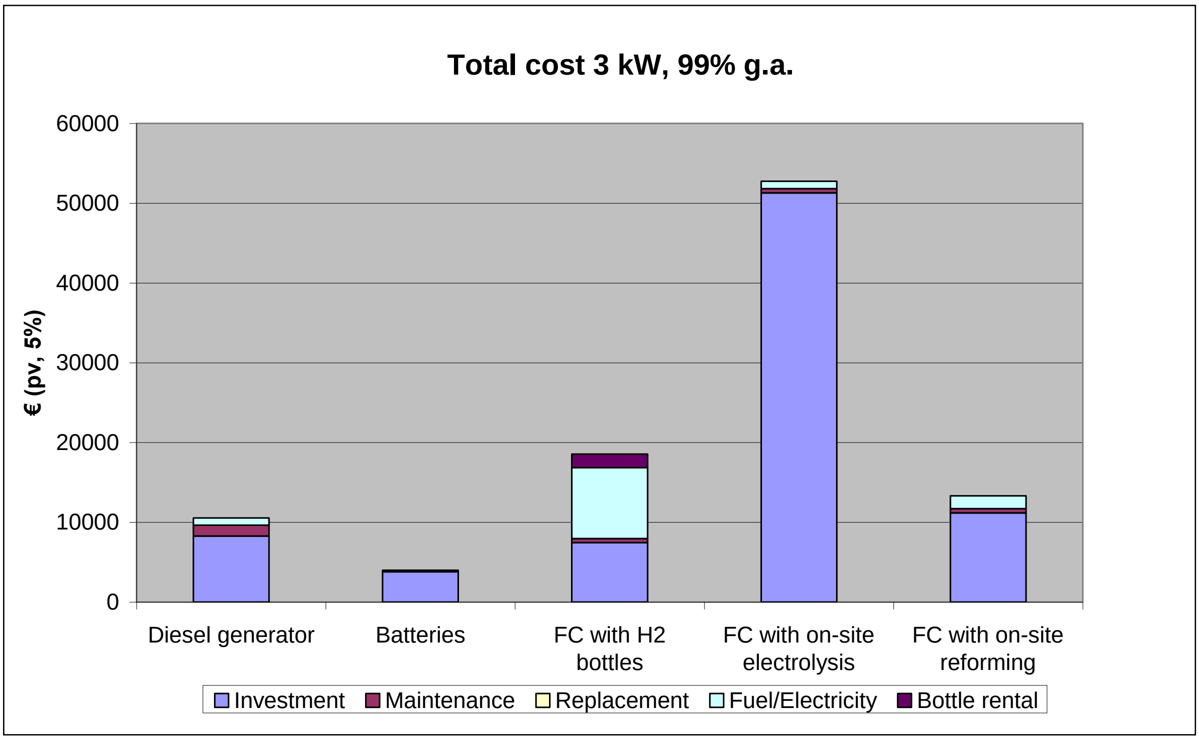

Figure 11.2: Total costs for each power system with a power demand of 3 kW and 99% grid availability

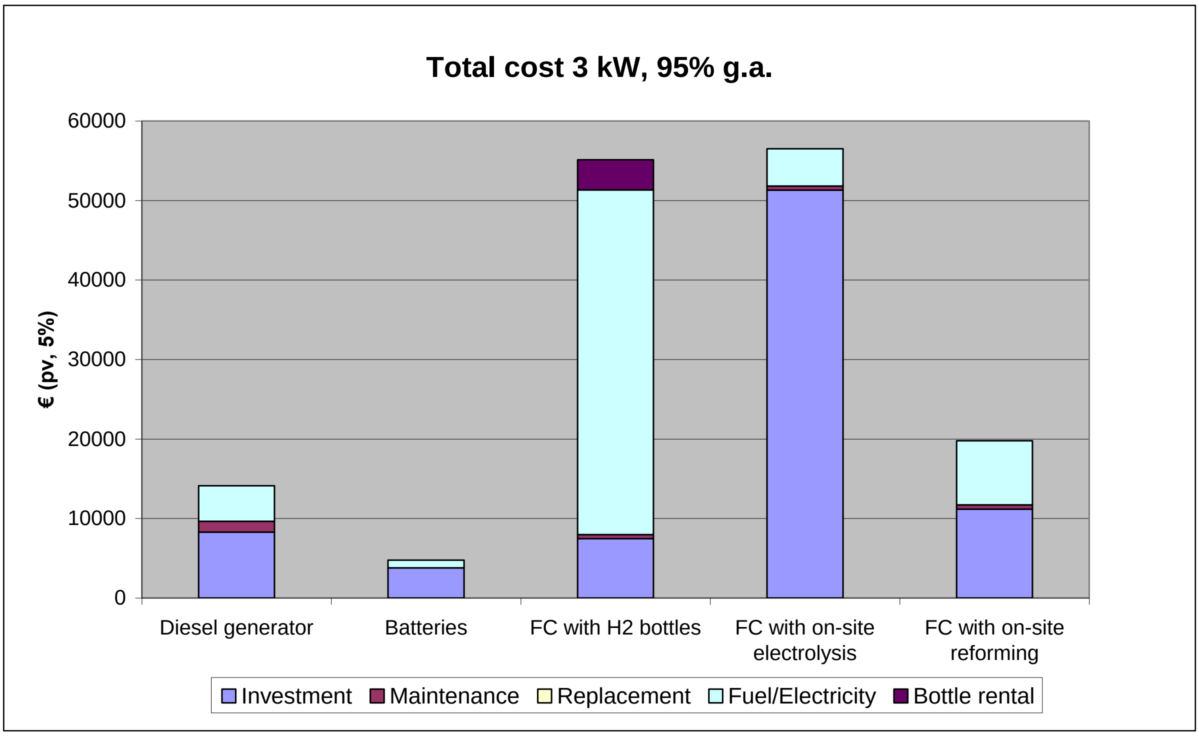

Figure 11.3: Total costs for each power system with a power demand of 3 kW and 95% grid availability

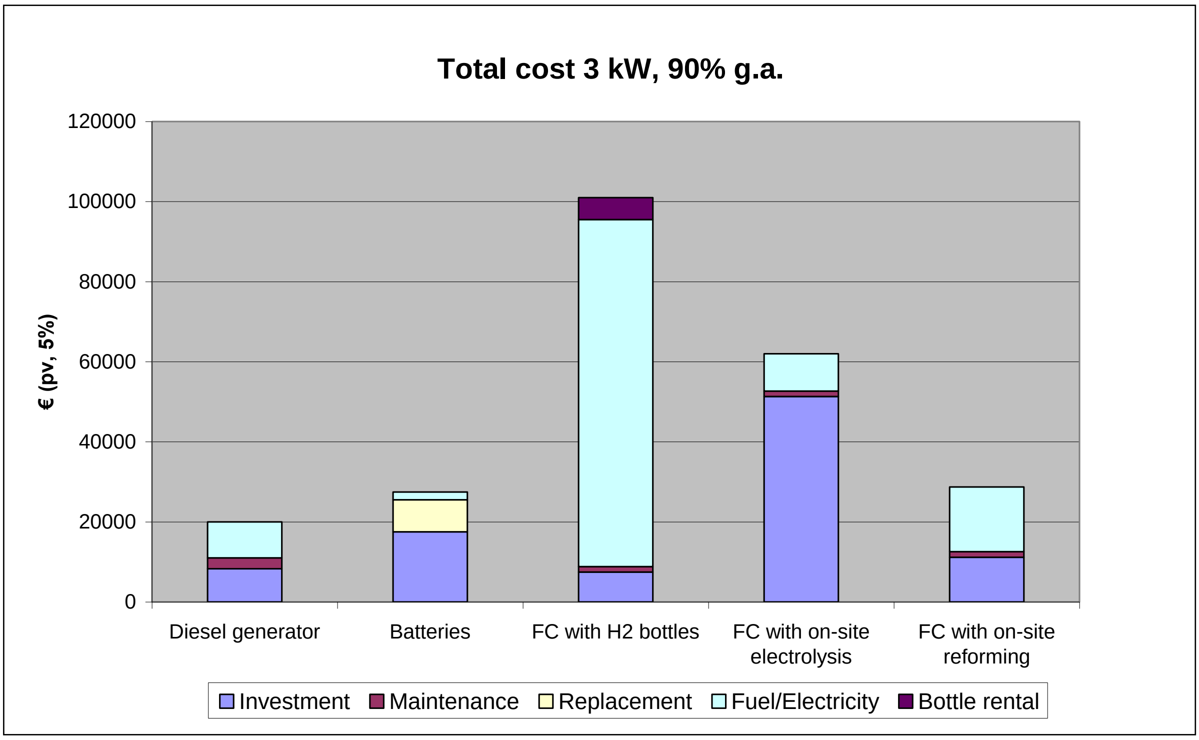

Figure 11.4: Total costs for each power system with a power demand of 3 kW and 90% grid availability

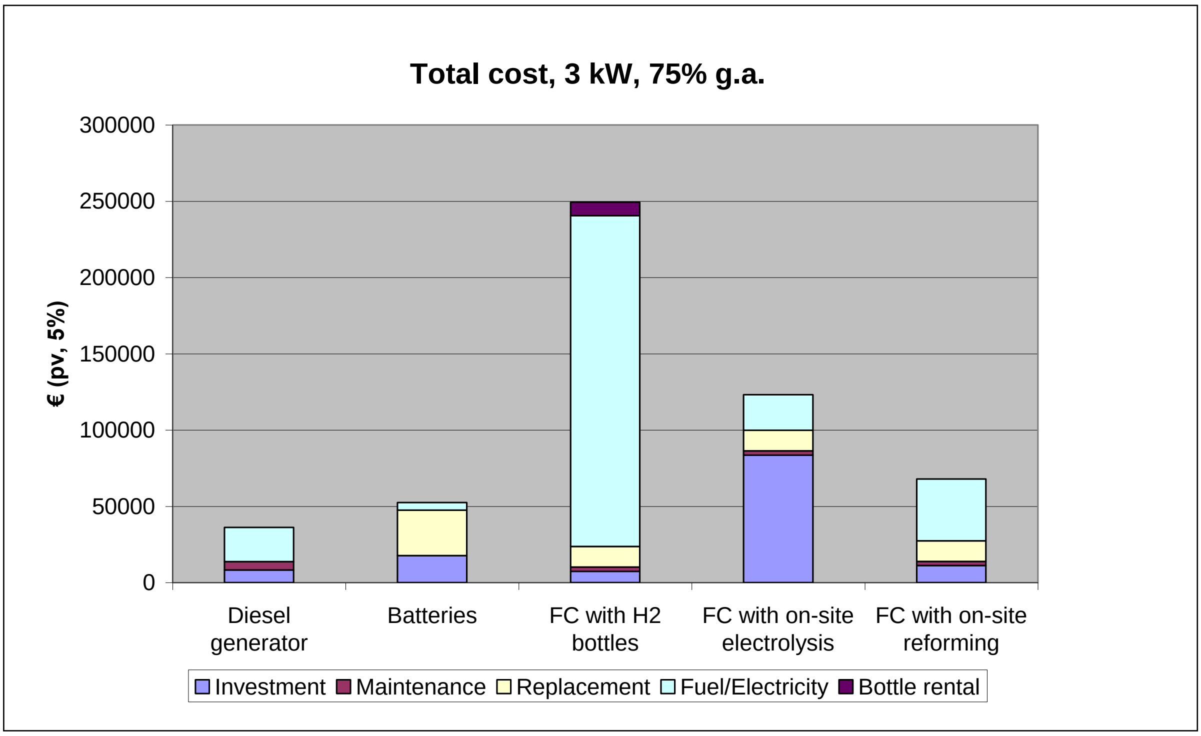

Figure 11.5: Total costs for each power system with a power demand of 3 kW and 75% grid availability

11.3 Discussion on cost results

The choice of interest (5%) does not have a significant impact on the results because of the short time perspective.

There are considerable uncertainties in the fuel cost calculations for diesel, methanol/water mix and H_2 bottles, since the transportation cost for the fuels is very dependent on the location of the site. The distribution system is more developed for diesel than for methanol/water mix and H_2 bottles. As a result of the difference in fuel availability, it might not be possible to find an alternative fuel that can compete with diesel.

There are also uncertainties in the price estimations of fuel cell systems, because of the immaturity of the technology. The market for fuel cells is still rather small and there are large differences in fuel cell system quality and production capacity among the suppliers. Price data for volumes of >1000 systems has be requested, but some suppliers can not provide those quantities at present. There is also a risk that the provided price data from the fuel cell suppliers is set rather low on purpose, since Ericsson is an interesting potential customer.

In the calculations, it is assumed that the replacement cost for the fuel cell system is equal to the investment cost. The replacement cost is probably lower if only the fuel cell stack is changed.

12 Environmental impact versus total cost

The purpose of this section is merely to provide an overview and for comparison of the results from the life cycle assessment and the total cost calculations. The results for all power demands are presented in Figure 12.1-Figure 12.4. Discussions on the results of the life cycle assessment and the total cost calculations are provided in section 10.3 and 11.3, respectively.

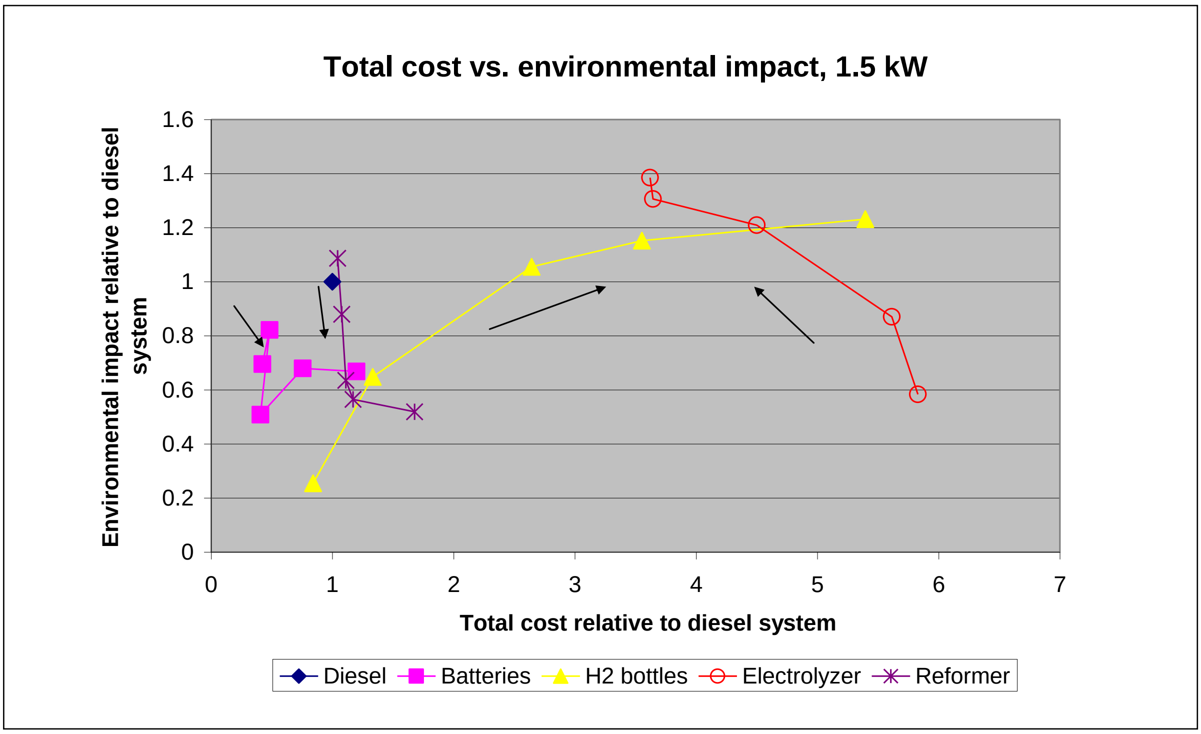

Figure 12.1: Total cost versus environmental impact for a power demand of 1.5 kW. The arrows indicate increasing number of outage hours.

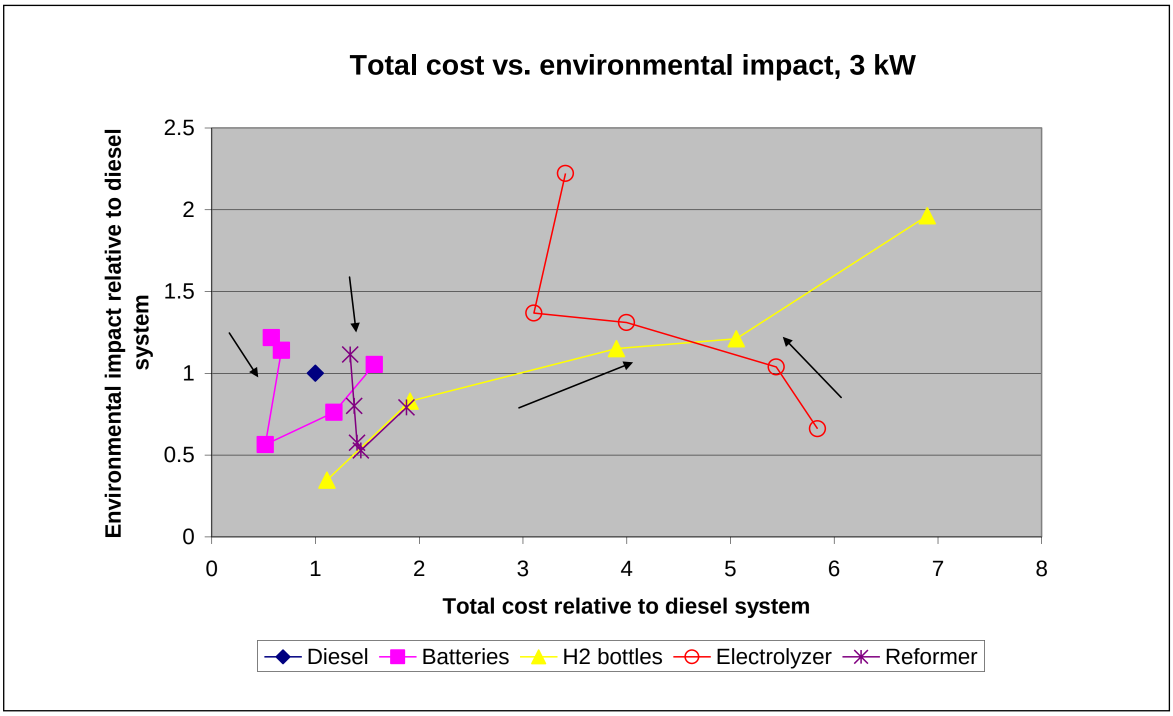

Figure 12.2: Total cost versus environmental impact for a power demand of 3 kW. The arrows indicate increasing number of outage hours.

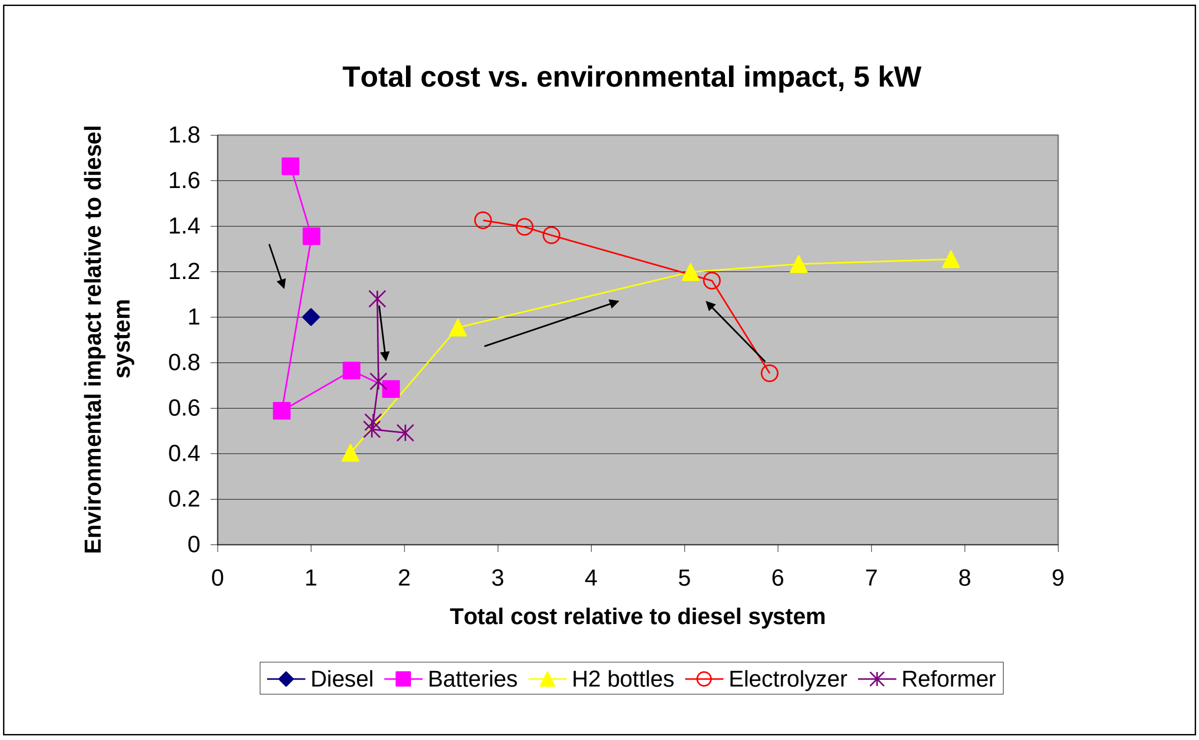

Figure 12.3: Total cost versus environmental impact for a power demand of 5 kW. The arrows indicate increasing number of outage hours.

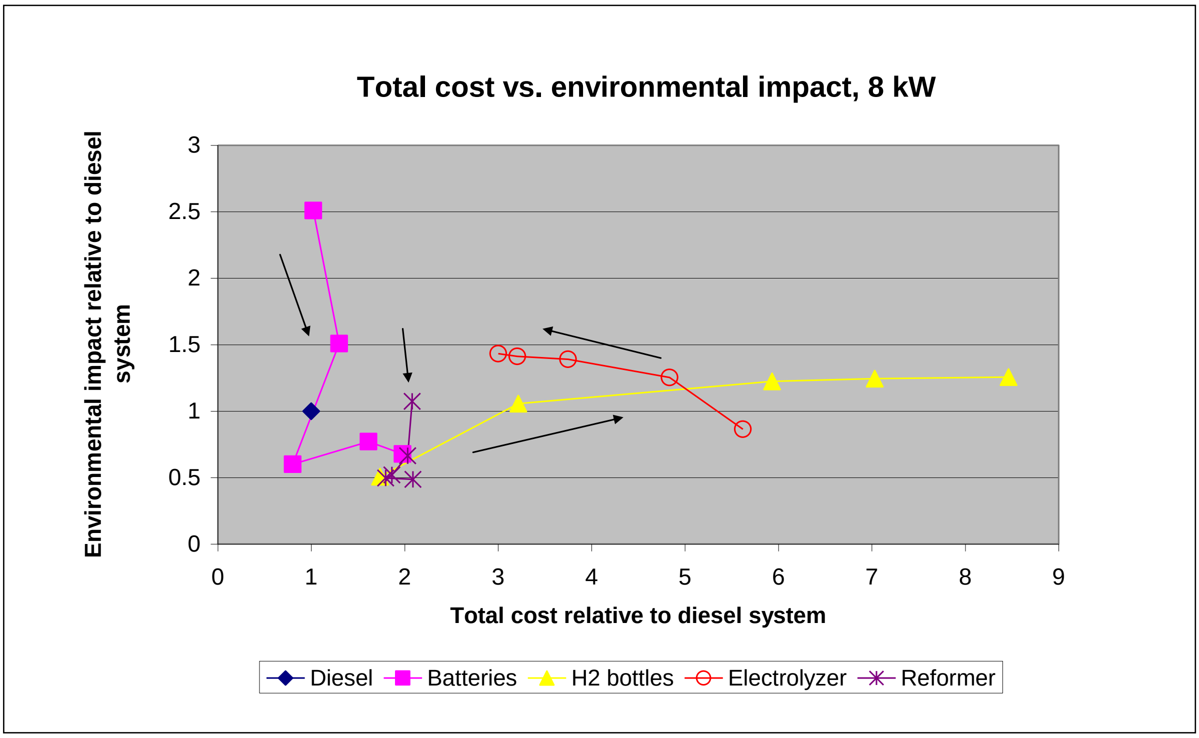

Figure 12.4: Total cost versus environmental impact for a power demand of 8 kW. The arrows indicate increasing number of outage hours.

13 Suggestions of subjects for further investigation

The configuration of battery systems is dependent on a number of different parameters. The variety of back-up battery systems in use has not been captured in this study. A specific study on battery systems on batteries should be conducted, focusing on finding combinations of parameters for which the battery system performs poorly.

Hybrid configurations of batteries and diesel generators are sometimes used for back-up in area with poor grid availability. Currently, fuel cell systems will not be an alternative because of the limited number of operation hours and the high investment cost.

The three fuel paths in the fuel cell systems were chosen because they are currently available on the market. Fuel from these sources is pure enough to be used as in fuel cells. A number of alternative fuel paths can be interesting in a longer time perspective. Central steam reforming of natural gas might be an alternative fuel path, but additional cleaning steps will be necessary. The environmental impact as well as the cost for purification requires further investigation. H_2 is also produced as a by-product during the chlor-alkali process, and could be a potential source of fuel in the long-term. Alternatives fuel paths for methanol production are also of interest.

Markets with beneficial conditions for fuel cell systems should be identified.

14 Conclusions

The fuel/electricity use is an important factor in the environmental investigation. Based on the four chosen impact categories, the battery system and the fuel cell system with a reformer have lower potential environmental impact than the diesel system. The two fuel cell systems with H_2 from electrolysis could have better environmental performance than the diesel system if the electricity is based on a significant share of renewable energy. However, it is important to remember that the choice of weighting factors has a significant impact on the ranking of the potential environmental impact of the different power systems.

The battery system is the cheapest for most of the combinations of power demand and grid availability, especially when there is no need for a change of batteries. Fuel cell systems with H_2 bottles or reformer can be a cost-competitive option for smaller power demands and grid availabilities down to 95%, if the site conditions are inappropriate for battery systems and if the investment cost for the fuel cells is lowered.

It is suggested that calculations should be performed for a variety of site locations, in order to eliminate some of the uncertainties in the estimates and to be able to identify sites were fuel cell systems can be used.

15 References

15.1 Literature, articles and web

Baumann, H., Tillman, A-M., *The Hitch Hiker's Guide to LCA – An orientation in life cycle assessment methodology and application*, 1st edition, Studentlitteratur, Lund, 2004

Bondesson, A., *Comparative LCA model on renewable energy solutions for off-grid radio base stations*, Master's Thesis at Royal Institute of Technology, Stockholm, 2010

Donovan, C., *Life cycle assessment of fiber optic submarine cable systems*, Master's Thesis at Royal Institute of Technology, Stockholm, 2009

Hailes, R., *Fuel cells for transportation: An inventory analysis of environmental interventions associated with a prototype stack component manufacturing route*, Diploma work at Imperial College of Science, Technology and Medicine, 1999

Handley, C., Brandon, N.P., van der Horst, R., *Impact of the European Union vehicle waste directive on end-of-life options for polymer electrolyte fuel cells*, Journal of Power Sources, 106 (2002), 344-352

ISO 14040, *Environmental Management – Life Cycle Assessment – Principles and framework*, International Organization for Standardization, Geneva, Switzerland, 1997

ISO 14041, *Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis*, International Organization for Standardization, Geneva, Switzerland, 1998

ISO 14042, *Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment*, International Organization for Standardization, Geneva, Switzerland, 2000

ISO 14043, *Environmental Management – Life Cycle Assessment – Life Cycle Interpretation*, International Organization for Standardization, Geneva, Switzerland, 2000

Karakoussis, V., Leach, M., van der Vorst, R., Hart, D., Lane, J., Pearson, P., Kilner, J., *Environmental emissions of SOFC and SPFC system manufacture and disposal*, F/01/00164/REP, Imperial College of Science, Technology and Medicine, 2000

Pehnt, M., *Life-cycle assessment of fuel cell stacks*, International Journal of Hydrogen Energy, 26 (2001), 91-101

Pehnt, M., *Chapter 4 in Handbook of Fuel Cells – Fundamentals, Technology and Applications: Life-cycle analysis of fuel cell system components*, John Wiley & Sons Ltd, Chichester, ISBN: 0-471-49926-9, 2003

Salari, H., *Evaluation of renewable based power systems for off-grid telecom sites*, Master's Thesis at the Royal Institute of Technology, Stockholm, 2006

Salmone, R., Monello, F., Lanuzza, F., Micali, G., Environmental assessment: An Eco-balance of recycling plant for spent lead-acid batteries, Environmental Management, 35 (2005), 206-219

van Rooijen, J., *A Life Cycle Assessment of the PureCell^{TM} Stationary Fuel Cell System: Providing a Guide for Environmental Improvement*, Master's Thesis at Delft University of Technology, 2006

15.2 Ericsson reports

Bergmark, P., Andrae, A., *Lead-acid battery manufacturing process*,
FCP 103 2560 Uen Rev A, 2001

Brehmer, M., *Battery Capacity Dimensioning Guideline*, 1/221 02-FGB 101 291 Uen, 2007

Hellmans, B., Fuel cells in RBS applications – a technology study,
EAB/PJR/S-06:0116 Uen, 2007

Minde, M., *Pre study of wind power solutions for RBS-sites in rural places in developing countries*, EAB-08:023886 Uen (2009)

Wallberg, I., *Fuel Cells in RBS applications – Supporting document*, 2007

15.3 Product declarations

ABB Automation, *Environmental Product Declaration: Converter Module DCS 400*, www.abb.com, 2009-05-25

16 Appendix A – Life cycle inventory

Aggregated life cycle inventory data for each power system is presented in this appendix. Additional common inventory for fuel cell systems can be found in section 16.6.

16.1 Diesel system

Table 16.1: LCI for diesel system (HCl, NO_x, and SO_2 emissions)

HCl (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.21	0.21	0.21	0.21
99	0.21	0.21	0.22	0.23
95	0.22	0.24	0.26	0.29
90	0.24	0.27	0.32	0.38
75	0.29	0.37	0.48	0.64

NOx (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	8.51	10.52	13.19	17.21
99	26.57	46.63	73.37	113.49
95	106.81	207.11	340.84	541.44
90	207.11	407.71	675.18	1076.38
75	508.01	1009.51	1678.18	2681.18

SO2 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	10.51	10.74	11.05	11.50
99	12.57	14.86	17.92	22.50
95	21.74	33.20	48.47	71.38
90	33.20	56.11	86.66	132.49
75	67.57	124.85	201.23	315.79

Table 16.2: LCI for diesel system (CO_2, N_2O, and CH_4 emissions)

CO2 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	2640	2759	2917	3154
99	3707	4892	6472	8843
95	8448	14374	22275	34127
90	14374	26226	42028	65732
75	32151	61781	101287	160546

N2O (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.028	0.037	0.048	0.066
99	0.107	0.194	0.311	0.486
95	0.457	0.895	1.479	2.355
90	0.895	1.771	2.939	4.690
75	2.209	4.398	7.318	11.697

CH4 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	7.8	7.9	8.0	8.1
99	8.4	9.0	9.9	11.1
95	10.9	14.0	18.2	24.5
90	14.0	20.3	28.7	41.3
75	23.5	39.2	60.1	91.5

Table 16.3: LCI for diesel system (use of energy resources)

Crude oil (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	16057	17870	20288	23915
99	32378	50512	74692	110961
95	104916	195588	316485	497830
90	195588	376933	618726	981416
75	467606	920968	1525451	2432175

Hard coal (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	11293	11314	11341	11382
99	11478	11683	11957	12367
95	12299	13324	14692	16744
90	13324	15376	18111	22214
75	16402	21530	28369	38626

Lignite (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	446	459	476	501
99	561	688	858	1113
95	1071	1708	2558	3833
90	1708	2983	4683	7232
75	3620	6807	11057	17430

Natural gas (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	11776	11859	11969	12134
99	12520	13346	14448	16101
95	15826	19958	25468	33733
90	19958	28223	39243	55773
75	32356	53018	80568	121892

16.2 Battery system

Table 16.4: LCI for battery system (HCl, NO_x, and SO_2 emissions)

HCl (kg)	Power demand (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.02	0.03	0.05	0.08
99	0.03	0.05	0.09	0.14
95	0.03	0.06	0.10	0.15
90	0.09	0.19	0.30	0.48
75	0.19	0.36	0.61	0.96

NOx (kg)	Power demand (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.91	1.82	2.73	4.55
99	1.56	3.11	4.98	7.79
95	1.97	3.93	6.35	9.98
90	6.51	13.63	22.11	35.13
75	13.63	26.35	44.22	69.66

SO2 (kg)	Power demand (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	11.60	23.20	34.80	58.01
99	19.37	38.75	62.00	96.88
95	19.78	39.57	63.37	99.07
90	56.40	120.53	193.16	305.96
75	120.53	229.47	386.31	604.18

Table 16.5: LCI for battery system (CO_2, N_2O, and CH_4 emissions)

CO2 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	349	698	1048	1746
99	622	1245	1998	3128
95	1060	2121	3458	5464
90	4040	8310	13620	21700
75	8310	16275	27240	43171

N2O (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.01	0.03	0.04	0.07
99	0.03	0.05	0.08	0.13
95	0.04	0.08	0.13	0.20
90	0.14	0.30	0.49	0.78
75	0.30	0.58	0.97	1.54

CH4 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1.50	3.00	4.51	7.51
99	2.63	5.27	8.45	13.22
95	4.05	8.11	13.18	20.80
90	14.82	30.64	50.07	79.72
75	30.64	59.79	100.14	158.44

Table 16.6: LCI for battery system (use of energy resources)

Crude oil (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	15224	30448	45672	76121
99	25374	50747	81195	126868
95	25374	50747	81195	126868
90	71046	152241	243586	385678
75	152241	289258	487172	761206

Hard coal (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1423	2847	4270	7117
99	2372	4745	7591	11862
95	2372	4745	7591	11862
90	6643	14234	22774	36059
75	14234	27045	45549	71170

Lignite (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	208	417	625	1042
99	347	695	1111	1736
95	347	695	1111	1736
90	972	2084	3334	5279
75	2084	3959	6668	10419

Natural gas (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	2270	4540	6809	11349
99	3783	7566	12106	18915
95	3783	7566	12106	18915
90	10592	22698	36317	57501
75	22698	43126	72633	113489

16.3 Fuel cell system with H_2 bottles

Table 16.7: LCI for FC system with H_2 bottles (HCl, NO_x, and SO_2 emissions)

HCl (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.04	0.06	0.08	0.11
99	0.07	0.11	0.14	0.20
95	0.16	0.24	0.35	0.50
90	0.23	0.38	0.57	0.82
75	0.46	0.80	1.22	1.83

NOx (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1.22	1.79	2.24	3.14
99	3.12	5.13	7.72	11.73
95	10.44	19.06	30.63	47.63
90	18.88	35.94	58.38	91.57
75	44.56	86.37	141.65	224.10

SO2 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	2.38	3.74	4.83	7.01
99	4.89	7.68	11.23	16.81
95	13.42	23.13	36.25	55.12
90	22.47	41.22	65.50	100.86
75	50.92	95.98	154.99	242.42

Table 16.8: LCI for FC system with H2 bottles (CO_2, N_2O, and CH_4 emissions)

CO2 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	648	1043	1381	2031
99	2461	4385	6904	10753
95	9825	18687	30551	48134
90	18603	36245	59577	94292
75	45107	88684	146503	232948

N2O (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.01	0.02	0.04	0.06
99	0.07	0.13	0.21	0.33
95	0.30	0.58	0.95	1.50
90	0.57	1.13	1.86	2.96
75	1.41	2.78	4.61	7.35

CH4 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1.76	2.75	3.69	5.38
99	7.27	13.22	21.05	32.93
95	30.41	58.66	96.43	152.65
90	58.51	114.85	189.61	301.19
75	143.10	282.94	468.82	747.10

Table 16.9: LCI for FC system with H_2 bottles (use of energy resources)

Crude oil (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	2319	3213	4199	5833
99	5813	9892	15279	23438
95	20587	38976	63546	100169
90	38590	74982	123299	195464
75	93371	183926	304355	484690

Hard coal (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	2853	4578	6368	9437
99	12854	23814	38300	60221
95	55430	107817	177794	282186
90	107500	211959	350726	558110
75	264346	524118	869714	1387342

Lignite (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	512	980	1280	1974
99	1068	1607	2244	3321
95	2353	3447	4987	6932
90	3230	5200	7504	10473
75	6294	10358	15289	22200

Natural gas (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	3475	5781	7470	11042
99	13554	23860	37255	57867
95	53268	100169	163051	255814
90	99792	193216	316397	499089
75	240118	469711	773757	1227746

16.4 Fuel cell system with on-site electrolysis

Table 16.10: LCI for FC system with on-site electrolysis (HCl, NO_x, and SO_2 emissions)

HCl (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.11	0.12	0.14	0.16
99	0.12	0.15	0.17	0.22
95	0.18	0.25	0.35	0.49
90	0.24	0.38	0.56	0.84
75	0.45	0.80	1.27	1.91

NOx (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	3.35	3.74	4.27	5.05
99	5.30	7.65	10.78	15.48
95	13.99	25.02	39.74	61.81
90	24.85	46.74	75.93	119.72
75	57.78	112.60	185.69	295.33

SO2 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	6.31	7.18	8.35	10.11
99	8.26	11.09	14.86	20.52
95	16.94	28.46	43.81	66.83
90	27.80	50.16	79.98	124.71
75	61.67	117.92	192.91	305.39

Table 16.11: LCI for FC system with on-site electrolysis (CO_2, N_2O, and CH_4 emissions)

CO2 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1491	1806	2226	2856
99	3573	5970	9165	13959
95	12825	24474	40006	63304
90	24390	47605	78557	124986
75	59254	117332	194769	310924

N2O (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.02	0.03	0.05	0.07
99	0.09	0.17	0.27	0.42
95	0.38	0.75	1.25	1.99
90	0.75	1.49	2.47	3.95
75	1.86	3.71	6.17	9.86

CH4 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	4.33	5.23	6.44	8.26
99	11.07	18.73	28.94	44.25
95	41.07	78.72	128.92	204.22
90	78.56	153.71	253.90	404.19
75	191.36	379.30	629.88	1005.76

Table 16.12: LCI for FC system with on-site electrolysis (use of energy resources)

Crude oil (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	7336	8204	9360	11095
99	11672	16876	23814	34221
95	30944	55419	88052	137002
90	55033	103597	168349	265478
75	128072	249675	411813	655019

Hard coal (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	6855	8569	10853	14280
99	19428	33715	52763	81336
95	75308	145473	239028	379359
90	145157	285172	471858	751888
75	355338	705533	1172460	1872851

Lignite (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	836	1065	1369	1825
99	932	1256	1688	2335
95	1357	2106	3105	4603
90	1889	3169	4877	7438
75	3918	7229	11642	18262

Natural gas (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	7020	8608	10725	13900
99	17912	30391	47031	71990
95	66320	127207	208389	330164
90	126829	248226	410088	652881
75	309113	612793	1017701	1625062

16.5 Fuel cell system with on-site reforming of methanol

Table 16.13: LCI for FC system with on-site reforming (HCl, NO_x, and SO_2 emissions)

HCl (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.24	0.25	0.26	0.28
99	0.24	0.25	0.26	0.28
95	0.24	0.25	0.26	0.28
90	0.24	0.25	0.26	0.28
75	0.26	0.28	0.32	0.38

NOx (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	7.35	7.54	7.80	8.18
99	7.49	7.82	8.26	8.92
95	8.11	9.06	10.33	12.23
90	8.88	10.61	12.91	16.35
75	11.56	15.96	21.82	30.62

SO2 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	11.97	12.63	13.51	14.83
99	11.97	12.63	13.51	14.84
95	11.98	12.65	13.54	14.88
90	11.99	12.67	13.57	14.93
75	13.34	15.36	18.06	22.11

Table 16.14: LCI for FC system with on-site reforming (CO_2, N_2O, and CH_4 emissions)

CO2 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	2915	3056	3244	3526
99	3430	4086	4961	6273
95	5720	8665	12593	18484
90	8582	14389	22133	33748
75	17335	31896	51311	80433

N2O (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	7.12	7.98	9.14	10.87
99	7.13	8.02	9.19	10.96
95	7.21	8.17	9.44	11.36
90	7.30	8.35	9.75	11.86
75	9.31	12.37	16.45	22.57

CH4 (kg)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	200.01	203.64	208.48	215.74
99	200.14	203.90	208.92	216.45
95	200.74	205.10	210.91	219.63
90	201.48	206.59	213.39	223.60
75	210.95	225.52	244.94	274.08

Table 16.15: LCI for FC system with on-site electrolysis (use of energy resources)

Crude oil (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	16056	16445	16963	17740
99	16081	16495	17047	17874
95	16194	16720	17421	18473
90	16334	17000	17889	19222
75	17526	19385	21863	25581

Hard coal (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	12717	13034	13456	14090
99	12720	13040	13466	14106
95	12734	13068	13513	14180
90	12751	13102	13570	14273
75	13436	14472	15853	17925

Lignite (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	696	914	1206	1644
99	708	938	1246	1708
95	761	1045	1424	1992
90	828	1178	1646	2348
75	1463	2448	3763	5734

Natural gas (MJ)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	14554	16245	18500	21883
99	26378	39894	57914	84946
95	78930	144998	233088	365223
90	144620	276378	452055	715570
75	342445	672028	1111472	1770638

16.6 Common inventory data for fuel cell systems

Table 16.16: Additional emissions for FC systems

	Amount of emissions per 1 kW stack (g)
Carbon tetrachloride	0.258
R12	0.205
R134a	0.623
R22	8.838
R23	0.564

17 Appendix B – Characterization results

Table 17.1: Characterization results for the diesel system

ADP (kg Sb-equiv.)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	18	19	20	21
99	24	31	40	53
95	51	84	129	196
90	84	151	240	374
75	184	352	574	909

AP (kg SO2-equiv.)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	16	17	19	22
99	28	42	60	88
95	83	151	243	380
90	151	288	471	745
75	357	699	1156	1841

EP (kg PO4-equiv.)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1.2	1.5	1.8	2.4
99	4	6	10	15
95	14	27	45	71
90	27	54	89	142
75	67	133	221	353

GWP (kg CO2-equiv.)	**Power demand (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	3153	3185	3221	3286
99	3248	3376	3538	3794
95	4173	5226	6622	8728
90	8285	13451	20329	30659
75	13426	23731	37462	58073

Table 17.2: Characterization results for the battery system

ADP (kg Sb-equiv.)	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	27.25	52.33	77.65	129.57
99	46.35	90.53	145.94	228.11
95	58.18	114.19	185.39	291.23
90	146.93	310.16	499.82	791.51
75	322.79	620.92	1044.21	1638.45

AP (kg SO2-equiv.)	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	15.75	30.65	45.62	76.26
99	26.39	51.73	83.17	129.72
95	29.54	58.04	93.69	146.73
90	77.51	164.61	264.21	418.09
75	167.60	320.43	539.48	844.30

EP (kg PO4-equiv.)	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.69	1.25	1.82	3.06
99	1.18	2.21	3.60	5.59
95	1.73	3.30	5.42	8.53
90	3.98	8.29	13.41	21.20
75	8.82	17.11	28.78	45.21

GWP (kg CO2-equiv.)	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1447	2599	3784	6383
99	2762	5178	8479	13233
95	5329	10312	17035	26971
90	11686	24022	39222	62223
75	26909	52744	88446	139819

Table 17.3: Characterization results for the fuel cell system with H_2 bottles

ADP (kg Sb-equiv.)	Power need (kW)			
Grid availability (%)	**1,5**	**3**	**5**	**8**
99.9	4,35	6,37	8,00	11,24
99	16,94	29,96	47,04	73,07
95	69,00	131,67	215,51	340,07
90	131,67	257,03	423,11	670,63
75	323,08	633,28	1045,29	1661,71

AP (kg SO2-equiv.)	Power need (kW)			
Grid availability (%)	**1,5**	**3**	**5**	**8**
99.9	3,65	4,87	5,53	7,25
99	9,58	15,29	22,67	34,10
95	32,43	58,85	94,30	146,41
90	58,85	111,67	181,15	283,92
75	140,11	269,30	440,12	694,90

EP (kg PO4-equiv.)	Power need (kW)			
Grid availability (%)	**1,5**	**3**	**5**	**8**
99.9	0,25	0,38	0,49	0,70
99	1,10	2,01	3,20	5,01
95	4,72	9,13	15,03	23,83
90	9,13	17,96	29,69	47,22
75	22,47	44,41	73,60	117,32

GWP (kg CO2-equiv.)	Power need (kW)			
Grid availability (%)	**1,5**	**3**	**5**	**8**
99.9	869	1271	1606	2258
99	3431	6093	9593	14918
95	14080	26942	44141	69715
90	26942	52666	86764	137611
75	65850	129558	214203	340871

Table 17.4: Characterization results for fuel cell system with on-site electrolysis

ADP (kg Sb-equiv.)	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	9.99	11.93	14.53	18.42
99	22.79	37.54	57.21	86.71
95	79.70	151.37	246.92	390.24
90	150.84	293.65	484.05	769.66
75	365.56	722.84	1199.20	1913.74

AP (kg SO2-equiv.)	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	8.92	10.14	11.77	14.21
99	12.33	16.97	23.14	32.41
95	27.50	47.30	73.71	113.31
90	46.46	85.23	136.91	214.44
75	105.37	202.71	332.48	527.15

EP (kg PO4-equiv.)	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	0.55	0.65	0.79	0.99
99	1.14	1.83	2.76	4.14
95	3.77	7.09	11.52	18.16
90	7.05	13.66	22.46	35.67
75	16.99	33.52	55.56	88.62

GWP (kg CO2-equiv.)	Power need (kW)			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1990	2431	3017	3898
99	4768	7985	12275	18710
95	17111	32672	53419	84541
90	32540	63530	104850	166830
75	79149	156690	260078	415159

Table 17.5: Characterization results for fuel cell system with on-site electrolysis

ADP (kg Sb-equiv.)	**Power need (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	19.81	20.95	22.48	24.76
99	25.39	32.11	41.08	54.53
95	50.19	81.72	123.76	186.81
90	81.20	143.73	227.11	352.17
75	175.51	332.10	540.89	854.07

AP (kg SO2-equiv.)	**Power need (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	16.68	17.60	18.83	20.67
99	17.40	19.04	21.23	24.51
95	20.60	25.44	31.90	41.59
90	24.60	33.45	45.24	62.93
75	38.63	61.17	91.21	136.28

EP (kg PO4-equiv.)	**Power need (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	1.05	1.10	1.16	1.26
99	1.17	1.34	1.57	1.91
95	1.71	2.42	3.37	4.80
90	2.39	3.78	5.63	8.40
75	4.50	7.99	12.64	19.62

GWP (kg CO2-equiv.)	**Power need (kW)**			
Grid availability (%)	**1.5**	**3**	**5**	**8**
99.9	3637	4043	4175	4636
99	4527	5824	7142	9384
95	8483	13736	20329	30483
90	13429	23626	36813	56857
75	28586	54233	87200	137441

18 Appendix C – Total cost diagrams for 1.5 kW

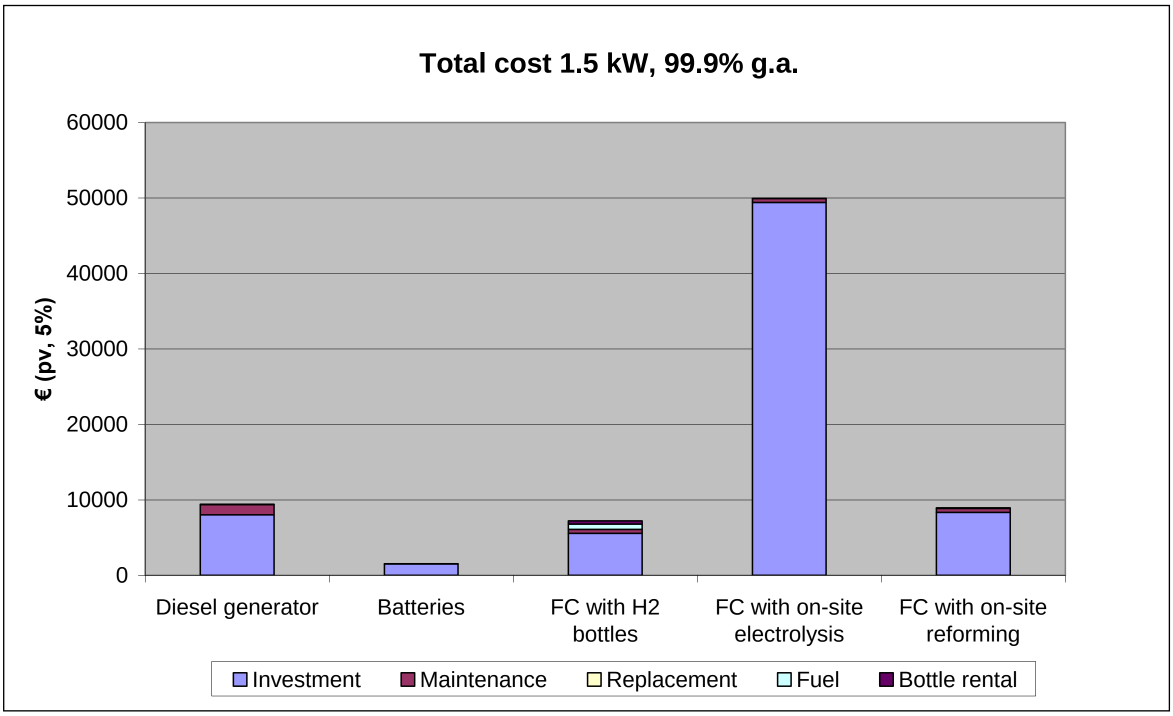

Figure 18.1: Total costs for each power system with a power demand of 1.5 kW and 99.9% grid availability

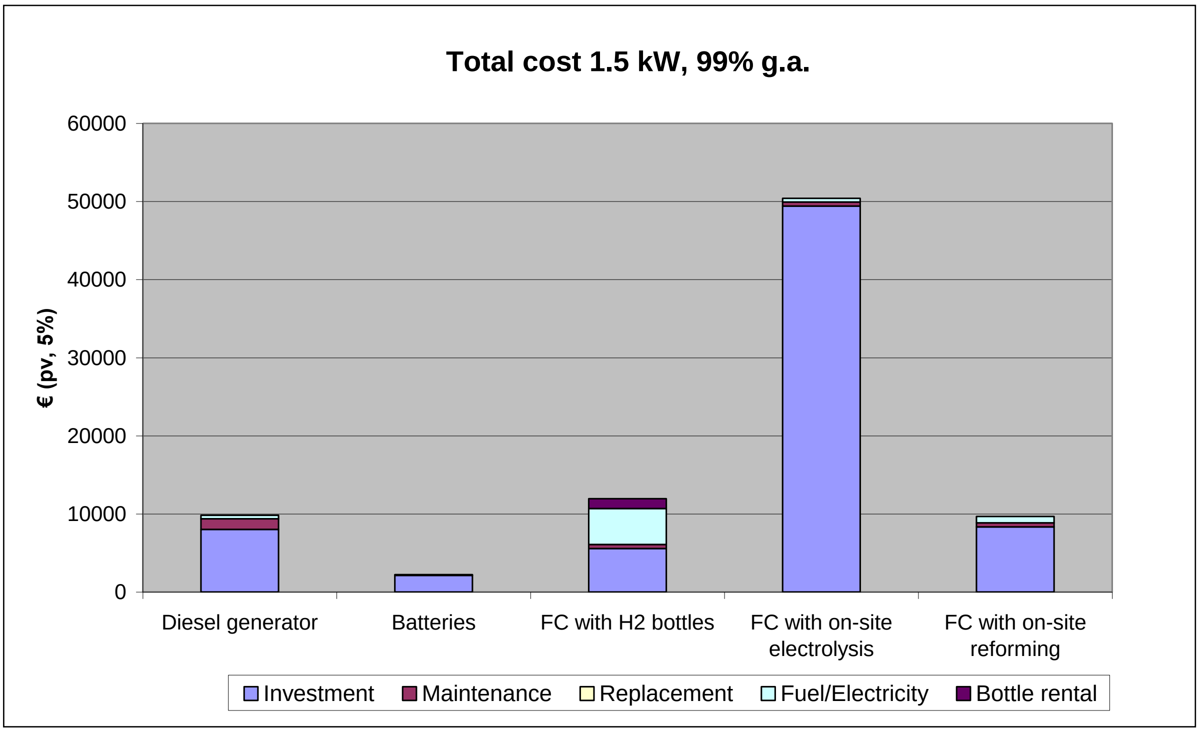

Figure 18.2: Total costs for each power system with a power demand of 1.5 kW and 99% grid availability

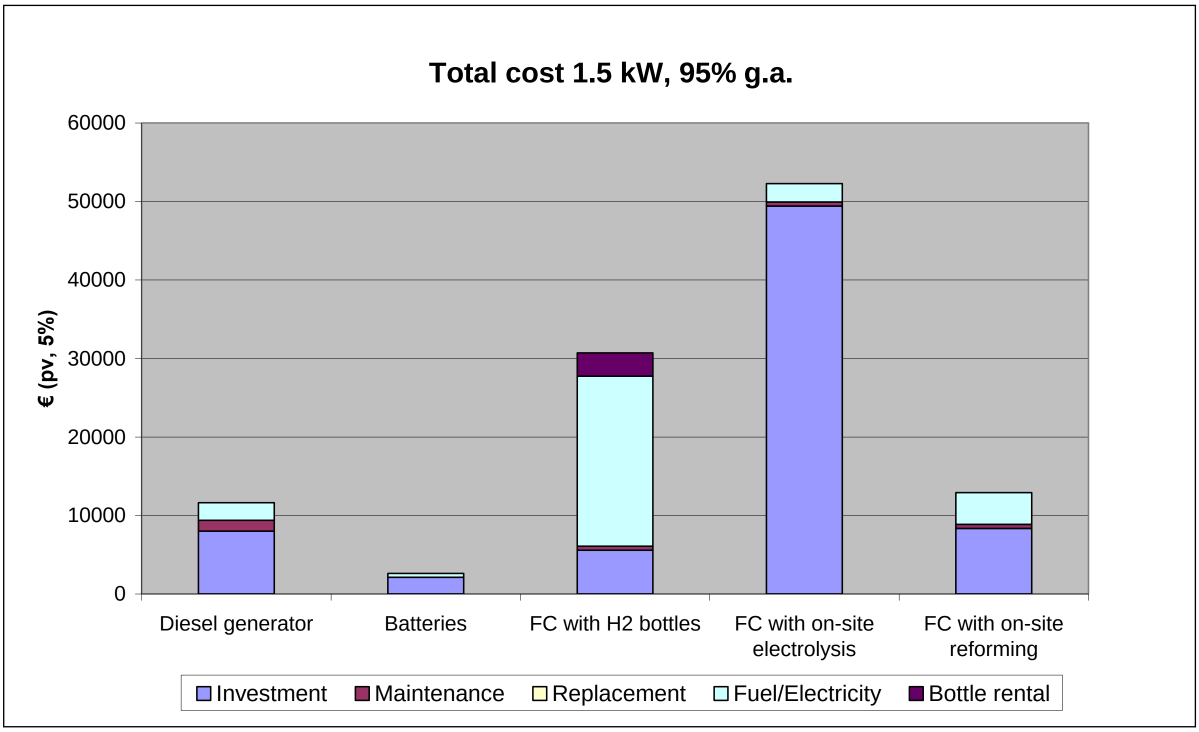

Figure 18.3: Total costs for each power system with a power demand of 1.5 kW and 95% grid availability

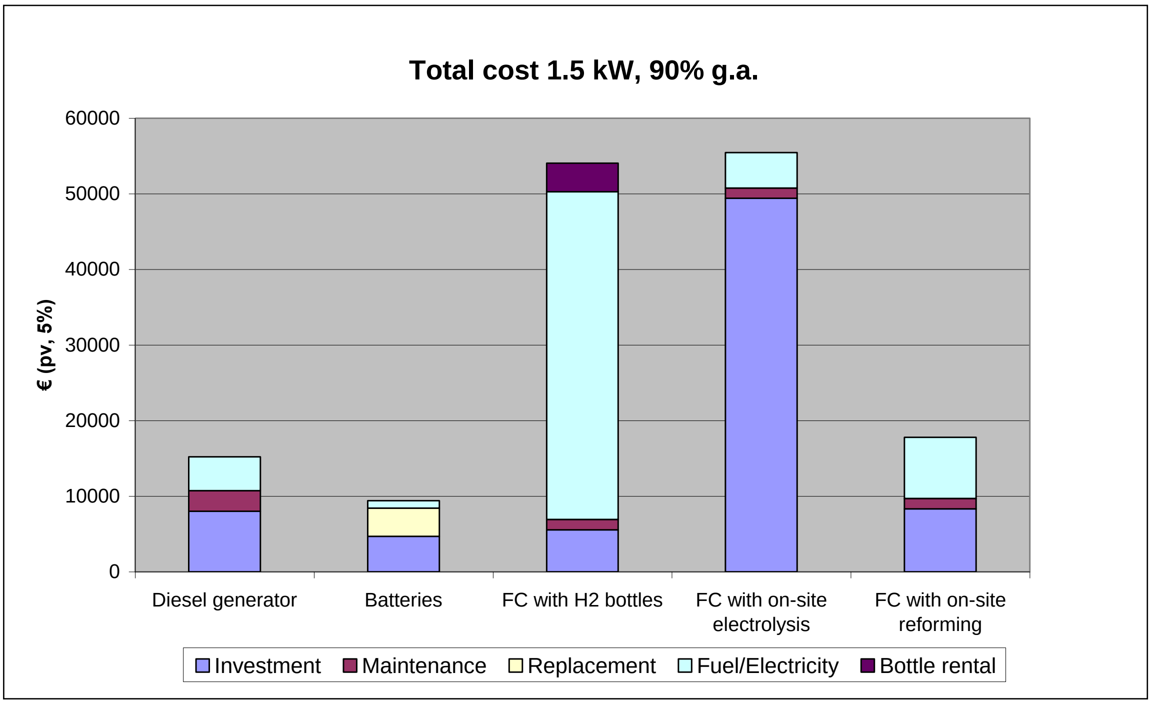

Figure 18.4: Total costs for each power system with a power demand of 1.5 kW and 90% grid availability

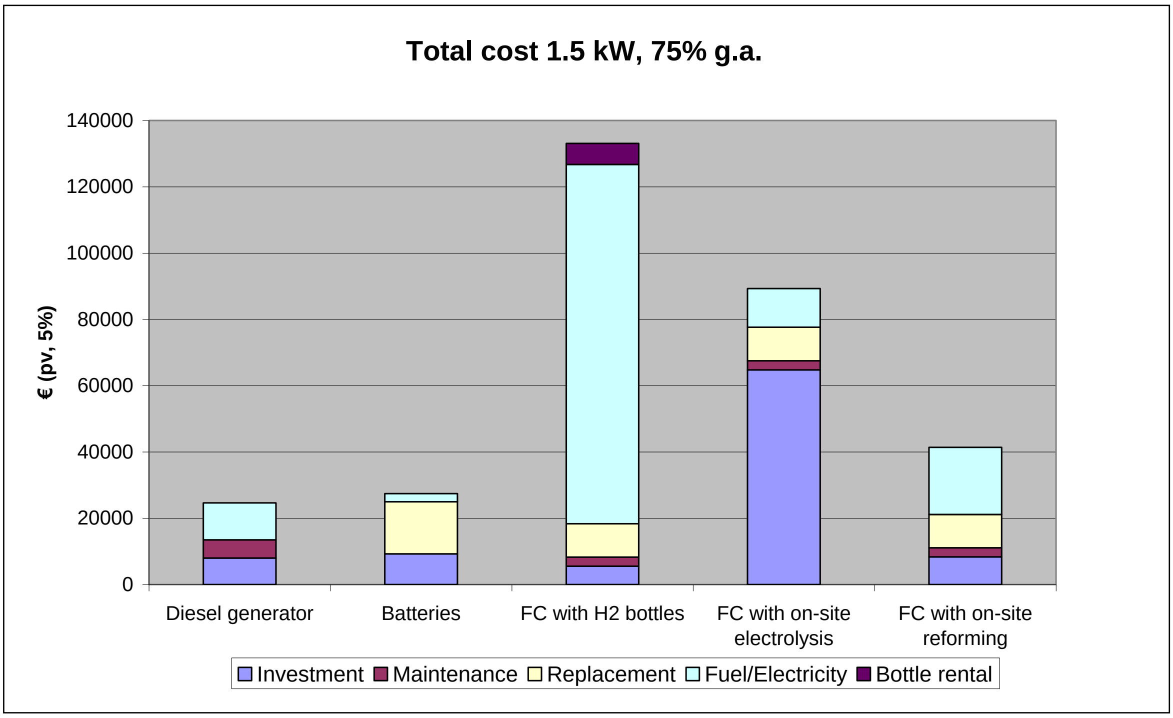

Figure 18.5: Total costs for each power system with a power demand of 1.5 kW and 75% grid availability

19 Appendix D – Total cost diagrams for 5 kW

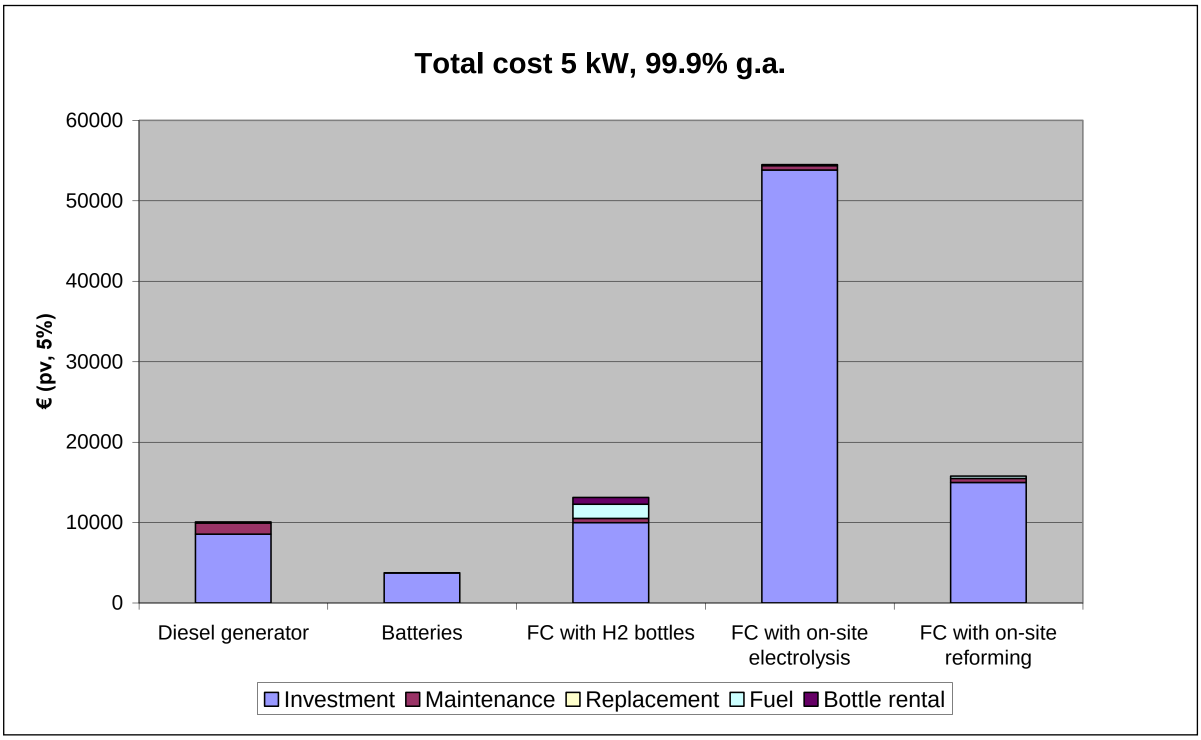

Figure 19.1: Total costs for each power system with a power demand of 5 kW and 99.9% grid availability

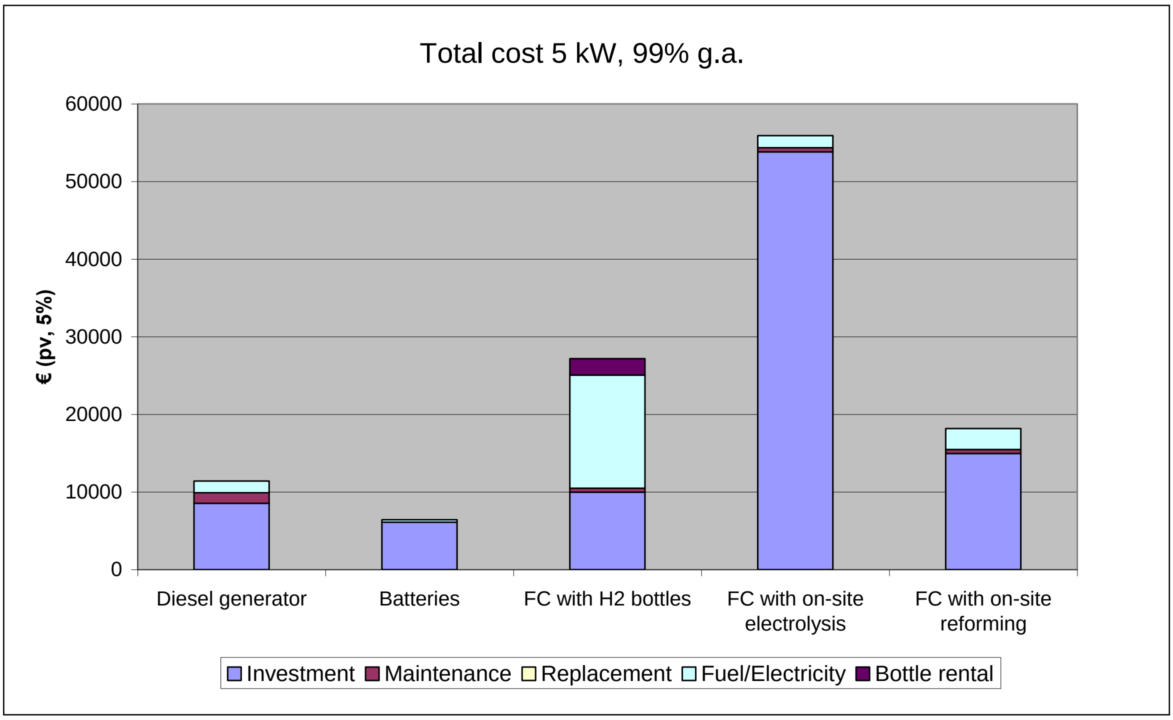

Figure 19.2: Total costs for each power system with a power demand of 5 kW and 99% grid availability

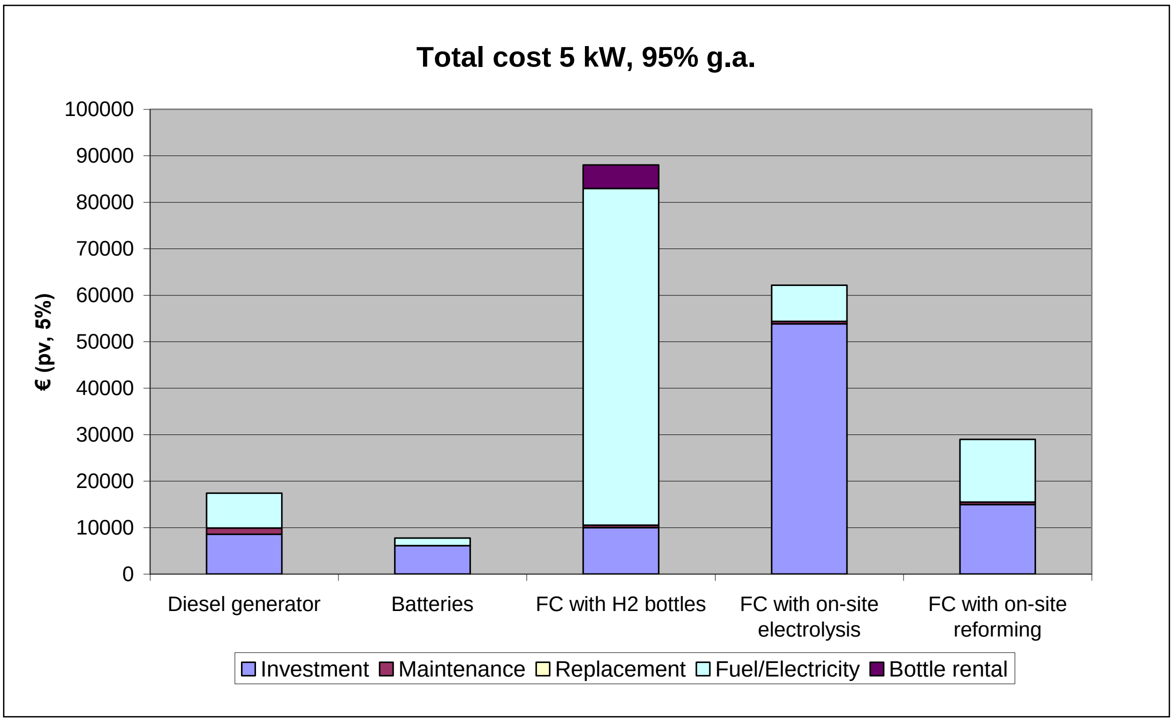

Figure 19.3: Total costs for each power system with a power demand of 5 kW and 95% grid availability

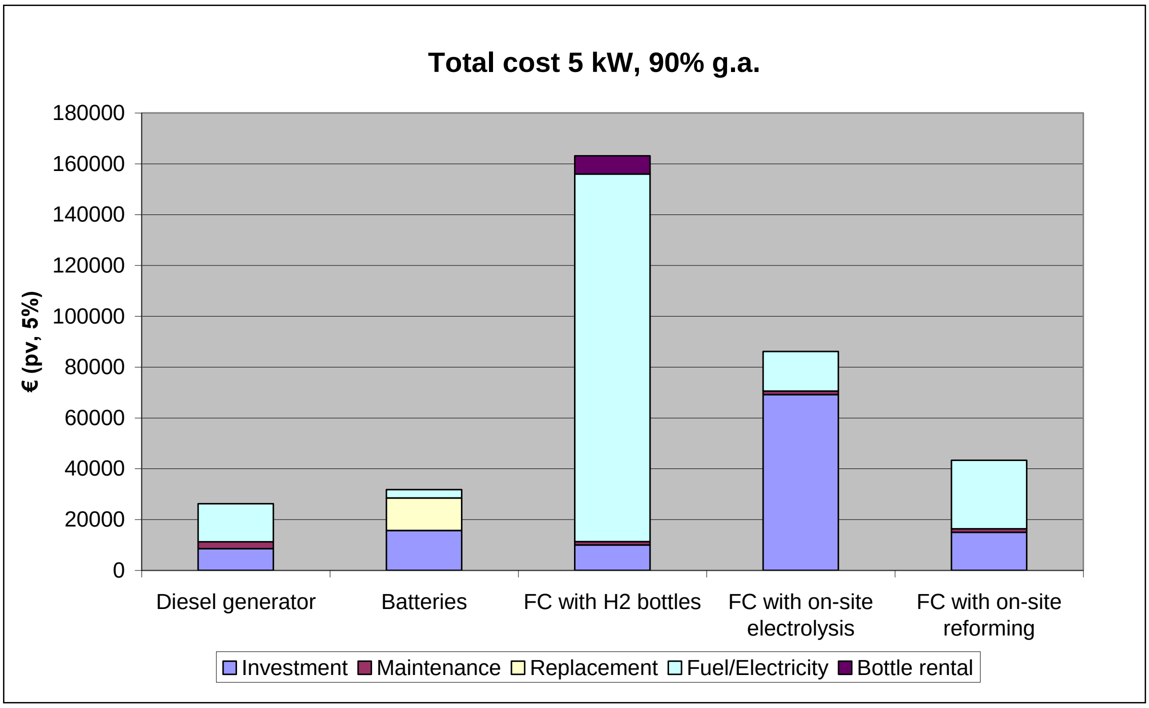

Figure 19.4: Total costs for each power system with a power demand of 5 kW and 90% grid availability

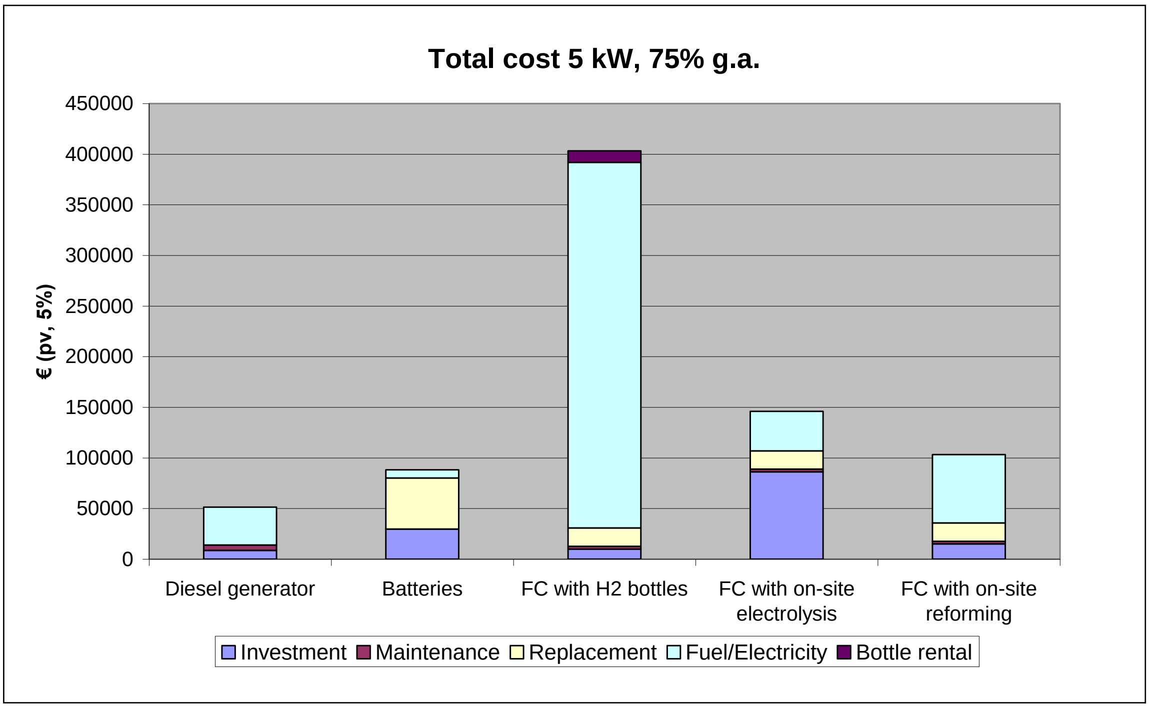

Figure 19.5: Total costs for each power system with a power demand of 5 kW and 75% grid availability

20 Appendix E – Total cost diagrams for 8 kW

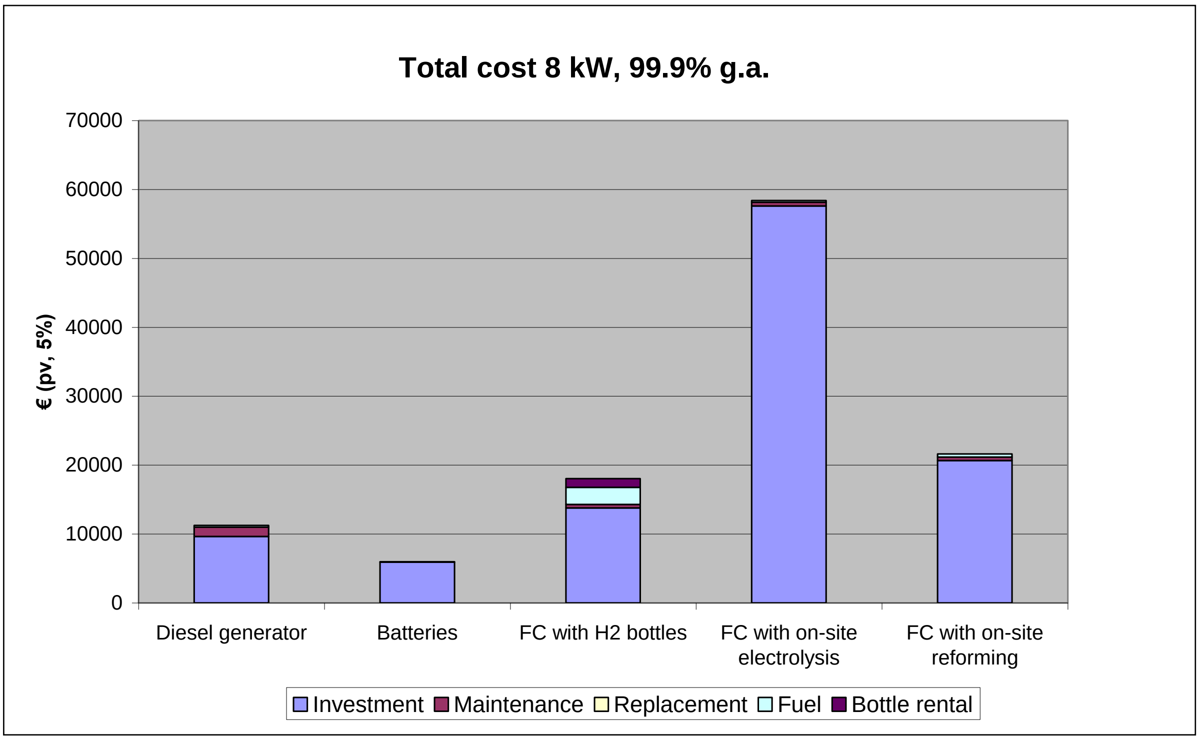

Figure 20.1: Total costs for each power system with a power demand of 5 kW and 99.9% grid availability

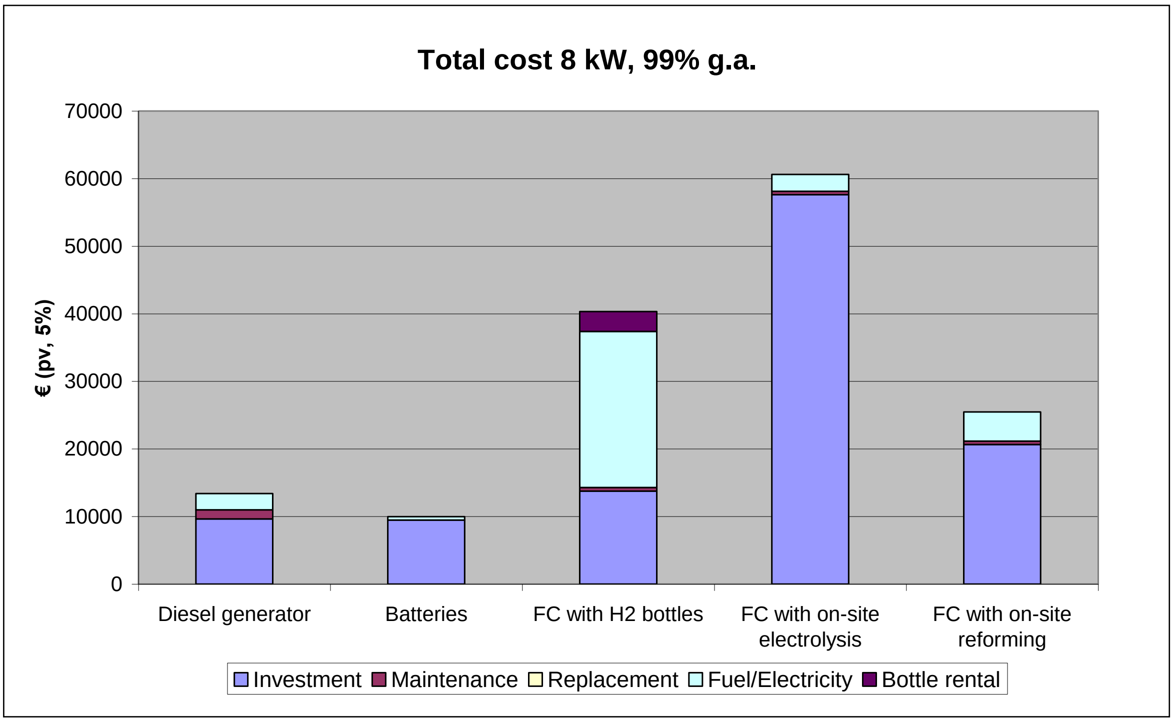

Figure 20.2: Total costs for each power system with a power demand of 5 kW and 99% grid availability

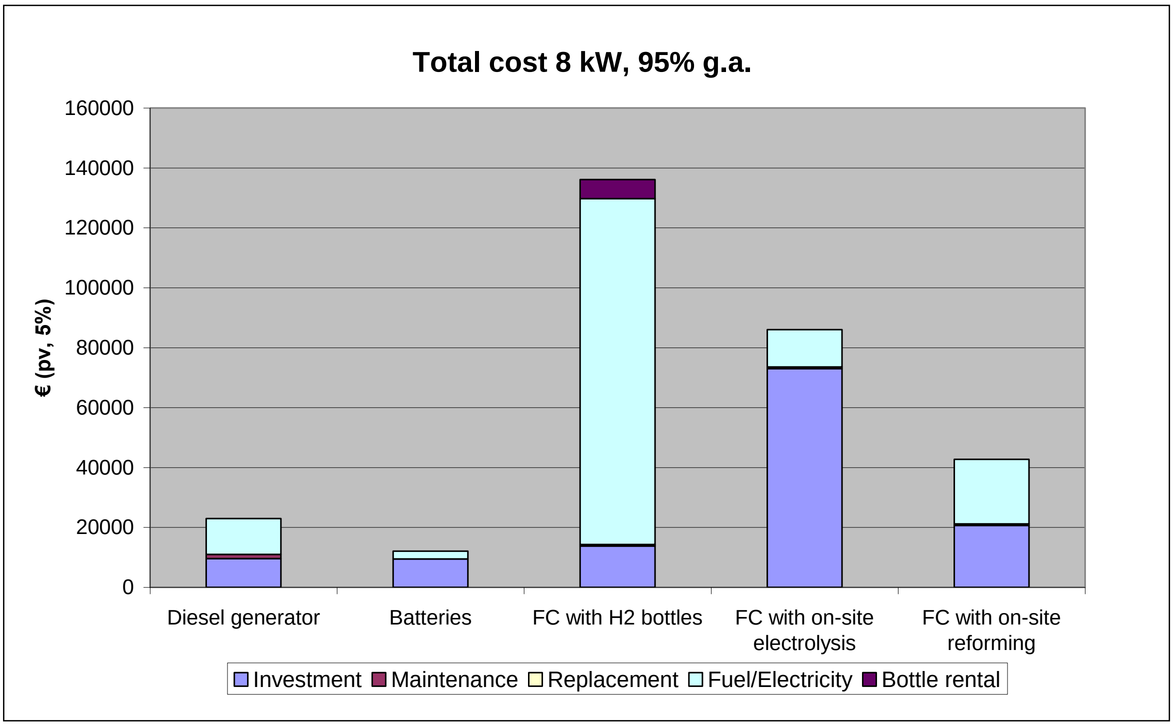

Figure 20.3: Total costs for each power system with a power demand of 8 kW and 95% grid availability

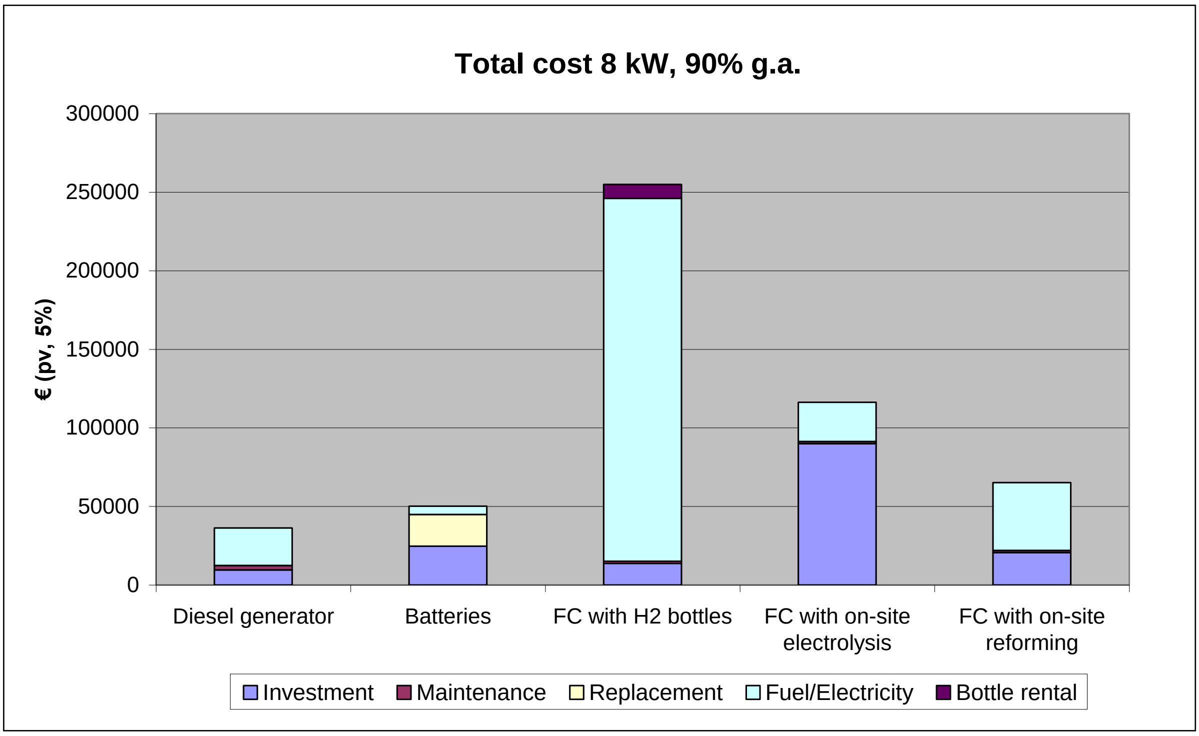

Figure 20.4: Total costs for each power system with a power demand of 8 kW and 90% grid availability

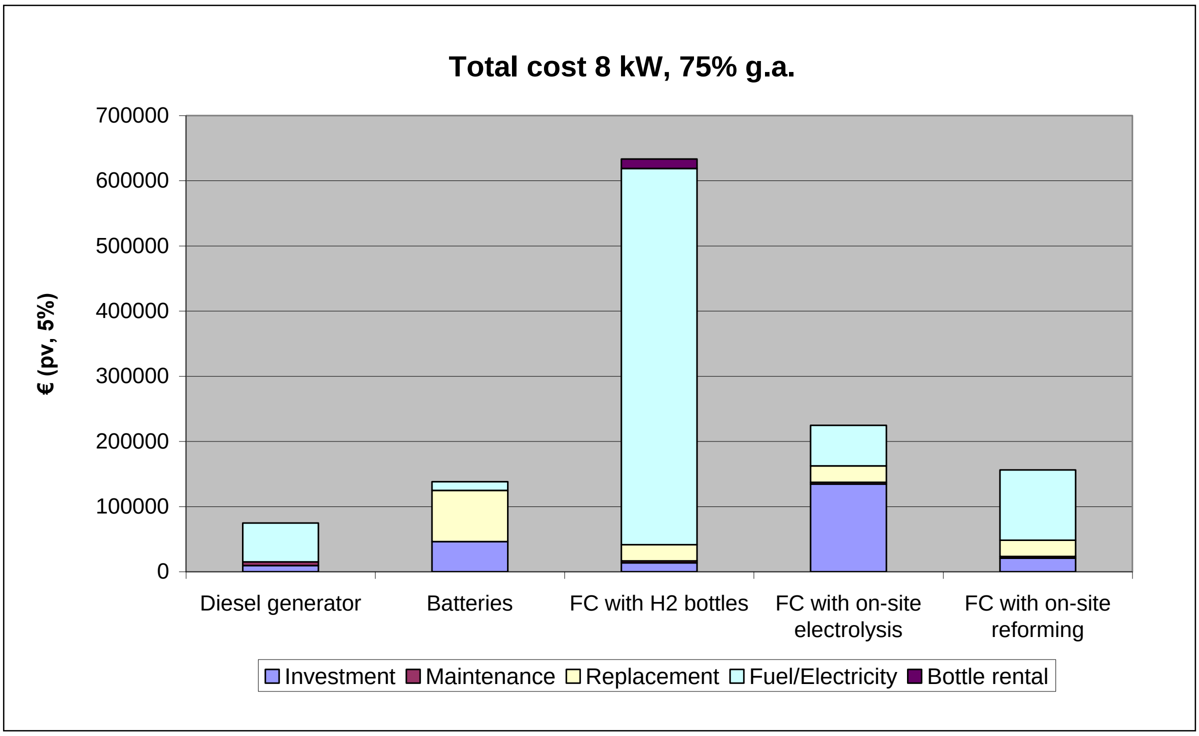

Figure 20.5: Total costs for each power system with a power demand of 8 kW and 90% grid availability