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Assessing the Environmental Costs and Benefits of Households Electricity Consumption Management

Ida Lund Segtnan

Master of Science in Energy and Environment

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Supervisor:	Edgar Hertwich, EPT
Co-supervisor:	Thomas Gibon, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

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Norwegian University
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MASTER THESIS

for

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Assessing the environmental costs and benefits of households electricity consumption management

Vurdering av miljøkonsekvenser ved styringssystemer for kraftbruk i husholdningers

Background and objective.

In 2010, the Norwegian Water Resources and Energy Directorate, NVE, announced that the rollout of advanced measurement and management systems (AMS) for electrical consumption of Norwegian households to be completed by 2018[1]. This technology can ensure a two-way communication between the consumer, the distribution and the energy production. In other words, it can provide the consumers with information about the cost of electricity at any time but can also communicate this information to the so-called "smart grid" which in turn adapts electricity production and distribution at a broader scale, in real time. Another option is the possibility to remote control the meter, which can avoid or switch peak demands at the consumer level.

Load-shifting becomes feasible at a large scale within a smart grid, as meters are able to shift the use of energy for appliances that can be run at an arbitrary time. As a consequence, peak loads can be levelled or shifted, which could lead to a more controlled use of backup carbon-intensive energy production technologies (such as gas turbines), in turn offering a potential mitigation of greenhouse gases emissions.

Electricity consumption management technologies are currently being developed by companies such as Scandinavian Electric AS[2]. In parallel, collaborative projects like REMODECE[3], which surveyed and modelled the load curves of households for a few European countries, have been carried out in order to collect data. Another energy efficiency (pilot) project has been carried out over several years by SINTEF, with real time metering of energy consumption of ca. 40 households in Malvik and electricity pricing according to the spot price. Representative data is available, including for the modelling of Norwegian load curve, in which households hold about a 20% share. Collaboration with the actors of this project is expected, both regarding data provision and result discussion. Network companies can also be contacted for the same purpose.

Economic impact assessment of advanced measurement and management systems are available in the literature, but, even though many discussions are held on this matter and eco-friendliness is often regarded as a major strength of the implementation of this technology, there is a lack of information considering its environmental impact of AMS.

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[1] http://www.nve.no/PageFiles/808/ams_juli10.pdf

[2] http://www.scel.no/SE_comweb.asp?ID=317&segment=3

[3] http://remodece.isr.uc.pt/

The following questions should be considered in the project work:

1. What environmental benefits can be expected from an advanced measurement and management technology for electricity consumption of households? What mechanisms are relevant and how can they be quantified? Provide an estimate of the benefits and a sensitivity analysis
2. What are the environmental costs of advanced measurement and management technologies? What are the trade-off patterns that can be observed? Assess the life-cycle impacts of installing and operating this type of equipment.
3. At a broad scale (Norwegian territory), what can be the effect of such a technology and what contribution to policies can be expected? Different scenarios should be explored.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

One – 1 complete original of the thesis shall be submitted to the authority that handed out the set subject. (A short summary including the author's name and the title of the thesis should also be submitted, for use as reference in journals (max. 1 page with double spacing)).
Two – 2 – copies of the thesis shall be submitted to the Department. Upon request, additional copies shall be submitted directly to research advisors/companies. A CD-ROM (Word format or corresponding) containing the thesis, and including the short summary, must also be submitted to the Department of Energy and Process Engineering

Department of Energy and Process Engineering, 24. January 2011

Olav Bolland
Olav Bolland
Department Head

Edgar Hertwich
Edgar Hertwich
Academic Supervisor

Research Advisors: Thomas Gibon, IndEcol,
External contact: Hanne Sæle, Sintef Energiforskning

Preface

This thesis was written during spring 2011 as the final part of my MSc degree in Energy and Environmental Engineering at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU).

Many persons have contributed with information and helped me during the work on this thesis and I want to direct my thanks to all of them. I would first like to thank my supervisors at NTNU, Edgar Hertwich, and especially my co-advisor Thomas Gibon, for all the good advices he has given me and for always having time to discuss my questions. I am also very grateful to my external contact Hanne Sæle from SINTEF Energy AS, who has provided guidance in the field of smart metering technology and helped me all along with my work.

Last, but not least, I would like to express my gratitude to my fellow students Christine Birkeland, Ingrid Haukeli and Kari Sørnes. Their support, their company and our discussions has been inspiring and motivating.

Ida Lund Segtnan

Ida Lund Segtnan

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Abstract

In this study the environmental costs and benefits of smart metering technology systems installed in households in Norway have been assessed. Smart metering technology systems enable mechanisms to manage electricity consumption by shifting loads .With the use of Life Cycle Assessment (LCA) and the ReCiPe method for impact assessment, the life cycle impacts of installation and operation of a system in a household have been found. Environmental benefits of using the systems to manage electricity consumption have been quantified.

The results of the study indicated that the environmental costs of smart metering technology systems mainly are caused by the production of system components and system electricity use during operation. For the production of system components, the use of electronics in the components was generally the major contributor to the total environmental impacts. Further, the systems metal depletion potential was high relative to other environmental impacts after normalization in impact assessment.

The main environmental benefits of smart metering technology systems in a Norwegian perspective will be in a critical supply situation of electricity to avoid use of reserve capacity gas power plants, and the results from the study showed that the systems in such a case can contribute to an avoided emission of greenhouse gases. Load shifting from a general basis may however not always have environmental benefits and this will depend on the existing alternatives for electricity production.

Sammendrag

I denne studien er det foretatt en vurdering av miljøkonsekvenser ved avanserte måle- og styringssystemer (AMS) for elektrisitetsbruk i husholdninger i Norge. AMS muliggjør mekanismer for å styre elektrisitetsforbruket ved å skifte last. Ved bruk av livssyklusanalyse og ReCiPe-metoden til påvirkningsanalyse, har livssykluspåvirkningene fra installasjon og drift av et system i en husholdning blitt funnet. Miljøfordeler AMS kan bidra med ved å styre elektrisitetsforbruket i husholdninger har deretter blitt kvantifisert.

Resultatet fra analysen indikerte at miljøkostnadene fra installasjon og drift av systemene hovedsakelig er forårsaket av produksjonen av systemkomponenter og elektrisitetsforbruk av systemet under drift. Videre var det bruken av elektronikk i komponentene som ga det høyeste bidraget til miljøpåvirkningene. Etter normalisering i påvirkningsanalysen hadde metallutvinning høy relativ viktighet sammenliknet med de andre miljøpåvirkningskategoriene.

Miljøfordelen ved AMS i Norge er hovedsakelig i en svært kritisk forsyningssituasjon av elektrisitet for å unngå bruk av reservekapasitet i form av gassturbiner. Resultatene fra studien viste at systemene i et slikt tilfelle kan bidra til et unngått utslipp av drivhusgasser. Lastskifting generelt vil på en annen side ikke nødvendigvis ha miljøfordeler og dette vil avhenge av de eksisterende alternativene for elektrisitetsproduksjon.

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Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ADSL	Asymmetric Digital Subscriber Line
AMS	(English) Advanced Metering Systems
AMS	(Norwegian) Avanserte Måle- og Styringssystemer
CC	Combined Cycle
DSO	Distribution System Operator
EE	Electrical and Electronic
ENSTO-E	The European Network of Transmission System Operators for Electricity
EU	European Union
GFR	Glass Fiber Reinforced
GHG	Greenhouse Gases
GPRS	General Packet Radio Service
GSM	Global System of Mobile Communication
HV	High Voltage
IEE	Intelligent Energy for Europe
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LCI	Life Cycle Inventory
LV	Low Voltage
MID	Measurement Instrument Directive
MV	Medium Voltage
NVE	Norwegian Water Resources and Energy Directorate
OED	the Norwegian Ministry of Petroleum and Energy
PC	Polycarbonate
PCB	Printed Circuit Board
PLC	Power Line Communication
RLC	Remote Load Control
TSO	Transmission System Operator
WEEE	Waste Electrical and Electronic Equipment

Terminology

Demand response
Outcome of action undertaken by electricity consumers in response to a factor (e.g. price)

Smart grid
“The European Smart Grid Task Force defines Smart Grids as electricity networks that can efficiently integrate the behavior and actions of all users connected to it — generators, consumers and those that do both — in order to ensure an economically efficient, sustainable power system with low losses and high quality and security of supply and safety” (EuropeanCommission, 2011a)

Smart metering technology systems
Systems to meter and control electricity consumption. In this study used for the Norwegian equivalent AMS (See abbreviations)

1 Background

1.1 Introduction to the report

1.1.1 Objective

The purpose of this study is to assess the environmental costs and benefits of smart metering technology systems, with a scope limited to households' electricity consumption management and Norway as geographical location.

The demand for electricity has increased as a consequence of the global development in welfare and growth of population. It is well known that the generation and transmission of electricity has significant effects on the environment, both related to climate change and other local and regional environmental impacts. The issue of climate change has lead to requirements regarding reduction of emissions of greenhouse gases (GHG).

In 2008, the European Union (EU) adopted an integrated energy and climate change policy, which included targets towards the year 2020 (EuropeanCommission, 2010). The targets are known as the 20-20-20-targets:

- 20% cut of GHG emissions from 1990s levels
- 20% renewable resources into the EU energy consumption mix
- 20% reduction in primary energy use with respect to projected levels

The targets have to be met also by Norway and in addition, the Norwegian Ministry of Environment have stated in 2008 that Norway should have 30% reduction of CO_2 emissions before 2020 and be carbon neutral before 2030 (Miljøverndepartementet, 2008). A key driver for reaching the targets is a future energy system, often referred to as smart grid, which will enable new technologies and mechanisms - and is expected to be a tool to address climate change. Smart grid can be described as an energy system that includes two-way communication between supplier and consumer, intelligent metering and monitoring systems (EuropeanCommission, 2011a).

The future energy system has to handle both the increasing demand of electricity and secure the supply of it, and at the same time as the generation and supply has to be in place it is of major importance that the environmental issues are managed accordingly. An essential point with electricity is that the quantities that can be stored are limited, and the time of consumption is therefore important. Smart metering technology systems can be used to manage electricity consumption patterns and influence at what time electricity is used.

A nationwide implementation of smart metering technology is currently going on in Norway, and is awaiting a binding resolution from the Norwegian Government of Water and Energy Resources (NVE). On the one hand, environmental aspects related to the technology concern the potential benefits from the systems functionality and on the other hand the costs of installation and operation. In this study, Life Cycle Assessment (LCA) is used to evaluate the environmental aspects. The goal of the LCA is to make an evaluation of installation and operation of a smart metering technology system in a household to identify possible trade-off patterns and contributions to environmental impacts throughout the life cycle. The objective is then to quantify environmental benefits that can be obtained by having smart technology systems operating in households.

The scope of the study is limited to Norway and the choices related to technology are made with respect to this as location. The geographical location in Norway is chosen as Trondheim, situated in the region of Central Norway. The choice is based on the fact that implementation of the systems is suggested by NVE to be carried out first for this region.With the objective of the study as background, the interpretation of the assignment has led to the following strategy for the work:

The principles of mechanisms enabled by smart metering technology will be explained from a generic perspective. To provide a picture of smart metering technologies place and potential in the future, some scenarios and studies are presented from literature. The study is however based on Norwegian conditions, and the quantification of environmental benefits will mainly be done with respect to this as scenarios. The motivation and reasons for the implementation of smart metering technology systems in Norway will be presented and is used as basis for establishing a case and scenarios for the quantification. For the benefits the main focus is on avoided emissions of GHGs, but other environmental impacts will be included as well.

For assessing the environmental costs of the installation and operation of systems in households, a general system will be defined, located in Norway. No previous LCAs on smart metering technology systems have been found to exist during the work on this study. As the choices of technological system solutions have been expected to lead to large variations in results, it is essential to understand the range of solutions that exist. The different choices will be presented to give a background of understanding the limitations of the study, before the system for the LCA is defined.

1.1.2 Structure

Chapter 1 provides the background for the study. An introduction is given to the power situation in Norway, smart metering technology and the environmental aspects.

Chapter 2 explains the methodology for LCA, its theoretical and mathematical aspects and the tools and methods used in this study.

Chapter 3 provides technological descriptions of the system chosen for the LCA, presents the life cycle inventories (LCI) and defines a case for quantification of environmental benefits.

Chapter 4 contains the results from the LCA and sensitivity analysis that has been performed.

Chapter 5 discusses the results that have been obtained.

Chapter 6 concludes the discussion and findings of this study.

1.2 Electricity in Norway

A brief introduction to the Norwegian power market and the supply situation is given here to provide a background for relevant aspects related to smart metering technology and mechanisms in a Norwegian perspective.

1.2.1 Actors involved in the power market

The Norwegian power market consists of a number of private and public participants. They can be divided into monopoly and market actors. An overview of the participants and their relations can be seen in Figure 1 (Sæle et al., 2011).

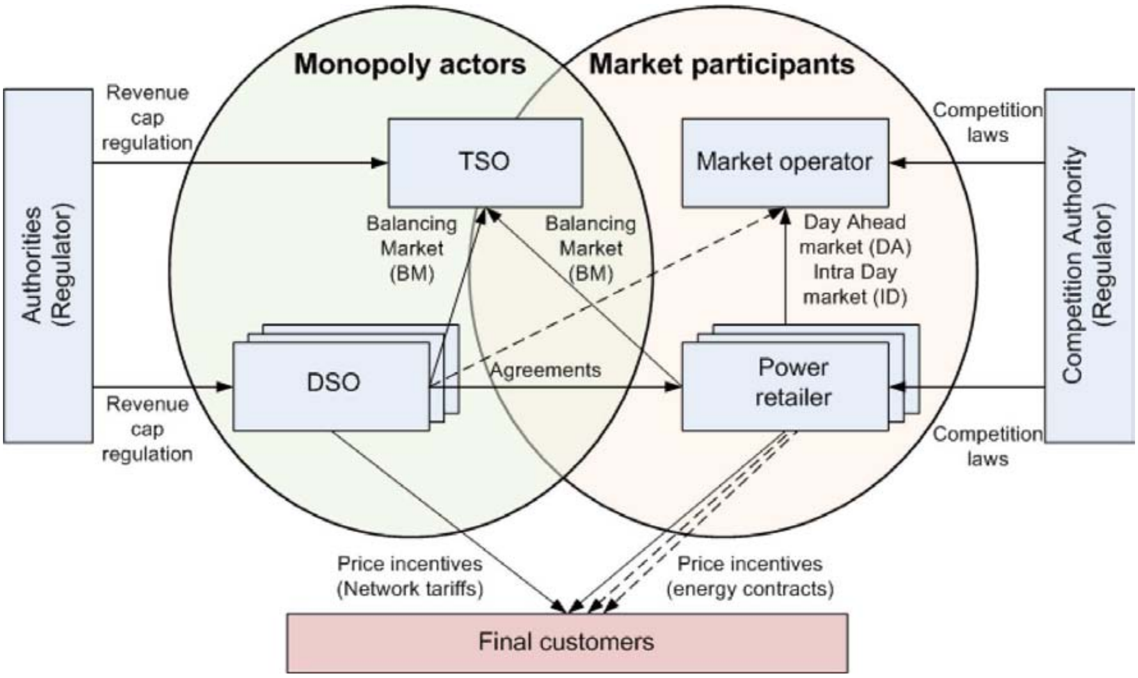

Figure 1: Overview of different actors in the Norwegian Power Market and their relations (Sæle et al., 2011)

The final customers are the end-users of electricity. They receive a network tariff from the monopoly side and an energy contract from the market side

The Distribution System Operators (DSO) are distributors of electricity to end-users and the owners of the local grids. They are monopoly participants and are obliged to supply consumers within their area with electricity. They are responsible for the metering.

The Transmission System Operator (TSO) is Statnett. The main responsibilities are to develop the Norwegian transmission grid and international connections, as well as the system safety of the Norwegian power system. Statnett owns 80% of the main grid (Statnett, 2011e).

The Market Operator is Nord Pool, the Nordic Power Exchange. Nord Pool operates the market for physical trading of electrical power.

Power suppliers/retailers produce and trade electrical power, either directly to consumers or through Nord Pool.

The Competition Authority regulates the market.

Authorities are represented by NVE as the regulator and licensing authority for the electrical power sector. NVE further reports to the Ministry of Petroleum and Energy (OED).

1.2.2 Production and consumption

In 2009 the total power production in Norway was 133 TWh and the total consumption 113 TWh. The generation mainly consists of hydro power, followed by some thermal power and wind power. Distributed between the different energy sources, the generation mix was 96% hydro power, 0,75% wind power and 3,5% thermal power. Compared to 2008, the thermal power production in Norway increased with 3,5 TWh in 2009. This was a consequence of gas works installed at Kårstø and Melkøya (NVE, 2011b).

The physical consumption mix of Norway in 2009, which is the generation of electricity including imports, can be seen in Figure 2 (NVE, 2009a).

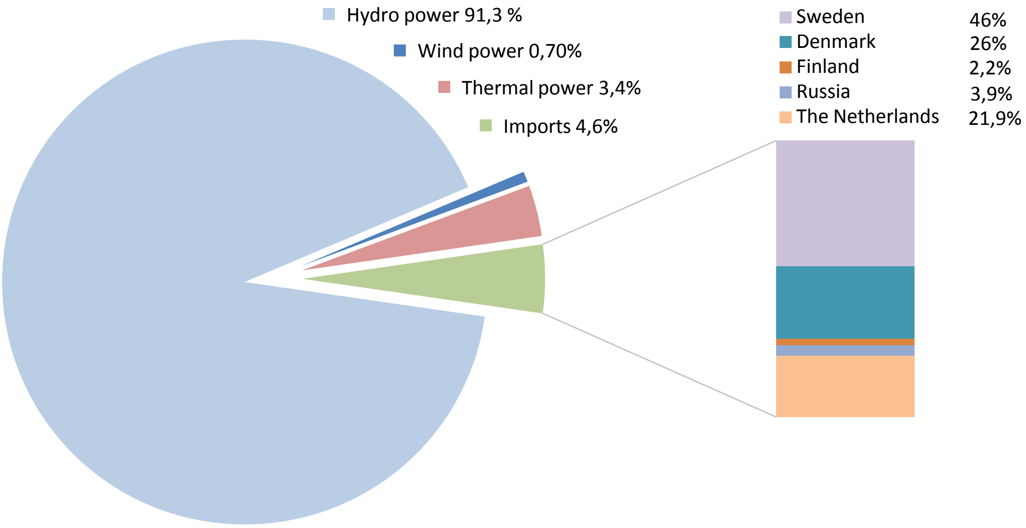

Figure 2: Physical consumption mix Norway, 2009 (NVE, 2009a)

As a general case, Norway is often an exporter of electricity during the day and importer during the night. This is based on the fact that the hydro power installed in Norway is the most convenient power to regulate to follow electricity consumption patterns and the demand of export and import from the continent. It is more beneficial to operate the installed thermal power continuously, as this is more expensive to regulate (NVE, 2009b). The average loads of consumption and production of electricity for a Wednesday in January 2008 is shown in Figure 3 (entsoe, 2008). Of the net consumption, housing had a share of 32%. The distribution of the net consumption between different sectors is showed in Figure 4 (entsoe, 2008).

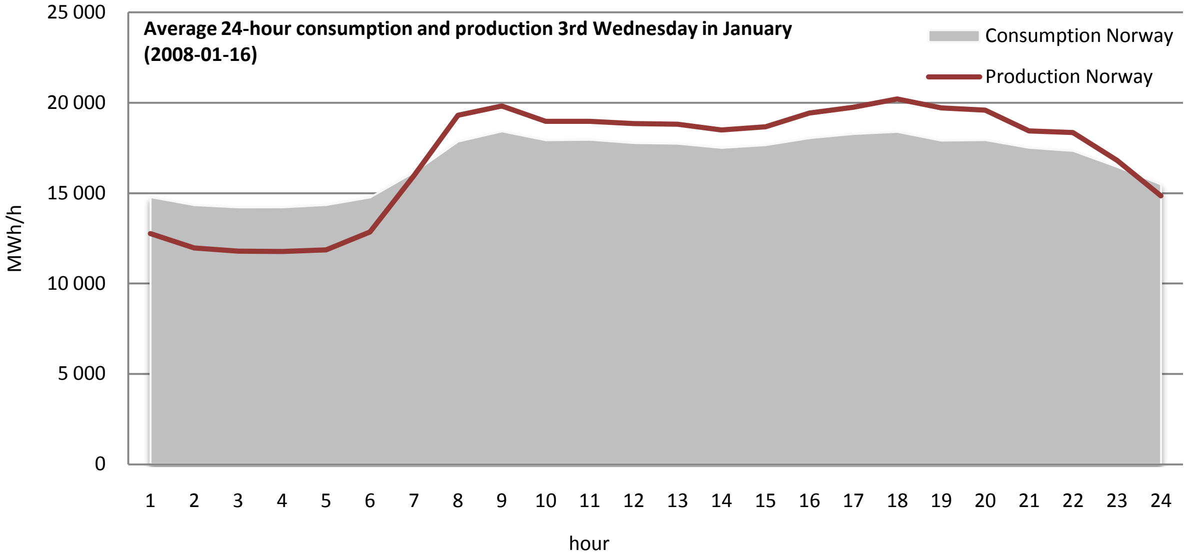

Figure 3: 24-hour consumption and production curves of electricity in Norway (entsoe, 2008)

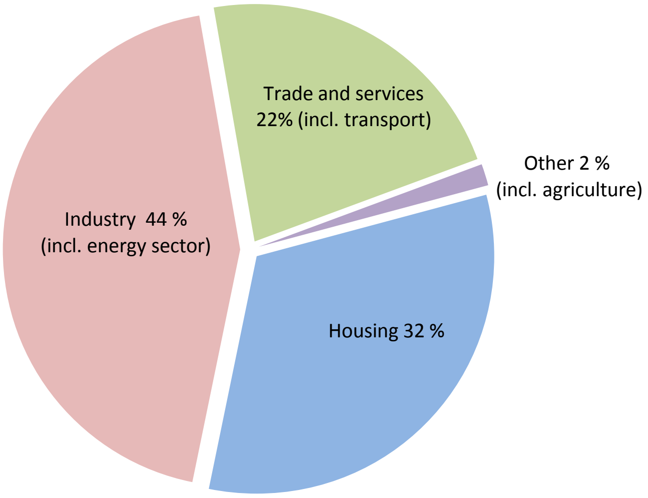

Figure 4: Net electricity consumption distributed on different sectors (entsoe, 2008)

1.2.3 Security of supply

Since the Norwegian electricity generation is mainly based on hydro, it has a large dependency on hydrological conditions. As a consequence, there is a large variation between generation in wet and dry years. The last decade, production varied between a maximum of 142 TWh in 2000 to a minimum of 106 TWh in 2001 (NVE, 2011b). In an average hydrological year, the production is around 118 TWh (Statnett, 2005). In addition to the uncertainty related to the hydrological conditions, there is a physical limitation of import capacity in interconnections. This is defined as transmission capability of electrical power, and is the amount of electricity possible to transfer in the network. If the amount of electricity to be transferred is larger than the capability, a bottle neck occurs. Bottle necks will mainly be controlled with price mechanics and price areas are defined. Norway is currently divided into five price areas and the area that has a surplus of electricity will lower the prices (NVE, 2011b). The power situation for the areas is assessed by Statnett continuously. Figure 5 shows the different areas and the five different levels of statuses that Statnett uses, for a case where all areas are defined as normal.

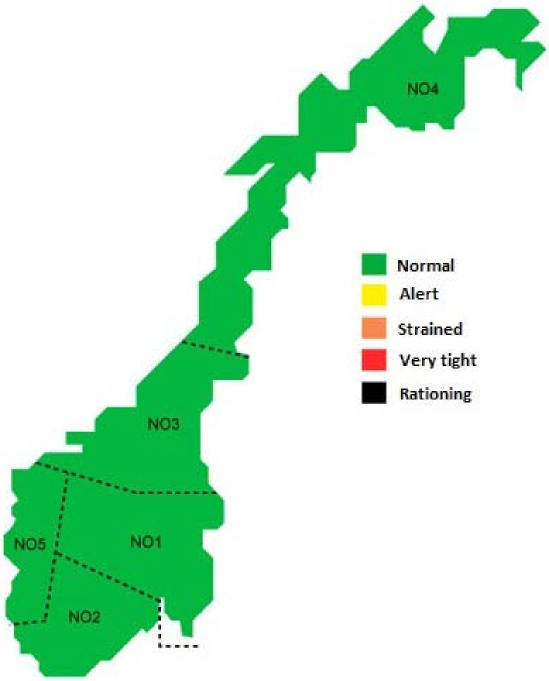

Figure 5: Statnetts assessment of power situations for the price areas in Norway (Statnett, 2011b)

Within its role as TSO, Statnett will be considered as the responsible concessionaire if a critical situation with lack of generating capacity occurs. Statnett has established a list of actions to handle these situations, defined as “very critical supply situations”. Firstly, detection and simple measures are performed, and if the situation is still not clarified after this, further actions are taken. The list of actions and order of implementation is (Statnett, 2011f):

1. *Establishment of separate Elspot areas*
2. *Gather detailed information from involved actors*
3. *Provide more detailed information to involved actors*
4. *Cancel of revisions*
5. *Information campaigns directed toward the municipality*
6. *Increase of import capacity to an area by system protection and/or reserve components*
7. *Disconnection of thermal loads that are not already disconnected*
8. *Special downward adjustment of production to ensure maximum import*
9. *Special downwards adjustment of production to secure water to especially important power plants*
10. *Operational connection with reduced operational security*
11. *Exercise of energy options*[1]
12. *Use of reserve capacity*

Reserve capacity is generating capacity available to Statnett and consist of two mobile gas power plants (Statnett, 2011c). As can be seen from the list, the use of the reserve capacity is the last alternative of the actions. The probability that a situation will end with rationing is a major decision criterion before this measure is taken. First of all, the chance that rationing will occur has to be higher than 50% for the situation to be defined as a very critical supply situation. Regulations further oblige that NVE approves the start-up of the reserve power gas plant.

Based on the issues of avoiding capacity deficit and to secure supply, the development of demand side flexibility of households is of interest for Statnett. Flexibility from big end-users, typically industry, is already implemented through energy options in the case of a tight situation.

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[1] Energy options are special agreements where actors voluntarily sell Statnett the right to reduce the actor's electricity consumption in the case of a tight situation.

1.3 Smart metering technology

Smart metering technology systems will enable new services that will affect the electricity consumption to better match the generation of electricity. The technology will increase the efficiency of the power market and further have potential to be used in critical supply situations. The Member States of EU are obliged to have 80% of all consumers equipped with smart metering before 2020 (EuropeanCommission, 2011a).

1.3.1 Functionality and mechanisms

The functionality of smart metering technology systems is to meter, communicate and control electricity consumption. The systems can be defined to consist of three levels:

1. A customer level that represents households and industrial locations with metering points for electricity consumption
2. A communication system to transfer data between customer and central level
3. A central level which represents DSO

The implementation of smart metering technology systems for households involves the replacement of present electronic meters with system components to facilitate the systems functionality. A detailed description of the system technology is given in Chapter 3.1.

The mechanism relevant for households with smart metering technology is the opportunity to modify the demand side load curve. This can be obtained when using the involved communication system for remote load control (RLC). RLC is especially interesting as a tool to avoid the peak loads that occur at the load curve at the so-called “peak hours” of the day.

Two definitions should be distinguished in terms of load management; peak clipping and load shifting. Peak clipping will modify the load curve by cutting the top of the curve, whereas load shifting will modify the load curve by shifting loads to off-peak hours (Bellarmine, 2000). This implies that peak clipping will reduce the total consumption during a day, while load shifting will shift the consumption to a different time of the day. A practical example of load shifting is the remote control of an appliance with a thermostat. This kind of appliance will overall require the same amount of electricity to maintain the temperature. If it is switched off for two hours, it will consume more electricity for heating when it is turned on again to reach the acceptable temperature.

In addition to the two mechanisms discussed above, smart metering technology also involves demand side actions at households that consist of local control of consumption. This control comprises the avoidance of use of energy intensive appliances at peak hours. Typical examples of these appliances are washing machines and tumble dryers.

1.3.2 The implementation process

The implementation of smart metering technology systems in Norway was initiated by OED and was issued through a letter of allotment for 2007 for NVE[2]. NVE started the process with

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[2] www.nve.no/ams

an evaluation of the socio-economic benefits a full-scale implementation would lead to. The evaluation was performed by an engaged consultancy firm, ECON, and the resulting report concluded that net benefits most likely would be positive (ECON, 2007). Based on the result from the report and other previous reports concerning the systems, NVE concluded that full-scale rollout should be conducted. OED gave their support to this conclusion in June 2007 (NVE, 2008).

A final hearing was released by NVE in February 2011. This hearing proposed that full-scale roll out should be complete before 1.1.2017. For the region Central Norway, it was suggested that installation should be complete for 80% of all metering points before 1.1.2014 (NVE, 2011a). However, the final resolution of the proposals has not been made at the current state. Presently, smart metering technology systems are installed for large electricity consumers in Norway, like industry, that have an annual consumption above 100 000 kWh (NVE, 2008). The full-scale implementation will involve installation of the systems for the customers that don't have this.

1.3.3 Motives and benefits

NVE has mandate to ensure that the countries water resources are environmentally managed and integrated. Besides this, they shall promote efficient energy markets, efficient energy use and cost-effective energy systems. The primary motive for the implementation of smart metering technology is the contribution to achieve the main goal of the Energy Act (NVE, 2011a). The main goal is stated in section 1.2 of the act and yields (Lovdata, 2001):

"The act shall ensure that the generation, conversion, transmission, trading, distribution and use of energy are conducted in a way that efficiently promotes the interests of society, which includes taking into consideration any public and private interests that will be affected"

The technology will help to achieve the goal by increasing the efficiency of the power market when electrical power can be better managed, distributed and used. Another important aspect is the usefulness it may have in the matter of preparedness. In a white paper issued on security of supply by OED in 2003, smart metering technology systems and RLC was among other measures mentioned as possible options to handle a future tight energy situation (Grande et al., 2008a).

The different actors in the power market will benefit from the increasing efficiency in several ways. Customers can benefit economically by reducing their consumption in high price hours. They will also benefit from an increase in security of supply. The DSOs' benefits are linked to the more flexible demand side that enables a smoother load curve. This leads to reduced network losses. Additionally, the investment costs for network components can be decreased. Power suppliers will benefit from a more flexible price, because this reduces their risk related to volume pricing. Nord Pool will benefit from a better balance between production, consumption and transmission. When such a balance is not achieved, the prices will be set on a nonproductive basis (Grande et al., 2007a).

1.3.4 Households electricity consumption and demand response

During the evaluation of implementing smart metering technology systems, a number of projects with focus on demand side flexibility and household electricity management have been carried out. Here three relevant projects for households' electricity consumption and remote load control are presented.

The project "Residential Monitoring to Decrease Energy Use and Carbon Emissions" (REMODECE)[3] was carried out from 2006 to 2008, within the Intelligent Energy for Europe (IEE) Programme of the European community. The objective was to increase the understanding of energy consumption for EU-27 households. As a part of the project, the distribution of Norwegian households' electricity consumption was metered. The distribution of electricity demand for different appliances for an average Norwegian household is shown in Figure 6.

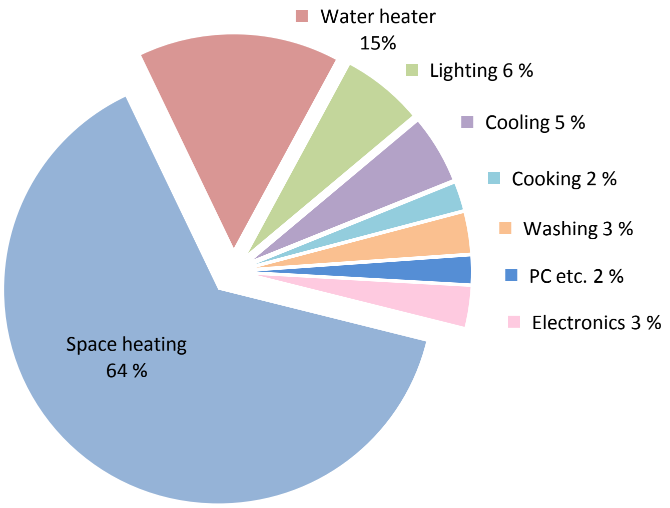

Figure 6: Yearly distribution of electricity consumption for an average Norwegian household (Sæle et al., 2010)

The figure shows that the biggest contributor for electricity demand is space heating, followed by water heaters that holds 15% of the total consumption. Electrical water heaters are common in Norway, and the installed power of typical water heaters are 2-3 kW. Water heaters are suitable appliances for remote control and can be used for load shifting. It can be defined as a low prioritized appliance, meaning that it can be disconnected for a limited amount of time without any significant comfort reduction for the customer (Grande et al., 2008a).

The demand response potential from water heaters in the morning hours was tested at a large scale with remote control of about 1250 customers. The test was done as part of a project[4] carried out by SINTEF between 2001 and 2004.The obtained demand response from the test

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[3] www.remodece.isr.uc.pt

[4] www.energy.sintef.no/prosjekt/Forbrukerflex/no_index.asp

for different hours can be seen in Figure 7 (Grande et al., 2008a). The largest potential was in the morning from hour 8 to 9 (0,6 kWh/h).

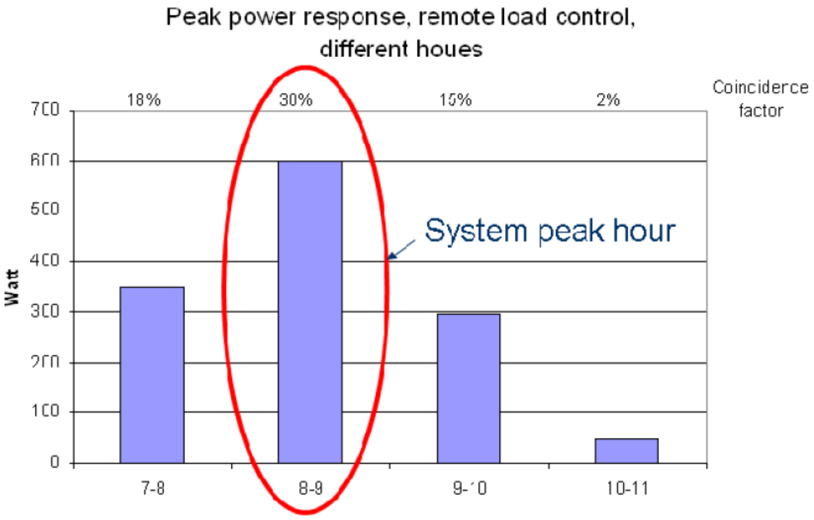

Figure 7: Demand response potential from water heaters in the morning hours (Grande et al., 2008a)

The “Market Based Demand Response” (MabFot)[5] research project had as a part focus on the potential of demand side response of households to reduce power deficit and avoid the use of special actions. The project was carried out by SINTEF from 2005 to 2008 with the main goal to *“stimulate to increased demand side flexibility and thereby contribute to a more efficient power market”* (Grande et al., 2008a).

As a part of the MabFot project, a pilot project with hourly metering of households’ electricity consumption was carried out in Sør-Trøndelag County in Central Norway. The DSO was Malvik Everk, which since 2002 have had advanced meter reading of all their customers. The project consisted of remote control of low prioritized loads for 41 households. The loads controlled were mainly water heaters, in addition to some electrical based waterborne space heaters. The households had Time of Day energy tariffs, a tariff based on the principle that the price varies over the day and is high at the expected peak hours. The households could based on this tariff reduce their costs if they changed their consumption pattern. At the defined peak hours, remote load control was carried out. The customers were also equipped with a small button to remind them to avoid usage of appliances like washing machine in the same hours (Grande et al., 2008a).

The average demand response (kWh/h) for the customers that were metered in the pilot is shown in Figure 8. The figure shows a turquoise line with responses from households with

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[5] www.energy.sintef.no/prosjekt/mabfot/

water based space heating and water heaters and a blue line for the households with water heaters only. The reference is shown in the pink line and is during the weekend, when no remote load control was carried out.

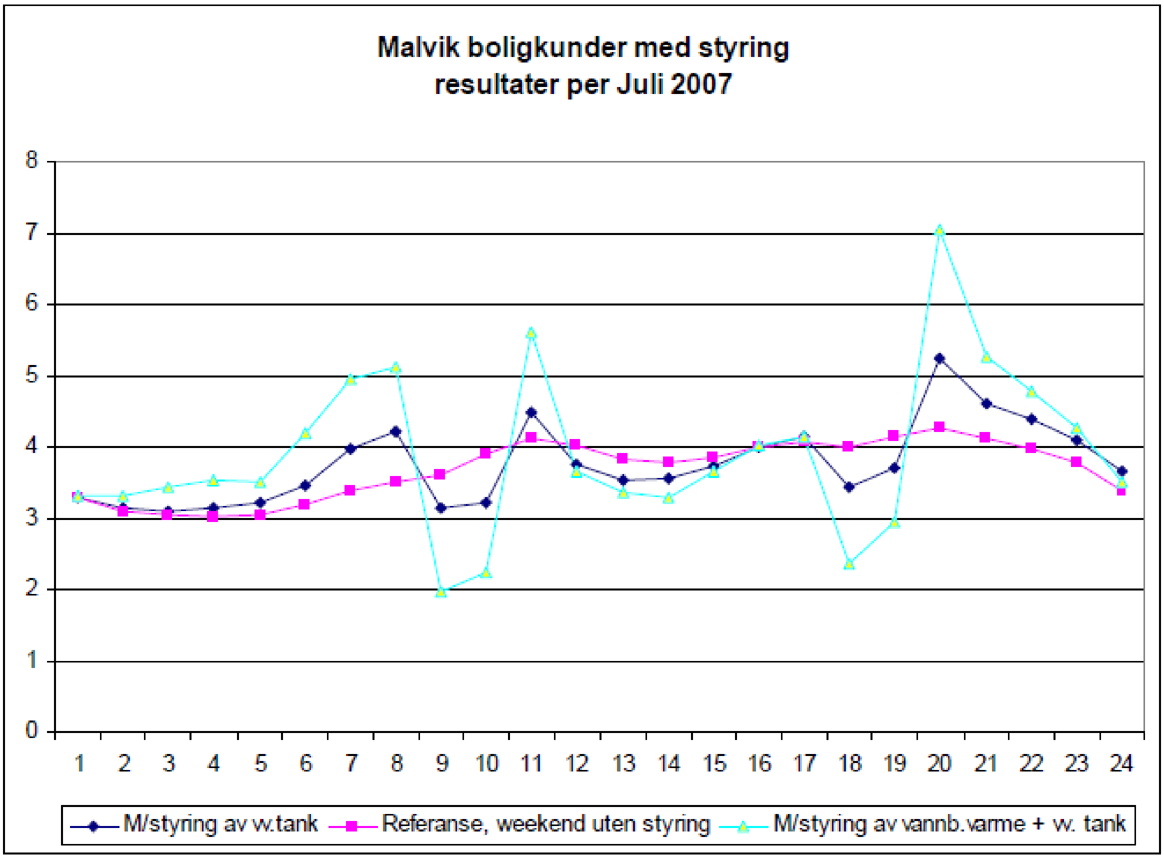

Figure 8: Average demand response Malvik-pilot, per July 2007 (Grande et al., 2007b)

The estimated average demand response from the project, for the two peak periods of the day, is listed in Table 1. The average demand response for customers with electric water heaters was 1kWh/h at the 9th hour of the day.

Table 1: Estimated demand response for peak periods of the day from the Malvik pilot project (Grande et al., 2008a)

	08:00-10:00	**17:00-19:00**
Customers with el. waterborne space heating system	~2.5-3 kWh/h	~1.3 kWh/h
Customers with el. water heater	~1 kWh/h	~0.5 kWh/h

1.4 Environmental aspects

This chapter explains how mechanisms related to demand side actions enabled by smart metering technology are connected to the environment. The environmental aspects are connected to the use of electricity and two essential factors – *when* it is used and *how much* that is used.

1.4.1 Peak load management

Since the generation of electricity instantaneously must match the consumption, it is essential *when* electricity is used. Smart metering technology enables load shifting and demand side actions to manage peak loads in a different way than presently. A typical 24-hour load curve for production of electricity is shown in Figure 9.

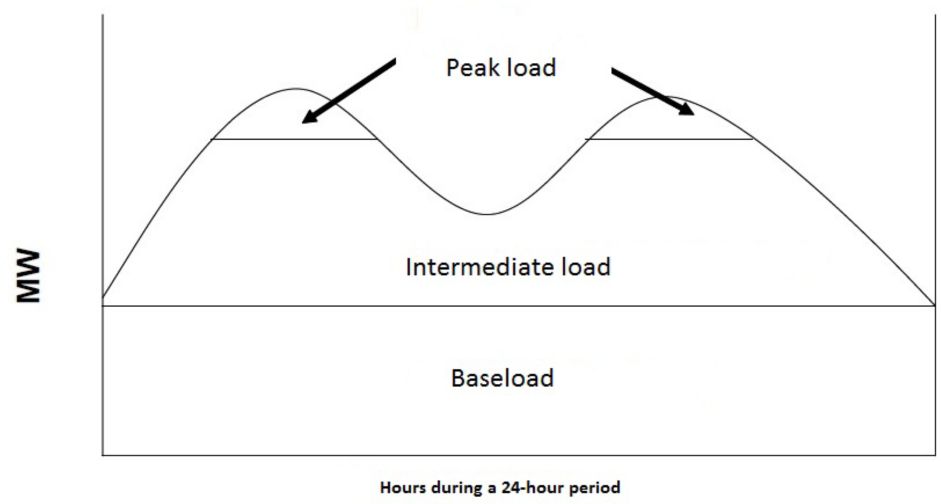

Figure 9: Typical 24-hours load curve for production of electricity (Wolfgang, 2008)

The figure illustrates that there will be a need for peak loads at certain hours of the day, and further distinguishes between baseload, intermediate load and peak load. What is interesting from an environmental point of view is the possibility to avoid the use of certain fossil power plants. Two types of fossil power plants can be distinguished: base load plants and peak load plants (PCE, 2009). The plants that are operating at peak load are typically less efficient than base load units, and require start-up and shut-down operations since they are operated only at the peak hours of the day. Base load plants are on the other hand operated continuously.

Creating a smoother load curve by avoiding peaks with demand response from households, can help avoid variations in thermal power production. The effect of reducing daily variation of thermal power production was discussed in (Wolfgang, 2008). Summarized, the environmental benefits from reducing variations in thermal power production are linked to the reduction of CO_2-emissions due to (Wolfgang, 2008):

- *“ Reduced production of low efficiency thermal power plants in peak hours and increased production from power plants with high efficiency*
- *Fewer incidents of producing units operating on partial load with reduced efficiency*
- *Fewer incidents of start up and stop of thermal power plants”*

As background for the reduction of variation of thermal power production in the mentioned report, was a scenario of increased capacity of hydro power in Norway and from this increased export from Norway of renewable power to the continent. The occurring increase of import for the continent could then contribute to reduce the continents variations of thermal power production. To reduce the same variations by modification of the consumption of electricity with RLC and smart metering technology, can provide the same benefits in terms of CO_2-reduction.

Although the general characteristics of peak and base load plants are as explained previously, the specific kind of installed generating units will vary depending on country-specific elements. Realistically, a number of external factors will also be necessary to know to determine the mix of generating units. When looking at production costs, the units operated for peak loads will be the ones with the highest marginal production costs. A typical example of a marginal cost curve for a region, combined with a daily load variation of production, is shown in Figure 10. It should be noted that the illustration is only meant as a general example, and the order of generating units is not always like this.

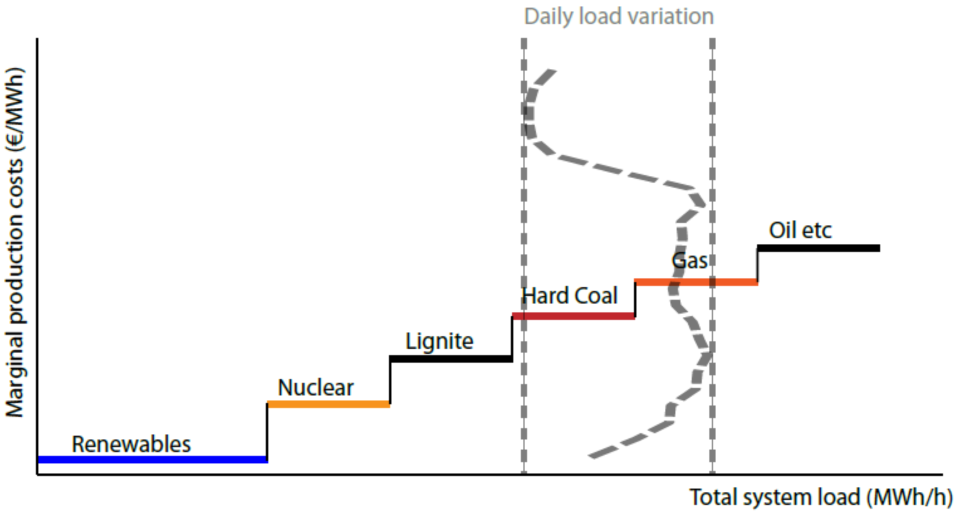

Figure 10: Combination of a marginal cost curve and production load variation for a region

The figure shows that depending on the daily variation of system load of electricity, the producing units for the region differ. The cheapest units are the ones that are below the load variation curve, and these units will be operating to cover the base load continuously. At parts of the day, hard coal and gas will be used to cover peak loads for this region. However, the order of the prices for the peak units will not necessarily be environmentally beneficial in all cases. If for example gas has a higher price than hard coal, as is the case in this figure, and the peaks are reduced so that hard coal units are the only generation units, CO_2-emissions for the peak production could actually increase when shifting a load in time.

To use hard coal and gas as an example to demonstrate differences, country averages of cumulative CO_2-emissions of electricity production from natural gas power plants in Europe range from 460 – 930 g/kWh_{el}, mostly depending on different averages in country-specific efficiencies of the plants (Dones et al., 2007). Combined Cycle (CC) tend to be used as base load plants, much more efficient than Single Cycle (SC) plants that often are used for peak loads. Production of electricity at a hard coal power plant will have cumulative emissions in the range 850 -1180 g CO_2/kWh_{el} (Dones et al., 2007). Shifting a load from gas power plants to hard coal power plants is thus likely to cause higher emissions of CO_2. However, if the marginal production costs are the other way around, a reduction of CO_2-emissions could occur. To quantify a reduction or increase in emissions, country-specific elements such as average efficiencies of the plants have to be taken into account. For gas power plants, the technologies that are used are essential, such as the share of steam power plants, CC or SC and number of gas turbines, and the mode of operation of the plant, that is number of peak hours and combined heat and power. Electricity production from hard coal power plants will depend on the emission factors of the plants (Dones et al., 2007).

Other factors, not discussed further here, that also will affect producing units, are import and export of electricity through interconnections in the transmission grid between different regions.

When the electricity production for peaks on the load curve is seen in a Norwegian perspective, it is an essential point that hydro power is used as regulating power. Hydro power is the most convenient power to use for regulation and it has the benefit of storage in reservoirs. For economic reasons, the thermal power installed in Norway is operated as base load (NVE, 2011b). A different situation will occur if the installed capacity and import capacity is not sufficient to cover the consumption of a region, and a very critical supply situation emerges. As a last resort for Statnett, installed reserve capacity gas power plants will then be used to cover the peak load. The environmental benefits from smart metering technology is the opportunity to avoid this use when the load can be shifted to another time of the day, and then be covered by the installed main capacity which is mainly from renewable energy sources.

Another aspect of peak load management is that through reduction of total peak power demand with demand response actions, installation of new generation and transmission capacity have potential to be avoided. This can contribute to avoid environmental impacts that will occur by such establishment.

1.4.2 Reduction of electricity use

While peak load management is related to *when* electricity is used, it is also expected that smart metering technology will contribute to a reduction of *how much* electricity is used in households. Environmental benefits will then be due to the fact that electricity generation is simply avoided. If there is a reduction of total electricity consumption after implementation of the systems relative to consumption as it was before, this is a resulting conservation effect. Smart metering technology can contribute to a conservation effect, and be a supporter for obtaining a sustainable consumption. The reduction of consumption requires that the consumer directly saves energy loads by adjustments in behavior, based on influencing factors such as tariffs and monitoring tools, which can be in-house displays giving feedback.

Several studies are conducted about the overall conservation effect of smart metering technology and customers that become more aware of their own consumption. The effect of providing household with different kinds of information on special in-house displays is especially interesting in this perspective. (Fischer, 2008) looked at the effectiveness that different kinds of feedback to households have, based on a psychological model illustrating how and why feedback works. The study concluded that among other factors successful feedback is likely to be based on actual consumption and given frequently over a longer period of time. A review of literature on metering, billing and direct displays was performed in (Darby, 2006). The report concluded that immediate direct feedback could be very valuable and necessary for energy savings.

The effect of feedback to households is however not likely to be the same for different groups of consumers, and factors such as welfare can influence the behavioral changes.

1.4.3 Large scale effects

As has been mentioned in the introduction in this study, smart metering technology is a part of the much larger term smart grid. Smart grid further comprises more technologies and mechanisms than smart metering technology alone. Besides peak load management, another mechanism related is a potential to increase the penetration of renewable resources. Presently, it is a challenge to integrate electricity from certain renewable energy sources to the grid. This is typically wind and solar power, which are intermittent and provide an inconstant supply of electricity. With smart grid and a more flexible demand side at a larger level, it can be possible to follow the production of energy from renewable sources with a more active load curve. When looking at the mechanisms enabled at a large scale and in a longer term, smart grid is expected to be a key enabler to reduce carbon emissions. A number of reports have been published and have explored the connection between the mechanisms enabled by smart grid and their effects on climate change.

The report "How green is the smart grid" aimed to quantify potential environmental benefits that smart grid can have for the US Power Sector, by examining two different scenarios (Hledik, 2009). The analysis of the scenarios was performed with a linear least-cost optimization model, which takes into account several input variables (RECAP)[6]. One of the scenarios modeled was a "conservative scenario", and it represented the use of available smart

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[6] RECAP is a model developed to examine large-scale resource planning and national electric policy issues. The model projects a regional state of optimal operation of the electricity system.

metering technologies. Based on the enabling technologies of dynamic pricing, automatic technologies and in-house displays and pilots and tests performed across North-America, the estimated effect of reduction in peak demand was modeled as 11,5% and the overall conservation was modeled as 4%. With these numbers as background for the potential impacts, model simulations of the conservative scenario lead to an annual 5% reduction of US power sector CO_2 emissions by 2030. This number was however not mainly from the load shifting effect. The results showed that for certain regions in the country, load shifting could contribute to reduce CO_2-emissions, while for other regions emissions increased. This was the case for regions where load shifting lead to an increase in the use of coal plants and reduction in the use of natural gas. The study hence supports the fact discussed previously; the effect of load shifting may not reduce emissions in all cases.

"Smart 2020: Enabling the Low Carbon Economy in the Information Age" is a report by The Climate Group on behalf of the Global eSustainability Initiative (GeSI). Figure 11 from this report, summarizes projections of the global impact of smart grid by 2020. The estimation is that 2,03 Gt CO_2-eq of a total power sector emission of 14,26 Gt CO_2-eq can be reduced through different smart grid technologies (BAU – Business As Usual).

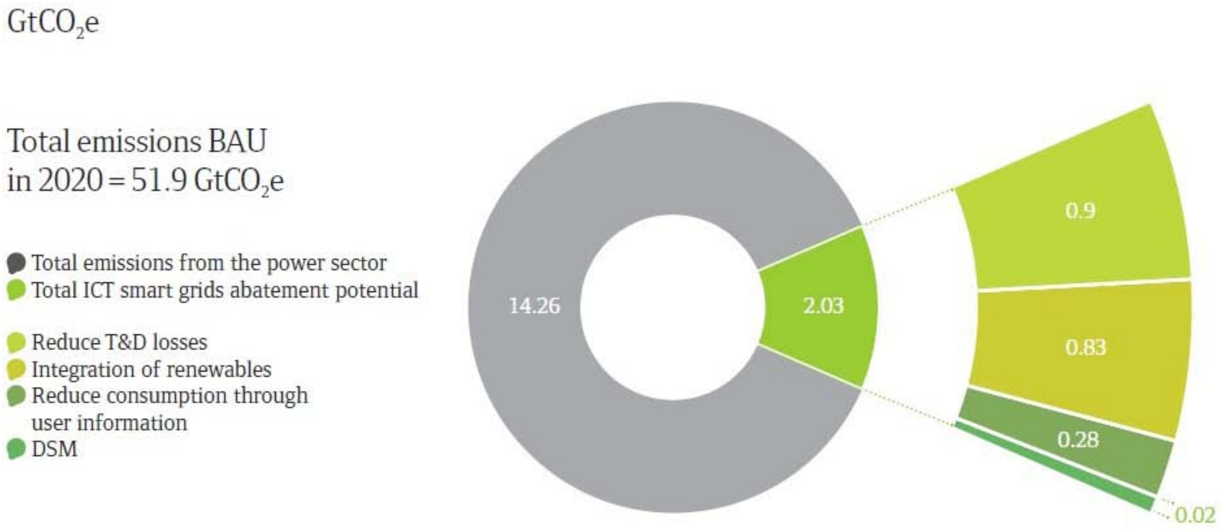

Figure 11: The global impact of smart grid in 2020 (GeSI, 2008)

The Electric Power Research Institute (EPRI) quantified the energy and emission savings from a US smart grid infrastructure in the report "The Green Grid" (EPRI, 2008). The estimates were that 60-211 Tg CO_2 emissions can be avoided by seven different smart grid mechanisms in the year 2030, illustrated in the reproduced summary from the report in Figure 12.

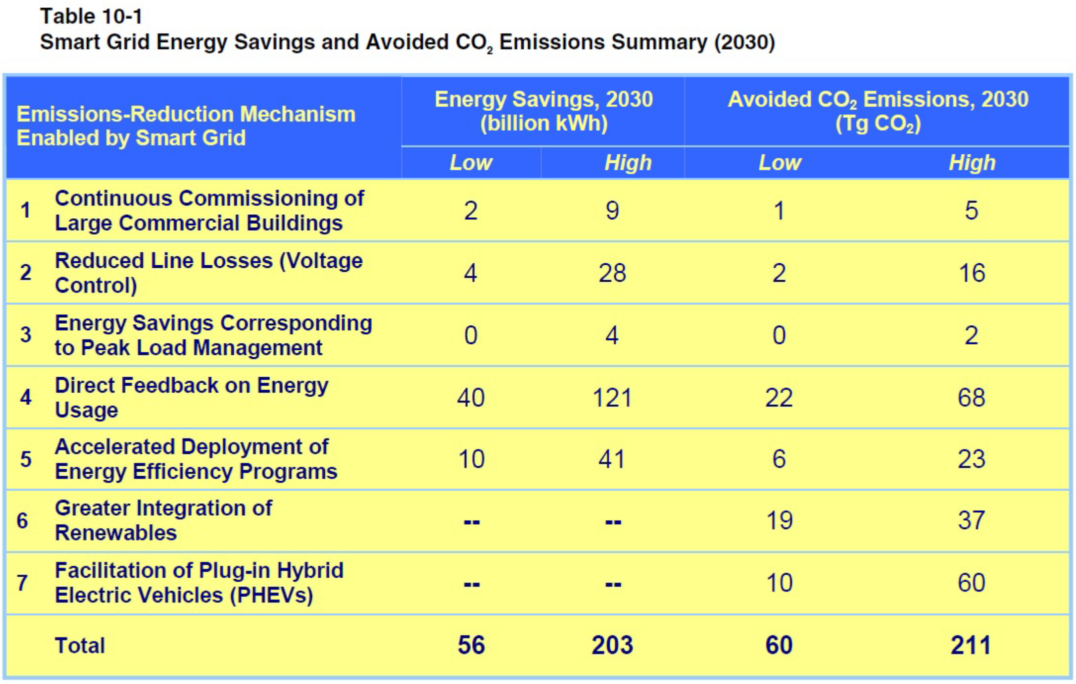

Table 10-1
Smart Grid Energy Savings and Avoided CO_2 Emissions Summary (2030)

Emissions-Reduction Mechanism Enabled by Smart Grid		Energy Savings, 2030 (billion kWh)		Avoided CO_2 Emissions, 2030 (Tg CO_2)	
		Low	*High*	*Low*	*High*
1	Continuous Commissioning of Large Commercial Buildings	2	9	1	5
2	Reduced Line Losses (Voltage Control)	4	28	2	16
3	Energy Savings Corresponding to Peak Load Management	0	4	0	2
4	Direct Feedback on Energy Usage	40	121	22	68
5	Accelerated Deployment of Energy Efficiency Programs	10	41	6	23
6	Greater Integration of Renewables	--	--	19	37
7	Facilitation of Plug-in Hybrid Electric Vehicles (PHEVs)	--	--	10	60
	Total	**56**	**203**	**60**	**211**

Figure 12: Energy savings and avoided CO_2 emissions with smart grid, by 2030 (EPRI, 2008)

2 Life Cycle Assessment Methodology

2.1 Theoretical framework

Life Cycle Assessment (LCA) is an analytical tool for systematic evaluation of environmental performance of products or processes. Through the assessment potential environmental impacts of a product or process can be found, taking into account all stages in the life cycle. The International Organization for Standardization (ISO) defines the principles and generic framework for performing a life cycle assessment in ISO 14040, illustrated in Figure 13 (ISO, 2006a).

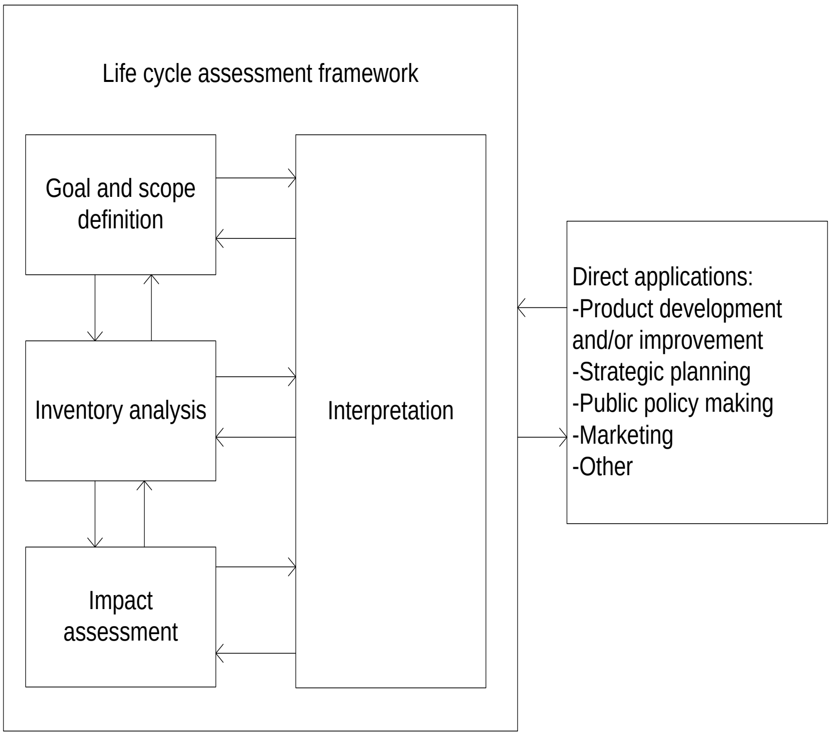

Figure 13: Stages of a LCA (ISO, 2006a)

The framework consists of four phases, which are described below (ISO, 2006a ; ISO, 2006b):

- **Goal and Scope Definition** is the first phase in which the purpose and boundary of the system to be studied is determined and a measurable property of the system, defined as the functional unit, is chosen. When choosing system boundary several life cycle stages, unit processes and flows should be considered. The choice of functional unit is based on the goal and scope of the study and it provides a reference for relating the inputs and outputs of the system.

- **Inventory Analysis** refers to establishment of a Life Cycle Inventory (LCI) for the defined system of study. The phase involves data collection and quantification of inputs and outputs for the system, such as material and energy inputs. The collection of data may continue far down the process chain, however, including all processes linked to a certain product will become too complex to carry out. To better complete the data established, databases with life cycle inventories can be used. To generate results for the inventory, the data collected has to be related to the reference flow of the chosen functional unit.

- **Impact Assessment** aims to identify the significance of potential impacts of the established inventory. Full transparency of the choices made and methods used in impact assessment is important to have, as these reflect a level of subjectivity. The phase consists of mandatory and optional elements. The mandatory elements are first the selection of impact categories, category indicators and a characterization model. The results from the inventory are assigned to environmental impact categories (classification) and category indicator results are calculated (characterization). Optional elements of impact assessment may among others include normalization and data quality analysis. With normalization, the value of the indicator result is calculated relative to some reference value, with the goal being to find its relative importance. Data quality analysis may include sensitivity analysis, which can show the effect that input data has on the results obtained.

- **Interpretation** is the last phase and is connected to all the other phases in LCA. Significant issues are identified, based on the results and according to the goal and scope of the study. An evaluation of the results should be undertaken, to find the reliability of the results. Conclusions, limitations and recommendations can then be drawn.

2.2 Basic mathematics of LCA

The calculations that are a part of the basic mathematics in LCA are explained in this chapter. When performing a LCA, a normal approach to carry out these calculations is by the use of mathematical modeling tools, such as MatLab, or by the use of LCA software, such as SimaPro. The nomenclature used in the basic calculations in LCA is listed in Table 2, alongside with the dimensions of vectors and matrices. The calculations and nomenclature explained here are based on (Strømman, 2010).

Table 2: Nomenclature used in basic mathematics of LCA

Symbol	Definition	Dimensions[i]
A	Matrix of inter process requirements	pro x pro
x	Vector of outputs for a given external demand	pro x 1
y	Vector of external demand of processes	pro x 1
L	The Leontief inverse, Matrix of outputs per unit of external demand	pro x pro
S	Matrix of stressors intensities per unit output	str x pro
e	Vector of stressors generated for a given external demand	str x 1
E	Matrix of stressors generated from each process for a given external demand	str x pro
C	Characterization matrix	imp x str
d	Vector of impacts generated for a given external demand	imp x 1
$\mathbf{D}_{\mathbf{PRO}}$	Matrix of impacts generated from each process for a given external demand	imp x pro
$\mathbf{D}_{\mathbf{STR}}$	Matrix of impacts generated from each stressor for a given external demand	imp x str

[i] Dimensions are given as process (pro), stressor (str) and impact (imp)

The columns in the matrix **A** gives necessary input to achieve one unit output of the respective process, for a given external demand **y**. The output vector **x** gives the output required for a given external demand:

$$Ax + y = x \qquad 2.1$$

The Leontief inverse matrix, **L**, has matrix coefficients that represent the output requirements per unit external demand on each process, and is defined as:

$$L = (I - A)^{-1} \qquad 2.2$$

Equation 2.1 can be rearranged and combined with equation 2.2:

$$x = (I - A)^{-1} y = Ly \qquad 2.3$$

For the environmental analysis in LCA, a matrix **S** of stressor intensities is defined. The stressors can be emissions or other environmental loads. The elements in **S** are the associated unit stressors intensities for each process. The total stressors for a given external demand are the elements in the vector of stressors **e**:

$$e = SLy \tag{2.4}$$

To be able to see process specific contributions to stressors the output vector **x** can be diagonalized and multiplied with the stressor matrix. This results in the matrix of stressors **E**:

$$E = S\hat{x} \tag{2.5}$$

In the impact assessment part of LCA a characterization method is chosen, aggregating the emissions found into more accessible terms, known as impact categories. For this operation a characterization matrix **C** is defined, specific for the method chosen. **C** has characterization factors to convert emissions of different substances into equivalents. The total impacts associated with the processes in the system and impacts associated with the emissions in the system can be found. The impact vector **d** contains the total impacts caused in the system for a given external demand:

$$d = Ce \tag{2.6}$$

By multiplication of the emissions matrix **E** and the characterization matrix **C** the impacts caused by each process in the system can be quantified in the matrix of impacts $\mathbf{D_{PRO}}$:

$$D_{PRO} = CE \tag{2.7}$$

The distribution of impacts on the stressors is found by multiplying the characterization matrix **C** with the diagonalized stressor vector **e** to find the matrix of impacts $\mathbf{D_{STR}}$:

$$D_{STR} = C\hat{e} \tag{2.8}$$

2.3 Tools and methods used

To perform the LCA in this study the software SimaPro[7], version 7.1.8 Multi User, has been used. With SimaPro, various databases can be accessed for establishing the inventory. The ecoinvent[8] database, version 2.0, has been used in this study to represent processes. The ecoinvent database contains LCI for a large range of processes, and it is the worlds' leading database for this purpose with more than 4000 datasets (ecoinvent, 2011).

In this study, the impact assessment will in addition to the mandatory elements include normalization and data quality analysis in the form of sensitivity analysis. The ReCiPe[9] method is used for impact assessment. The ReCiPe method has the choice of midpoint and endpoint indicators and impact categories. The difference between midpoint and endpoint is the position along environmental mechanisms. A midpoint impact category addresses a place where mechanisms common for several substances appear. An endpoint impact category is modeling of impacts beyond midpoint. The ReCiPe method has 18 midpoint categories and 3 endpoint categories, each with three scenarios of perspectives. The perspectives represent factors related to subjective choices, such as time perspective and expectations to future technology. For this study, the default ReCiPe midpoint method, Hierarchist version, is used.

The 18 impact categories at midpoint level are displayed in Table 3 with their respective indicators names and units of the indicator results.

Table 3: Midpoint impact categories, units and indicators for the ReCiPe method (Goedkoop et al., 2009)

Impact category	**Unit (of indicator result)**	**Indicator name**
Climate change	kg CO2 eq	infra-red radiative forcing
Ozone depletion	kg CFC-11 eq	stratospheric ozone concentration
Human toxicity	kg 1,4-DB eq	base saturation
Photochemical oxidant formation	kg NMVOC	hazard-weighted dose
Particulate matter formation	kg PM10 eq	PM10 intake
Ionising radiation	kg U235 eq	absorbed dose
Terrestrial acidification	kg SO2 eq	base saturation
Freshwater eutrophication	kg P eq	phosphorus concentration
Marine eutrophication	kg N eq	nitrogen concentration
Terrestrial ecotoxicity	kg 1,4-DB eq	hazard-weighted concentration
Freshwater ecotoxicity	kg 1,4-DB eq	hazard-weighted concentration
Marine ecotoxicity	kg 1,4-DB eq	hazard-weighted concentration
Agricultural land occupation	m2a	occupation
Urban land occupation	m2a	occupation
Natural land transformation	m2	transformation
Water depletion	m3	amount of water
Metal depletion	kg Fe eq	grade decrease
Fossil depletion	kg oil eq	upper heating value

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[7] www.simapro.co.uk

[8] www.ecoinvent.org

[9] www.lcia-recipe.net

The normalization factors in ReCiPe are based on reference systems with the choice of Europe or the world. The reference situation exists of the environmental profile of the areas, and the reference year is 2000 (Sleeswijk et al., 2008). In this study, European values are used for normalization.

3 System, inventories and case

This chapter presents the system, assumptions and data for the life cycle inventories and the case for quantification of environmental benefits.

3.1 Technological descriptions

3.1.1 Smart metering technology systems

Smart metering technology involves several technological options, and at the current state, where full-scale rollout is not yet complete in Norway, there is no defined standard. As a result of the many technological choices involved, the overall system will be different from one DSO to another, depending on geography, density of customers and other factors like investment costs. Based on the definitions and technological choices made, the system that will be defined in this study aims to represent a typical system solution.

Defining the boundary of a smart metering technology system first requires a definition of the system value chain for metering, and a choice related to which parts of the value chain to include in the analysis. An overview of the system value chain can be seen in Figure 14. The grey blocks are the units that are a part of the system that is necessary for collecting metered values.

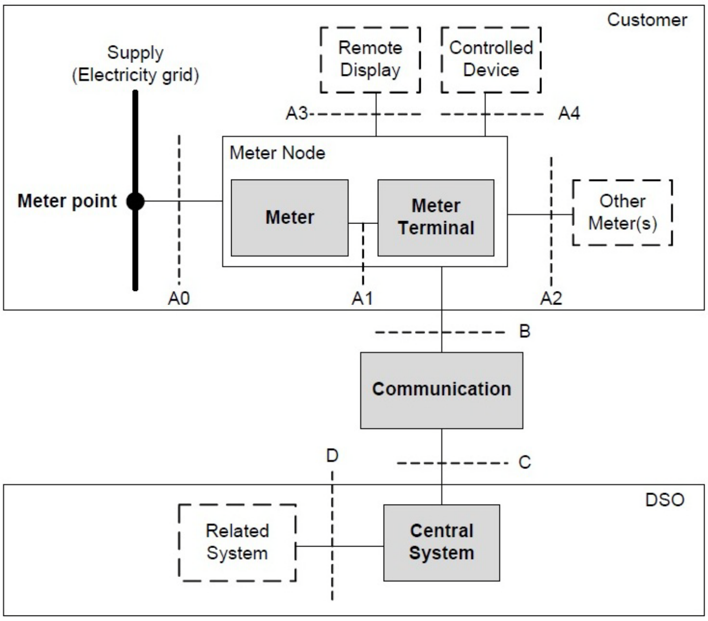

Figure 14: System value chain (Grande et al., 2008a)

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For the LCA, the grey blocks are the included parts considered. The LCA will then comprise what is defined as the “basic smart metering technology system” in ongoing work on requirement specifications (Graabak et al., 2011). The overall system boundary can be seen to include three subsystems: a meter node in a household, communication system(s) and a central system. The three subsystems are defined below.

3.1.1.1 *The meter node*

The meter node is located in a household and will in this study include the equipment necessary for metering electricity consumption, transmitting/receiving data and turning on/off power supply to the household. This is an electronic meter, a communication module dependent on the choice of communication system and a switch. The choice is based on suggestions regarding what equipment of the system are to be considered mandatory and what are to be considered additional, presented in the latest hearing document published by NVE in February 2011 (NVE, 2011a). Here, the mandatory equipment includes meter with possibility to remote control loads and necessary technology to supports different choices of communication mediums. The mandatory equipment will be financed by the DSOs, while the additional equipment will be purchased by customers. The additional equipment can among others be in-house displays that can show real time prices and consumption to the customer.

3.1.1.2 *Communication system*

The communication system(s) enables the two-way communication in smart metering technology systems and the function to be fulfilled is to send data at predefined hours or by request. The report “Smart metering technology systems – Additional Services. Third Part Access” was done on commission from NVE and defined the communication chain for the systems to consist of the following four parts (THEMAConsultingGroup et al., 2011):

- Basic communication
    - Communication between the metering point at a customer and the DSO. Various technologies can be adapted. Examples are available open infrastructure like fiber and ADSL (Asymmetric Digital Subscriber Line) or closed channels such as Power Line Communication (PLC).
- Additional communication for additional services
    - Communication between the additional services offered and the metering point. To transfer data between the meter and appliances considered additional in a household, for example in-house displays.
    - Communication between DSO and a third party. This communication can occur at given times or by request.
    - Communication between third party and end-user. This is communication between additional appliances and a third party, for example an in-house display only connected to the smart metering technology system channel. Normally internet would be chosen for households to send information.

This study will consider the basic communication, between metering point and DSO. The basic communication can further be split into two kinds of technologies; technologies specifically installed for the purpose and technologies that use available infrastructure. The most relevant technologies for communication between customer and DSO, defined by NVE, are (NVE, 2008):

- GPRS/GSM (General Packet Radio Service / Global System for Mobile Communication)
- Radio communication
- PLC
- Fiber
- Permanent telephone

An evaluation of communication technologies considerable for full scale roll-out of smart metering technology systems in Norway was performed in a master thesis at NTNU in 2010, concluding with the first four of the listed technologies as relevant (Haugen, 2010).

The overall structure of the communication system is generally in one of two ways; point-to-point (1-1) or point-to-multipoint (1-n). This implies that there either is direct contact between the meter node and the central system or there is an intermediate link in middle of the chain, usually a concentrator. At this mid-level the data can be converted to another form and transmitted to central level through a different communication system. For households, 1-n is predominantly the strategy considered, based on the fact that the density of metering points is large and this will keep the costs of data collection down (Amundsen, 2006). The choice of communication system for the DSOs that presently have installed the systems, are between the metering points and the concentrator mostly PLC and some radio networks, due to the fact that these are available technologies. Communication systems often chosen between concentrator and central level are GSM, PLC and some fiber (Amundsen, 2006).

The choices of communication systems in this study are based on the availability of data for different systems related to both their infrastructure and operational requirements. Systems chosen are GSM network from DSO to concentrator and PLC from concentrator to household. The structure is thus a 1-n system, as this is the predominant strategy for households. A concentrator is then a necessary component, and included in the analysis.

3.1.1.3 *The central system*

The central system is located at the DSO. Depending on the communication system involved, a specific front-end system exists. The central system receives all inputs of data metered by the meters and processes the data for a given specification. For the study, the components necessary for this purpose are included and involve two servers. Details around the solution will be discussed in Chapter 3.1.2.7. Adjacent systems at central level are not included. The adjacent system manages processing and other tasks that are administrative and may include charging of customers, reporting and web-services.

3.1.2 Chosen system for LCA

This chapter provides a closer description of the system that has been chosen for the LCA and the parts that have been defined to be included. Figure 15 gives an overview of the system components and communication systems involved and their locations.

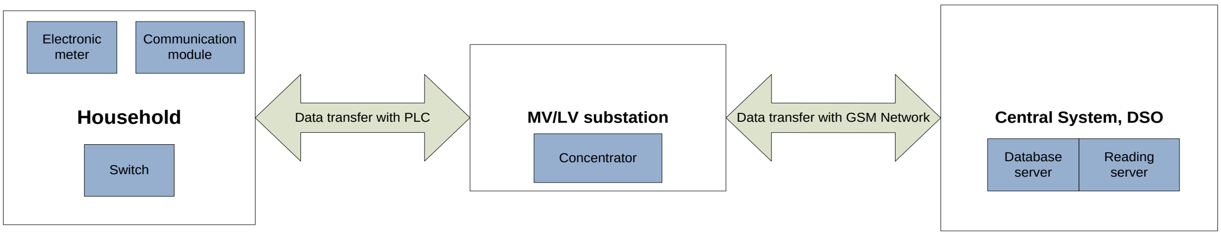

Figure 15: System solution chosen for the LCA

3.1.2.1 *Electronic meter*

An electronic meter's main function is to meter and show electricity consumption as kWh. This was in the past done with mechanical meters that consisted of a spinning disk and a mechanical counter, and manual reading of the metered values was necessary. The meters used for smart metering technologies are digital and have the functionality of digitalizing the metered values, and then use two-way communication to transmit them.

The development of digital meters started several years ago and the term smart meter came into existence as a consequence of the technology changes on the field. The term "smart metering" is not universally defined and several definitions exist in literature. The European Smart Metering Alliance's (ESMA) definition of smart metering is (Koponen, 2008):

- *Automatic processing, transfer, management and utilization of metering data*
- *Automatic management of meters*
- *2way data communication with meters*
- *Provides meaningful and timely consumption information to the relevant actors and their systems, including the energy consumer*
- *Supports services that improve the energy efficiency of the energy consumption and the energy system (generation, transmission, distribution and especially end use)*

In the meter, the metered values are digitalized and received by a microprocessor. The microprocessor can either be accessed directly from the surrounding communication system, or an additional unit, a terminal, works as an interface. Depending on its complexity, terminals can analyze the signals to obtain for example voltage and active and reactive power. Internal software runs the circuits in the meter. The possibility of remotely update of the software is one of the advantages two-way communication provides (Amundsen, 2006).

The term “integrated meter” is often used when a meter and a terminal are integrated in the same component. If the terminal and meter are two separate components, an additional communication level is required (Amundsen, 2006). As integrated meters are the most common on the market nowadays the term “meter” will from now be used for “integrated meter”.

The Measuring Instruments Directive (MID) specifies the minimum requirements for all utility meters used for billing purposes in Europe, in addition to the quantities that meters must be able to measure. For electricity this is kWh of active energy. Other quantities that are possible to measure are for example reactive energy, instantaneous power, and maximum demand and consumption data. These are additional services compared to what a mechanical meter can provide. A meter today generally comes with additional functionalities and they support several interfaces. Examples are digital inlets and outlets that can be used for sensors for water and alarms, and the performance of remote load control.

3.1.2.2 *Communication module*

The communication module is specific for the communication system used. The function is to transmit the data stored in the meter through the selected communication system. Depending on if the communication solution is 1-n or 1-1, the communication is to a concentrator or DSO. The module itself can be an integrated part of the meter or it can be put in place in the meter during the installation at the household. The possibility to choose between different communications systems is a key point to provide flexibility, and this is made possible when the meters support several communication modules.

3.1.2.3 *Switch*

A switch provides the opportunity to remotely switch on and off power supply, for example if a customer’s residence is empty for a period of time. It can be delivered separately or preassembled to the meter. The switch is connected to a semi-conductor relay in the meter, which receives data from the system at central level. During operation, the system at central level can either control the electricity consumption of the customer completely or partially. If partially control is performed, the customer has the opportunity to push a button on the meter to turn on the power supply.

3.1.2.4 *Concentrator*

The concentrator is a central part of a 1-n network structure and connects to meters in several households. Its function is to receive data from household’s meters and transmit the data further through to the DSO. It can also store the data for later retrieval by the system at central level.

3.1.2.5 *Power Line Communication (PLC)*

PLC is a well-known technology for the transmitting of data and it can be used for communication over all levels in the system. The technology uses existing infrastructure for electricity distribution to send data. The solution can be used at all voltage levels of the grid and can be separated in three different parts with respect to this; communication on high voltage grid (HV), medium voltage grid (MV) and low voltage grid (LV).

The principle for sending data is modification of the frequency of the signals. There are several techniques available for the modification and different system suppliers often have different choices. One technique is to modulate the signal between two defined frequencies, known as frequency shift keying. Another way is phase shift keying, which modulates the phase of the carrier signal, normally with 180°.

The components necessary to use PLC will vary depending on the voltage of the transmission grid and number of metering points in the system. In this analysis a low voltage distribution grid between concentrator and households is chosen. The concentrators are installed in MV/LV substations.

3.1.2.6 *GSM network*

Global System for Mobile communication (GSM) is a digital cellular system used for connecting two devices and exchanging data, in Norway operating at radio frequencies 900 MHz and/or 1800 MHz (Amundsen, 2006). General Packet Radio Service (GPRS) is a data extension of GSM, using the existing infrastructure of GSM to send data. The GSM network has a good coverage in Norway and is accessible from most locations. 99,9% of the population is covered by the leading provider of mobile communications (Telenor, 2011).

Related to the communication system, the central system usually has GSM modem pool, which is a communication solution for contacting the concentrators and request data. The concentrator has a GSM modem to communicate with the central system (Amundsen, 2006).

3.1.2.7 *Central system components*

The central data system is the interface between the communication system towards the metering points and other adjacent systems to exchange information with. The central system’s task is to collect data from the metering points and transfer it to the adjacent systems. The adjacent systems are for example customer information system, information about the network and a database for meter values.

Hardware components and setup for the central system depends on the system solution and requirements, but it will at least involve two types of servers, database server and reading server, and a communication setup. Some system solution examples are shown in Figure 16, based on example solutions provided from a supplier of smart metering technology (Aidon, 2011).

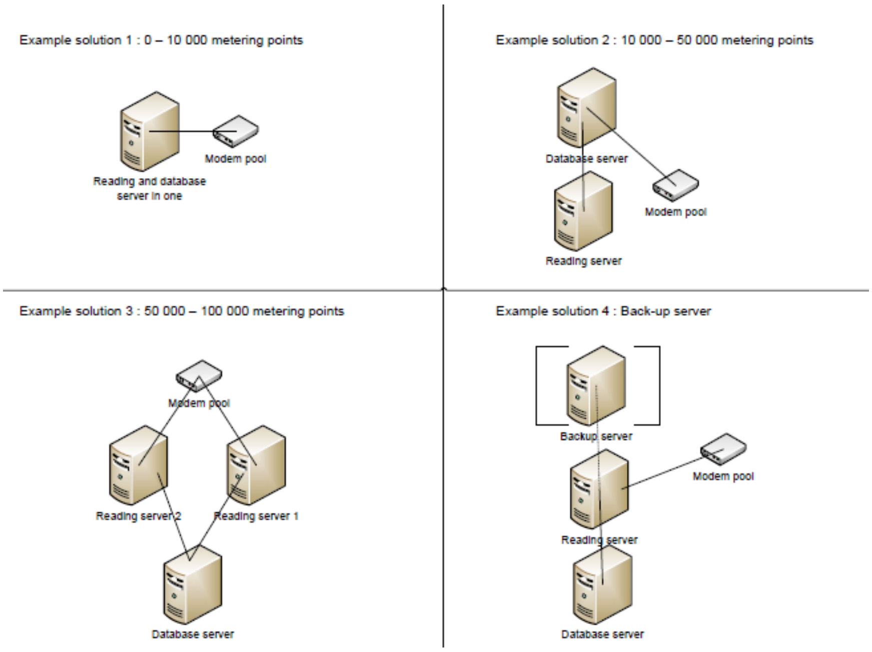

Figure 16: Some possible system solutions for central system, adapted from (Aidon, 2011)

The figure shows that the number of metering points affects the number of necessary components in the system and it will be scaled after this parameter. Additional components such as back-up servers are also possible to include. The communication setup included also depending on the number of metering points. Such a setup can include an additional server and a collection of communication modems adjusted to the system involved.

3.2 Life Cycle Inventories

3.2.1 System boundary

The smart metering technology system chosen for the LCA was shown in Figure 15. The installed system and the operational phase of the system are connected as shown in the system flow chart in Figure 17. The processes that have been created in SimaPro are according to this flow chart.

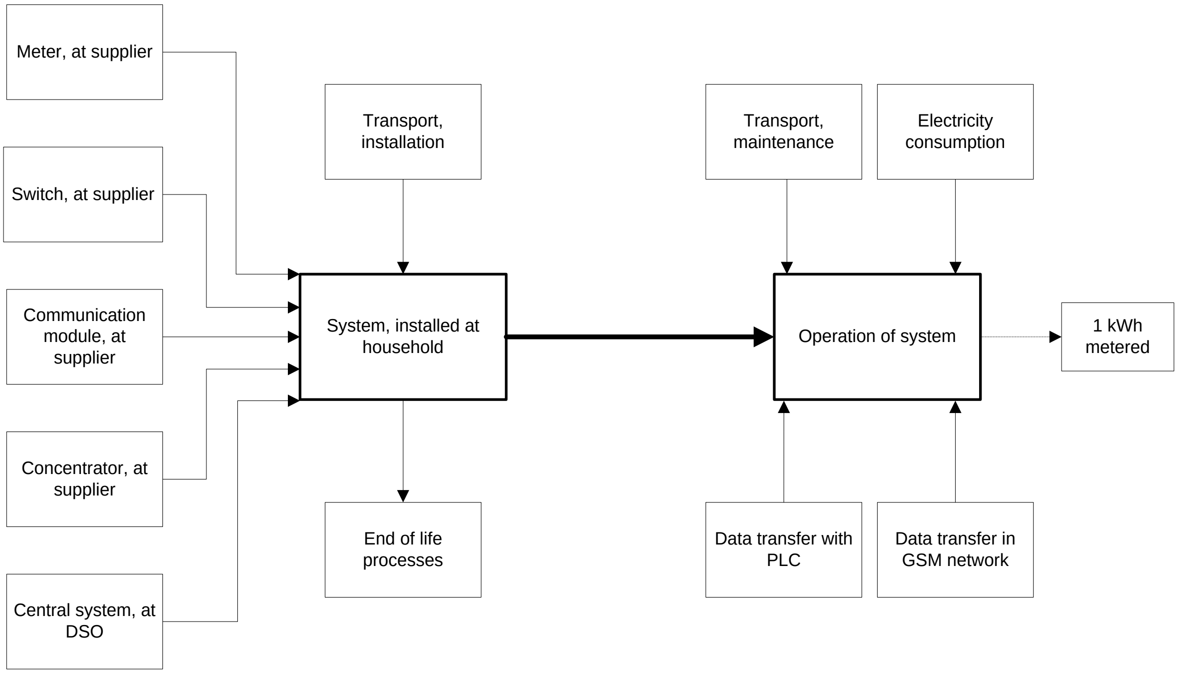

Figure 17: System flow chart of the processes created in SimaPro

The LCA includes all life cycle stages of the system. For an installed system at household, the included elements are material, processing and energy requirements for manufacturing of the physical components in the system and related transport, installation efforts and end of life processes. The module also includes additional physical components needed during the systems lifetime. The operational phase of the system includes maintenance efforts, electricity consumption and use of communication systems. The main focus is however not on the communication systems, and detailed assessments of communication systems are considered beyond the scope of the study.

For operation of a system the functional unit is 1 kWh metered by a meter in a household. Put another way, this is a kWh consumed in a household. The choice of this as functional unit will make it possible to use the results from the analysis in scenarios for electricity generation to find environmental benefits.

3.2.2 Main system data

A main assumption for the smart metering technology system is the number of households and hence metering points for DSO. The number of metering points will affect the amount of concentrators and central system solution. Further, the distance from DSO to the households will affect all transport related to installation and operation of the system.

To have all environmental impacts for operation of the system per kWh metered in the household (the functional unit), the average annual electricity consumption of a household in Norway is used. The main data for the system are summarized in Table 4.

Table 4: Main data used for the smart metering technology system

Data for system	Value	Unit	
Number of household for DSO	10 000	-	Case of a DSO[10]
Distance DSO – MV/LV substation	10	km	(Haugen, 2010)
Distance DSO - Household	12	km	Based on the distance to MV/LV substation
Annual electricity consumption household	16 858	kWh/a	(SSB, 2009)

The amount of households and concentrators needed per household is based on the case of one DSO, which currently has installed the infrastructure for PLC in almost all their MV/LV substations. This is 10 000 customers and approximately 650 MV/LV substations, which gives a total of 15,4 customers per substation. The average value based on total households and total MV/LV substations in Norway is 17 (Engan, 2010).

The central system solution is based on the solution involving 10 000 metering points that was shown in Figure 16.

Transport distance to a household and to the location of the concentrator varies significantly depending on geographical location in Norway. The average distance will vary for different DSOs and also depends on the amount of customers. As estimation, a distance of 10 km to concentrator has been used, based on estimations from (Haugen, 2010), which estimated this as distance from DSO to LV/MV substation. To household from DSO 12 km has been used as average, accounting for some additional distance from the substation to household.

Overview of the system components can be seen in Table 5, shown per DSO and per household.

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[10] Stange Energi

Table 5: Overview of physical components in the system

Subsystems	Components	Amount per DSO	Amount per household
Metering node	Meter	10 000	1
	Switch	10 000	1
	Communication module	10 000	1
Communication systems (PLC and GSM Network)	Concentrator	650	0,065
Central system	Reading server	1	0,0001
	Central server	1	0,0001

3.2.3 Installed system

The parts defined as input to the “System, installed at household” in Figure 17 are described in this chapter. The full inventory lists with ecoinvent processes that have been used are given in Appendix A.

For the physical components, the general flow chart for manufacturing of the components and transport is modeled as shown in Figure 18. The physical components that are included in the system were listed in Table 5.

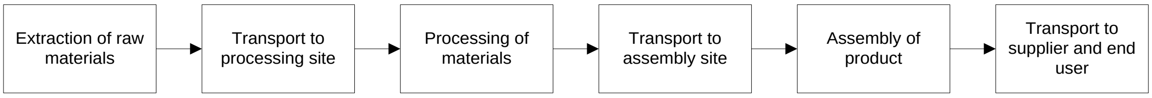

Figure 18: Flow chart for the manufacturing of physical components

3.2.3.1 *Electronic Meter*

Data used to establish the inventory of an electronic meter has been compiled by personal communication with two suppliers[11], three DSOs[12] and the study of product descriptions and data sheets of several electric meters.

A large number of different electronic meters and vendors are available on the market today. Common suppliers for digital electronic meters already installed in the Norwegian household market was found by accessing a register provided by the Norwegian Metrology Service (Justervesenet, 2011) and personal communication with DSOs that partially or fully have installed smart metering technology systems. Some big suppliers are Landis+Gyr, Kamstrup AS and General Electric.

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[11] Aidon, European supplier of smart metering technology systems
Landis+Gyr, global supplier of smart metering technology systems

[12] Stange Energi, Valdres Everk, Lier Everk AS

Table 6 gives an overview of a selection of available meters on the market with variations of technical specifications.

Table 6: A selection of electronic meters and technical specifications

Model	Weight (kg)	Communication module	Measurement principle
Landis+Gyr E120Gi	1,4	Integrated GSM-module	3-phase
Landis+Gyr E120LiME	1,6	Integrated PLC-module	3-phase
Kamstrup 351 Generation B	0,70	Not integrated	1-phase
This study	1	Not integrated	3-phase

The weight of meters can vary significantly depending on the integration of a communication module and other technological features that might be installed in the meter in advance. Some producers offer external communication modules only while others provide integrated meters. A supplier estimated 1 kg as weight of a 3-phase meter. For this study 1 kg is chosen as the weight, assuming the meter is without integrated communication module. The reason for the choice is the estimation from the supplier and the fact that a detailed composition of the meters components is not known and it has been more accurate to look at the communication module and meter as two separate components.

An estimation of the composition of different materials in the meter was provided by a supplier to be 60% plastic, 25% metals and 15% electronics. Further material distribution is compiled from the product descriptions published or provided by producers of meters. The composition of plastic is based on information from a supplier and technical details in a product description of one meter (Landis+Gyr, 2008). The plastic is a Glass Fiber Reinforced (GFR) blend of polycarbonate (PC) and Acrylonitrile Butadiene Styrene (ABS). The blend is assumed to have 20% content of glass fiber, based on material data sheets available online of common plastic blends (Matweb, 2011). The share of PC and ABS is not known and is based on literature on compositions of ABS/PC (PolymerTechnology, 2011 ; Utracki, 1998).

The processing of the plastic is assumed to be by injection molding and molded in one piece (GE, 2007). The injection molding processing is further assumed to occur in the same plant as the delivery of the final plastic materials. Material losses in processing are based on estimated material loss from the ecoinvent manufacturing process of injection molding, where 1 kg is required for 0,994 kg finished product.

The location of plastic production is assumed to be situated in Europe. A representative mix of the major producing countries of plastic was made based on recent statistics (PlasticsEurope, 2010). The electricity mix used for processing is adjusted based on this.

The composition of metals in the meter is estimated by a supplier and is mainly copper, tin without led, steel and iron. From product sheets, it was observed that the meter contains a number of screws. These are assumed to be made out of steel. Of the metals, 15% is approximated to be steel and the rest is equally distributed between the other metals due to lack of further data. Processing of metals is based on general production processes available in ecoinvent. These were only available for steel and copper.

The electronic components are assumed to primarily be produced in China, based on information from a supplier that the electronics used in the meters are primarily delivered from there. A detailed specification of electronic components in the meter has not been possible to access and a process for manufacturing of unspecified electronic components is used as an estimate.

After the different components of the meter are manufactured, they are brought to a site for assembly. The location of this site is assumed to be in the United Kingdom (UK), which is given as the main location for production of residential meters for a supplier.

The electricity use for the assembly of the meter is based on information from one company delivering electronic meters and other products related to electrical energy measuring, electric protection- and control, quality and metering[13]. Based on this data the energy used in production is solely electricity. The used value is an average value for all units produced by the factory. The electricity mix used is for UK.

The transport distance used for the plastic from manufacturing to assembly is an average of distances from the major producing countries, and calculated from distances on maps. The mode of transport is assumed as lorry and freight. The transport of electronics is assumed to happen by lorry and freight to Europe from China. Transport from producer to port in China was assumed to be 200 km. Transport of the metals is with standard distances for transport of metals (Frischknecht et al., 2007).

Table 7 shows materials inputs for production of a meter and the energy used for assembly.

Table 7: Material and energy for assembly input for production of one meter

Electronic meter	
Material	kg
PC	0,29
ABS	0,19
Glass fiber	0,12
Steel	0,15
Copper	0,033
Iron	0,033
Tin	0,033
Electronics	0,15
Energy for assembly	kWh
Electricity	2,92

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[13] Personal communication with Scandinavian Electric, by e-mail, dated 21.02.11

3.2.3.2 *Switch*

The inventory data of the switch is based on the user manual and data sheet of EPS32 Power Switch from Landis+Gyr (Landis+Gyr, 2010). The weight of the switch is 600 g. The components in a switch are electronics including a printed circuit board (PCB), metal and plastic.

The amount of plastic was estimated by calculation of the surface area of the plastic casing after dimensions given in the data sheet. The composition of the plastic is assumed to be the same GFR PC/ABS mix as for the meter. Typical density of such a blend was used to calculate the total plastic weight (Matweb, 2011). The assumptions related to plastic composition are further the same as for the meter, also regarding production sites.

The weight of PCB is calculated based on its surface area estimated from pictures and typical surface weight of PCB (Hischier R., 2007). The rest of the weight of electronic is taken as unspecified electronic components. The metal in the switch is assumed to mainly consist of copper in wires, based on pictures available.

The assembly of the switch components is assumed to be at the same site as for the meter, in UK. The electricity use for assembly is taken as the same value as for the meter, due to the fact that this was an average value distributed on all the units the factory produces. The electricity mix used is for UK.

The same transport assumptions as for the meter also apply for the electronics, plastic and metal in the switch.

Table 8 shows material and electricity inputs for the switch.

Table 8: Material and energy for assembly input for production of one switch

Switch	
Material	kg
PC	0,21
ABS	0,14
Glass fiber	0,087
Copper	0,09
Printed Circuit Board, led free	0,013
Electronics	0,067
Energy for assembly	kWh
Electricity	2,92

3.2.3.3 *Communication module*

The inventory data of a PLC communication module are based on a data sheet of a communication module for power line communication (Kamstrup, 2005). The communication module is a printed circuit board with mounted electronic components. A process for printed circuit board with mounted electronic components is used.

The production of the communication module is assumed to be located in China with the same transport assumption as for the electronic components in meter and switch, except that the transport is assumed to go directly to the location in Norway. This is based on the fact that the module is an external device and installed in the meter during installation of the system in a household. Table 9 shows material input for production of one communication module.

Table 9: Material input for production of one communication module

Communication module	
Material	kg
Printed circuit board with components	0,06

3.2.3.4 *Concentrator*

The inventory for the concentrator is established based on a concentrator with low voltage PLC and GSM as possible communication systems. The data is mainly from specifications in the user manual and data sheet (Landis+Gyr, 2007). The weight of the concentrator is 1,45 kg.

The concentrator consists of a plastic casing, metals and electronic components including a LCD[14]-glass in front. The weight of the plastic part was calculated based on dimensions of the concentrator and density of assumed plastic mix (Matweb, 2011). The plastic mix for the concentrator is assumed to be the same as used for the meter, based on the fact that the required protection class[15] is the same for both components. The assumptions related to plastic production are the same as for the meter.

Of the remaining weight of the concentrator, the share between metals and electronics is assumed the same as for the meter due to lack of information. The rest is then 15% metals and 25 % electronics. Metals are assumed to be the same metals as for the meter. The distribution is approximated to 50 % steel, 25 % copper, 12,5% iron and 12,5 % tin (own assumption based on pictures in user manual).

Electronic composition is unspecified except for the LCD glass, with an assumed weight of 20g (own assumption). The remaining weight is approximated with the process for unspecified electronics.

The final manufacturing and assembly of the concentrator is assumed to be located in Finland, based on information on production site written on the concentrators' data plate in a picture in the user manual. Due to lack of data, the energy use in manufacturing is taken as the same average value that was used for the meter and the switch. The electricity mix is adjusted to Finland.

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[14] Liquid Crystal Display (LCD)

[15] IP (International Protection) Code is an international standard classifying degrees of protection for electrical enclosures.

The transport of metals is assumed with standard distances for metals (Frischknecht et al., 2007). Transport distances for plastic and electronics are from the same locations of production sites as for plastic and electronics used in the meter. Transport from the manufacturer in Finland to Norway is assumed to be by lorry and boat.

Table 10 gives material and energy inputs for the concentrator.

Table 10: Material and energy for assembly input for production of one concentrator

Concentrator	
Material	kg
Polycarbonate	0,37
ABS	0,36
Glass fiber	0,18
Steel	0,17
Copper	0,087
Iron	0,043
Tin	0,043
Electronics	0,20
Energy for assembly	kWh
Electricity	2,92

3.2.3.5 *Central system*

The data for inventory for the central system is based on information provided from one supplier about example servers used for the central system and solution model (Aidon, 2011). The solution model was chosen in Chapter 3.2.2., dependent on the amount of metering points for DSO, and consisted of two servers and a communication solution.

The inventory is compiled based on technical specifications available from assumed producer of the servers and life cycle inventory of the module “Desktop computer, without screen, at plant/GLO U” from ecoinvent. The ecoinvent process represents a desktop computer with a typical weight of 11,3 kg. The input for the process is up-scaled based on the servers’ weight.

The two servers are assumed to be from the same producer, Hewlett-Packard (HP). HP is a major supplier of computers to Europe (www.mapsofworld.com, 2011). The types of servers chosen are HP ProLiant DL380 G5, based on the information from the supplier. Technical specifications of the specific model were not available from HP online, so HP ProLiant DL380 G6 technical specification sheet was used instead. The weight of the unit depends on installed number of hard drives. The reading server has less hard drives installed than the database server and the weight is approximated after technical specifications and comparison of maximum and minimum weight. Table 11 shows specifications of the two servers used for the central system.

Table 11: Technical specification of central system servers

	Reading server	Database server	Source
Disks	2 X HP 146GB 3G SAS 10K SFF SP HDD	8 X HP 146GB 3G SAS 10K SFF SP HDD (2 for OS, 6 for reading data)	(Aidon, 2011)
Weight	23 kg	25 kg	(HP, 2011)

The communication solution of the central system consists of a RADIUS[16] server and a modem pool. The RADIUS server is assumed to be located at the telecom operator and is not included within the system boundary. The modem pool consists of GSM modems linked to the computers. The supplier estimated that the number of modems for the system solution of the study would be maximum 3. Technical specifications available online of GSM modems, showed that the weight of the modems is minor compared to the other components in the central system. Typical weights observed were less than 1 kg (RFSolutions, 2011). Based on this the GSM modems are left out of the analysis.

The ecoinvent process adapted for the servers accounts for materials used in production and their manufacturing, infrastructure of a production factory, electricity for assembly, the water consumption and industrial waste water, the required transport for input materials, the packaging and the disposal of the computer. The geographical location of the assembly of the servers is assumed to be in Europe and the electricity mix is according to the European average. Distance for transport is from location of a HP site in UK, with lorry and tanker.

3.2.3.6 *Summary of data for physical components*

This chapter summarizes the main data that has been presented of the physical components in the system and the distances that have been used for transport of materials and components. Table 12 gives a summary of weight, materials and location of assembly for the physical components in the system.

Table 12: Summary of data for physical components

	Electronic meter	Switch	Commu-nication module	Concentrator	Central system components
Weight (kg)	1	0,6	0,06	1,45	48
Materials	60% plastic 25% metals 15% electronics	72% plastic 15% metals 13% electronics	Mounted PCB	62% plastic 24% metals 14% electronics	Composition of ecoinvent process
Location of assembly	UK	UK	China	Finland	UK

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[16] Remote Authentication Dial In User Service (RADIUS) server is used for authentication of IP-addresses

The transport is as far as possible based on actual distances from suppliers and producers to Trondheim, Norway. Transport distances on road and water are found from maps available online[17]. Table 13 gives a summary of the locations and distances that have been used for the physical components.

Table 13: Summary of locations and distances for transport for physical components

Locations		**Distances**		
From	**To**	**Road (km)**	**Rail (km)**	**Water (km)**
Average of plastic producers, Europe	Assembly UK/FI	793/2209		60/232
Metal production site, Europe	Assembly UK/FI	100/100	200/200	
Electronics production site, China	Assembly UK/FI	468		19115/20902
Assembly site, UK/FI	DSO, Trondheim	1468/1151		672/213

The location of the assembly plant in UK is based on the location of a Landis+Gyr site located in Peterborough. The location of the assembly plant for the concentrator is based on the location of Landis+Gyr in Finland.

The transport of plastic to the assembly plants is based on the average distance from the composition of the five major plastic producers in Europe (PlasticsEurope, 2010). Transport of metals was assumed with standard distances for metals.

Transport of electronics was assumed from China to assembly plants, with the exception of directly to Oslo for the communication module. In Norway the components have been assumed to arrive in Oslo if they come by boat, and then be transported to Trondheim to DSO by lorry.

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[17] www.searates.com and www.maps.google.com

3.2.3.7 *End of life processes*

The meter, switch, communication module and concentrator are electronic products and contain some level of environmental toxins. Their end of life will be according to regulations concerning electrical and electronic (EE) equipment, to treat the toxic substances and avoid harm on nature and humans.

The end of life processes for the two servers in the system is included in the processes that were used for the manufacturing and will not be considered further here.

The Waste Electrical and Electronic Equipment (WEEE) Directive is the EU legislation restricting the use of hazardous substances in EE equipment (EuropeanCommission, 2011b). In Norway the requirements of the WEEE directive are covered under the Regulation for Recycling and Treatment of Waste (Lovdata, 2004). Some of the key points of the legislation are that producers and/or importers of EE equipment are obliged to have membership in a recycling company. Retailers are further obliged to receive EE products they have sold and are responsible that the waste is passed on to an approved reception point or treatment plant. A typical waste treatment procedure is companies and individuals bringing EE products to collection points, where the waste is sorted into categories. After the sorting the equipments are brought to end-treatment plants where environmental toxins in the products are removed and materials recycled. Example of a procedure can be seen in Figure 19 (RENAS, 2004).

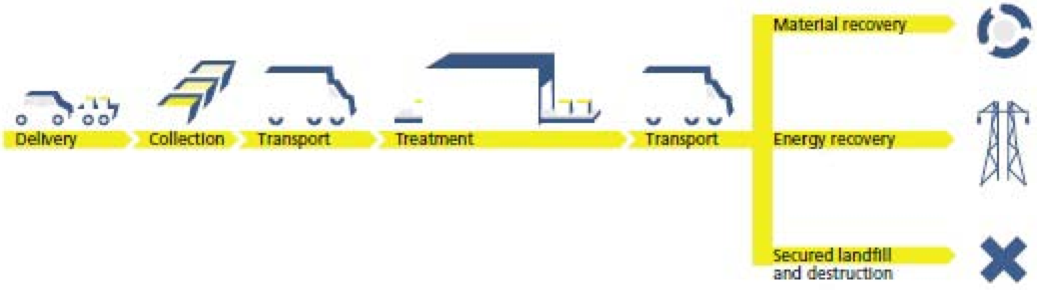

Figure 19: Example of waste treatment procedure (RENAS, 2004)

The dismantling process is a mix of mechanical and manual treatments, and the further treatment processes are specific for the various parts dismantled. After information from one recycling company[18], the electronic components specified by the WEEE directive are first removed manually, printed circuit boards are removed mechanically and the dismantling is mechanically and then partially automatic for sorting of fractions.

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[18] WEEE-Recycling AS, personal communication, by e-mail, dated 23.03.11

General ways of disposal for EE waste collected by RENAS[19] and ways of disposal for a specific WEEE product group given from the recycling company can be seen in Figure 20. The specific product group “measurement- and control equipment” products includes smoke detectors, thermostats, appliances for adjusting purposes and other appliances and instruments of similar category (Lovdata, 2004).

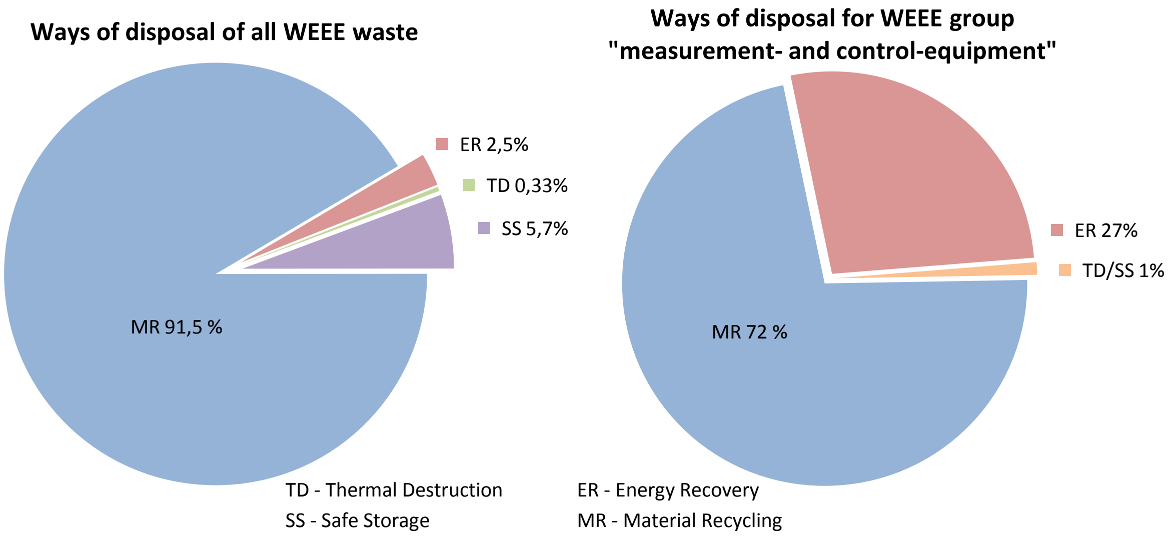

Figure 20: Ways of disposal of WEEE waste

Figure 20 shows that material recycling makes up a substantial part. The major contributing materials in general EE waste for recycling are steel, aluminum, copper and other metals, and plastics (RENAS, 2008). The rates for recycling of specific products are hard to predict because several products are mixed during the waste processes, and detailed statistics fort this has not been found.

Due to the lack of detailed data of end of life for the components in the system, the ecoinvent process ‘Disposal, industrial devices, to WEEE treatment’ is used as a basis to determine which disposal processes could be suitable to use. The process contains a statistical mix of disposal ways for WEEE equipment in Switzerland, where on a weight basis 77% is dismantled mechanically and 23% is dismantled manually (Hischier R., 2007). The process is used as estimation for the composition of treatments of meter, switch and concentrator. For the communication module the process “Disposal, treatment of printed wiring boards/kg/GLO” is used, since the communication module is a printed circuit board.

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[19] RENAS is managing a nation-wide system for collection and environmental handling of discarded EE waste from industrial and commercial sources in Norway

All the disposal processes involved are modified so the electricity use is based on the Norwegian production mix. Table 14 shows end of life data used for meter, switch and concentrator.

Table 14: End of life data used for meter, switch and concentrator

Waste treatment of WEEE product	Input
Dismantling, industrial devices, manually	23 % of product weight
Dismantling, industrial devices, mechanically	77 % of product weight

The recycling of plastic is not accounted for, because it has all been modeled as glass fiber reinforced plastic. The reinforcement with glass fiber reduces the recyclability (STENA, 2011). The metals used as input for manufacturing of the components are generally compositions of primary and secondary metals and accounts for recycle in this way.

The transport considered related to end of life is transport from household to a waste treatment facility. Transport distance used for end of life of the components is based on a distance of 20 km, from Trondheim centre where the location of the household is assumed, to a treatment facility for WEEE equipment in Central Norway[20]. The transport is assumed to happen with van.

3.2.3.8 *Installation*

The installation of smart metering technology systems requires transport of the components to the households and to the substations for concentrators. The main data used for installation efforts related to the system is shown in Table 15.

Table 15: Main data used for installation of a smart metering technology system

Main data for installation	Value	Unit	
Distance (DSO - Household) x 2	24	km	Based on (Haugen, 2010)
Distance (DSO – MV/LV Substation) x 2	20	km	(Haugen, 2010)
No. visited per installation	5	-	(Graabak et al., 2008)
Total transport of all system components per household	0,0084	tkm	Calculated from main data and weight of components

---

[20] WEEE-Recycling AS

Who is responsible for installation of the systems is up to the respective DSO. Some will hire external workers while others only use their own employees. The distance used is based on the distance assumed from DSO to a household, and back. The installation of the system is expected to be completed after one visit only. Number of households visited per trip is accounted for and based on experiences from installation of such systems that has been performed (Graabak et al., 2008). The number of households visited per trip is 5. The same number is assumed for the concentrator installations. The transport is assumed to occur with van.

3.2.4 Operation of system

The processes defined as input to “Operation of system” in Figure 25 are described in this chapter. The complete inventory lists with the processes used from ecoinvent are given in Appendix A.

3.2.4.1 *Maintenance*

Maintenance requirements are split in planned and unplanned maintenance. Prospective maintenance that occurs related to typical “start-up”-problems of the system, mistakes during installation and similar is not included in the analysis, as the system is assumed to be installed and running as planned. The rate of maintenance for household and concentrator will be considered as the same.

Planned maintenance of the system is zero. This has been informed by all contacted actors, both DSOs and suppliers of components. The components are designed for unattended use and updating of system software is done remotely trough the communication medium. Planned maintenance in the form of replacement of components is discussed separately in Chapter 3.2.4.2.

Unplanned maintenance will require transport of a worker to a household or MV/LV substation. The components considered here are the ones outside the location of the site of DSO. The central system is assumed to be maintained by own workers at DSO. Example of situations that will lead to a visit to either household or concentrator are problems related to coverage in the GSM network and metering points that are not responding to requests. Like the meter, the concentrator is updated remotely. It is easier for a DSO to visit a concentrator than a household, since this only involves the DSO and not an end-customer.

Two DSOs with smart metering technology installed for their household customers were contacted for experiences with unplanned visits. They did not have specific numbers, but estimated some rates of visits. It is considered that the visits they estimated might rely significantly on the communication system(s) involved. Experiences of unplanned visits were also given from a software provider[21] for smart metering systems. For the study, the number of required visits chosen is based on the software provider’s experiences, which is from systems operated in Sweden. Table 16 lists the data related to unplanned visits.

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[21] Personal communication with Powel, by e-mail, dated 29.03.11

Table 16: Main data used for estimation of unplanned maintenance

Estimated rate of unplanned visits yearly	Number of customers	DSO
~ 0,5-1%	12 800	Valdres Energi
~ 0,11%	11 150	Lier Everk
In this study		
0,075% of metering points per data collection		
0,27% of metering points per year (Collection occurs once per 24 hours, 0,075 % x 365 = 0,27%)		

Transport related to installation is assumed to happen with a personal car. The distance assumptions are the same as for installation, but because the maintenance can be both to household and network station 11 km, the average distance of the two sites, were used. Additionally, for maintenance only one site is assumed to be visited per trip.

3.2.4.2 *Replacement*

Data of lifetime of components is as far as possible based on an ongoing work on requirement specifications of smart metering technology systems, which will be completed after NVE develops final instructions (Graabak et al., 2011). The requirement of lifetime of the system, including meter, communication system and central system, will most likely be 18 years. This implies that after installation of the system, change of communication system and changes in central level system shall not be necessary. The communication system is, based on this, assumed to remain unchanged during the lifetime in the analysis. Table 17 shows the components and data related to lifetime and replacement.

Table 17: Data used for replacement of components

Component	Lifetime (years)	Total components needed, per household (18 years)	Times of additional transport
Electric meter	18	1	0
Communication module	7	2,6	2
Switch	18	1	0
Concentrator	15	0,078[22]	1
Central system	18	0,0001[23]	0

The meter and switch will be assembled together during installation and based on this the lifetime of the switch is assumed the same as for the meter. Even though the communication system is assumed to remain the same during system lifetime, the communication module installed in the meter is not a part of the basic equipment with a lifetime of 18 years. It is the

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[22] 15,4 households per concentrator

[23] 10 000 households per central system

component expected to be replaced first in the system, based on the fact that it is more like a transmitting device like a cell phone. Its assumed lifetime is 7 years. The concentrator is not a part of the basic system and its lifetime is assumed to be 15 years.

Replacement of components occurring due to regulations has also been considered to bring into the analysis. The Norwegian Metrology Service has the national responsibility of the metrology service and hence the replacement and check routines of electronic meters. If the meters satisfy the technical requirements given they will be operated and there is no standardized time of replacement. There are however samples taken at random and if these samples reveal errors a whole group of the specific meters will be replaced. The contribution from this kind of unexpected replacement is not included in the analysis, as it is rather uncertain. The regulations regarding this are currently expected to be unchanged after implementation of the new technology[24].

The transport assumptions for replacement follow the same assumptions as for installation, but the number of sites visited per trip is one.

3.2.4.3 *Electricity consumption*

The electricity consumption of the transmitting components in the system during operation depends on the power consumption during transmitting and idle state. To find the time used for transmitting data it is necessary to know the size of the data sent and the bandwidth of the communication system, which defines amount of data that can be sent per second. Table 18 shows the factors relevant for data transmission in the communication systems in the study.

Table 18: Main data used for communication systems

Communication system	Bandwidth system (kbit/s)	Source	Data transfer from-to	Packet size of data sent[25] (kbit)
PLC	4	(Landis+Gyr, 2007)	Household - Concentrator	0,735
GSM	9,6	(Scharnhorst et al., 2006)	Concentrator - Central system	6,8

Requirement specification from (NVE, 2010) suggests hourly metering observations sent from metering point once per twenty-four hours. Amount of data sent is based on this requirement, which means 365 times annually.

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[24] Personal communication with the Norwegian Metrology Service, by e-mail, dated 03.03.2011

[25] Packet size sent is based on observed size of a sample of received/sent data from a household to concentrator to DSO. This value is based on hourly metering observations and transmitting once per 24 h. The involved concentrator is connected to 16 households.

The transmission time has been estimated as packet size/data bandwidth. As a simplification, the transmission times calculated is only based on the data sent from the households to the concentrator and from the concentrator to the DSO. Data traffic the other way, from DSO to household, is not included in transmission calculations. This can be request for values, signals of load control and system updates. The amount of data transfer that actually will occur in such a system is complex and would require significant effort to model; as a result of this the simplification is made.

The power consumption of the components in the system is taken from the components listed technical specifications. For the meter, the consumption is made as an average from given values in a figure provided by a supplier of consumption of different meters on the market. For the two servers in the central system, the electricity consumption was found with HP power advisor, a tool available online for estimations of power consumption of HP products (HP, 2011). The specific details of the example servers provided were used as basis for the estimation and the utilization of use of the product was assumed to be 100%. Power consumptions, calculated annual transmission time and calculated annual electricity consumption of components are listed in Table 19.

Table 19: Main data used for electricity consumption of system components

Component	Power consumption (W)	Transmitting time (h/a)	Total electricity consumption (kWh/a)	Source
Meter	2.25	-	72	Personal communication[26]
Communication module PLC	< 500 m (idle) < 4 (transmit)	0,019	4,4	(Kamstrup, 2005)
Switch	0.2	-	1,8	(Landis+Gyr, 2010)
Concentrator	6 (idle) 8.5 (transmit)	0,37	3,4	(Landis+Gyr, 2007)
Reading server	224	-	1965	(HP, 2011)
Database server	281	-	2464	(HP, 2011)
Total electricity consumption per household			82 kWh/a	

Per household, the share of electricity consumption of the components in the system is as shown in Figure 21.

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[26] Personal communication with Aidon, by e-mail, dated 23.02.11

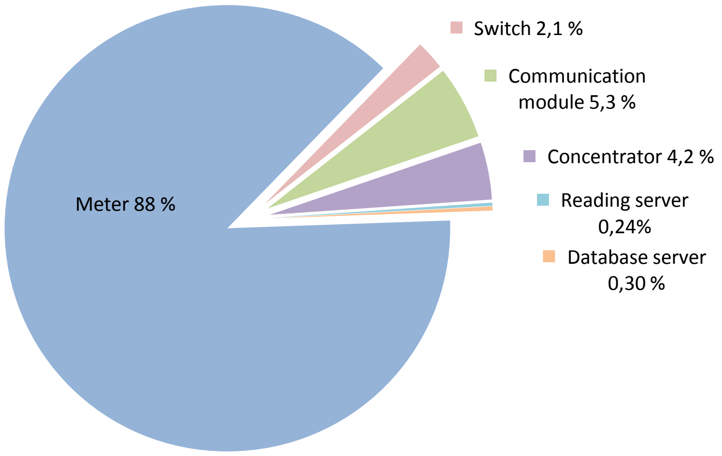

Figure 21: Share of electricity consumption of system components, per household

Per household in the system, the meter is the device consuming the largest amount of electricity, followed by the communication module, the concentrator and the switch. The servers are operated for a large amount of households and the contribution per household is hence small. The Norwegian consumption mix of electricity is used for the input.

3.2.4.4 *Power Line Communication (PLC)*

PLC as communication system uses the existing infrastructure for transmission of electricity and will not require any new establishment of infrastructure related to the transmission network. The use of the transmission grid as communication system is accounted for with the electricity consumption of the communication module in transmitting state, calculated as presented in Chapter 3.2.4.3. The Norwegian consumption mix of electricity is used for the input.

3.2.4.5 *GSM Communication*

The infrastructure of a GSM network exists in Norway and has 99,9 % coverage of the population (Telenor, 2011). Based on this, infrastructure impacts of the network related to manufacturing and maintenance of components is not included in the analysis. Another reason for the choice is the allocation that would have to be made of use of the network with respect to total traffic. It is expected that the data transfer from the system considered, with one DSO and 650 concentrators, will be a small part of the total transmitted data. Market statistics available from the Swedish Post and Telecom Agency (PST) shows that total data traffic in mobile networks in Norway was about 22 000 Terabytes first half-year of 2010 (PST, 2010). This value is not for the GSM network alone, but the data transmission from a concentrator in the system considered is 6,8 kbit, or 0,85 kbyte per day[27].

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[27] 1 byte = 8 bits

The use of the GSM network requires electricity consumed by the network components. This consumption is included for central components in the GSM network. The data of electricity use and main components are based on a LCA conducted on mobile networks, where the functional unit of the data that has been used is Gbit transferred from mobile phone to mobile phone in a GSM Network (Emmeneger et al., 2003). It is further assumed that the transfer of 1 Gbit from mobile phone to mobile phone will give the same consumption of electricity for the considered network components, as transfer of 1 Gbit data from concentrator to DSO will. Of the main components in the GSM network, the base stations (7,7 kWh/Gbit) and phone central (4,1 kWh/Gbit) has been included. The electricity use for administrative causes is not included. A reproduced table from the study showing the values that have been used can be found in Appendix A. The Norwegian consumption mix of electricity is used for the input.

Table 20 shows the main data for use of the GSM Network.

Table 20: Input data for use of GSM Network

Data	Value	Unit	Source
Electricity consumption GSM network per Gbit data transferred	11,8	kWh/Gbit	(Emmeneger et al., 2003)
Annual data transfer one concentrator- DSO	6,8 x 365 = 2482[28]	kbit	See Chapter 5.3.5

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[28] To get the value per household it was divided by 16 (16 households were connected to the concentrator that transmitted the data)

3.3 Case for quantification of benefits

As has been presented previously in this report, smart metering technology systems enables load shifting based on the demand response from households and be used in a critical supply situation of electricity. To quantify the environmental benefits that can be obtained from having smart metering technology installed in households in Norway, a case is defined for the region Central Norway and two scenarios are defined as alternative solutions.

3.3.1 Case

The Central Norway region consists of the counties Sør-Trøndelag, Nord-Trøndelag and Møre and Romsdal. The region is located as shown in Figure 22. The figure also shows example of flow of electrical power between the different Elspot areas, here from the expected peak hour 8-9 in the morning at a regular week day during the winter (04.01.2011).

Figure 22: Location of Central Norway region and flow of electricity for a regular week day in January 2011 (Statnett, 2011a ; StatensKartverk, 2011)

In Central Norway region there are a total of 297354 households, distributed between the counties as shown in Table 21.

Table 21: Number of private households in Central Norway (SSB, 2011a)

County in Central Norway	Number of households
Møre and Romsdal	107908
Sør-Trøndelag	133322
Nord-Trøndelag	56124

The electricity supply situation for Central Norway has been under concern and considered during the last years. The area has a substantial amount of energy intensive industries installed, which has been growing and hence increased the regions demand for electricity (Statnett, 2007). In 2009, the net consumption in the region was 18504 GWh, where households and agriculture had a share of 27,3%. The production in the region the same year was 15496 GWh. For the winter 2010/2011, the balance between production and gross consumption of electricity was as shown in Figure 23 (SSB, 2011b).

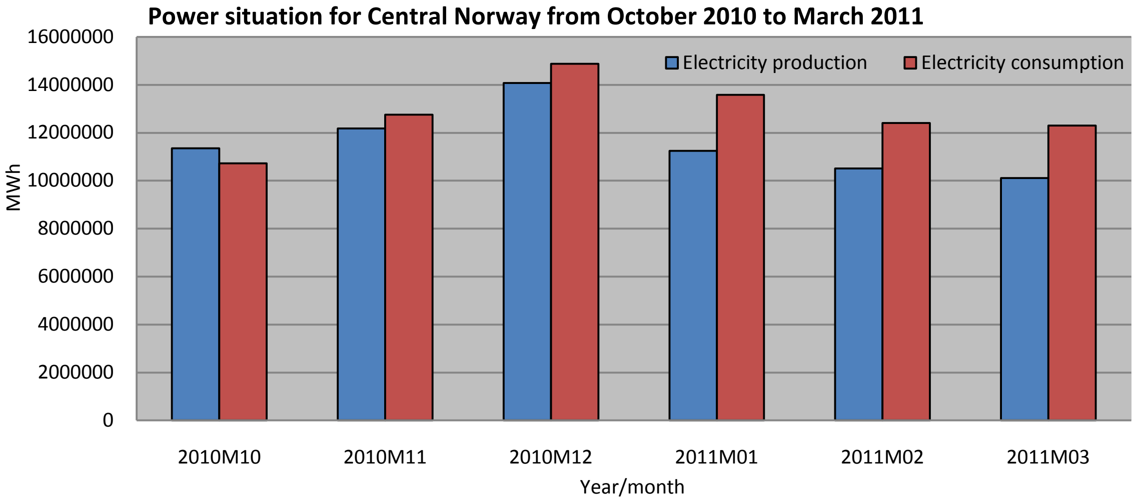

Figure 23: Power situation for Central Norway winter 2010/2011 (SSB, 2011b)

The figure shows that the consumption has been higher than the regions production for the last five months. This is characteristic for the region, which generally relies on import. The power deficit is in hydrological *normal* years estimated by Statnett to be 8000-9000 GWh (Statnett, 2011d). In normal years, it should be possible to cover the consumption with available production, existing import capacity and alternative measures like energy options, but a concern is related to the hydrological dry years. With low temperatures during the winter combined with limited amount of production capacity, this can lead to a situation where the regions' consumption is not possible to cover. The high load on the distribution grid also leads to a higher risk for faults to happen. The measure of using reserve capacity in a critical supply situation in Central Norway is relevant. The region has reserve power in the form of two mobile gas power plants, 150 MW each, installed in 2009 and owned by Statnett (Statnett, 2011c). As a result of the unsecure situation in 2011, Statnett was at one point exempted from the regulations concerning start-up approval by NVE, and could from week 1 to 20 start the turbines if necessary on own initiative (Statnett, 2011d).

The balance between production and consumption of electricity has to be maintained at all times, and if a situation occurs and the consumption is not possible to cover with available production and import, additional measures must be taken. The environmental benefits from smart metering technology systems installed are then the possibility to avoid the use of the reserve capacity when 150 MW from gas power plants can be replaced by remote load control of water heaters in households in the region. Because of this, there will be an avoided emission of GHGs per kWh consumed in the household. One reserve capacity gas power plant will have CO_2-emissions of 0,68 ton/MWh (Statnett, 2011d).

Table 22 shows the main data for calculation of the total load that is shifted. It is assumed that 50% of the households in Central Norway can be disconnected. The obtained demand response is the results from the Malvik pilot, presented in Chapter 1.3.4. The total load that can be shifted in the region is 149 MWh/h.

Table 22: Main data for the case of a very critical supply situation in Central Norway

	Unit	**Value**	**Source**
Average demand response 9th hour	kWh/h	1	(Grande et al., 2008a)
Number of households in region	-	297354	(SSB, 2011)
Controlled households in region	%	50	(Grande et al., 2008b)
Total load shifted Central Norway 9th hour	kWh/h	148677	

3.3.2 Scenarios

The case that has been defined for Central Norway is based on very critical supply situation occurring and is illustrated in Figure 24.

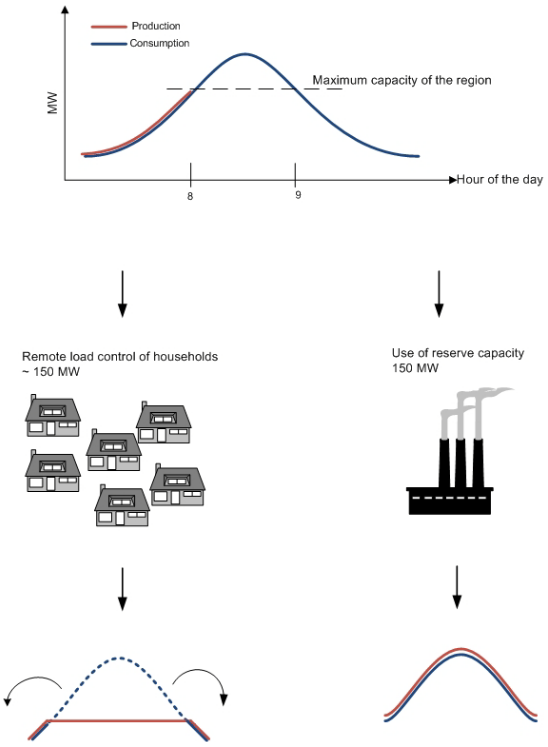

Figure 24: Illustration of the case and two possible scenarios

As can be seen in the figure, two scenarios are defined as alternative scenarios. The difference between the scenarios is the way the peak load will be managed and the electricity produced.

3.3.2.1 *Smart metering technology scenario*

In the smart metering technology scenario smart metering technology systems are installed in the region and 50% the households can contribute with 1 kWh/h at the 9th hour of the day, which is the average demand response from the Malvik pilot project. A flow chart of the scenario is shown in Figure 25.

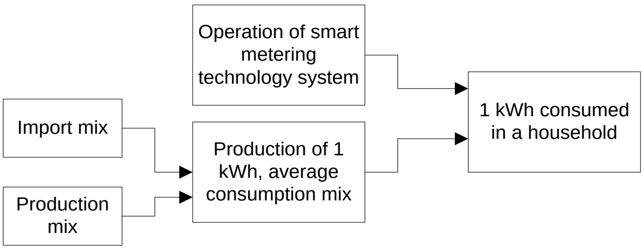

Figure 25: Flow chart of the smart metering technology scenario

The production of electricity is based on the average Norwegian consumption mix from 2009 (NVE, 2011b). This mix includes import. As estimation for the Russian production mix the CENTREL mix was used. The share of thermal power production in the Norwegian production mix is based on composition of the production from 2008, because 2009 composition was not available (entsoe, 2008). The mix was however adjusted to account for the increase in thermal power production that occurred from 2008 to 2009 (NVE, 2009a).

Table 23 lists shares of import and production mixes used. The full list of ecoinvent processes accessed is given in Appendix A. They are according to processes used in existing production mixes in ecoinvent, but numbers are adjusted for the mix from 2009.

Table 23: Data for electricity production of Norwegian consumption mix

Electricity production of average consumption mix Norway	**1**	**kWh**
Import mix	0,046	kWh
Sweden	45 %	
Denmark	26 %	
Finland	2 %	
CENTREL	4 %	
Netherlands	22 %	
Electricity, production mix Norway	0,954	kWh
Hydropower, at power plant	95 %	
Hydropower, at pumped storage power plant	0,46 %	
Wind power plant	0,73 %	
CHP, district heating	0,09 %	
CHP, industry	0,46 %	
Gas turbines etc.	3,02 %	

3.3.2.2 *Reserve capacity scenario*

In the reserve capacity scenario smart metering technology systems are not installed and to secure the supply the reserve capacity gas turbines installed in the region must be started to cover the consumption.

The scenario thus represents the production of electricity from the installed reserve capacity gas turbines in Central Norway. The effect of the gas turbines installed are 150 MW and they have an efficiency of 36% (Statnett, 2011d). The process “Electricity, natural gas, at turbine, 10 MW, GLO U” is used to model the electricity production. This process uses an estimated average of net efficiency of a gas turbine, with global efficiencies in the range 25-39%.

4 Results and sensitivity analysis

This chapter first gives the results of the life cycle assessment for an installed system and the operation of a system. Secondly, the sensitivity analyses related to these results are presented. In the end of the chapter the results from the defined case and scenarios are presented.

4.1 Environmental impacts from installed system

The total impacts caused in each impact category for installed system per household are listed in Table 24, also showing normalized results with ReCiPe factors. One installed system has a lifetime of 20 years.

Table 24: Total impacts caused for one installed system, per household

Impact category	**Value**	**Unit**	**Normalized**
Climate change	1,1E+02	kg CO2 eq	1,0E-02
Ozone depletion	1,3E-05	kg CFC-11 eq	6,0E-04
Human toxicity	2,5E+01	kg 1,4-DB eq	4,2E-02
Photochemical oxidant formation	4,4E-01	kg NMVOC	7,8E-03
Particulate matter formation	2,4E-01	kg PM10 eq	1,6E-02
Ionising radiation	4,8E+01	kg U235 eq	7,7E-03
Terrestrial acidification	7,3E-01	kg SO2 eq	2,1E-02
Freshwater eutrophication	6,9E-03	kg P eq	0
Marine eutrophication	1,3E-01	kg N eq	0
Terrestrial ecotoxicity	2,1E-02	kg 1,4-DB eq	2,6E-03
Freshwater ecotoxicity	5,4E-01	kg 1,4-DB eq	5,0E-02
Marine ecotoxicity	8,4E-01	kg 1,4-DB eq	2,0E-01
Agricultural land occupation	1,9E+00	m2a	4,3E-04
Urban land occupation	6,5E+00	m2a	1,6E-02
Natural land transformation	3,2E-02	m2	2,0E-01
Water depletion	1,5E+00	m3	0
Metal depletion	1,6E+02	kg Fe eq	2,2E-01
Fossil depletion	3,2E+01	kg oil eq	1,7E-02

The normalized results gave a factor of zero for three categories: freshwater and marine eutrophication and water depletion. Highest impact after normalization was for metal deplation, natural land transformation and marine ecotoxicity.

The breakdown of the contribution from the different processes to the total impacts can be seen in Figure 26.

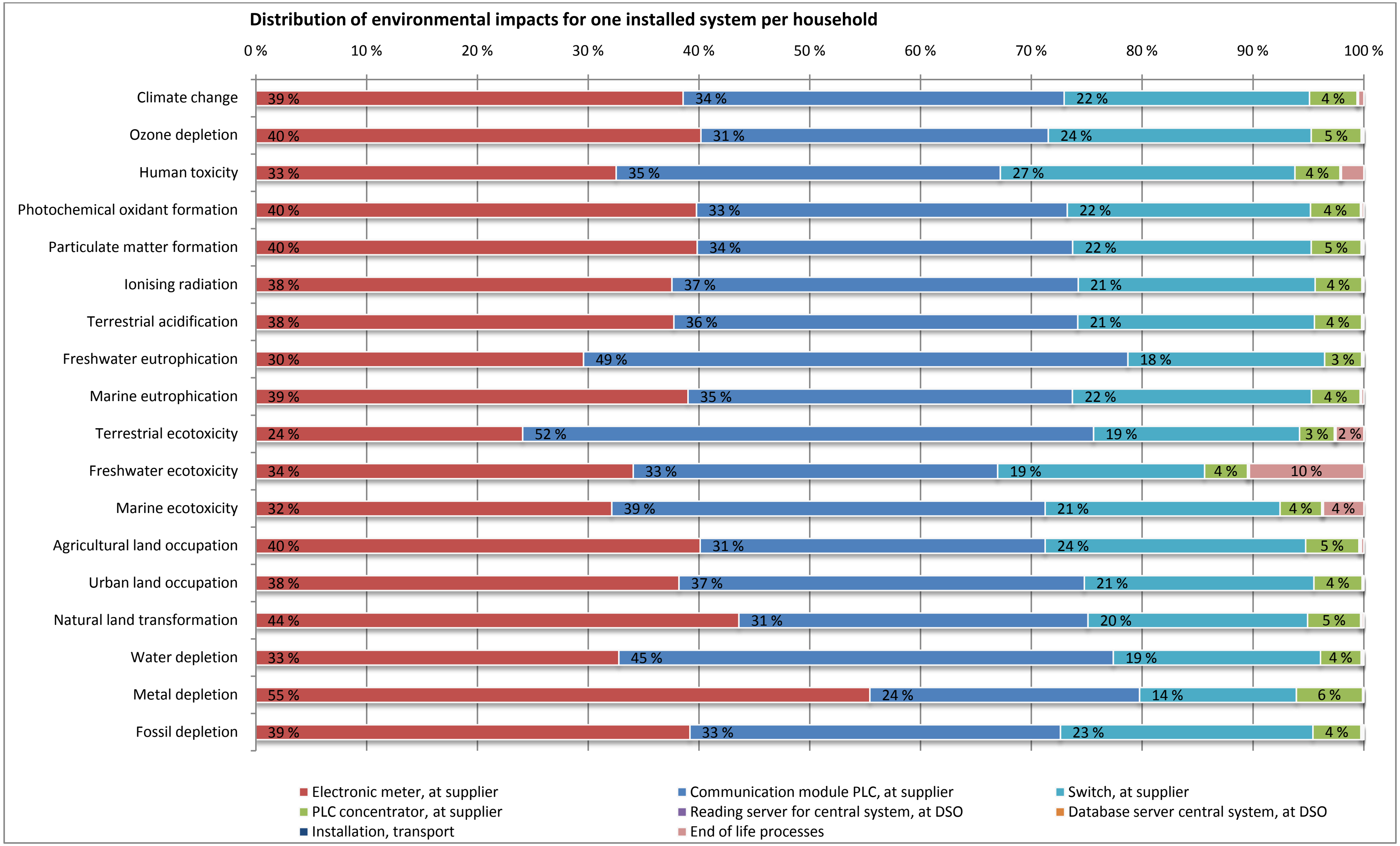

Figure 26: Distribution of contributions of impacts for one installed system per household

Figure 26 shows that of all the processes the physical components are contributing the most to the total environmental impacts for all categories. The components with largest contributions are electronic meter, communication module and switch. The electronic meter contributes in the range of 24% (terrestrial ecotoxicity) to 55% (metal depletion). The communication module is in the range of 24% (metal depletion) to 52% (terrestrial ecotoxicity). The switch contributes between 14% (metal depletion) to 27% (human toxicity). The impacts from the concentrator are between 3% and 6%. The servers contributes minor and the maximum contribution from these are 0,12%. The installation efforts (transportation to household from DSO) contributes with 0,02% as a maximum and is negligible compared to the other processes.

The end of life processes of the components have minor contributions to the most of the total impacts. The maximum contribution from the end of life processes is 10% (freshwater ecotoxicity). After this, it is the other ecotoxicity categories and human toxicity that has the highest contribution from end-of-life processes.

The detailed contributions to environmental impacts caused by the physical components in the system is shown in Figure 27 for the electronic meter, which besides the communication module was the dominating for total impacts caused for an installed system. This is then for an electronic meter when it is delivered at the assumed location of DSO in Trondheim. The different background processes have been aggregated into the categories plastic, electronics, tin, copper, steel, iron, transport and electricity for assembly. The material categories defined then now contain both material and processing inputs.

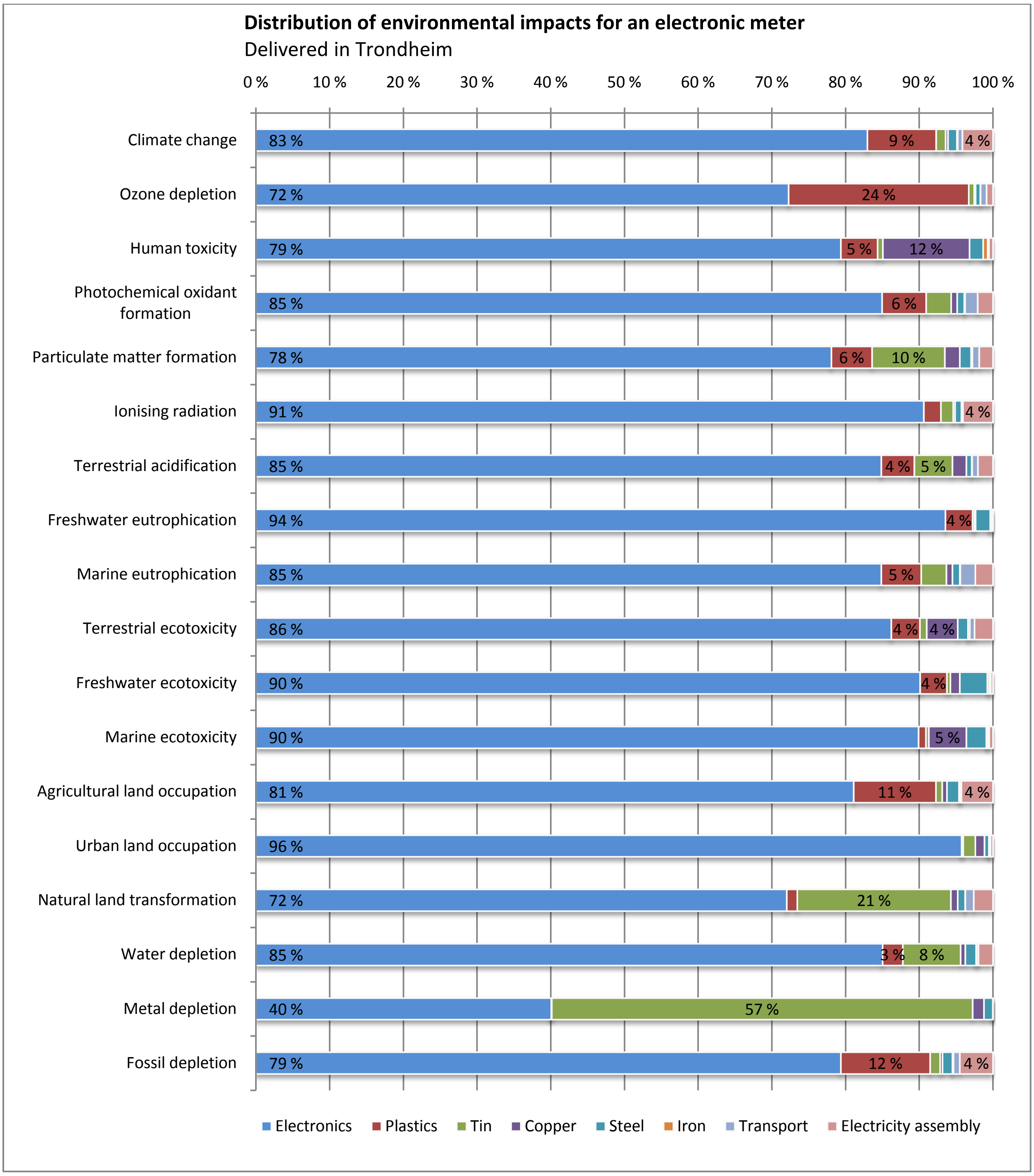

Figure 27: Distribution of contributions of impacts for electronic meter

Figure 27 shows that the environmental impacts are strongly dominated by the electronics, except for metal depletion impact where tin contributes the most with 57%. For metal depletion impact the electronics causes 40% of the total impact. The production of electronic components is for the rest of the categories in the range of 72-96% of total impacts. The use of plastic contributes the most with 24% (ozone depletion).

The detailed distribution of contributions of environmental impacts for the switch and concentrator are given in Appendix B. The outlines of the results for the switch, concentrator and communication module are described here:

The production of the concentrator was analyzed, and due to the fact that it is based on same material use as for the meter the contributing factor is the electronic component production for all categories, except metal depletion where use of tin is dominating with 54% of total impact. The production of electronic components has 42% of the share for metal depletion and for the remaining impact categories contributions between 72-95%.

The impacts from production of the switch are also dominated by production of electronic components in all categories. The contribution ranges from 50-92%. Next to this, a significant contribution from the use of copper is in ecotoxicity and toxicity categories, with 32% as a maximum (human toxicity). For metal depletion, marine ecotoxicity and terrestrial ecotoxicity impacts the use of copper has contributions from 12-17%. The production of the printed wiring board used in the switch contributes with 20% as maximum for terrestrial ecotoxicity.

For the communication module the impacts in all categories is almost solely due to the production of printed circuit board with electronic components. The transport is negligible.

4.2 Environmental impacts from operation of system

The results from operation of the system per functional unit, which was 1 kWh metered by the meter in a household, is presented here. The total environmental impacts caused in the different categories are listed in Table 25.

Table 25: Total impacts for 1 kWh metered with a smart metering technology system at household

Impact category	Value	Unit	Normalized
Climate change	7,5E-04	kg CO2 eq	9,7E-03
Ozone depletion	7,9E-11	kg CFC-11 eq	5,4E-04
Human toxicity	1,8E-04	kg 1,4-DB eq	4,2E-02
Photochemical oxidant formation	2,6E-06	kg NMVOC	7,6E-03
Particulate matter formation	1,4E-06	kg PM10 eq	1,6E-02
Ionising radiation	2,5E-04	kg U235 eq	7,7E-03
Terrestrial acidification	3,7E-06	kg SO2 eq	2,1E-02
Freshwater eutrophication	2,7E-08	kg P eq	0
Marine eutrophication	7,3E-07	kg N eq	0
Terrestrial ecotoxicity	2,8E-07	kg 1,4-DB eq	2,6E-03
Freshwater ecotoxicity	2,4E-06	kg 1,4-DB eq	4,9E-02
Marine ecotoxicity	4,4E-06	kg 1,4-DB eq	2,0E-01
Agricultural land occupation	2,3E-05	m2a	4,3E-04
Urban land occupation	2,9E-05	m2a	1,6E-02
Natural land transformation	2,5E-07	m2	2,0E-01
Water depletion	6,8E-06	m3	0
Metal depletion	6,4E-04	kg Fe eq	2,2E-01
Fossil depletion	2,2E-04	kg oil eq	1,6E-02

As can be seen, 0,75 g CO_2 eq. are emitted from an operating system per kWh metered in a household. After the normalization step, impact categories with a factor of zero were freshwater and marine eutrophication and water depletion. The three categories with highest values after normalization were metal depletion, marine ecotoxicity and natural land transformation.

Figure 28 shows the distribution of the total impacts on the different system processes.

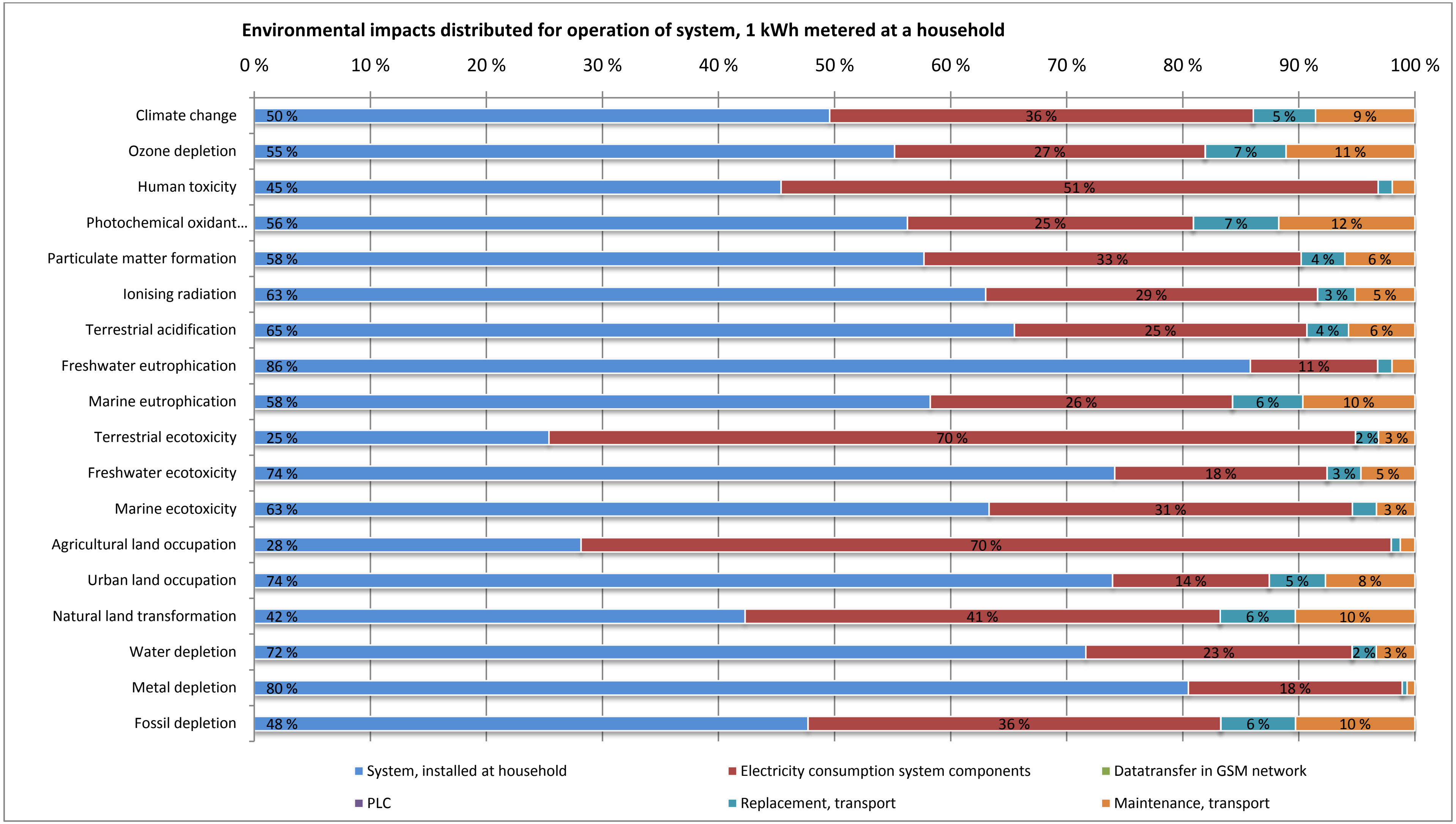

Figure 28: Environmental impacts distributed for operation of a smart metering technology system

Figure 28 shows that the installed system at household is the major contributor in most impact categories, except for human toxicity, terrestrial ecotoxicity, agricultural land occupation and natural land transformation. In these four categories electricity consumption of the system components during the operating phase is dominating and is in the range of 41–70%. For the categories where the installed system is the dominant contributor, the contribution from this is in the range of 42% (natural land transformation) to 86% (freshwater eutrophication).

For climate change impact, the installed system contributes with 50%, electricity consumption of the system components with 36%, transport for maintenance with 9% and transport for replacement with 5%. Metal depletion impact, which is the category with highest value after normalization, is dominated 80% by the installed system, followed by 18% for electricity consumption of system components.

Transport from maintenance contributes with 10-12% in five categories; ozone depletion, photochemical oxidant formation, marine eutrophication, natural land transformation and fossil depletion. For the other categories the contribution is below 10%. Transport related to replacement contributes with 7% as maximum.

The contributions from PLC and data transfer in the GSM network are negligible compared to the other processes.

4.3 Sensitivity analysis

4.3.1 Installed system

4.3.1.1 *Lifetime communication module*

The communication module showed a large contribution for all environmental impact categories for an installed system in a household. It was assumed as a basic assumption to have a lifetime of 7 years. A sensitivity analysis was performed to see the effect of the lifetime on the impacts caused by an installed system at household. Figure 29 shows the change for the impact categories metal depletion and climate change for a range of lifetimes.

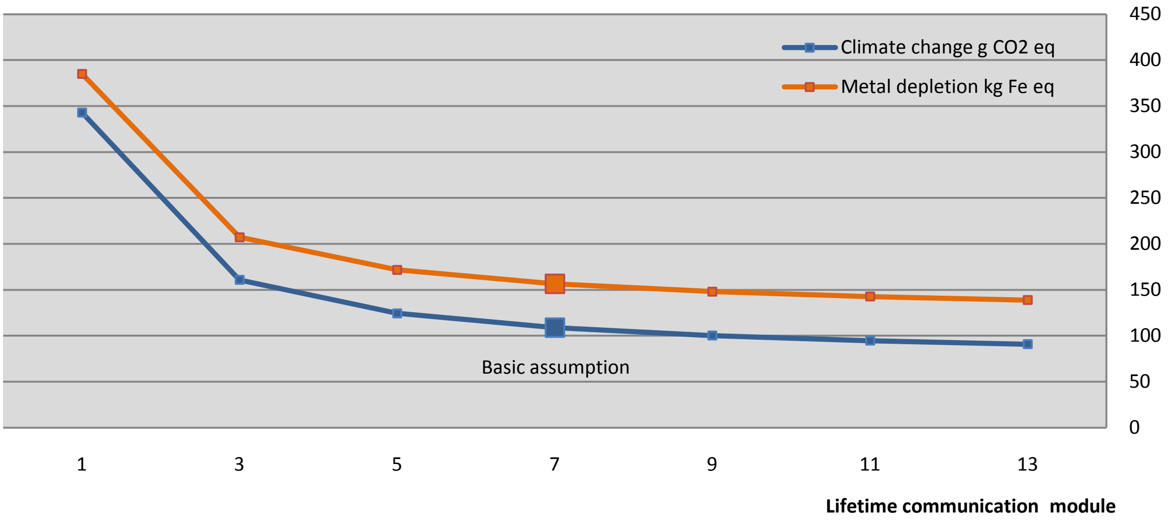

Figure 29: Sensitivity analysis of lifetime of communication module and climate change and metal depletion impacts

The results from the other impact categories are given in Appendix C, only a summarization of the results is given here. A shorter lifetime of the communication module than 7 years increases the impacts in all categories. For a shorter lifetime than 3 years, impacts will be significantly higher. If the lifetime had been increased to 11 years, the decrease in impact categories range between 8% for metal depletion, to a maximum decrease of 19% for terrestrial ecotoxicity.

It should be noted that this sensitivity analysis is done to see the effect on the impacts caused by an installed system at household. The transport related to replacement of the components is not included in this module, but in the module for operation of the system. What is included here is transport for first time installation and additional input of the component. When transport related to replacement of the component increases for reduced lifetime of components, impacts would increase further also for operation of the system.

4.3.2 Operation of system

4.3.2.1 *Electricity consumption*

The electricity consumption of the components in the system was generally the second largest contributor to total environmental impacts for operation. To see the effect of this parameter on the total environmental impacts from operation, the system electricity consumption was increased from the basic assumption (82 kWh/a). The effect on climate change impact can be seen in Figure 30.

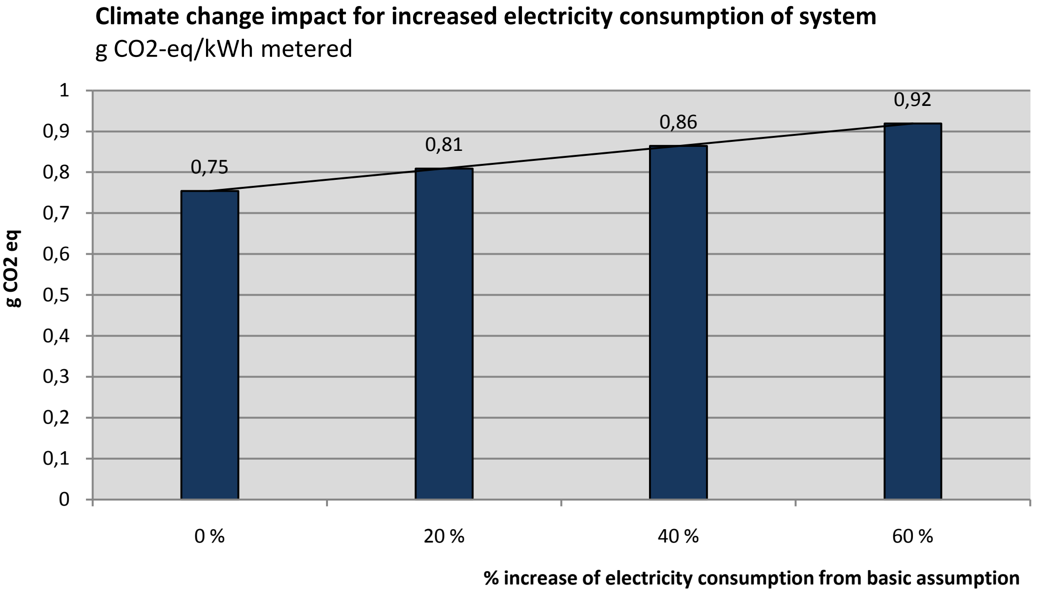

Figure 30: Sensitivity analysis of system electricity consumption and climate change impact

4.3.2.2 *Maintenance*

The maintenance relies on two parameters; transport distance to the household and frequency. The impacts from maintenance are connected to the transport and emissions from the operation of a personal car.

The basic assumption of frequency of visits to the customers was 0,08% per collection of data for DSO. This makes 0,27% of total customer mass yearly. The rate of unplanned maintenance was set to zero to see the maximum effect of a decrease. It decreased fossil depletion and ozone depletion with 15%. Climate change impact decreased with 12%.

The rate of unplanned maintenance was increased to see the effect is has on the total impacts caused by the operation of the system. The transport needed increases and the total impacts in all categories hence increased, for certain impact categories significantly. Figure 31 shows the increase in some chosen impact categories from the original values obtained with the basic assumption of a rate of 0,08% visits per collection. The categories ozone depletion, freshwater eutrophication, photochemical oxidant formation and fossil depletion are increasing the most.

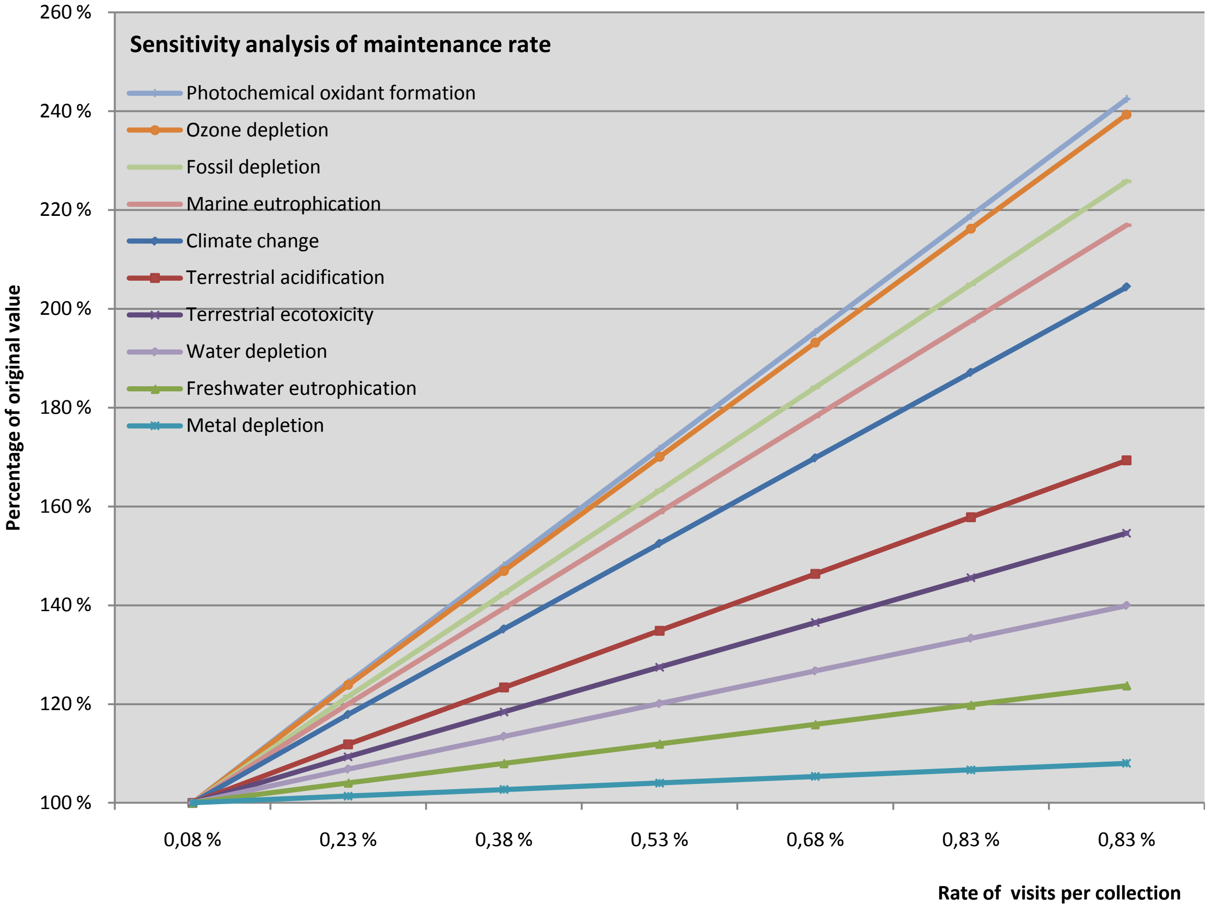

Figure 31: Sensitivity analysis of maintenance rate for a selection of environmental impacts

The distance to a household was taken as basic assumption to be 12 km and 10 km to network station. Increasing the distances to the double, lead to increase in total impacts as listed in Table 26. It is clear that distance from DSO will vary greatly from household to household. With the functional unit as 1 kWh metered at a household, the differences in contribution transport has to total impact could be large for cases where population density is low and distances large.

Table 26: Increase in impact categories for increased distance (+100%) to household

Impact category	Unit	Increase from basic assumption
Climate change	kg CO2 eq	117 %
Ozone depletion	kg CFC-11 eq	122 %
Human toxicity	kg 1,4-DB eq	103 %
Photochemical oxidant formation	kg NMVOC	120 %
Particulate matter formation	kg PM10 eq	110 %
Ionising radiation	kg U235 eq	110 %
Terrestrial acidification	kg SO2 eq	109 %
Freshwater eutrophication	kg P eq	103 %
Marine eutrophication	kg N eq	116 %
Terrestrial ecotoxicity	kg 1,4-DB eq	106 %
Freshwater ecotoxicity	kg 1,4-DB eq	107 %
Marine ecotoxicity	kg 1,4-DB eq	105 %
Agricultural land occupation	m2a	102 %
Urban land occupation	m2a	111 %
Natural land transformation	m2	117 %
Water depletion	m3	106 %
Metal depletion	kg Fe eq	101 %
Fossil depletion	kg oil eq	121 %

4.3.2.3 *Data traffic in GSM Network*

The impact from use of the GSM Network showed a minor contribution to the total impacts caused. The data traffic accounted for was as the basic assumption the transmission of data from concentrator to DSO. As an approximation, to account for data sent the other way, the size of data sent was doubled. Double data transmission showed no effect on the total impacts, and it was still minor compared to the other contributions.

4.4 Case for quantification of benefits

The results from the case and the two scenarios defined in Chapter 3.3 are presented here. The case that was defined was a very critical supply situation of electricity for the region Central Norway, with two possible scenarios as solutions:

The smart metering technology scenario represented production of 1 kWh of the average Norwegian consumption mix of electricity, and the operation of a smart metering technology system, metering 1 kWh at a household and making it possible to shift a load.

The reserve capacity scenario represented the production of 1 kWh from the reserve capacity gas power plants.

A comparison of the scenarios are thus basically comparing two different electricity production scenarios, but with an included input in the smart metering technology scenario to operate the systems. The comparison of the scenarios and the potentially avoided GHGs when smart metering technology is used to remote control loads in households can be seen in Figure 32. The values of emissions are per kWh consumed in a household.

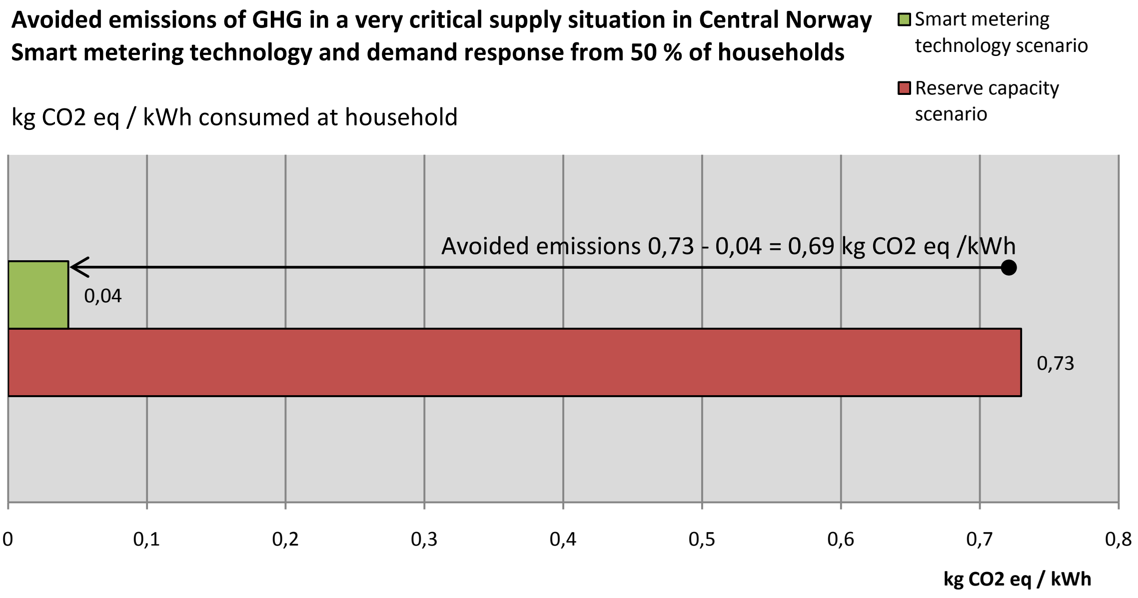

Figure 32: Avoided emissions of GHG with smart metering technology and RLC

There is a potential to avoid 94% of the emissions that will occur with the use of reserve capacity, when using remote load control of households as an alternative. Figure 33 shows the avoided emissions for a single household for cumulative peak electricity amount. The horizontal axis thus represents kWh consumed at the household.

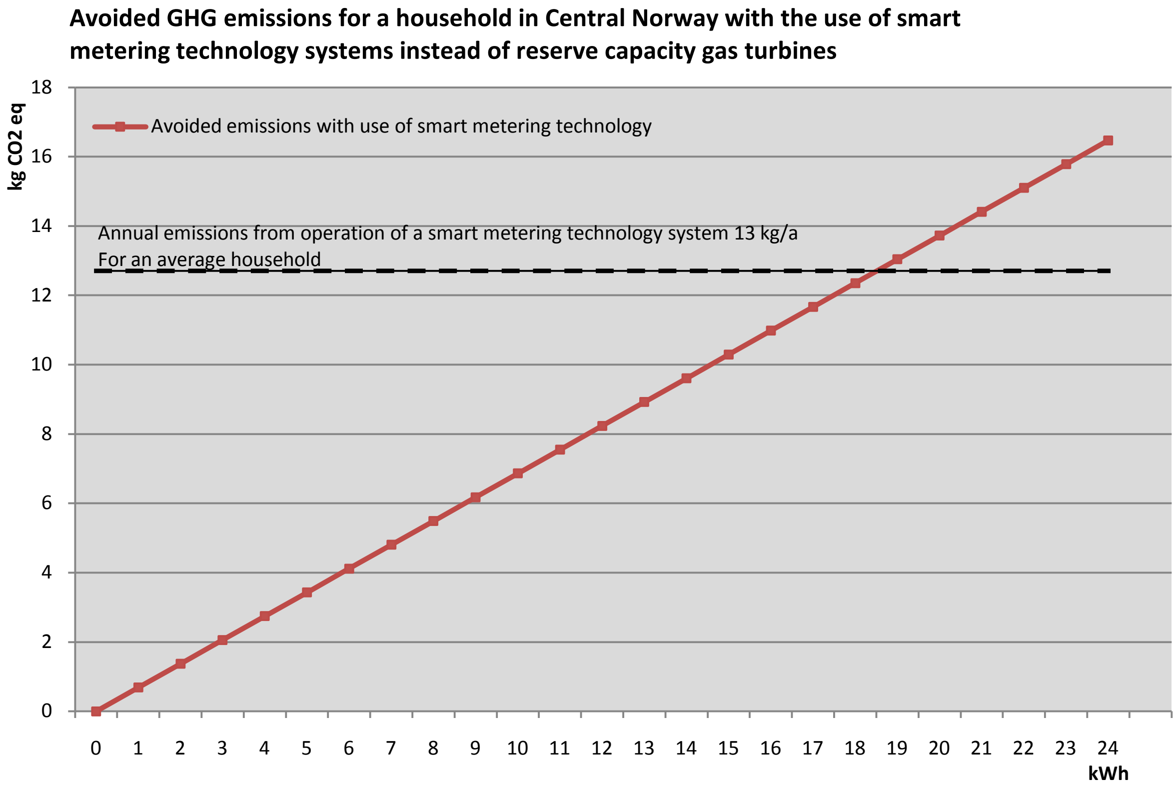

Figure 33: Avoided GHG emissions for an average household for cumulative annual peak electricity amount

In Figure 33 the emissions from the operation of the smart metering technology systems, presented in Chapter 4.2 are up-scaled for a year for a household[29] and shown as the blue line (13 kg CO_2 eq/a). Further, the red line is the emissions that can be avoided per kWh for the defined scenarios. During one year, if 19 kWh is shifted for a household and the alternatives for electricity generation are the two scenarios, the annual emissions from operation of the system and emissions avoided are equal for the household.

When up-scaling the results from the scenarios to the case defined of Central Norway, the avoided emissions of GHGs would be 103 tons CO_2 eq. Table 27 lists the total impacts in each category, up-scaled for the defined case. The normalized results for the scenarios are also shown here.

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[29] Based on the average household consumption 16858 kWh/a and emissions from operation of smart metering technology system 0,00075 kg CO_2 eq/kWh

Table 27: Total environmental impacts for scenarios for the case of a very critical supply situation in Central Norway

				Normalized, ReCiPe	
Impact categories	**Unit**	**Reserve capacity Scenario**	**Smart metering technology scenario**	**Reserve capacity Scenario**	**Smart metering technology scenario**
Climate change	kg CO2 eq	1,1E+05	6,5E+03	3,9E-06	6,5E-05
Ozone depletion	kg CFC-11 eq	1,4E-02	5,4E-04	1,7E-07	4,2E-06
Human toxicity	kg 1,4-DB eq	4,2E+02	5,1E+02	5,7E-06	4,6E-06
Photochemical oxidant formation	kg NMVOC	2,9E+02	1,3E+01	1,6E-06	3,4E-05
Particulate matter formation	kg PM10 eq	6,4E+01	7,2E+00	3,3E-06	2,9E-05
Ionising radiation	kg U235 eq	2,7E+02	1,9E+03	2,0E-06	2,9E-07
Terrestrial acidification	kg SO2 eq	1,8E+02	1,3E+01	2,6E-06	3,4E-05
Freshwater eutrophication	kg P eq	7,8E-02	3,8E-02	0	0
Marine eutrophication	kg N eq	9,6E+01	4,0E+00	0	0
Terrestrial ecotoxicity	kg 1,4-DB eq	1,8E+00	2,8E+00	2,3E-06	1,5E-06
Freshwater ecotoxicity	kg 1,4-DB eq	5,6E+00	5,0E+00	3,1E-06	3,5E-06
Marine ecotoxicity	kg 1,4-DB eq	3,2E+01	7,3E+00	1,2E-05	5,1E-05
Agricultural land occupation	m2a	1,8E+01	2,8E+02	4,2E-07	2,6E-08
Urban land occupation	m2a	4,2E+01	3,9E+01	6,5E-07	6,8E-07
Natural land transformation	m2	2,2E+01	2,4E+00	9,9E-05	9,1E-04
Water depletion	m3	1,5E+01	3,5E+01	0	0
Metal depletion	kg Fe eq	3,4E+02	3,5E+02	3,3E-06	3,2E-06
Fossil depletion	kg oil eq	4,6E+04	1,9E+03	6,8E-06	1,6E-04

Figure 34 shows a comparison of the environmental impacts for the two scenarios and the distribution of contributions in the smart metering technology scenario. The impacts in each category are normalized with respect to the highest impact.

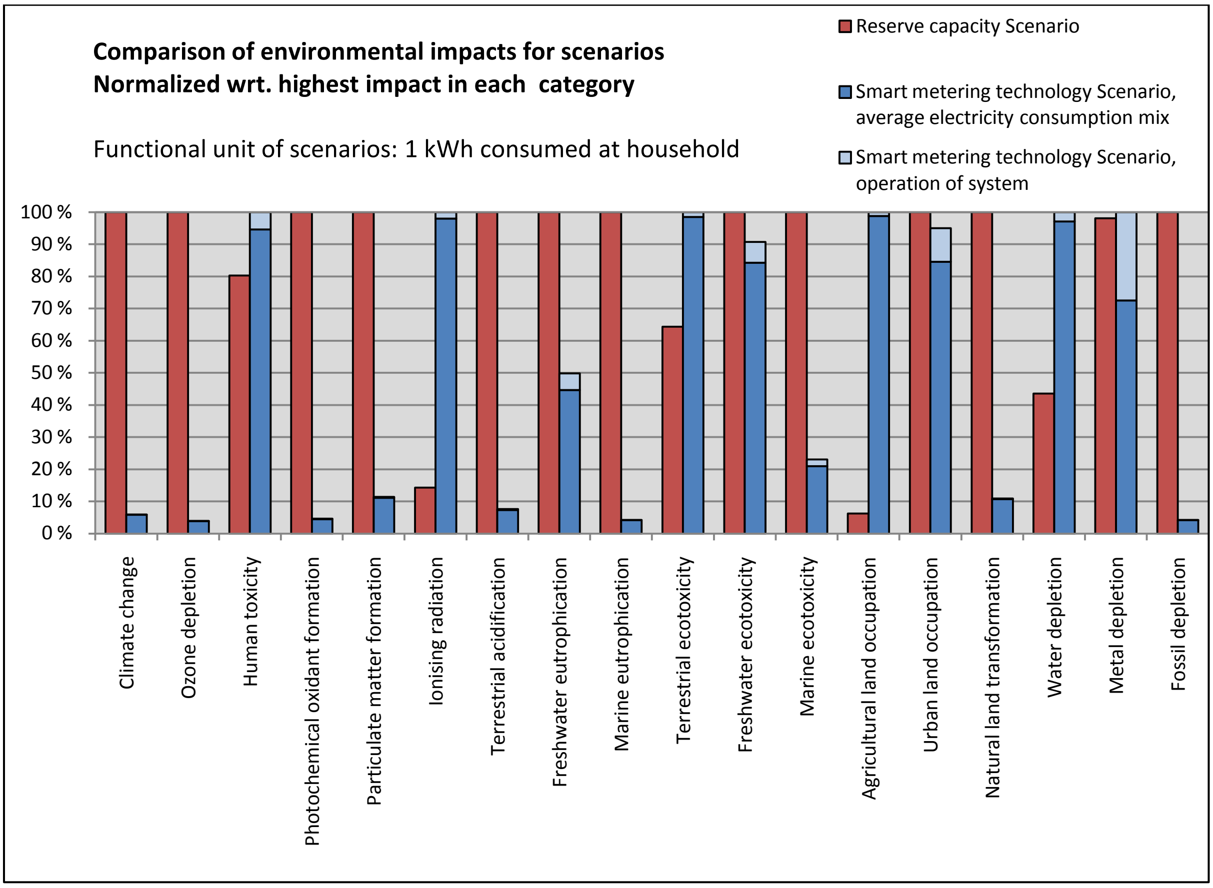

Figure 34: Comparison of total environmental impacts for scenarios

Figure 34 shows that operation of the system is the minor contributor to total impact all impact categories. The production of electricity dominates. The category where operation contributes the most is for metal depletion, with 19%. For all other impact categories the contribution is less than 10%. For climate change, the contribution from operation of the system is responsible for 1,7% of the total impact.

The reserve capacity scenario has highest impact for 12 of 18 categories. Of these, the categories with the largest difference in impacts are fossil depletion, marine eutrophication, terrestrial acidification, photochemical oxidant formation, ozone depletion and climate change. For these categories, the smart metering technology scenarios impacts are less than 8% of the respective impacts in the reserve capacity scenario. Figure 35 further shows that the smart metering technology scenario causes larger impact in the categories human toxicity, ionizing radiation, terrestrial ecotoxicity, agricultural land occupation, water depletion and metal depletion.

For the 6 impact categories where the smart metering technology scenario had a higher impact than the reserve capacity scenario, the processes of electricity production contributing to this were identified. Human toxicity impact is mainly caused by electricity production from combustion of wood based fuel and the disposal of wood ash. The same applies for terrestrial ecotoxicity. Ionizing radiation is caused by the import of electricity produced with nuclear power. Agricultural land occupation impact is mainly from electricity production from combustion of wood and the requirement of wood chips. Water depletion is caused by electricity production with hydro power, natural gas and import of electricity produced with nuclear. Metal depletion is from electricity production from hydro and wind power. Secondly, it is from the installed smart metering system at household.

Figure 35 shows the normalized total environmental impacts with ReCiPe normalization factors. Categories that were zero for both scenarioes are excluded, and these were marine eutrophication, freshwater eutrophication and water depletion.

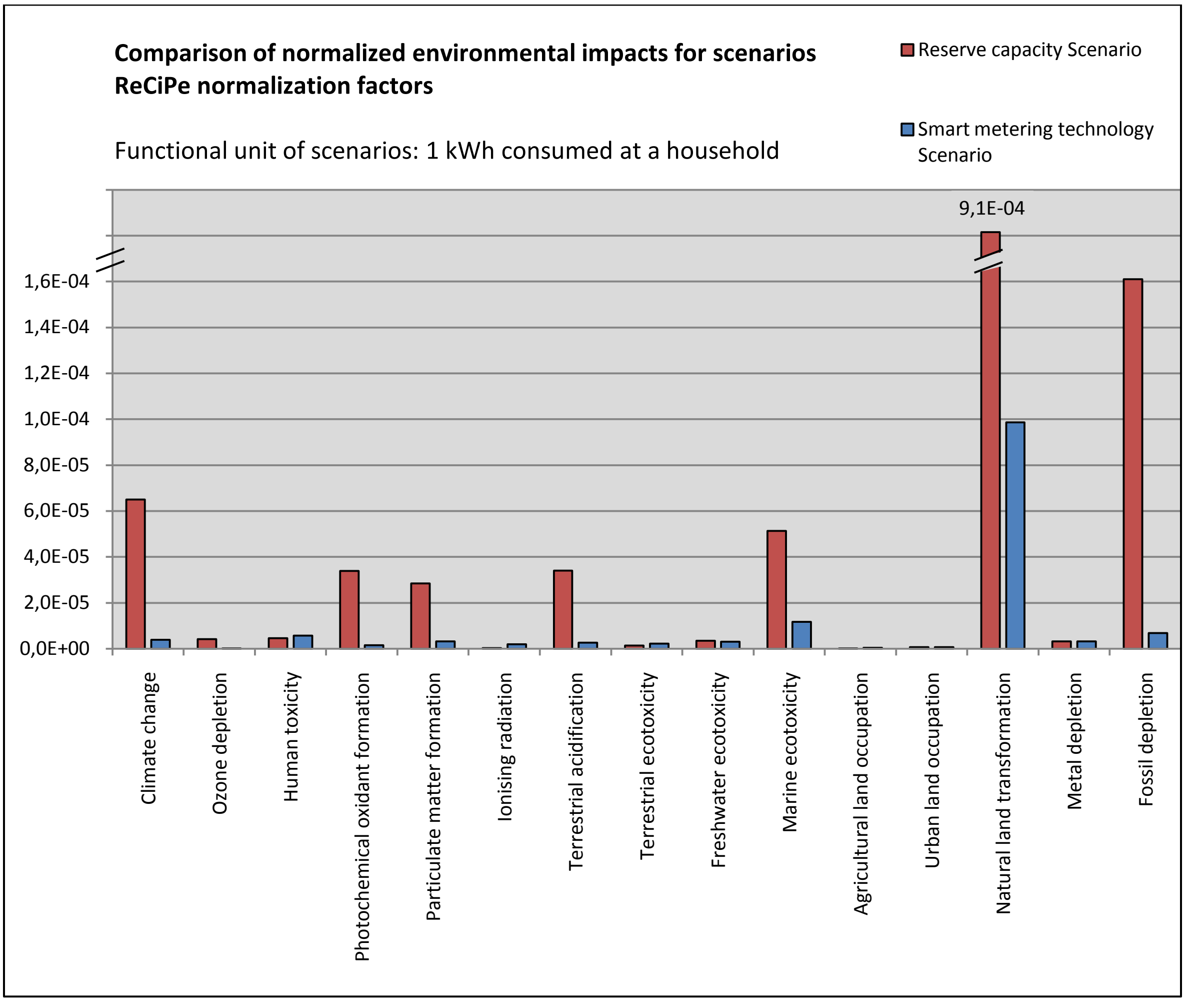

Figure 35: Comparison of normalized environmental impacts for scenarios (ReCiPe)

In Figure 35 it can be observed that the largest values after normalization are for natural land transformation, fossil depletion and climate change, all categories where the reserve capacity scenario causes larger impact than for the smart metering technology scenario. In the reserve capacity scenario fossil depletion impact is mainly from the production of natural gas and climate change impact is from combustion of the gas.

5 Discussion

5.1 Data quality and uncertainty

LCA as a method to evaluate environmental impacts has some weaknesses. Conventional LCA generally aims to include the major stages and inputs for a product or process throughout the life cycle, but in reality this is difficult to carry out. To model all inputs and environmental burdens related to them is too complex to perform, and limitations are made. As a result of factors such as subjective boundary definition, inflexibility and issues related to data verification, conventional LCA has by several been considered *"a flawed tool that cannot deliver what it promises"*, as stated in (Joshi, 1999).

The qualities of data used in LCA are of vital importance to the results obtained. In this study the data has been collected from a large amount of various sources, which is a consequence of a large system that involves many different actors. The quality of data can be discussed, as this contributes to increase the uncertainty related to the results.

The inventories established for *installed system* with the material use for physical components meter, switch and communication module should be fairly good to represent a typical "average product". The processing of raw materials is based on general processes available due to lack of detailed information. It has been necessary to use information from several producers and suppliers, because detailed information on one specific product has not been possible to access. To get the analysis as complete as possible, own estimations of material use based on dimensions listed in technical specifications listed, has been used. There is a larger uncertainty related to the material use in the concentrator than the other products. The reason for this is that information was not available at the same detailed level as for the other products, and the material use is therefore to a certain extent based on the assumption that type of materials used are similar as for the electronic meter. The requirements of energy in the assembly of the physical components are uncertain. The inventories for the meter, switch and concentrator contain estimations of the energy requirements for their assembly, which is an average value given from a producer. It was given that the energy use for assembly was solely electricity, but it can be questioned if the assembly efforts also would require some heat. Additionally, potential direct emissions or waste from the assembly site has not been taken into account as this has not been known.

The *power consumption* of the system components during operation is calculated based on given specifications and averages and should be good enough to give an indication for the defined system. Uncertainty is however related to the transmitting time of the communication module. This is calculated based on only data traffic one way. The effect that increasing power consumption had on total impacts was therefore checked with sensitivity analysis.

The assumptions related to *maintenance* are uncertain, and has been checked with sensitivity analysis. The value used in the basic assumption was from experiences of operation of smart metering technology systems in Sweden. A main difference between smart metering technology systems in Sweden and Norway are the location of the meters, which in Sweden often is placed outside the household and therefore are accessible at all times for maintenance. In Norway, the meters are placed inside households and visits require the customer to be home. Technical differences of systems and other factors, such as geographical influence on communication system, contribute to the uncertainty of this value.

The assumptions related to *replacement rate* are based on requirement specifications for smart metering technology systems. Except for the communication module, the lifetime of the components is rather “beneficial” for the system, meaning that some factors that might could have influenced the replacement rate have not been taken into account. These are factors such as commercial lifetimes of the products and advancing technology, which maybe would lead to a more frequent replacement than what has been assumed. The communication modules lifetime was checked with sensitivity analysis, as it was considered the most uncertain lifetime.

The choice of *electricity mix* for the study for Norwegian conditions can be discussed. The inputs of electricity are important and the decision of using Norwegian consumption mix has influenced the results obtained. An alternative to the Norwegian consumption mix is the NORDEL[30] mix in ecoinvent, the last being based on the average composition of production between Denmark, Sweden, Finland and Norway. The NORDEL mix will have higher emissions of CO_2 than the Norwegian consumption mix[31] and would have contributed to different results in the study. The mix that was chosen to use for the Norwegian conditions is based on the physical consumption mix for Norway given by NVE for 2009, as shown in Figure 2 previously in the report. The emission from this consumption mix that was made was compared to the existing production and import mix for Norway from ecoinvent. Because of the increase in thermal power production that occurred in 2008 that was accounted for, the new mix made has higher emissions of CO_2 (+0,01 kg CO_2/kWh).

The fact that some of the environmental impact categories are more uncertain than the others should be taken into account. This is especially the case for the human toxicity and marine ecotoxicity categories, where there is large uncertainty related to some characterization factors (Hischier et al., 2010). Marine ecotoxicity was an impact category which had large relative value after the normalization step for installation and operation of the systems, but the uncertainty of this result is thus significant.

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[30] The European Network of Transmission System Operators for Electricity (ENSTO-E) took over operational tasks for NORDEL from 2009

[31] Ecoinvent NORDEL production mix 0,183 kg CO_2 eq/kWh
Ecoinvent NO production mix + import 0,0336 kg CO_2 eq/kWh

5.2 Environmental costs

The results from the life cycle assessment of a smart metering technology system showed that when the system is installed and operating, the majority of environmental impacts are from the installed system. For climate change impact, the installed system is responsible for 50%, followed by electricity consumption of the components with 36%. Transport related to installation and maintenance contributes together with 14%. This means that the results in this study shows that the contribution from the use of the communication systems is negligible, which is the common finding of all the impact categories. Normalized results with ReCiPe factors further gave that metal depletion, natural land transformation and marine ecotoxicity had highest relative importance for operation of the systems.

For the installed system, the components necessary for every household contribute the most to the total impact. These are the electronic meter, the communication module and the switch. The electronic meter and communication module are the major contributors. The general finding is further that electronics contribute significantly to impacts. Smart metering technology will require production of electronics on a larger scale than the old metering systems. On a quantitative level, when comparing the old systems with only a meter as the necessary component in a household to the increased amount of WEEE components needed for smart metering technology, this is likely to cause a trade-off issue for the new systems. WEEE products are a concern for the environments because of the environmental toxins in the products with potential to harm humans and environment. The specific kind of environmental toxins depends on the type of product. For products handed in nowadays in the group “fire-and burglar alarms, control panels and metering equipment”, considerable amounts can be found of components that are radioactive, contain mercury, has lead batteries and capacitors with PCB (RENAS, 2009). The harmful effects of the toxic substances in components like this are evident and have been documented in several studies (Sepúlveda et al., 2010 ; Robinson, 2009).

The environmental costs related to production of WEEE products are one hand related to the energy intensive methods required for production of the electronics. Cost pressure has led to the fact that electronic production previously undertaken in Western Europe, which has not been relocated to China, has moved to Central and Eastern Europe (REEDElectronicResearch, 2011).The production is therefore likely to be situated in countries that have a significant share of un-renewable energy sources in their electricity production.

Environmental costs of WEEE products also concern the depletion of metals as the production requires extraction of precious and limited raw materials. From the results, the direct use of tin in the meter and concentrator contributed significantly to their metal depletion impact (>54%), followed by electronics. A list of “potentially critical” raw materials has been prepared by the EU, and a selection of these materials and the use of them in WEEE products were given in (Ongondo et al., 2011). Some of the materials listed were silver, gold, bismuth, cobalt, copper and tin. In this study the exact compositions of metals has not been known, and the direct use of it in the components was accounted for by including four major metals. Additionally, the electronic components process used from ecoinvent will account for the use of metals in the electronics. The compositions in the study are just estimations, and to really assess the metal depleting potential of smart metering technology systems more details would have to be known. The recycle of the materials should then also be considered. Data collected from waste handling firms said that material recycling rate of WEEE products were quite high (>72 %). It was not known which of the specific materials in the products this applied for, and due to the large uncertainty related to it, the recycle was left out of the analysis. Recycle of metals has been accounted for by using the average mixes available in ecoinvent of primary and secondary metals. A question can however be made on how one should have evaluated the use of the precious metals in WEEE products. (Ongondo et al., 2011) highlighted a sight that weight-based approaches to take-back and recycle of WEEE products might lead to inaccurate policy decisions. This because the quantities of it in products is trace on a weight basis and due to this it might seem that recovery is not the most important way to reduce environmental impacts. The value of recovering some of the precious metals cannot however not be compared to for example recovering the plastic, and a weight based approach would therefore not be the most accurate way to go.

A detailed modeling of the end of life of the products was not done in this analysis, but was estimated with an average treatment process for WEEE equipment. It was assumed a take-back factor of the products of 100%. This means that it is assumed that all the products will be handed back for proper treatment. The results showed that the end of life phase had minor contribution; highest impact was for freshwater ecotoxicity with 10%. If all the products are not handed back, the environmental impacts can increase due to lack of proper waste treatment. Proper treatment and take-back routines of the system components is important, both to recover the materials that are possible to recover and to handle the toxic substances correctly. This also concerns the old electronic meters that now will be replaced, which will have the same issues related to end of life as has been discussed here for WEEE equipment. Although the replacement of systems will only occur once, it will involve a large number of components when it is being done on a national scale.

Once the new systems are in place, a frequent replacement of the system components will lead to a larger amount of WEEE to handle, a larger potential for environmental damage and a higher rate of metal depletion. The fact that advancing technology and commercial lifetimes may cause shorter lifetimes than necessary, could be a concern. A recent study presented an increase in growth of WEEE in EU every 5th year with 16-28 % (Ongondo et al., 2011). Smart metering technology will contribute to this increase. The ongoing work on requirement specification of smart metering technology suggests a lifetime of 18 years for the system, including the communication system(s) involved (Graabak et al., 2011). If the communication system used is changed during the lifetime, this will require a change of communication module installed in the meter. Sensitivity analysis performed on the lifetime of the communication module showed that a frequent replacement will increase environmental impacts for all categories. The communication module is basically electronic components, and it is not surprising that this will increase the impacts since the electronics are found to be the general dominating contributor.

Also related to end of life is the recycle of the plastic in the components. It was not included in the analysis because of the composition with glass fiber. The use of glass fiber as additive to plastic mixes makes the recycling process more difficult. The use of GFRP have had a general increase the last 50 years, and techniques for recycle are currently being investigated (NSK, 2011 ; STENA, 2011). In the future, new technology could contribute to the possible recycle of the plastic used in the components, and this could potentially change their environmental impacts.

Next to the contribution to the environmental impacts from the installed system, the electricity consumption of the system components during operation was the biggest contributor. The total electricity consumption of the components is relatively small compared to the average annual consumption by a household (0,5% of total household consumption). The meter is the component in the system that consumes the most electricity per household, so to choose a meter with low electricity consumption would be largest contributor to reduce the impacts related to electricity consumption for the defined system. The results further gave that 0,75 g CO_2 eq was emitted per kWh metered in the household. Clearly, the electricity consumption for the components in such a system during operation would contribute more to the total impacts in a country where the electricity production is not based on renewable sources and increase this value. However, the LCA is based on the geographical location of Norway, and the results cannot be used directly to represent other geographical locations. But, related to choice of electricity mix, if the NORDEL mix had been chosen, results would have been influenced by the fact that the NORDEL mix has higher emissions, and the contribution from electricity consumption of the components during operation of the system would have increased.

The smallest contribution to total impacts for operation was from the communication systems, and this impact was negligible. The impacts that did occur from data transmission were the ones caused by the electricity consumption of the network components. An important aspect to consider when evaluating this result is the technological choices that have been made, to understand the limitation of the analysis. The communication systems that were chosen (PLC and GSM Network) are systems with already existing infrastructure. If a communication system is installed solely for smart metering technology purposes this could potentially change the results drastically. As example, a radio network would require a large amount of additional components, with similar potential environmental impacts as has been discussed related to production of WEEE products. It was considered that a detailed assessment of communication systems was out of the scope of the study, and additionally, to model a communication system realistically requires detailed data from the suppliers of such systems. These are data that have not been possible to access during this study. If one were going to assess the environmental impacts of a communication system, such as a radio network installed solely for smart metering technology purposes, this is a major work. Generally, a communication system will consist of several physical and non-physical parts and to aim to include all physical components in the system is very likely to be time consuming and impractical. All the different elements in such a system are although needed to achieve the main function or services(s) the system provides, in this case, transferring of data from smart meters to DSOs and back. The environmental impacts of communication systems is a wide topic, and has among other sources been discussed in the report “Understanding the Environmental Impact of Communication Systems” (Forster et al., 2009).

The communication system is not the only part that potentially could increase the impacts for a smart metering technology system. An aspect that has been discussed related to the full scale roll out of smart metering technology systems is the need for standardization of interfaces, to avoid several central systems running in parallel at a DSO. In general, one communication system alone will often not be enough to reach all metering points for one DSO. For a central system that only supports one communication system and is delivered from a specific supplier for this, two central systems can be necessary and this will increase the amount of components.

Additional system components for a communication system or central system would also lead to increased electricity consumption during operation and increase the need of installation and maintenance efforts. Sensitivity analysis showed that increasing maintenance rate for this system potentially can increase climate change impact for operation of the system with more than 200% from the original assumption. When it comes to the planned maintenance of operation of smart metering technology systems, this is expected to be zero since it will occur through remote updates, which limits the need for physical visits. The planned maintenance rate would however have to be reconsidered if different communication system were installed.

In the end, the results from this study indicates that the main environmental costs of installation and operation of smart metering technology systems are the impacts caused by production of the system components and the impacts from electricity consumption of the system during operation. The production of system components requires electronics which contain toxins that can harm human and environment. Additionally there is a metal depletion potential caused both by the use of metals directly in the products and in the electronics. There are factors that could increase the size of a smart metering technology system further than what has been defined in this study, such as a communication system installed solely for smart metering technology purposes. To increase system size by adding additional components will increase both main environmental costs.

5.3 Environmental benefits

The results from the scenarios defined showed environmental benefits with the use of smart metering technology systems as an alternative to use the reserve capacity gas turbines. Per kWh consumed at a household during a peak hour in a very critical supply situation, the potentially avoided emission of GHGs was 0,69 kg CO_2 eq/kWh. The case defined of Central Norway involved up-scaling of the results from the two scenarios, and showed that with smart metering technology installed in households in Central Norway, and remote load control of water heaters in 50% of the households in the region, there is potential to avoid 103 tons of CO_2 eq emissions for a peak hour.

The use of smart metering technology as opposed to reserve capacity gas turbines will also be beneficial for other environmental impact categories. Largely reduced are ozone depletion, photochemical oxidant formation, terrestrial acidification and fossil depletion. For 6 of the 18 impact categories, the smart metering technology scenario had highest impacts. It was found that these were due to different aspects concerning electricity production, and not from the operation of the smart metering technology system. These categories could be defined as trade-off impact categories, but in this case it does not make sense to define it in that way. The relevancy of the impacts categories should be considered, and in this case the avoided emission of CO_2 is the objective. The average consumption mix of electricity is further the mix that will be used on a daily basis, and operation of the systems will occur continuously.

Depending on the amount kWh shifted by a smart metering technology system for a household during a year in a situation where reserve capacity is the alternative, the annual avoided emissions increase. The annual emissions of CO_2 eq from operation of the smart metering technology system in a household were found to be 13 kg[32]. Results further showed that if the systems can be used to shift 19 kWh for the household during the year, so this load is being produced as the average consumption mix instead of with the reserve capacity gas turbines, the emissions from operation of the systems will equal the emissions avoided for the single household. However, the situation should be looked at on a broader scale, and it was assumed that 50% of the households in the region contributed with demand response in the case defined. This means that there would be 50% households in the region with systems operating and not being used to shift a load. These households would still have the emissions related to operation of the systems. Another assumption made, is that the environmental impacts related to operation of the smart metering technology system will be the same for all the households in the region. This assumption is definitely a simplification and it is clear that technological difference and hence impacts from different systems installed in the region will vary. As was also discussed previously about environmental costs of smart metering technology, there are factors that potentially can increase the impacts that are found in this study.

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[32] Based on average household consumption 16858 kWh/a

The condition for the environmental benefit resulting in this study from smart metering technology systems is that a very critical supply situation occurs and all the alternative measures available besides use of reserve capacity gas power plants fail. This is *not* a regular situation and to conclude that the environmental costs from operating the systems are very likely to be "paid back" by the avoided emission found in this study cannot be done. The results of avoided emissions found in this study do not reflect the power market on a "regular" day. At a regular day, electricity consumption will be covered by the installed main capacity and import capacity to the region. The electricity production in Norway will then generally consist of a small amount of thermal power as base load and hydro power as regulating power. The benefits of smart metering technology and remote load control are in this perspective foremost linked to regulate the balance of consumption and production, and advantages as mentioned previously in this report, will occur for the different participants in the power market.

One issue that can be discussed related to the defined case is the obtainable demand response in the region. The assumption that 50% of the regions' water heaters is possible to disconnect is important to achieve the same effect as one of the installed gas turbines for reserve capacity. It is also important that they could all be re-connected to the grid at the same time, without problems, after the peak hour. The technical aspects around this, and other technical aspects concerning start-up time of the gas turbines etc., have not been considered any further in this study. The fact that the scenario of reserve capacity did not include any environmental impacts from the present metering systems installed in the household should also be mentioned, since the smart metering technology scenario included operation of the smart metering technology systems. Nevertheless, including additional inputs to the reserve capacity scenario would potentially just increase the impacts caused in this scenario.

The operation of the smart metering technology systems was the efforts of operation per kWh metered at a household, and it is assumed that as a part of this operation it is possible to remote control the water heater in the household. Realistically, there will be data transmission additional to what is included in the modeled operation of the systems, but it has not been known how large this data traffic will be. Based on the results from the sensitivity analysis of increasing data transfer in the GSM network (doubled), the effect this had on the final results was zero.

Related to the result of avoided emission of GHG, the resulting emission of CO_2 eq from electricity production in the reserve capacity scenario in the analysis (0,79 kg/kWh) is somewhat higher than the value Statnett uses for the turbines CO_2 emissions (0,68 kg/kWh) (Statnett, 2011d). However, the fact that the climate change impact gives CO_2 eq and not just CO_2 should be taken into account here. Additionally, if the NORDEL mix had been used as electricity mix for the smart metering technology scenario, the avoided emissions would have decreased because of the higher emissions related to the NORDEL mix.

The scope of this study has been limited to a Norwegian perspective, and the quantification of environmental benefits therefore reflects a large contrast between the electricity productions in the scenarios that was defined. The possibility to shift loads from peak hours and avoid electricity produced by gas turbines, to hours where electricity is produced by mostly renewable sources, is clearly a major CO_2 saver. An aspect to consider is the fact that the Norwegian power production and the large amount of hydro power is a unique situation compared to electricity production in other countries. If one is to look at the situations in other countries that have a larger share of un-renewable energy sources in the production, the environmental benefits of smart metering technology have to be considered from a different basis. What is clear is that if smart metering technology contributes with a conservation effect, a reduction of total consumption compared to presently; environmental impacts are reduced by simply avoiding electricity generation. For the mechanism load shifting, on the other hand, the potential of reducing emitted CO_2 will depend on a number of external factors. With load shifting the number of peak hours per year can be reduced, but the alternative ways of generating the electricity will always be essential for determining the environmental influence. The type of installed capacity for a region, the efficiency of the capacity and import and export patterns are among the factors that will affect this. The marginal production costs of different electricity generating units are also important, and the fact that these prices are not necessarily in an “environmentally friendly” order. If a load is shifted and this leads to operation of coal-fueled plant instead of a gas-fueled plant, emissions could actually increase, as was presented in an example in Chapter 2.3.1. The detailed relationship between consumption and production of electricity for a specific region would be necessary to model to provide an estimation of the emission reduction potential of load shifting. To forecast such realistic scenarios for electricity production has not been within the scope of this study, and would additionally require use of modeling tools.

To summarize the discussion of environmental benefits of smart metering technology: The main environmental benefit from smart metering technology and remote load control of households in Norway is the possibility to avoid use of reserve capacity gas power plants. In hydrological dry years, the smart metering technology systems and households demand response could help to handle critical supply situations in a different way than what is presently listed as the alternative actions, and would be a more environmentally friendly measure than the option that is available of use of reserve capacity.

6 Conclusions and further work

Smart metering technology systems will be implemented in Norway for all end-users of electricity. There are many options available for technological system solutions, and in this study a system has been defined to include the basic components to support the systems functionality and use communication systems with existing infrastructure. The environmental costs of operation of the defined smart metering technology system in a household are foremost related to the production of the installed system components and electricity consumption of the system components during operation. For an installed system, the general finding for the different environmental impact categories are that electronic components used in the products contribute the most to total impacts. The normalized results (ReCiPe) gave metal depletion a high value relative to most of the other impact categories.

Because of large thermal loads, particularly in the form of electric water based heaters, the Norwegian households have a significant potential to contribute with demand response. Central Norway is a region with a challenged power situation and reserve capacity gas turbines are installed. The demand response from households can help avoid start-up of these, which has environmental benefits. In such a situation, there will be avoided GHG emissions when shifting a load with the smart metering technology systems.

In a Norwegian perspective, the main environmental benefit of smart metering technology systems installed in households will be in a situation where electricity supply cannot be secured and the alternative is to use the reserve capacity gas power plants. However, the environmental benefits of load shifting in general rely significantly on the options available for electricity generation. The reason it is beneficial in Norway is because the alternative is almost solely renewable electricity generation. From a general origin, an important condition for emission reduction to occur with load shifting is that the load is shifted to electricity generation that has lower emissions than the alternative.

To quantify potential environmental benefits of load shifting, further work that could be performed is an assessment based on a modeling of electricity scenarios. With the use of modeling tools, relevant factors such as import, export and production mix could be determined and provide a basis for the quantification. Interesting in this perspective is to identify cases where load shifting will cause higher emissions.

To continue to assess the environmental costs of smart metering technology systems, a comparative LCA between the different alternative communication systems can be carried out. This could further be done for three alternative forms of PLC, that is, high, medium and low voltage. A LCA like this could provide a background for choosing communication system to minimize environmental costs.

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Appendices

Appendix A: Inventory lists

Inventory list with processes from ecoinvent for physical components

Component	Value/component	Unit
Electronic meter[i]	**1**	**p**
Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER U	0,193159	kg
Polycarbonate, at plant/RER U	0,289738	kg
Glass fibre, at plant/RER U	0,120724	kg
Copper, at regional storage/RER U	0,033333	kg
Injection moulding/Adjusted mix	0,603622	kg
Steel, low-alloyed, at plant/RER U	0,15	kg
Cast iron, at plant/RER U	0,033333	kg
Tin, at regional storage/RER U	0,033333	kg
Copper product manufacturing, average metal working/RER U	0,033333	kg
Steel product manufacturing, average metal working/RER U	0,15	kg
Electronic component, unspecified, at plant/GLO U	0,13	kg
LCD glass, at plant/GLO U	0,02	kg
Transport, lorry >16t, fleet average/RER U	1,73006	tkm
Transport, transoceanic freight ship/OCE U	2,867174	tkm
Transport, barge tanker/RER U	0,832	tkm
Transport, freight, rail/RER U	0,05	tkm
Electricity, medium voltage, production GB, at grid/GB U	2,92	kWh
Switch[ii]	**1**	**p**
Polycarbonate, at plant/RER U	0,207653	kg
Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER U	0,138435	kg
Glass fibre, at plant/RER U	0,086522	kg
Electronic component, unspecified, at plant/GLO U	0,067435	kg
Injection moulding/Adjusted mix	0,43261	kg
Copper, at regional storage/RER U	0,09	kg
Copper product manufacturing, average metal working/RER U	0,09	kg
Printed wiring board, surface mount, lead-free surface, at plant/GLO U	0,00385	m2
Transport, lorry >16t, fleet average/RER U	1,084649	tkm
Transport, transoceanic tanker/OCE U	1,528892	tkm
Transport, freight, rail/RER U	0,018	tkm
Transport, barge tanker/RER U	0,503401	tkm
Electricity, medium voltage, production GB, at grid/GB U	2,92	kWh

Communication module	**1**	**p**
Printed wiring board, surface mounted, unspec., Pb free, at plant/GLO U	0,06	kg
Transport, lorry 3.5-16t, fleet average/RER U	0,03684	tkm
Transport, transoceanic freight ship/OCE U	1,211652	tkm

Concentrator[ii]	**1**	**p**
Polycarbonate, at plant/RER U	0,372071	kg
Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER U	0,359668	kg
Glass fibre, at plant/RER U	0,179834	kg
Injection moulding/Adjusted mix	0,899171	kg
Cast iron, at plant/RER U	0,043455	kg
Tin, at regional storage/RER U	0,043455	kg
Steel, low-alloyed, at plant/RER U	0,17382	kg
Copper, at regional storage/RER U	0,08691	kg
Copper product manufacturing, average metal working/RER U	0,08691	kg
Steel product manufacturing, average metal working/RER U	0,17382	kg
Electronic component, unspecified, at plant/GLO U	0,188584	kg
LCD glass, at plant/GLO U	0,02	kg
Electricity, medium voltage, production FI, at grid/FI U	2,92	kWh
Transport, lorry >28t, fleet average/CH U	4,212468	tkm
Transport, transoceanic freight ship/OCE U	4,359754	tkm
Transport, freight, rail/RER U	0,069528	tkm
Transport, barge tanker/RER U	0,515849	tkm

Central system servers	**1**	**p**
Desktop computer, without screen, at plant/GLO U	1*X_i	p
Transport, lorry >16t, fleet average/RER U	2,05*X_i	tkm
Transport, barge tanker/RER U	0,222*X_i	tkm

X_i= W_i/(11,3 kg)

i = 1, 2

W_1	*23*	*kg*
W_2	*25*	*kg*

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[i] Calculations for weight of GFR PC/ABS based on assumption of 60% of total weight. Calculation of weight of GF based on assumption of 20 % GF of total GFR PC/ABS weight. Calculation of weight of PC and ABS based on assumed plastic mix with 60% PC and 40% ABS

[ii] Calculations of weight (m) of GFR PC/ABS based on surface area from technical specifications of chosen components and assumed thickness of plastic casing of 2 mm.

$m = \rho \cdot V \qquad \rho = density\ of\ plastic \qquad V = volume\ of\ plastic$

Calculation of weight of GF based on assumption of 20% GF of total GFR PC/ABS weight.Calculation of weight of PC and ABS based on assumed plastic mix with 60% PC and 40% ABS

Inventory List for installed system

Process	Value	Unit	Remark
Installed system at household	**1**	**p**	**1 installed system per household with lifetime of 18 years**
Electronic meter	1	p	
Switch, at supplier	1	p	
Concentrator	0,078	p	Divided by households sharing it and accounts for additional components - Has lifetime 15 years
Communication module	2,57	p	Accounts for additional components - Has lifetime 7 years
Reading server for central system	0,0001	p	Divided by households sharing it
Database server central system	0,0001	p	Divided by households sharing it
Installation, transport	1	p	
End of life processes			
Disposal, meter, to WEEE treatment	1	kg	
Disposal, concentrator to WEEE treatment	0,113	kg	Weight component*amount needed
Disposal, switch, to WEEE treatment	0,6	kg	
Disposal, treatment of communication module/NO U	0,154	kg	Weight component*amount needed
Installation, transport	**1**	**p**	**Installation of system**
Transport, van <3.5t/RER U	0,0084	tkm	Transport of all components for first time installation (excluding transport of additional components, this transport is included in replacement)
Disposal, 'component', to WEEE treatment	**1**	**kg**	**Ecoinvent process that has been modified 'component' (meter, concentrator or switch)**
Dismantling, industrial devices manually, at plant/NO U	0,23	kg	All sub processes which require electricity adjusted to Norwegian mix
Dismantling, industrial devices, mechanically, at plant/NOU	0,77	kg	All sub processes which require electricity adjusted to Norwegian mix
Transport, van <3.5t/RER U	0,02	tkm	Other transport processes are removed
Disposal, treatment of communication module/NO U	**1**	**kg**	**Ecoinvent process that has been modified**
Disposal, treatment of printed wiring boards/kg/GLO	1	kg	All sub processes which require electricity adjusted to Norwegian mix

Inventory lists for operation of system

Process	**Value**	**Unit**	**Remark**
Operation, system	**1**	**p**	**1 kWh metered with system**
System, installed at household	3,30E-06	p	(1 installed system) /(t*Q)
Electricity consumption system components	0,00488	kWh	(Annual system el. consumption) / Q
Gbit datatransfer in GSM network	9,20E-09	p	(Annual data transfer in Gbit per household)/ Q
PLC	4,42E-09	p	(El cons. transmitting communication module annually) / Q
Replacement, transport	3,30E-06	p	(Replacement efforts during t)/(t*Q)
Maintenance, transport	1,62E-05	p	(Annual maintenance rate per household)/ Q

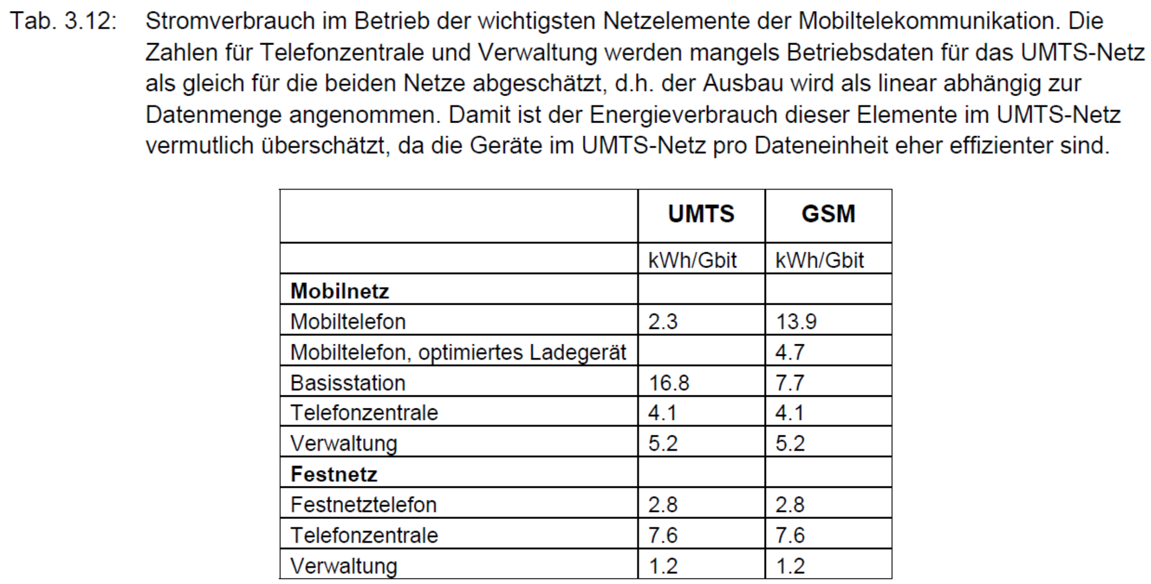
Q = 16858 kWh/a Average annual electricity consumption household
t = 18 years Lifetime system

Gbit datatransfer	**1**	**p**	**Gbit datatransfer from DSO-Central system**
Electricity, low voltage, at grid/NO U new	11,8	kWh	Electricity for base station + telephone central
PLC	**1**	**p**	
Electricity, low voltage, at grid/NO U new	1	kWh	
Replacement, transport	**1**	**p**	
Transport, passenger car/RER U	68	personkm	Transport related to replacement during 18 years
Maintenance, transport	**1**	**p**	
Transport, passenger car/RER U	22	personkm	Transport related to maintenance
Electricity consumption system components	**1**	**kWh**	
Electricity, low voltage, at grid/NO U new	1	kWh	

Electricity production mixes updated to 2009

Process	Unit	Value	Remark
Production mix Norway + imports	**1**	**kWh**	**Consumption mix from 2009**
Import mix	0,046	kWh	
Electricity, hydropower, at power plant/NO U	0,908656	kWh	
Electricity, hydropower, at pumped storage power plant/NO U	0,004344	kWh	
Electricity, at wind power plant/RER U	0,007	kWh	
Electricity, hard coal, at power plant/NORDEL U	6,36E-04	kWh	
Electricity, oil, at power plant/FI U	2,34E-04	kWh	
Electricity, natural gas, at power plant/NORDEL U	2,50E-02	kWh	
Electricity, industrial gas, at power plant/NORDEL U	3,80E-03	kWh	
Electricity, at cogen ORC 1400kWth, wood, allocation exergy/CH U	4,36E-03	kWh	
Import mix	**1**	**kWh**	**Updated after 2009 mix**
Electricity, production mix SE/SE U	0,45	kWh	
Electricity, production mix DK/DK U	0,26	kWh	
Electricity, production mix FI/FI U	0,022	kWh	
Electricity, production mix CENTREL/CENTREL U	0,039	kWh	used instead of Russia
Electricity, production mix NL/NL U	0,219	kWh	

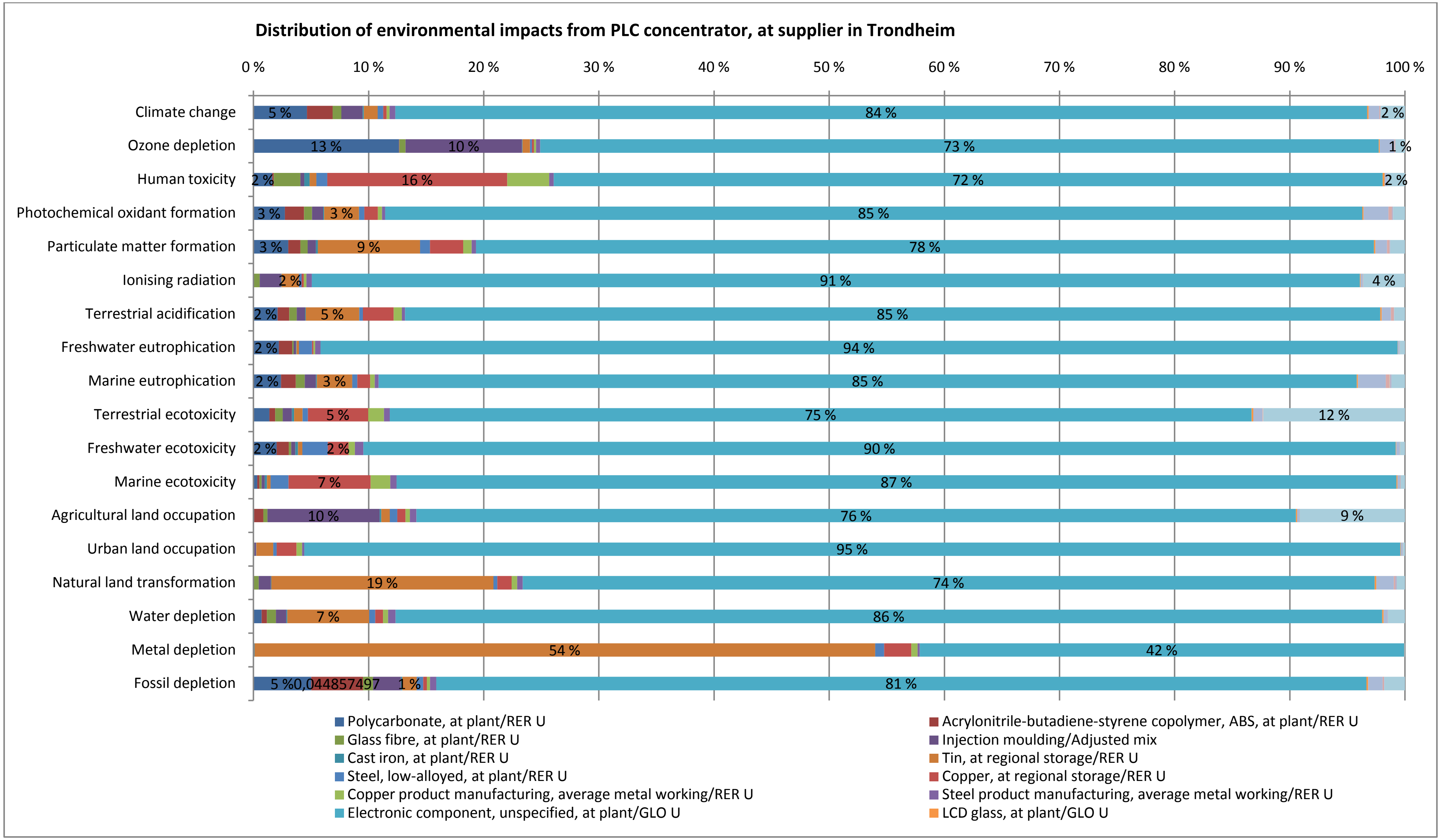
Data used for electricity consumption of central system components in a GSM Network (Emmeneger et al., 2003)

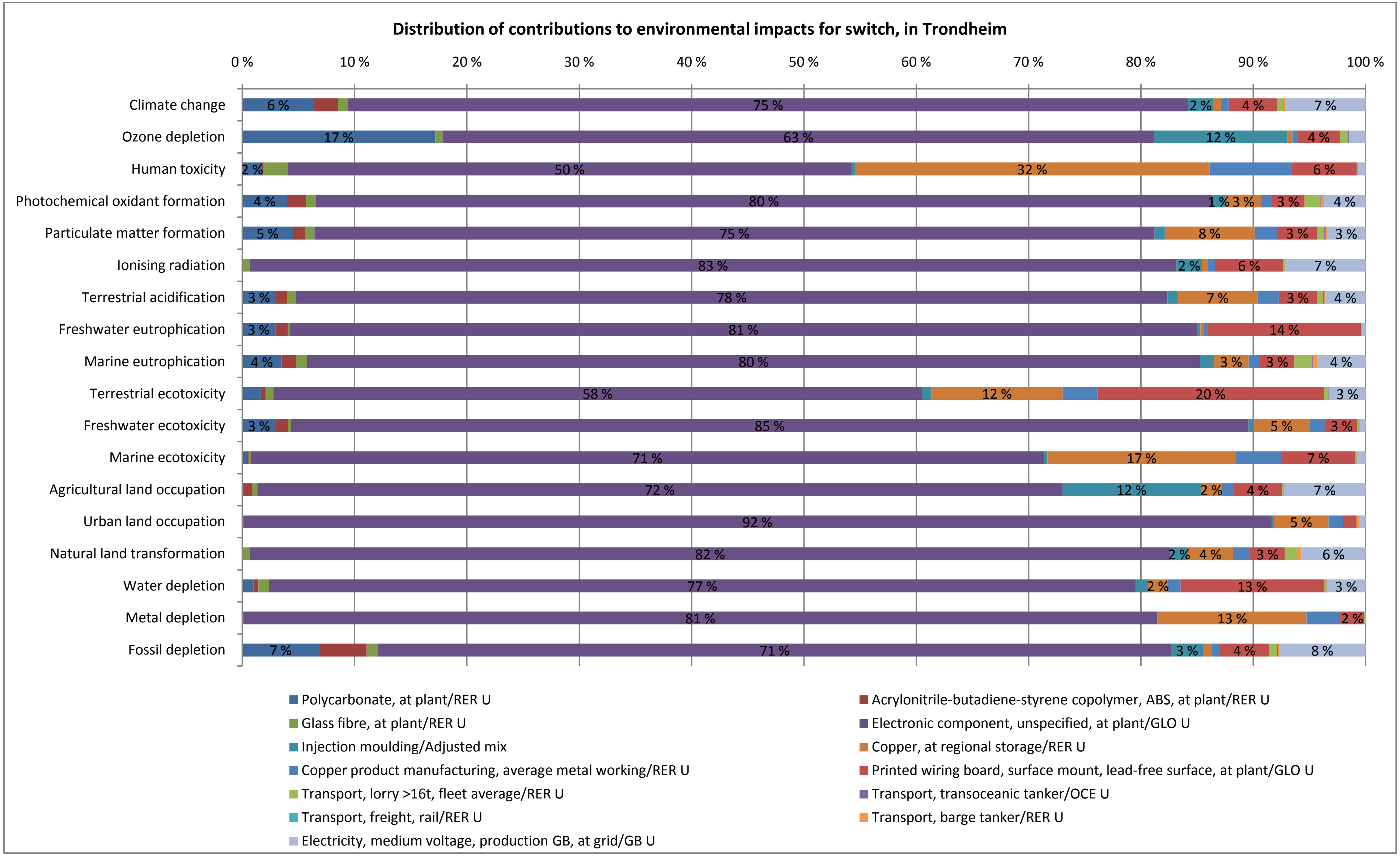


Tab. 3.12: Stromverbrauch im Betrieb der wichtigsten Netzelemente der Mobiltelekommunikation. Die Zahlen für Telefonzentrale und Verwaltung werden mangels Betriebsdaten für das UMTS-Netz als gleich für die beiden Netze abgeschätzt, d.h. der Ausbau wird als linear abhängig zur Datenmenge angenommen. Damit ist der Energieverbrauch dieser Elemente im UMTS-Netz vermutlich überschätzt, da die Geräte im UMTS-Netz pro Dateneinheit eher effizienter sind.

	UMTS	**GSM**
	kWh/Gbit	kWh/Gbit
Mobilnetz		
Mobiltelefon	2.3	13.9
Mobiltelefon, optimiertes Ladegerät		4.7
Basisstation	16.8	7.7
Telefonzentrale	4.1	4.1
Verwaltung	5.2	5.2
Festnetz		
Festnetztelefon	2.8	2.8
Telefonzentrale	7.6	7.6
Verwaltung	1.2	1.2

Appendix B: Results LCA – Contribution analysis of concentrator and switch




Distribution of contributions to environmental impacts for switch, in Trondheim

Appendix C: Results sensitivity analysis - Lifetimes of communication module

Total increase/decrease in environmental impacts for different lifetimes of communication module divided by original assumption (7 years)

Lifetime (years)		**1**	**3**	**5**	**7**	**9**	**11**	**13**
Impact category	**Unit**							
Climate change	kg CO2 eq	315 %	148 %	114 %	100 %	92 %	87 %	83 %
Ozone depletion	kg CFC-11 eq	306 %	146 %	114 %	100 %	92 %	87 %	84 %
Human toxicity	kg 1,4-DB eq	310 %	147 %	114 %	100 %	92 %	87 %	84 %
Photochemical oxidant formation	kg NMVOC	306 %	146 %	114 %	100 %	92 %	87 %	84 %
Particulate matter formation	kg PM10 eq	309 %	146 %	114 %	100 %	92 %	87 %	84 %
Ionising radiation	kg U235 eq	320 %	149 %	115 %	100 %	92 %	87 %	83 %
Terrestrial acidification	kg SO2 eq	323 %	150 %	115 %	100 %	92 %	86 %	83 %
Freshwater eutrophication	kg P eq	399 %	167 %	120 %	100 %	89 %	82 %	77 %
Marine eutrophication	kg N eq	313 %	147 %	114 %	100 %	92 %	87 %	84 %
Terrestrial ecotoxicity	kg 1,4-DB eq	412 %	169 %	121 %	100 %	88 %	81 %	76 %
Freshwater ecotoxicity	kg 1,4-DB eq	301 %	145 %	113 %	100 %	93 %	88 %	85 %
Marine ecotoxicity	kg 1,4-DB eq	335 %	152 %	116 %	100 %	91 %	86 %	82 %
Agricultural land occupation	m2a	288 %	142 %	112 %	100 %	93 %	89 %	86 %
Urban land occupation	m2a	319 %	149 %	115 %	100 %	92 %	87 %	83 %
Natural land transformation	m2	289 %	142 %	113 %	100 %	93 %	89 %	85 %
Water depletion	m3	369 %	160 %	118 %	100 %	90 %	84 %	79 %
Metal depletion	kg Fe eq	246 %	132 %	110 %	100 %	95 %	91 %	89 %
Fossil depletion	kg oil eq	312 %	147 %	114 %	100 %	92 %	87 %	84 %