NTNU
Innovation and Creativity

Integrating LCA in the local energy planning for heat supply of buildings

Johanne Hammervold

Master of Science in Energy and Environment
Submission date: August 2007
Supervisor: Edgar Hertwich, EPT
Co-supervisor: Bjørn Bakken, SINTEF

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

Problem Description

The aim of the thesis is to develop an approach to integrate LCA of different fuels and energy conversion technologies into an energy planning tool, such as e-Transport, using Trondheim as a case study.

Assignment given: 14. March 2007
Supervisor: Edgar Hertwich, EPT

Integrating LCA in the local energy planning for heat supply of buildings

Johanne Hammervold

August 9, 2007

PREFACE

This report constitutes the final thesis for my Masters degree in Technology, Energy and Environment, with a specialization in Industrial Ecology. The work was conducted at the Department of Energy and Process Engineering and at the Industrial Ecology Programme at the Norwegian University of Science and Technology (NTNU).

The academic supervisor has been Prof. Edgar Hertwich and co-supervisor has been Doc. Bjørn H. Bakken at SINTEF. I wish to thank both for valuable advice throughout this study. I would also like to thank all co-students and employees at Industrial Ecology; I find it most motivating to work in such a progressive and engaged environment! Especially, I would like to mention Marte Reenaas, Christian Solli and Kyrre Sundseth for guidance and motivating discussions during this study.

Johanne Hammervold
Trondheim
August 9, 2007

SAMMENDRAG

Formålet med denne oppgaven har vært å utvikle og beskrive en metode for å benytte LCA-data og -beregninger i energiplanleggingsverktøyet eTransport. Enkle LCA'er er foretatt på relevante energivarer, infrastruktur og transporttjenester. Resultatene av disse er behandlet og presentert i en form funnet passende for implementering i eTransport.

Valg av metode for implementering påvirkes av mange faktorer, disse er forsøkt belyst gjennom rapporten og tatt hensyn til ved valg av metode.

For å illustrere metoden, er LCA-resultatene benyttet på 2 scenarier for Trondheim Kommune. Beregningene er etterfulgt av en beskrivelse av hvordan dette kan gjøres i eTransport.

Dette er et grunnarbeide vedrørende implementering av LCA i eTransport, og skal følges opp i videre studentarbeid der metoden er tenkt utprøvd i praksis.

SUMMARY

The objective of this study was to develop an approach to integrate LCA of different fuels and energy conversion technologies into the energy planning tool eTransport. Course LCA's for relevant energy commodities, infrastructure and transport services was performed, and the results from these prepared for implementation in eTransport.

In the choice of methodology for integration, a lot of aspects needs consideration. These are described throughout the report and emphasized in the choice of methodology.

The methodology is illustrated by a case study on Trondheim municipality, followed by a description on how this would be done in eTransport.

This project is a groundwork regarding implementation of LCA in eTransport, and will be followed up by further student work, testing the method in practice.

Contents

List of Figures

List of Tables

ABBREVIATIONS

AP	Acidification Potential
ADP	Abiotic Depletion Potential
EP	Eutrophication Potential
DH	District Heating
FAETP	Freshwater Aquatic Ecotoxicity Potential
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFO	Light Fuel Oil
LPG	Liquefied Petroleum Gas
MAETP	Marine Aquatic Ecotoxicity Potential
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
TETP	Terrestrial Ecotoxicity Potential

1 Introduction

SINTEF is developing the energy planning software tool eTransport, and a need for implementation of environmental impacts, in a life cycle perspective has been pronounced. This work aims at developing a method for such implementation, and it is planned to be followed up by further student work, in carrying out the implementation in practice.

A energy planning tool, with LCA implemented, shall provide decision makers overall environmental consequences of the modeled investment alternatives. This will instigate environmentally sound solutions for energy supply, and in this way serve as a tool for national targets regarding energy and environment.

The implementation method chosen, is calculation of impact results for relevant product and services using LCA. These results are thought implemented in eTransport and connected to the consumption of the appurtenant commodities during the optimization process. Course LCAs are obtained for the most relevant energy commodities, infrastructure components and transport services. These results are used in a case on Trondheim municipality, to illustrate the methodology.

2 Energy and environment

Energy consumption is a considerable source of a wide range of environmental problems. Combustion of various fuels contributes to global warming, air pollution (e.g. ozone and particulates), acidification and toxic effects on humans and ecology [21]. Stationary energy consumption constitutes a large share of the total energy use in Norway, and it has been a political issue for years to stimulate more environmental sound consumption for stationary purposes.

The environmental problems we can observe from energy consumption are mainly of a global character, and they need to be addressed with a holistic approach. It is necessary to include all environmental aspects and all effects occurring independently of geographical borders. Such approach will prevent shifting the burden "out of sight". Burden-shifting can occur from one location to another, from one environmental problem to another, from one release medium to another and from one life-cycle stage to another [20].

LCA is a method developed to systematize holistic analyses, by including all the environmental aspects throughout the whole life-cycle of for instance a product; from extraction of raw materials, production, transport, use and end-of-life treatment. Such an approach is especially suited regarding choice of system for energy supply, as such systems will differ a lot regarding where in the life-cycle stage the most environmental effects occur. For instance; investment-intensive systems has the largest impacts in the early life cycle stages, in the use of raw materials and production, and very little impacts in the use phase. Systems with high operational inputs, the other hand, will have large environmental impacts in the use phase.

A relevant illustrative example here is the DH system versus the electricity system. In many ways these systems are similar; from various resources, energy (heat/el) is produced and delivered to a grid (pipes/cables) and transported to end users. If only direct emissions are calculated, the production of DH will be included, but the production of electricity would not, and thus represent a great advantage for electricity use versus use of DH.

2.1 Local energy planning

The Norwegian energy legislation [30] shall ensure that production, conversion, trade, distribution and use of energy is performed in a socioeconomic efficient manner. This implies that environmental effects must be taken into consideration in local energy planning. There is therefore a need for a tool for local energy planning that includes both economical end environmental aspects, as a grounds for decision-making.

Energy planning based on environmental impacts calculated using LCA, will in turn be an driving force for cleaner production and conversion, as well as a shift in energy commodity consumption. It will also have the potential to be a good tool regarding national emission targets, for instance on reductions of greenhouse gas emissions nationally.

3 eTransport

3.1 Energy system planning tool

eTransport is an optimization model developed, and still being developed, by SINTEF [4]. The model minimizes total energy system costs of meeting predefined energy demands of electricity, space heating and tap water heating within a geographical area, over a given planning horizon. The object function includes investment, operating and environmental costs. The model includes several infrastructures for multiple energy carriers: electricity, natural gas, liquid natural gas, oil, biomass/waste and district heating.

eTransport stands out from other energy planning tools, optimizing a whole energy system within a given area, including all physical components and the geographical topology for the different energy infrastructures. Transmission distances and alternative locations are accounted for, and the competition between different energy commodities is implicitly handled by the algorithm.

eTransport is separated into an *operational* and an *investment model.* In the operational model there are component libraries with sub models for each energy carrier and for conversion components. The technology modules implemented in the library at present are listed in table 1.

Table 1: Implemented technology modules in eTransport

Energy sources	**Conversion and storage**	**Transport**	**Energy loads**
Electricity supply Gas supply Oil supply Waste supply Ambient heat Biomass supply Energy markets	CHP plants Boilers AC/DC converter Warm water tanks Heat pumps LNG plants Storage Power plant w/emission flows	Electric network District heating network Gas pipelines Discrete transport LNG ship	Electricity loads Heat loads Warm tapwater loads Gas loads Dwellings (aggregated load model) Energy markets Gas market
Mass source	**Industrial technologies**	**Mass transport**	**Mass sinks**
Industrial CO_2 source	CO_2 capture plant CO_2 liquefaction plant CO_2 storage CO_2 injection pump	CO_2 pipeline CO_2 ship	Industrial CO_2 load Industrial CO_2 market

The user can easily link the components together, and define various attributes for the components; like efficiency, max effect and emission coefficients of conversion components, energy commodity prices, effect requirements at loads etc. The operational model solution finds the cost-minimizing operation for the case defined by the user. The typical time-step in the operational model is 1 hour, for an investment analysis the planning period can be over 20 years, so these analyses are separated. Annual operating costs are calculated by repeatedly solving the operational model, with different segments (like peak, intermediate and low load seasons) and periods (e.g. 5 year intervals) pre-defined. Annual operating and environmental costs for different periods and energy system designs are sent to the investment model that finds the investment plan that minimizes the present value of all costs over the planning horizon.

There are two alternatives of including environmental impacts in eTransport at present. If emission coefficients are defined in the conversion components, the emissions of the substances are accounted and listed in the end result. This will not affect the optimization in any way. The other alternative is to define emission penalties in the conversion components, then this will be a part of the operational costs and affect the optimization. For both alternatives, only direct emissions generated in conversion of the fuel are regarded. It is a stated goal to implement life cycle analyses in the further development of eTransport [3].

A graphical user interface is implemented in MS Visio to increase the user value. It consists of three main parts; the *Component Library*, the main *Drawing Area* and the *Operation and Investment Analysis Window*. The various investment alternatives are ranked according to total cost at the bottom right. This is formatted as a directory tree as several components can be included in each investment alternative. There is a link between this tree structure and the Drawing Area, and clicking on one alternative or component will highlight the respective component(s) in the Drawing Area, making it easier to identify specific components in a large system. Both standard parameters embedded in the library components and case specific parameters entered by the user are stored in an MS Access database linked to the graphical user interface. When complete case data are inserted, the problem is exported to the COIN solver which performs the optimization. The results are returned to the database and displayed in the Result Window.

One option in eTransport is to export all the outputs from the analysis to Microsoft Excel. The various investment plans are listed and ranked by economical profitability. For each investment plan the investment and operational costs are given, as well as direct emissions of the substances CO_2, NO_x, SO_2 and CO. More detailed information for each investment plan is given in separate work sheets. For each supply component in the model,the usage, max usage and cost are listed. For each boiler the fuel consumption and the energy production, per time step, are listed.

The nomenclature for parameters, variables and sets used in eTransport is given in appendix 1.

3.2 Integration in eTransport

Figure 1 provides an overview of the overall system for energy delivery, including waste, gas, wood, briquettes, fuel oil, district heating and electricity. The upstream processes are shown for the energy commodities, except for electricity, which are just shown as Norwegian and NORDEL production mixes available at the national grid.

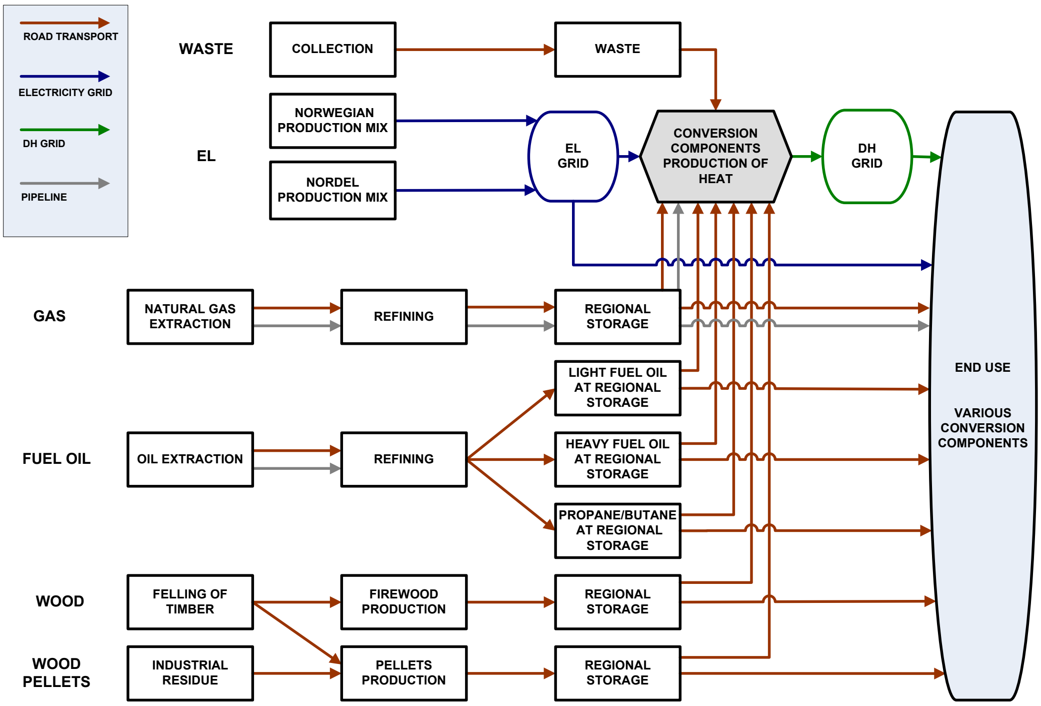


Figure 1: Coarse overview of energy systems

A lot of issues needs to be considered regarding implementation of LCA in eTransport; like how to perform calculations, how to implement results or methods of calculations, what data to base the calculations on, what modules to obtain results for (like for instance total life cycle of fuel versus results for each process in life cycle), user-friendliness, possibility to optimize regarding environmental impacts for investment alternatives and updating requirements and procedures of the software. These issues are addressed below, in chapter 4 and through calculations in chapter 5. The choice of methodology concerns both how LCA is implemented in eTransport (discussed in next section) and how the inventories (data on e.g. material and substance inputs and outputs for processes) are calculated (discussed in chapter 4.

3.2.1 Methods for implementation

There are principally three ways calculations of life cycle environmental impacts for investment alternatives can be implemented in eTransport; calculations performed prior to implementation (*prior*), calculations performed within eTransport (*within*) and calculation performed after optimization (*after*).

Prior
This would be done by calculating LCA results for relevant products and services independently of eTransport. Results from these would be implemented in the eTransport database and during optimization be linked to the appurtenant consumption for the various investment alternatives. This method does not require knowledge of LCA from the user of eTransport. Updating of the software would thus require LCA expertise. This method allows the LCA results for the investment alternatives made part of the optimization calculations.

Within
LCA databases or IO tables (described in section 4) can be implemented fully in eTransport, and the LCAs calculated within eTransport during optimization. The consumption of various materials would have to be linked to the relevant material in the database. In some cases, this would require a licence (for instance the ecoinvent database), which might represent an unacceptable extra costs for the users. This solution would also require more detailed inputs from the user, like amounts of various materials used for the investment alternatives. The level of detail required depends on what kind of data that is implemented. This method allows the LCA results for the investment alternatives made part of the optimization calculations.

After
Resulting outputs from the optimization could in turn be used for LCA calculations, for instance in an LCA software or in IOA calculations. Using this method one would not be able to make the LCA results part of the optimization calculations, and is therefore not regarded as a feasible solution.

3.2.2 Inventory calculations

Methods for calculation of inventories regarded here, are Input Output Analysis and Life Cycle Assessment. Methodology for these are presented in the chapter 4, rounded up by description on how these methods fits the implementation methods *prior* and *within*.

3.2.3 External costs

One possibility to implement calculations of environmental impacts in eTransport, is to add external costs to consumption of fuel, infrastructure and transport. This would be relatively easy to implement, as these costs would be added to the operational and investments cost for the investment alternatives. The environmental effects would then become an integrated part of the optimization. The problem with this method is data availability and validity on external costs for various commodities. Monetary values on environmental effects are hard to obtain objectively, and are also very vulnerable regarding validity over time. Both economical aspects and research regarding environmental aspects will affect the external costs.

4 LCA theory

Two methods for the making of environmental inventories of goods and services are presented in the following.

4.1 Life Cycle Assessment - LCA

Life Cycle Assessment is a methodological framework for estimating and assessing the environmental consequences attributable to the life cycle of a product. The performance of an LCA is explained in short below, based on the framework given in ISO 14041 (1998) [5] shown in figure 2.

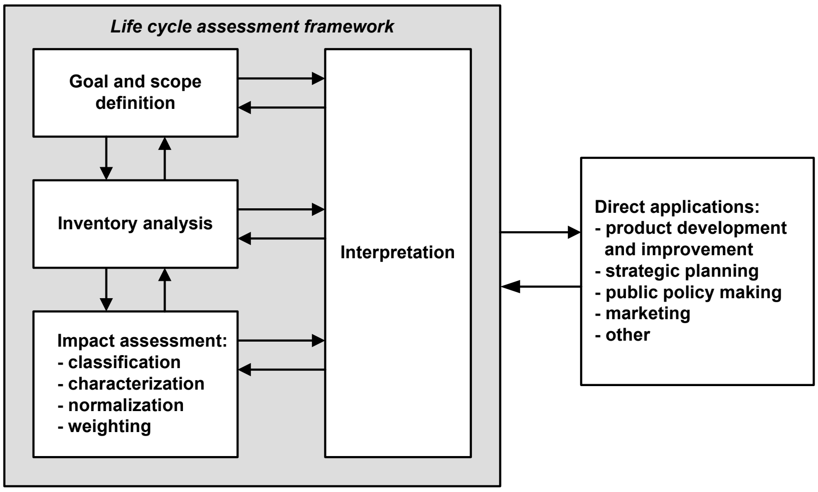


Figure 2: LCA framework

Goal and scope definition

In order to be able to make relevant methodological choices in the subsequent modeling, a specific purpose of the study should be formulated. Examples of purposes can be; revelation of the life cycle process that contributes the most to the products environmental impacts, possibilities for improvement in the products life cycle, environmental consequences of changing certain processes in the life cycle in various ways or comparison of environmental performance for different products.

Deciding the scope of the study implies making choices and assumptions regarding various aspects; choice of which options to model, choice of impact categories to include as well as choice of method for impact assessment (including choice of categorization and weighting factors, whether to perform weighting or not). System boundaries needs to be defined (e.g. what processes to include, what kind of emissions to consider etc). One also has to consider data quality requirements, related to the goal of the study. The *functional unit* for the system studied must be defined. The functional unit reflects the function the product is fulfilling; for instance for the heating of buildings the function of the various energy commodities is to deliver heat. A logical functional unit in this case would be heat delivered to building, expressed in joules or watt hours (one might also include time and size perspective, like the heating of one m^2 per year). Principles for allocation must also be considered. For instance if data for an entire production cite is obtained, the inputs and outputs has to be allocated to obtain data for the single process of interest, and how to do this must be clarified. [5]

Inventory analysis
A process flow chart displaying the different steps in the life cycle of a product is constructed, including the production of its most important components.
For each process unit (production cite, building, truck etc) taking part in the life cycle of the product and the production of its most important components, inputs and outputs are mapped, and *environmental stressors* (CO_2, PM_{10}, Hg, NH_3 etc.) related to these are accounted. These inventory data must be handled consistently, in order to be able to aggregate them further in the analysis. Obtained data often needs to be recalculated to be valid for for example one functional unit of the product [5]. Inputs can be raw materials, materials, components, chemicals and energy. Outputs can be products, residual products, energy, waste and emissions to water, soil and air. Sources of inventory data can be companies, suppliers and producers, environmental reports, company and/or public statistics, earlier LCA studies, LCA experts, public or computer program specific databases etc [32]. The system boundaries of the study determines what processes and stressors are included.

Impact assessment
The impact assessment is a method to convert the inventory data into more graspable environmentally relevant information, reflecting the impacts the emissions and resource uses has on the environment. Impact assessment can be performed in 4 steps; classification, characterization, normalization and weighting. These steps are presented in the following.

All the various environmental stressors throughout the life cycle are summarized, and then *classified* into impact categories, according to what environmental impact the stressors contribute to.

Characterization is a quantitative step, calculating environmental impact per category using *equivalency factors*. These factors are based on the physicochemical mechanisms of how different substances contribute to the different impact categories. Characterization methods in LCA are based on scientific methods, drawn from environmental chemistry, toxicology, ecology etc for describing environmental impacts. The effects of deposition in geographical areas with different sensitivities to pollutants is disregarded, meaning that impacts calculated represents the maximum impact; i.e. potential impacts are calculated. [5]

The characterization method *CML characterization scheme 2001* [16] is applied in this study, and contains the following impact categories;

Depletion of abiotic resources
This category is related to extraction of minerals and fossil fuels resulting from inputs in the system. The abiotic depletion factor is determined for extraction of various minerals and fossil fuels based on concentration reserves and rate of de-accumulation. Factors are expressed relative to antimony (Sb) equivalents/kg extraction. [16]

Global warming
The characterization factors are based on the characterization model developed by the Intergovernmental Panel on Climate Change (IPCC). Factors for various greenhouse gases (e.g. CH_4 and N_2O)are expressed as Global Warming Potential for a time horizon of 100 years (GWP100), relative to kg CO_2 equivalents/kg emission. [16]

Stratospheric ozone depletion
The characterization model is developed by the World Meteorological Organization (WMO) and defines ozone depletion potential of different gasses (e.g. CFCs, HCFCs and Halons). Factors are expressed as kg CFC-11 equivalents/kg emission. [16]

Toxicity
This category includes many types of impacts (e.g. neurological damage, carcinogenic and mutagenic effects) and many substances (e.g. organic solvents, heavy metals, pesticides). The toxicity category is therefore often (as the case for CML2001) divided into human toxicity and eco-toxicity. Eco-toxicity is further divided into freshwater aquatic, marine aquatic and terrestrial ecotoxicity [5]. Characterization factors are calculated with USES-LCA[1], describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance, factors are expressed as 1,4-dichlorobenzene equivalents/kg emission. [16]

---

[1] A characterization method witch employs a global fate model

Photochemical ozone creation

Ozone, together with other photo-oxidants, in the lower atmosphere are characteristic of photochemical smog. This causes health problems such as irritation to respiratory systems and damage to vegetation. The photo-oxidant creation potential of a substance is based on a 5-day trajectory model of pollutant transportation over Europe. Since ozone creation depends on background NO_x concentration, high- and low-NO_x POCPs are developed. For Scandinavia, low-NO_x POCPs are used. Factors are expressed relative to kg ethylene equivalents/kg emission. [5]

Acidification

Acidifying pollutants (SO_2, NO_x, HCL and NH_3) form acidifying H^+ ions. Potential for acidification is measured by the pollutants capacity to form H^+ ions, and the factors are expressed relative to SO_2 (H^+ ions formed per kg substance emitted, relative to SO_2). [5]

Eutrophication

Excessively high levels of certain nutrients leads to shifts in species composition and increased biological productivity, for example algal blooms. Which in turn leads to oxygen consumption and lower oxygen levels in the water, and thereby detrimental effects on aquatic ecosystems. Factors of eutrophication are expressed as kg PO_4^{3-} equivalents/kg emission. [5]

The next step in the impact assessment is the *normalization*. This implies that the characterization results are related to an actual (or predicted) magnitude for each impact category. This magnitude can be total impact for a whole country or region, or it can be on a per person level. For example can impacts in the GWP category resulting from the LCA of a product, be compared to total impact in GWP for the country where the product is used. The aim of the normalization is to gain a better understanding of the magnitude of the environmental impacts caused by the system under study [5].

The final step in the impact assessment is *weighting*, a qualitative or quantitative procedure where the relative importance of an environmental impact category is weighted against all the other. This is done in order to get one single indicator for the overall environmental performance of the product. Weighting can for example be based on political targets, critical impact limits or willingness to pay [32]. Weighting is not always performed in an LCA, as it implies subjective valuation of environmental issues up against each other, and therefore is a topic of controversy.

Interpretation

Interpretation is the process of assessing results in order to draw conclusions.

As shown in figure 2 the performance of an LCA is an iterative process, and the work on one part of the LCA will often lead to adjustments in other parts.

4.1.1 Ecoinvent database

The project ecoinvent 2000 was launched in 2000, where several Swiss Federal Offices and research institutes agreed to joint effort to harmonize and update Life Cycle Inventory (LCI) data for its use in LCA. The work built on several previous LCI database projects of the involved institutions [12]. The ecoinvent database [22] comprises LCI data covering different economic sectors and several LCIA methods (e.g. EDIP 1998, Ecoindicator 99, CML 2001, EPS 2000). With the ecoinvent database and its actual data v1.1, a consistent set of more than 2 500 product and service LCIs is available.

4.2 Input-Output Analysis - IOA

IOA is an economic method used to analyze the economic relations in an economy. National input-output tables lists industry sectors vertically and horizontally. Industry sectors are aggregations of similar industries, and the detail level varies for different countries. For instance does the Norwegian table contain about 50 sectors, while the table for USA contains about 2 500 sectors. If the horizontal numbers listed for one sector is summarized, one get the total output for that sector that year. The numbers vertically shows the input from other sectors to the sector on top.

Flow table example, 2 sectors

Sector	1	2	FD	Output
1	z_{11}	z_{12}	y_1	x_1
2	z_{21}	z_{22}	y_2	x_2
VA	v_1	v_2	0	v

z_{ii} = intra-industry flow from sector i to sector i
z_{ij} = inter-industry flow from sector i to sector j
y_i = the flow to final demand in sector i
x_i = the total flow (output) of sector i
VA = value added

The sum of the flows from one industry sector to the other sectors and the flow to final demand, equals the total output for that sector:

Sector	1		2		FD		Output
1	z_{11}	$+$	z_{12}	$+$	y_1	$=$	x_1
2	z_{21}	$+$	z_{22}	$+$	y_2	$=$	x_2
VA	v_1	$+$	v_2	$+$	0	$=$	v

In order to perform calculations with the system, it is preferable to have the flows on a per unit basis. This is achieved by normalization of the flows;

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{1}$$

For n sectors;

$x_1 = a_{11}x_1 + a_{12}x_2 + \cdots + a_{1i}x_i + \cdots + a_{1n}x_n + y_1$

$\cdot$

$\cdot$

$x_i = a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{ii}x_i + \cdots + a_{in}x_n + y_i$

$\cdot$

$\cdot$

$x_n = a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{ni}x_i + \cdots + a_{nn}x_n + y_n$

In matrices:

$$x = \begin{pmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ x_n \end{pmatrix} \qquad A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdot & & & \\ \cdot & & & \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \qquad y = \begin{pmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ y_n \end{pmatrix}$$

The equations for n sectors in matrix form;

$$x = Ax + y \tag{2}$$

Normally, the A matrix and the y vector are known. To calculate the output, x, equation 2 can be rearranged into;

$$x = (I - A)^{-1} \cdot y \tag{3}$$

Where I is the identity matrix of the same size as A. The matrix $(I - A)^{-1}$ is called the Leontief inverse[1], L. The vertical column *i* in L gives the outputs in all sectors *per unit demand* for sector *i*. The output, x, gives all outputs from each industry sector required to meet the demand y. This implies that if one unit demand from sector *i* is set on the system, required output in sector *i* is found as well as the outputs from all the other sectors needed as inputs in sector *i* for the production and so on. For example, production of a car requires inputs from various sectors, like energy, rubber, steel and other materials as well as services from other sectors (e.g. cleaning). Each of these sectors will in turn require inputs from other sectors to produce their outputs and so on.

Total emissions, e, from all the sectors due to a demand y, can be found by using an emission coefficient matrix. This is a matrix of normalized emissions of

---

[1] After the inventor of input-output analysis, Wassily Leontief

various stressors per industry sector, where element F_{ij} is total yearly emission of stressor i in sector j, divided by total yearly output in sector j.

$$e = F \cdot x = F \cdot (I - A)^{-1} \cdot y \tag{4}$$

The vector e contains total emissions of each stressor (element e_k is total emissions of stressor k), due to the demand y set on the economy. In this manner, emissions from all industries affected by the demand are accounted for.

As described for LCA, the stressors can further be characterized and weighted. Mathematically the characterization is done by multiplying the vector of stressors, e, by a characterization matrix C. The element C_{mn} in matrix C is the Characterization factor for impact category m and stressor n:

$$d = C \cdot e \tag{5}$$

Weighting is done by multiplying the vector of impacts, d, by a vector of weighting factors, w (where element w_o is the weighting factor for impact category o:

$$v = w \cdot d \tag{6}$$

v is an aggregate measure (one single number) of the overall environmental performance.

The fundamental assumption of IOA are:
Fixed relationship between input/output
Constant returns to scale (no economies of scale)
No substitutions between inputs

4.3 Methodology suitability for eTransport

4.3.1 LCA

LCA calculations for all commodities relevant to eTransport could be calculated *prior* to implementation, independently of eTransport. These would be linked to the relevant consumption in eTransport simultaneous to the optimization. The system borders of these LCAs would determine the detail level of the data inputs from the energy planner. For example the transport of an energy commodity from the production cite to the end use. If generic data for this is included in the LCA for the energy commodity, input for this transport is not needed, but if this transport was not included, the user would be required to insert data on magnitude of this transport and this would be calculated separately. This alternative requires attention to what commodities (product and services) it is needed LCA results for, how these are computed (system borders, generic or specific data) and how the results are scaled (functional unit; what amount of consumption the results are calculated for). The results has to be logically scaled according to calculations and inputs in eTransport.

LCA inventory data consists of physical amounts of materials and substances. This makes these data quite valid over time. Changes in data would be due to changes in design and technology (like cleaner production and less material intensive production). Improvements on characterization methods due to new research would also affect the validity of the LCA results.

LCA can be calculated fully *within* eTransport, by for instance implementing the ecoinvent database in the software. Consumption of fuels, materials and transport would be linked to the relevant process in the ecoinvent matrix and in turn with the characterization matrix. In this way, the LCAs would be performed during the optimization procedure.This would require great care to connect each consumption to the correct process, and it would also require quite detailed inputs from the eTransport user. For instance on amounts of various materials used in the building of infrastructure. Implementing the ecoinvent database would also require a licence for each user of eTransport.

4.3.2 IOA

Environmental impact results calculated using IOA *prior* to implementation would technically be implemented in the same way as results obtained using LCA. Advantages by using IOA is that all upstream processes would be included, so it would be easier to be consistent regarding system borders for all the commodities.

As IOA inventory data are comprised of monetary values, they are less valid over time than LCA data. Changes in data would be due to changes in economic interrelations between the sectors in addition to the factors affecting changes for LCA data.

For IOA calculations *within* eTransport, one option could be to include the Norwegian input-output table, containing all sectors and their associated environmental impacts. Use of energy commodities, infrastructure and conversion components calculated in eTransport should place a demand for the relevant process in the matrix. The advantage of such an approach would be that the purchase of specific commodities from the economy would form the basis of the calculations. In this way, one could operate with costs only.

However, the Norwegian IO table is very coarse, it consists of only 50 sectors. Further, not all products and materials relevant for the investment plans are produced in Norway, and hence their production is not reflected in the Norwegian IO table. One solution could be to apply an EEA (European economic area) table. This would probably cover up for all the products, and most likely be less aggregated than the Norwegian table. It would, however, be necessary to look into how well this would apply to Norwegian conditions. It might be a good alternative to obtain a specifically hybrid table, covering both Norwegian conditions and all relevant commodities.

4.3.3 Choice of methodology

Regarding data availability, data validity over time and user-friendliness, it is found most feasible to apply the method of results calculated using LCA prior to implementation into eTransport. This is the method that would be the most valid over time. At present, eTransport is not completed and updating procedures are not determined. As it is, there is not much need for updating as the data that are integrated in the software are of a durable character, like for instance efficiencies, loss factors and electricity line capacities [2].

The chosen method does not require any knowledge of LCA from the user, or even of the advantages of using LCA. The user would not have to make decisions on which data that are required and why, but just get the environmental impacts as an output as optimization is performed. This is regarded as a great advantage for now, as LCA is not widely used or known amongst energy companies and regional authorities. The method does not require much modification of eTransport as it is, as the impact results for the most can be linked to consumption already calculated within eTransport during optimization.

5 Data for implementation

In order to obtain LCA results for implementation in eTransport, course LCA's are performed on relevant energy commodities, infrastructure and transport services. These LCA's are mainly performed using the LCA software tool SimaPro [7], based on processes already assessed and defined in the ecoinvent database. Some modifications on the processes has been done, and some new processes are established. Due to the time scope on this project and the amount of LCA's needed, the LCA's are quite course, and a lot of simplifications and assumptions are made. Each LCA and the appurtenant assumptions and simplifications are described in the following paragraphs.

For gas, wood, pellets and fuel oils, life cycle environmental impacts are calculated from "cradle to gate", that is from the extraction of raw materials to conversion at end user. Environmental impacts are calculated per MWh (fuel input to conversion components), in accordance to the calculations of consumption done in eTransport optimization. Impacts related to production and construction of electricity grids, DH grids and natural gas pipelines are calculated per length unit and year, based on earlier studies and ecoinvent. Environmental impacts related to the use phase of these are mainly due to losses and the the excessive need for energy to cover up for this. Losses and excessive need for energy are taken into account in eTransport. The boilers used for DH production, are assumed to be of various types already defined in ecoinvent, and the use of these are included in the environmental impacts related to the use of the various fuels.

SimaPro
The LCA software tool SimaPro is developed by PRè Consultants[1], a Dutch enterprize with partners worldwide. SimaPro is a tool for modeling and analyzing complex life cycles in a systematic and transparent way, following the ISO 14040 series[2]. It has several LCI databases and LCIA methods integrated (including the full ecoinvent databases).

---

[1] Product ecology Consultants

[2] Series of standards for Life Cycle Assessment

5.1 Energy commodities

In eTransport, fuel consumption in boilers are calculated and expressed in MWh, therefore the LCAs for the energy commodities have 1 MWh as functional unit, according to fuel use in conversion components. Process chains, data used and assumptions are described for each commodity and illustrated by a figure of the process chain (for most of the commodities). Heating values and densities used in calculations are taken from the Norwegian Emission Inventory 2006 [21].

The results for all the energy commodities are compared for each impact category, relative to the commodity with the highest score in the respective category. This is shown in figure 7, paragraph 5.2.

5.1.1 Fuel oil

Environmental impact from fuel oils are calculated based on processes in ecoinvent. The main processes has been modified to be more representative for Norwegian conditions. Changes made, are that the crude oil is produced in Norway only instead of a European mix, the electricity input in various processes are set to be *NORDEL electricity mix* (the choice of electricity mix is explained in section 5.1.7). However, inputs like diesel use for transport of fuel oil, is not adjusted to be produced in Norway, as this is assumed to contribute marginally to the overall impacts for the use of fuel oils. For all oil products, transport service by lorry (tkm) per kg product, is changed to 0.072 tkm (from 0.0337 tkm given for the European data). This is calculated from SSBs lorry survey from 2006 [8], where total transported amount of coal, coke, oil- and chemical products are given as 21.7 million tons, and total transport service 1562.2 million ton km, which gives an average transport service of 0.072 tkm per kg. The transport service is adjusted due to geographical differences between Norway and a European mean. Infrastructure components, like refinery and boilers are not adjusted in any way, European averages are used.

The changes are made consistently throughout the relevant production chains for all relevant oil products, like refinery gas and naphta inputs to the "*..., at refinery*" processes.

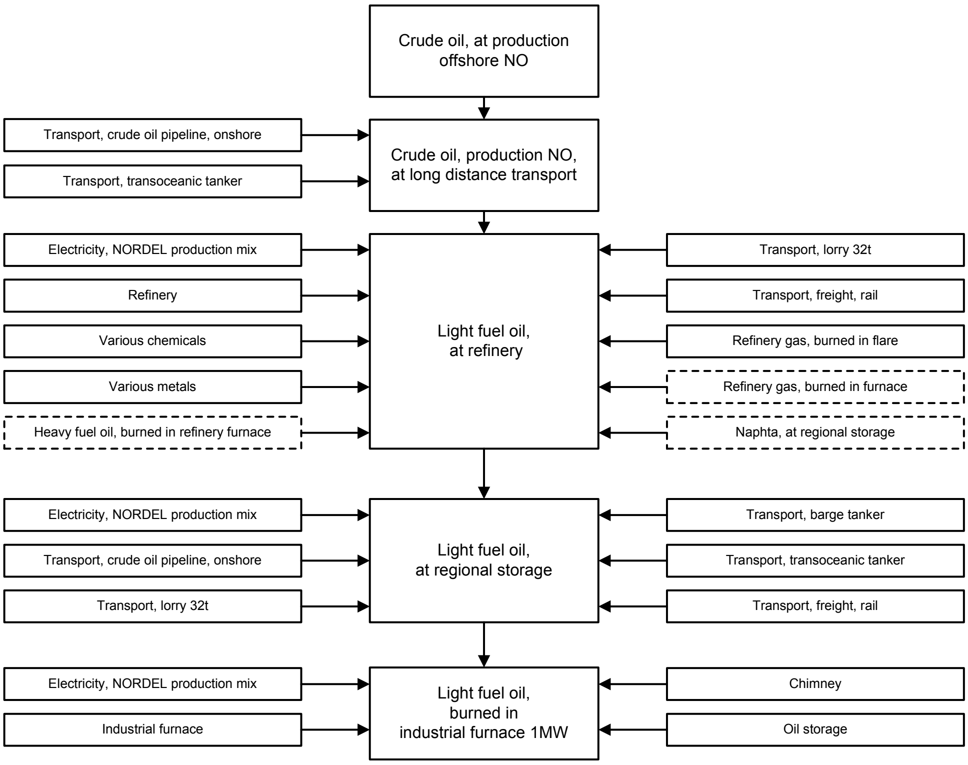


Figure 3: Process chain for light fuel oil

Figure 3 shows the process chain for *light fuel oil, burned in industrial furnace* as an illustrative example for fuel oils. This process is appropriate for combustion of light fuel oil in for instance DH production. The boxes represents various processes, already defined in ecoinvent. Each process has assigned inputs and outputs from nature (raw materials, emissions) and technosphere (use of other processes/materials, waste treatment). The main processes for light fuel oil are shown by the large boxes in the middle. Boxes with dotted lines indicates processes that has been modified. For example for the process *Naphta, at regional storage*, various input processes has been replaced by similar processes, more relevant for Norwegian conditions (like crude oil produced in Norway and NORDEL El-mix). Inputs for *crude oil production, offshore* are not included in the figure.

Two types of fuel oils has been assessed; light fuel oil and heavy fuel oil. For light fuel oil, two alternative uses has been assessed; private and industrial consumption. These are assessed with respectively large furnace (1 MW) and small boiler (10 kW). Industrial end use are supposed to be applied when larger furnaces are used, and private end used for small boilers in private houses. This is because of different combustion technology for different sized boilers; larger furnaces results in slightly higher impacts due to material use and production of the boiler, but the combustion in a larger boiler leads to less emission per unit heat produced. Heavy fuel oil is not used in the private sector [13], so this is not assessed. The three calculated impact vectors are listed in table 4.

Table 2: Impact vectors for fuel oils

	Light fuel oil Private	**Light fuel oil Industry**	**Heavy fuel oil Industry**
Name of vector	LFOpriv	LFOind	HFOind
Unit	Per MWh	Per MWh	Per MWh
ADP	1.89E+00	1.88E+00	1.97E+00
GWP	2.95E+02	2.93E+02	3.05E+02
ODP	1.05E -06	9.45E -07	9.57E -07
HTP	3.59E+01	3.79E+01	2.10E+02
FAETP	2.56E+00	1.36E+00	1.86E+01
MAETP	3.14E+04	3.16E+04	1.75E+05
TETP	3.01E -01	2.15E -01	6.73E+00
POCP	2.64E -02	2.64E -02	8.71E -02
AP	4.31E -01	4.57E -01	2.05E+00
EP	2.67E -02	3.55E -02	5.84E -02

For most of the categories, the differences in combustion technologies between private and industrial sector does not result in very big differences in the overall impacts. The impacts are slightly lower for industrial end use. The exceptions are the categories HTP, AP and EP, where the impacts for industrial end use are higher than for the private end use. This is most likely due to differences in material use in production of the boiler and furnace. And as expected, impacts for heavy fuel oil are higher in all categories, mostly due to higher emissions in combustion.

5.1.2 Gas

In Norway, not much natural gas is used for heating purposes at present, and only a few pipeline networks are constructed (in Stavanger and in the Karmøy-Haugesund region). 1670 GWh of natural gas was consumed in 2005 (excluded the consumption at the methanol plant and the other natural gas works at Tjeldbergodden and the natural gas power plant at Kårstø) [1]. Natural gas can also be distributed as bulk in tanks or in liquified (LNG) or compressed (CNG) phase by ship or lorry. Natural gas distributed both by pipeline and by lorry (liquefied form) are assessed here, for industrial and private end use. The two alternative end uses differs in the the same manner as for light fuel oil.

Natural gas distributed by pipelines
There are already defined process chains for natural gas distributed to end users by pipelines for several countries, for instance Sweden. This is assumed

to be applicable to Norwegian conditions. The only modification made is the electricity input that is changed from Swedish to Norwegian. The natural gas input was already defined as produced in Norway.

Liquefied natural gas distributed by lorries
Process chains for natural gas distributed by lorries in liquefied phase are not ready defined, so this is made. Figure 4 shows the process chain for natural gas to industrial sector end use, as it is assembled in ecoinvent. This process is relevant for use of natural gas in heating of large buildings (i.e large boilers used) or in the production of district heating.

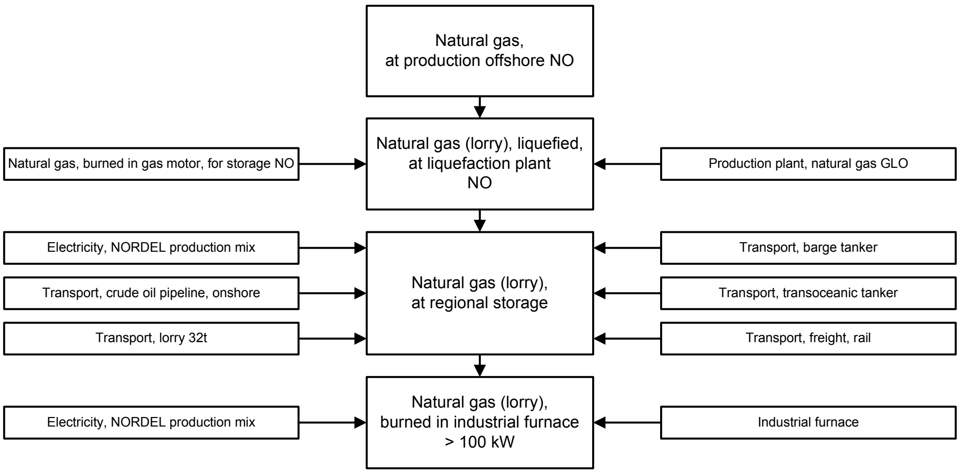


Figure 4: Process chain for natural gas

The process *Natural gas (lorry), liquefied, at liquefaction plant NO* is made on the basis of the process *Natural gas, liquefied, at liquefaction plant DZ* that is made from data from an Algerian plant. It is slightly modified by changing the inputs of natural gas to be of Norwegian origin. The next process *natural gas (lorry), at regional storage* is in fact copied from the similar process for light fuel oil, assuming that the distribution pattern of natural gas is similar to that of light fuel oil. This can be justified by the fact that oil and gas to a great extent is extracted, produced and refined at the same locations. Distance to the users of the oil and gas products will also be quite similar. This process includes, in addition to transport of the product from the refinery to end user, operation of storage tanks and petrol stations, emissions from evaporation and treatment of effluents, as shown in figure 4. These latter issues will probably differ for LNG, as the storage of LNG requires an approximate temperature of -160° Celsius, to keep it liquid. It is, however, assumed to be a good enough approximation for the purpose of this project.

In table 3 the resulting impact vectors for natural gas for both distribution alternatives and both end uses are listed.

Table 3: Impact vectors for gases

	Natural gas Private	**Natural gas Industry**	**Natural gas Private**	**Natural gas Industry**
Distribution	Lorry	Lorry	Pipe	Pipe
Name of vector	GASpriv lorry	GASind lorry	GASpriv pipe	GASIND pipe
Unit	Per MWh	Per MWh	Per MWh	Per MWh
ADP	2.18E+00	2.05E+00	1.78E+00	1.77E+00
GWP	2.26E+02	2.12E+02	2.20E+02	2.18E+02
ODP	9.26E -07	7.97E -07	1.68E -05	1.67E -05
HTP	4.98E+01	4.34E+01	4.39E+01	4.03E+01
FAETP	1.30E+00	5.80E -01	1.17E+00	5.25E -01
MAETP	2.88E+04	2.60E+04	2.32E+04	2.20E+04
TETP	1.24E -01	7.36E -02	1.07E -01	6.35E -02
POCP	9.19E -03	6.56E -03	9.95E -03	7.84E -03
AP	8.45E -02	7.85E -02	7.05E -02	6.94E -02
EP	1.60E -02	1.58E -02	1.51E -02	1.58E -02

These results indicates that natural gas distribution by pipeline networks gives less environmental impacts than distribution by lorry. This is, however based on pipelines with annual natural gas transport of 30 TJ, and length of pipelines are based on German statistics. The relative impact of the pipeline network to the overall impact for the whole life cycle of heat from natural gas, distributed by pipeline, will vary according to annual natural gas transport, lifetime and length of the network. For instance could a pipeline network with relatively low annual transport of natural gas result in higher environmental impacts for the heat from natural gas process with pipeline distribution than for the one with lorry distribution.

The differences between industrial end use and private end use for the two alternatives are due to same reasons as for heat oils.

5.1.3 Liquefied Petroleum Gas

There is no pre-defined process for combustion of propane in ecoinvent. There is, however, a process called *Propane/butane at refinery*. This is used as a basis to develop a process chain for propane, where the final stage is production of heat in an industrial furnace or private boiler. The industrial end use process, shown in figure 5, would be appropriate for DH production (where the most propane is used [13]). The dotted boxes indicates that the certain process has been modified.

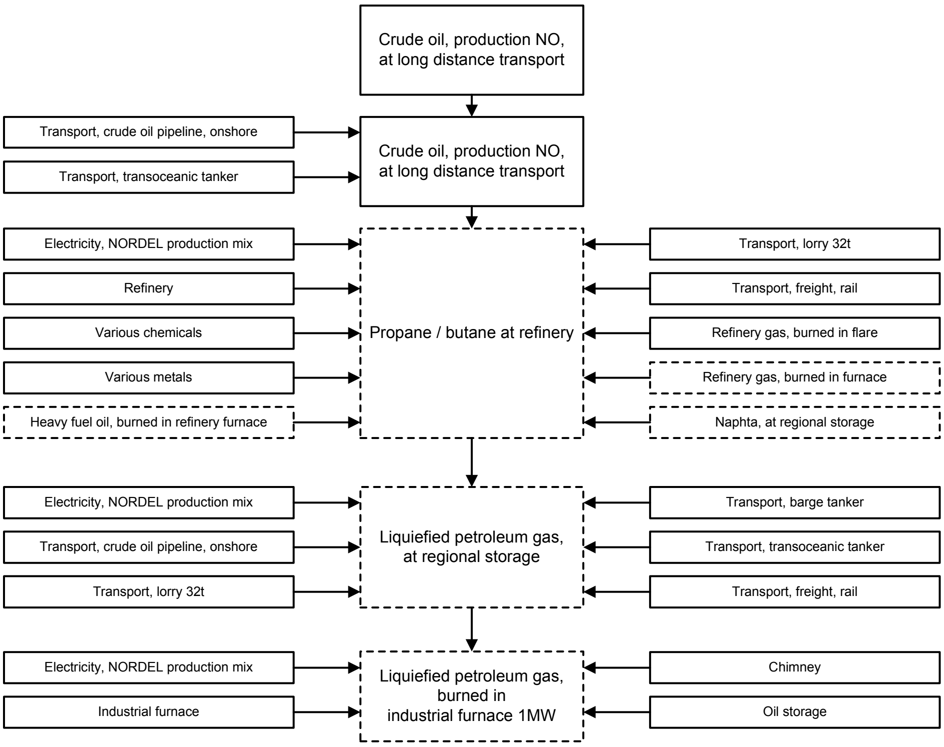


Figure 5: Process chain for propane

It is assumed that propane undergoes a similar distribution system as light fuel oil, so the process *Liquefied petroleum gas, at regional storage* is the same as the process *Light fuel oil, at regional storage* (The same process for heavy fuel oil is also identical). The process *Liquefied petroleum gas, burned in industrial furnace* is given the same inputs as light/heavy fuel oil; industrial furnace, chimney, electricity and oil storage tank at the same amounts. The direct emissions used is taken from *Norwegian Emission Inventory* [21] and EPA [35]. (It can be mentioned that in SimaPro it is already assumed the same furnace for heating oil and natural gas). Further, it is assumed an energy content of 46.1 GJ/tonne for propane, and an efficiency on the boiler of 95 %.

Table 4: Impact vectors for liquefied petroleum gas

	LPG Private	**LPG Industry**
Name of vector	LPGpriv	LPGind
Unit	Per MWh	Per MWh
ADP	1.78E+00	1.77E+00
GWP	2.68E+02	2.67E+02
ODP	1.01E -06	9.65E -07
HTP	1.37E+02	1.34E+02
FAETP	1.38E+00	7.80E -01
MAETP	2.83E+04	2.75E+04
TETP	6.61E -01	6.47E -01
POCP	1.83E -02	1.85E -02
AP	3.39E -01	3.76E -01
EP	4.40E -02	5.44E -02

The differences between industrial end use and private end use for the two alternatives are due to same reasons as for heat oils and natural gas.

5.1.4 Wood

Two impact vectors for wood firing in private housings are obtained. One is based on a process in ecoinvent with no modifications and the other is based on an LCA of wood based heating in Norway, performed in 2007 [31].

Ecoinvent process
The process *Heat, mixed logs, at heater 6 kW* in ecoinvent is used to obtain LCA results. It is assumed a net efficiency of 75 % for one year operation (average of technology available on market) and the emission factors for the combustion from measurements were adjusted based on operation experiences of installed boilers. The firewood consists of 72 % softwood and 28 % hardwood. The inventory is valid for boilers with capacity up to 20 kW. The process includes infrastructure (wood furnace and chimney, whole life cycles), wood (whole life cycle) requirement, emissions to air, transport of the wood and disposal of the ashes.

LCA of Wood Based Heating in Norway
In this paper 4 cases are analyzed; new[1]and old stoves, both with local and long traveled wood. Efficiencies are assumed 70 % for new stoves and 50 % for old stoves, and birch (hardwood) used for firewood. The LCA includes stove (whole life cycle), wood (whole life cycle) requirement, emissions to air and transport of the wood. These results are used to obtain a mean average impact vector for wood heating for Norway. The emission factors for combustion of the wood are taken from an SSB report on emissions to air from wood firing

in Norway [18].

Statistics from SSB concerning Norwegian firing habits [15], estimates the following distribution of fireplaces used in Norway;
Open fireplace: 4 %
Closed fireplace, old technology: 78 %
Closed fireplace, new technology: 18 %
Based on this it is assumed 81 % old fireplaces and 19 % new fireplaces. Further it is assumed 80 % local and 20 % long traveled wood. The resulting impact vector is given in table 5.

5.1.5 Pellets

For pellets already defined processes are used, the only modifications done is that electricity used in the production chain is changed to be of NORDEL production mix. Pellets has also been assessed for both industrial and private end use. The industrial furnace applied is valid for efficiencies between
30 - 100 kWh, and the private boiler assessed are valid for efficiencies between 10 - 30 kWh.

5.1.6 Waste

For waste incineration, a new process has been developed using SimaPro in order to obtain an impact vector; *Heat, from waste incineration.* It is already a defined process for waste incineration in ecoinvent, but as data for the plant in Trondheim (HVS) is available, these are used. Some information is taken from the pre-defined incineration process, like use of slag compartment, residual material landfill facility and process-specific burdens. Data for direct emissions are taken from Bergsdal [6], which in turn are based on a report from *Trondheim Energi* [10]. These numbers are assumably relevant for other incineration plants in Norway as well. Use of the waste incineration plant is included (defined process in ecoinvent), as well as process-specific burdens which covers the operation of the plant independent on the composition of the waste incinerated. A slag compartment and the operation of this is also included. This is a defined process in SimaPro, assessing a slag compartment for treatment of bottom ash from municipal solid waste incineration. It is described as a sealed-off part of a sanitary landfill, with a use phase of 30 years, and an aftercare phase (recultivation and monitoring) of 75 years. It is informed to be well applicable to modern landfilling practices in Europe. However, it is not checked how good this process fits the treatment plant at Langøya, where most of the slag from municipal incineration in Norway is treated. The heating value for the waste is assumed to be 10.84 MJ/kg [14].

---

[1] clean-burning stoves, produced in 1998 and later

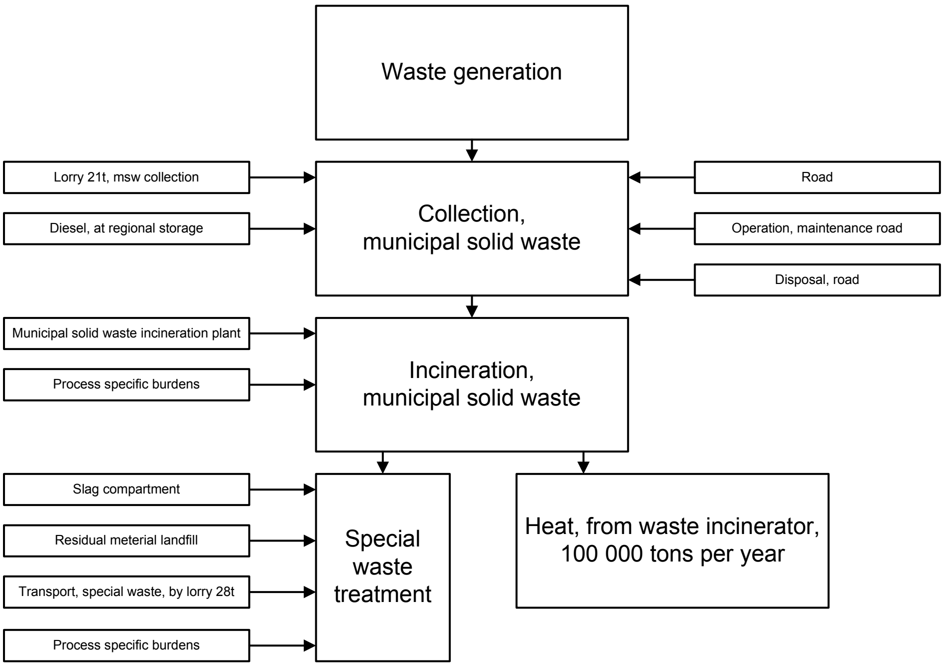


Figure 6: Process chain for heat, from waste incineration

The municipal waste incinerator are assumed to have a lifetime of 40 years and 100 000 ton per year capacity.

The transport related to collection of waste is not included in the process described above. Neither is transport of residues from the combustion of the waste. This is because the transport distances and waste amounts, and therefore also the amount of transport service needed, will vary locally. These transport services are computed in separate processes, one for local collection, one for long distance transport of the waste and one for transport of special waste. These are described further in paragraph 5.4.

Avoided treatment of waste

Incineration of waste does in many cases replace landfilling of the waste, and in some cases recycling of materials. Most of the incinerated waste in Norway is done with energy recovery. The avoided treatment could be included in the LCA of heat production from waste. Like for instance for the case where incineration replaces landfilling, the overall greenhouse gas emissions would in fact be negative. This is because the methane leakage by landfilling of the waste contributes more to the greenhouse effect, than if the same amount of waste is incinerated. This is because methane is a 21 times as strong greenhouse gas than carbon dioxide, that is formed when the waste is incinerated.

Table 5: Impact vectors for biofuels

	Wood Private [31]	**Wood Private ecoinvent**	**Pellets Private**	**Pellets Industry**	**Waste**
Name of vector	Wood priv	Wood priv	Pellets priv	Pellets ind	Wasteinc
Unit	Per MWh	Per MWh	Per MWh	Per MWh	Per MWh
ADP	-	7.08E -02	1.79E -01	1.66E -01	3.04E -02
GWP	1.27E+02	3.14E+01	3.08E+01	2.82E+01	4.78E+01
ODP	-	1.00E -06	2.64E -06	2.52E -06	5.09E -07
HTP	8.09E+03	4.95E+01	4.66E+01	4.37E+01	1.35E+01
FAETP	-	3.48E+00	3.20E+00	2.25E+00	1.56E+00
MAETP	-	6.75E+03	1.06E+04	9.43E+03	8.45E+03
TETP	-	2.51E -01	4.13E -01	3.88E -01	1.05E+00
POCP	5.15E+00	2.31E -01	1.80E -02	1.43E -02	4.79E -02
AP	4.79E -01	3.66E -01	2.71E -01	2.71E -01	1.02E+00
EP	1.17E -01	1.23E -01	7.21E -02	7.26E -02	1.13E -01

Of the bio fuels, waste seems as the most environmentally sound alternative. One reason for this, is that the transport services are omitted in the waste life cycle. Another reason is that waste incineration has been subject to strict regulations regarding emissions to air [25]. In addition, the process chain differs from the other biofuels, in that it does not include any use of raw materials or production. For pellets, private end use results in higher impacts in all categories. Wood and pellets are fairly even for most categories, except for POCP and EP, where wood have quite high results (compared to all energy commodities, see figure 7).

5.1.7 Electricity

The energy commodity electricity differs from the others in that its produced from other energy sources and commodities. Most electricity in Norway is produced from hydropower (99 %). The rest is from wind and thermal power (waste, waste heat, oil, gas and coal) [28]. Norway has since 1996 been a member of a common scandinavian electricity market, including all nordic countries from 2000. NORDEL is an association for electricity co-operation in the Nordic countries, with the "mission to promote the establishment of a seamless Nordic electricity market as an integrated part of the North-West European electricity market and to maintain a high level of security in the Nordic power system" [29]. Based on this, the electricity use in Norway should be of a NORDEL production mix, as it is a joint market. However, as choice of electricity production mix is an issue of controversy, an impact vector for electricity based on a Norwegian production mix is also obtained. This renders comparison and assessments on how different choices about this can affect environmental performance for different investment alternatives.

Processes for electricity in all three voltage levels are defined for numerous countries in ecoinvent, including Norway. The process *Electricity, low voltage, at grid/ NO* is used to assess environmental impacts for electricity produced in Norway plus the import (based on the situation in 2000). The process *Electricity, low voltage, production NORDEL, at grid* is used to assess the environmental impacts related to NORDEL production mix. This process is based on production statistics for each member country (except Iceland) in 2000. The mix in 2000 was approximately; 61.1 % hydropower, 19.4 % nuclear power, 17.9 other thermal power and 1.6 % other renewable power. These numbers are taken from annual statistics from NORDEL [27], in ecoinvent more detailed statistics for each country are used (Norwegian production mix used is given in table 15 in the appendix).

Results for both electricity mixes delivered end users are given in table 6

Table 6: Impact vectors for electricity mixes

	Electricity NORDEL mix	**Electricity Norwegian mix**
Name of vector	El nordel	El no
Unit	Per MWh	Per MWh
ADP	1.02E+00	9.38E -02
GWP	1.53E+02	1.82E+01
ODP	8.94E -06	7.75E -07
HTP	1.07E+02	7.93E+01
FAETP	7.43E+00	4.56E+00
MAETP	9.84E+04	1.05E+04
TETP	9.26E+00	9.08E+00
POCP	2.57E -02	6.58E -03
AP	5.83E -01	1.44E -01
EP	4.89E -02	9.51E -03

5.2 Results energy commodities

For comparison of the energy commodities, figure 7 shows the impacts for each energy commodity in each impact category, relative to the commodity with the highest score per category. For wood firing the results from the ecoinvent process are applied.

From the bar charts some general results can be seen:
Heavy fuel oil stands out with high impact in all categories, NORDEL electricity mix has high impact in most categories, and light fuel oil, natural gas, LPG and wood have high impact in some categories. Waste incineration, pellets and Norwegian electricity mix has, in general, the lowest impact results.

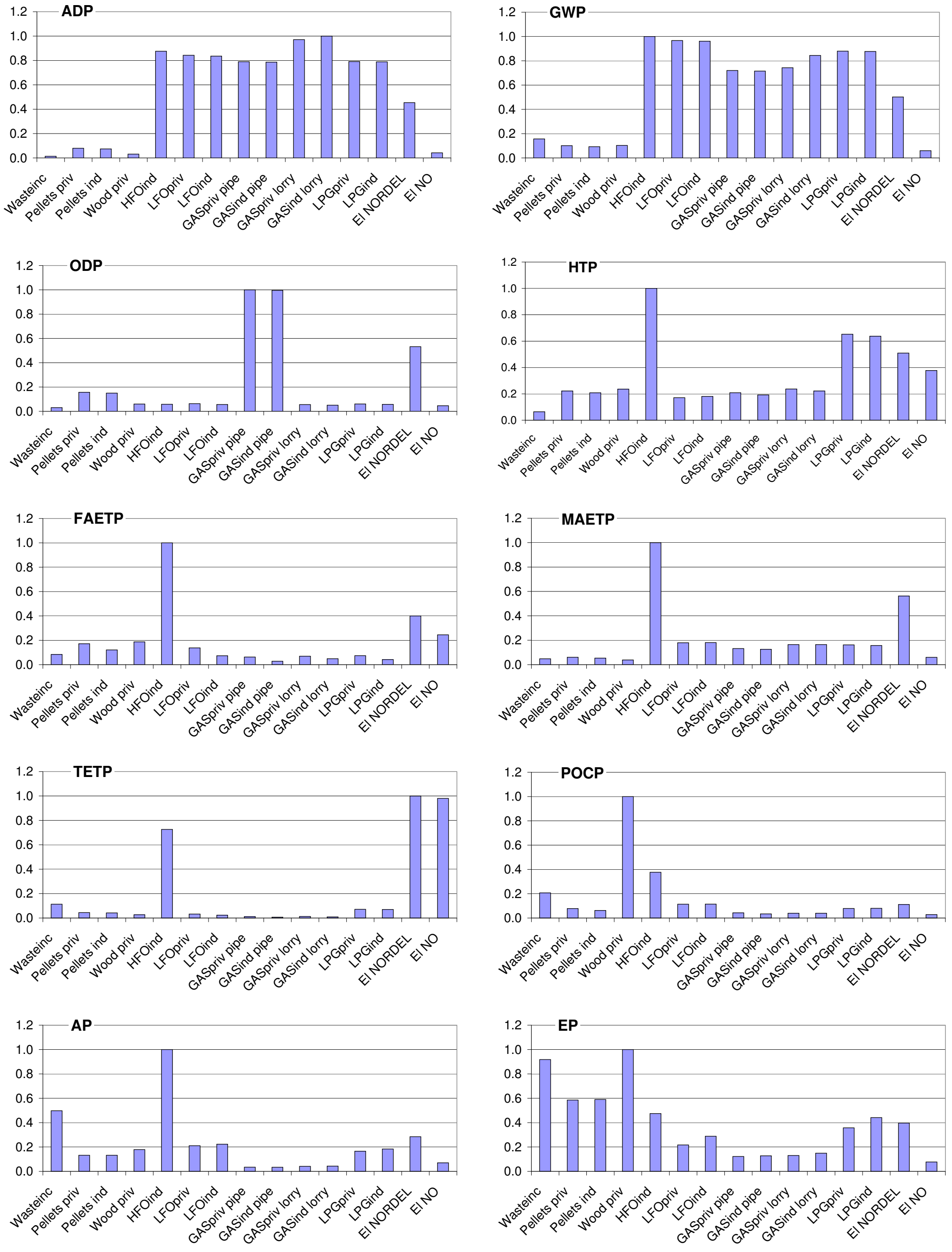


Figure 7: Relative impacts for each energy commodity and impact category

5.3 Infrastructure

Environmental impacts due to building of new infrastructure and conversion components should be distributed throughout the component's lifetime and use. Use of conversion components and most infrastructure and transport is already covered in LCAs for various fuels. It might seem feasible to assess impacts for building new components for the various investment alternatives, but one could not treat this as one single impact that occurs the moment the component is being built. This would give a peak in impacts, and give unfairly high impact for some investment alternative, if the investment period is shorter than the lifetime of the component. This makes it more adequate to assign use of conversion components, like boilers and furnaces, as a part of the fuel use. And as a conversion component generally contributes a low share of the total Life Cycle environmental impacts, generic data for this is assumed to be sufficient.

When it comes to DH grid, the use of this can not be implemented in the use of the energy commodities for the heat production, as the mix of energy commodities used will vary both in time and between systems. The design of the grids will also vary. This fact makes it necessary to assess the DH grid separately, both the existing grid and for potential expansion of grid.

The LCAs of electricity to end user includes electricity losses and wearing of infrastructure; both underground and overhead lines as well as voltage switching stations. This means that consumption includes wearing of a relative share of the total grid, so the electricity grid shall not be assessed in addition to the electricity consumption. This would in fact also be impracticable, as it would be an impossible task to determine how much and what kind of grid to assign to a certain amount of electricity used. However, it is found appropriate to assess the building of new electricity infrastructure, as long as this new infrastructure is needed for an investment alternative.

In eTransport, yearly consumption will be calculated for defined segments (like peak, medium and low load), This yearly consumption will in turn be valid for each year in one period, which can consist of 5 years. This calculation procedure makes it coherent to distribute the environmental impacts from infrastructure components during their lifetime to each year of their lifetime. The LCAs for the infrastructure components will thus have a functional unit of length and year. The length units of the infrastructure components will be the same as used in eTransport when modeling investment alternatives including the relevant infrastructure.

5.3.1 DH pipes

A Swedish study on DH pipes is used as basis for calculation of impact matrices for DH pipes. The Swedish study consists of three parts; one for the production of pipes, one for the laying of pipes and one for the use phase of the pipes (heat delivery). These three parts constitutes an article series published in The International Journal of Life Cycle Assessment. The results presented in these articles are given for 4 different pipe dimensions in 4 impact categories (ADP, GWP, POCP and AP). The parts concerning production and laying are presented in FOU reports, and contains detailed information on inventory, assumptions and system borders of the study. The complete inventory of used and emitted substances and materials is given as appendixes. The LCA results given in the articles are found insufficient, as there is only 4 categories included. Therefore, the inventory for the pipe producing factory given in the FOU report *Miljöbelastning från produktion av fjärrvärmerör* [17], is used as a basis for the construction of a new process using SimaPro. The inventory for the pipe producing factory contains various inputs of materials, excessive materials, energy use, auxiliary chemicals and emissions and waste from the facility. The full inventory is listed in table 8 in the appendix. These inputs and outputs are covered by already defined processes in ecoinvent, as far as possible. Some of the information is too limited, for instance is some of the waste only given as "other industrial waste". It is chosen to leave this outside the LCA, as it is impossible to assume what this consists of and what kind of waste treatment it goes to. For the same reasons, it is uncertain how large error the omittance of this represents.

Figure 8 shows the processes in production and laying[1] of District Heating pipes, and the materials and processes needed in each of these processes.

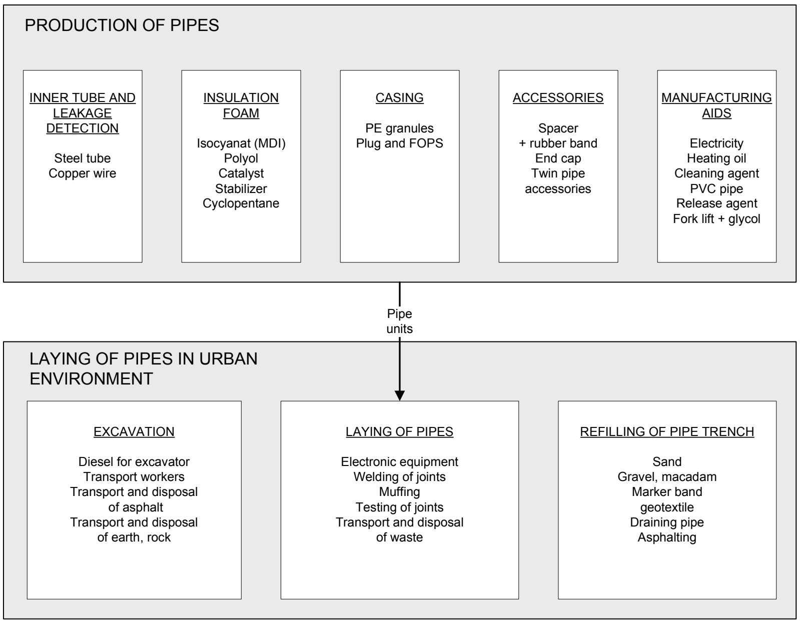


Figure 8: Production and laying of District Heating pipes

The environmental impacts generated in the use phase of the DH pipes, are due to heat losses. This instigates an excessive need for energy commodities to cover heat requirement for end user.

The pipes are produced according to European standards, and have a lifetime of 30 years. Environmental impacts are assessed for 2 types of pipes; twin and single pipes. The twin pipes (DN25 Twin) contains two pipes, for both tour and detour water, and are produced in small dimensions only. The single pipes are assessed in three dimensions; DN25 Single, DN100 Single and DN500 Single. The pipes are made in segments of 12 m (except the DN500 which is made in 16 m segments), and the functional unit for the pipes are the segment length and 1 year.

---

[1] Laying of the pipes is not included in the LCA

Table 7: Impact vectors for DH pipes

	DN25 Twin	**DN25 Single**	**DN100 Single**	**DN500 Single**
Name of vector	DN25 Twin	DN25 Single	DN100 Single	DN500 Single
Unit	Per 12 m and 1 year	Per 12 m and 1 year	Per 12 m and 1 year	Per 16 m and 1 year
ADP	6.33E -02	3.93E -02	1.38E -01	1.48E+00
GWP	5.6E+00	3.37E+00	1.24E+01	1.29E+02
ODP	1.73E -07	9.20E -08	4.20E -06	4.20E -06
HTP	1.25E+01	9.17E+00	1.83E+02	1.83E+02
FAETP	2.84E+00	1.48E+00	6.80E+00	7.10E+01
MAETP	3.83E+03	2.09E+03	8.87E+03	9.17E+04
TETP	9.17E -02	6.00E -02	1.84E -01	1.74E+00
POCP	3.11E -03	1.94E -03	6.63E -03	6.53E -02
AP	4.57E -02	3.21E -02	8.80E -02	8.67E -01
EP	5.13E -03	3.07E -03	1.13E -02	1.15E -01

The results seem logical, as the twin scores slightly higher than the single pipe in the same dimension, and that for single pipes the impacts increases by increased dimension.

5.3.2 Electricity grid

The processes *Transmission network, electricity network, low voltage*, *-medium voltage* and *-high voltage* in ecoinvent are used, without any modifications. These are based on Swiss data. Low voltage is less than 1 kV, medium voltage is between 1 kV and 24 kV while high voltage is more than 24 kV. The low voltage process includes medium to low voltage switching stations, and the medium voltage process includes high to medium voltage switching stations.

The LCA results for the electricity networks at each voltage level are given in table 8 and the functional unit is 1 km network and 1 year.

Table 8: Impact vectors for electricity network

	Low voltage	**Medium voltage**	**High voltage**
Name of vector	Elgrid lowvolt	Elgrid medvolt	Elgrid highvolt
Unit	Per km and 1 year	Per km and 1 year	Per km and 1 year
ADP	3.27E+00	3.80E+00	9.80E+00
GWP	3.80E+02	5.77E+02	1.32E+03
ODP	1.81E -05	3.11E -05	6.57E -05
HTP	7.00E+03	8.80E+03	5.10E+03
FAETP	3.05E+02	4.00E+02	5.77E+02
MAETP	4.53E+05	9.40E+05	2.81E+06
TETP	8.73E+02	1.23E+03	8.03E+00
POCP	4.47E -01	5.03E -01	7.07E -01
AP	1.01E+01	1.15E+01	7.60E+00
EP	4.80E -01	5.23E -01	8.83E -01

5.3.3 Gas pipelines

The processes *Pipeline, natural gas, low pressure distribution network/CH* and *Pipeline, natural gas, high pressure distribution network/CH* are used, without any modifications. The processes are described as infrastructure needed for Swiss low (<0.1 bar), middle (0.1 - 1.0 bar) and high (>1.0 bar) pressure distribution network, with a lifetime of 40 years and an annual transport of 30 TJ/km/year. The process *...high pressure...* covers both high and medium pressure networks. The resulting impacts are divided by 40 to obtain results per year, and are listed in table 9.

Table 9: Impact vectors for natural gas pipeline networks

	Low pressure	**High pressure**
Name of vector	Gaspipe lowpr	Gaspipe highpr
Unit	Per km and year	Per km and year
ADP	1.32E+01	1.49E+01
GWP	1.65E+03	1.75E+03
ODP	9.80E -05	1.37E -04
HTP	8.73E+02	8.78E+02
FAETP	5.70E+02	7.15E+02
MAETP	9.45E+05	1.05E+06
TETP	1.87E+01	2.06E+01
POCP	5.78E -01	7.13E -01
AP	7.68E+00	8.83E+00
EP	1.23E+00	1.80E+00

5.4 Discrete transport

Transport services needed for waste collection will vary greatly between regions. This is therefore assessed separately. This also applies to the transport of the residue from waste incineration to the special waste treatment cite. Transport service processes in ecoinvent are used to obtain LCAs for relevant trucks.

Transport data in ecoinvent represents average conditions of transport conditions in Switzerland and Europe. Transport service is expressed in tkm, which means transport of 1 kg over a distance of 1 kilometer. It is taken into account that the lorries are not fully loaded all the time as they perform the freight service, certain load factors are assumed for the different lorries (for instance will the lorry be empty on the way to collect the goods). The load factors for the lorries assessed here vary between 42 and 50 %. [33]
The transport services in ecoinvent includes; lorry, operation and maintenance of lorry, disposal of lorry, road, operation, maintenance of road and disposal of road.

5.4.1 Transport of waste locally

The process *Transport, municipal solid waste collection, 21t lorry* in ecoinvent is used. This lorry has a gross capacity of 8.2 tons, and an average load factor of 50 %.

5.4.2 Transport of waste over long distance

Long distance transport of waste for incineration are assumed to be done in 40 ton lorries. These have an average load factor of 46 %. Covered by process *Transport, lorry 40t* in ecoinvent. Choice of lorry is based on calculations performed in the impact study for the expansion of the DH system in Trondheim [14], where it is assumed that waste transported from long distances is transported in 30 tons per vehicle. A lorry of 40 tons is the closest transport service defined in SimaPro (weight of the vehicle is included in the 40 tons).

5.4.3 Transport of special waste

Assumed to be done with 28 ton lorries, as used in [6].

5.4.4 Transport of oil products and pellets

It might be an alternative in implementation in eTransport to exclude the transport of oil products and pellets of their respective LCAs, and assess this separately. The reason for this, is that the distance from the refineries will vary between regions. Transport of oil products and pellets are assumed to be on 32 ton lorries, as is the case for transport of oil products in the processes in ecoinvent.

The impact vectors for the transport services are given in table 10

Table 10: Impact vectors for waste transport services

	Local waste transport	**Long waste transport**	**Special waste transport**	**Oil products transport**
Name of vector	Transp waste local	Transp waste long	Transp special waste	Transp oilprod
Unit	Per tkm	Per tkm	Per tkm	Per tkm
ADP	8.37E -03	1.22E -03	1.61E -03	1.20E -03
GWP	1.31E+00	1.65E -01	2.23E -01	1.65E -01
ODP	1.96E -07	2.73E -08	3.63E -08	2.31E -08
HTP	2.59E -01	3.45E -02	4.44E -02	3.82E -02
FAETP	1.75E -02	7.52E -03	8.88E -03	7.10E -03
MAETP	9.54E+01	2.14E+01	2.67E+01	2.39E+01
TETP	1.01E -03	3.32E -04	4.14E -04	3.26E -04
POCP	2.25E -04	2.52E -05	3.46E -05	3.16E -05
AP	5.80E -03	8.66E -04	1.22E -03	9.63E -04
EP	1.19E -03	1.79E -04	2.56E -04	1.92E -04

5.5 Conversion components

Boilers and furnaces are not assessed separately, as discussed earlier. It might be an idea to assess large heat pumps, used in for instance DH production, as this will not be a natural part of any energy commodity life cycle. The predefined processes for heat pumps in ecoinvent is, however, on too small heat pumps for such processes.

5.6 Power and heat production units

In some cases, local energy planning can include the building of new power and heat production units. Like wind power plants, hydro power stations, small hydro-electric power stations, bio thermal power stations etc. It is difficult to obtain LCA results for such infrastructure in advance, as various installations will vary a great deal in size and design. It is also uncertain when it would be required to compute results for such infrastructure separately. As for electricity production, this is already handled as being comprised of different kinds of production alternatives (Norwegian included imports or NORDEL mix). Adding a new producing unit, distributed to electricity use according to lifetime and capacity, would probably not affect the overall results regarding electricity use of any significance. For heat production, it is more important to include the producing unit, as is done for the case of waste incineration, as these would be isolated production units. To illustrate an approach to this problem, waste incineration is given as an example. For waste incineration, the incineration plant contributes to the overall environmental impacts in various amounts in the different categories; ADP: 25 %, GWP: 2.5 %, ODP: 20 %, HTP: 7 %, FAETP: 40 %, MAETP: 8 %, TETP: 1 %, POCP, AP and EP: $<$ 1 % (see figure 8 in appendix). Note that these numbers are valid for waste incineration, excluded the transport (incl collection) of waste to the incineration plant and special waste to special waste treatment. Were these included, the shares of the plant to the impacts would have been lower. In the three categories the plant has most relative impacts, the total process for heat from waste incineration has very low impact compared to the other energy commodities (figure 7). Based on this, it could be argued that an omittance of the plant would not affect the overall results very much (apart from the category FAETP, where the ranking of the various energy commodities would shift if the plant was excluded from the LCA). However, whether this would be the case for other heat producing units is highly uncertain.

5.7 Comments on the LCAs

HFO, LFO and LPG

The transport services for the process chains for these commodities should be looked closer into, and adjusted for Norwegian conditions. It could be a good solution to assess the transport services separately, at least the lorry transports. LCAs for these energy commodities has covered both industrial and private end use. The difference between these two alternatives are not very big, and it might be sufficient to use results for one type of end use.

Wood

The two LCAs for wood firing gives very different results, especially in the HTP and POCP categories. For HTP, the Norwegian LCA gives over 100 times as high impact as the ecoinvent process, for POCP the impact is about 16 times higher for the Norwegian LCA. For these categories, the use phase (combustion) is the far most contributing process in the Norwegian study [31]. Looking into the processes reveals that this difference is mostly caused by very different emission factors for the combustion of wood. Both LCAs have used emission factors for combustion based on measurements on operation of installed stoves. The differences can be explained by different technology applied and different measurement methods. Also, there is used an overall higher efficiency in the ecoinvent process, and different types of wood are applied.

Waste
The heating value for waste is dependent on the composition and moisture of the waste. Especially important is the plastic content. It might be an idea to use different values for the heating value dependent on whether there is plastic sorting for recycling or not. The heating value is inserted in the conversion component in eTransport, so this will not require different LCAs.

Avoided treatment of waste is not included in this study. Avoided treatment will vary between regions, depending on the waste sorting regime in the relevant municipality. It might, however, be a feasible alternative to include some kind of Norwegian mean for avoided treatment in the heat from waste-process, in order to get a more realistic result regarding especially greenhouse gases for the heat generation from waste, compared to heat generation from other energy commodities.

A new regulation [25] on waste incineration became operative in January 2003. Already existing plants are obliged to follow these regulation within January 2006. The emission factors used in this study are based on statistics for 2004, that is when old regulations applied. It should be obtained new emission factors for waste incineration, as both new and old plants now have better smoke cleaning.

The process for waste incineration could be improved by obtaining a new process for a special waste treatment plant, using environmental data for Langøya available in [6].

DH grid
It is recommended to obtain data for laying of DH pipes and include this in the LCAs for the DH pipe segments.

Electricity grid
It is uncertain how suitable the electricity network applied is for Norwegian conditions, regarding technology, voltage levels and geography. The electricity grid is, however, not of great importance regarding environmental impacts from electricity use, so it might not be of importance to adjust this perfectly to Norwegian conditions.

Infrastructure
It is recommended to obtain an LCA for large heat pumps for implementation in eTransport.

The need for predefined LCAs for Power and heat producing units should be further looked into, as well as other means of implementing LCA on such infrastructure in eTransport.

6 Case study

A case study for the energy supply in Trondheim municipality is developed in order to illustrate the methodology for implementation. Data for consumption in 2004 makes the foundation for the base scenario and consumption prognosis for 2013 constitutes a future scenario. Only consumption for heating purposes are assessed, as data for this is available from the preliminary study.

In eTransport, two or more investment alternatives would be compared. Here, it is rather changes in consumption patterns over time that are compared.

The consumption of energy commodities, infrastructure and transport services are associated with the relevant impact results, obtaining overall environmental impacts from heating of buildings in Trondheim. The analogous calculations that would be done in eTransport are described subsequently.

For electricity NORDEL production mix is applied, and for wood the ecoinvent process is used.

6.1 Energy commodity consumption

The consumption data for 2004 are calculated based on statistics from local energy reviews from 2004 [24], 2005 [9] and 2006 [26] and the Energy Accounts on municipality level from SSB [13]. Based on consumption prognosis for Trondheim presented in the local energy reviews, a future scenario is developed.

Table 11: Consumption of energy commodities in Trondheim 2004 and 2013

Energy commodity	**Consumption 2004**	**Consumption 2013**	**Unit**
Waste	226 920	459 510	MWh
LFO private	34 750	30 745	MWh
LFO industry	184 620	152 340	MWh
Pellets industry	35 290	53 460	MWh
LNG[1]industry	61 600	52 293	MWh
LPG private	500	400	MWh
LPG industry	61 600	52 293	MWh
Wood private	118 400	89 630	MWh
HFO industry	4 680	0	MWh
Electricity	1 053 530	945 460	MWh
Total	1 781 890	1 836 131	MWh

Electricity is the main contributor to the heating of buildings in Trondheim, constituting over 50 % of the total consumption in both 2004 and 2013. Consumption of electricity depends on its price and access to other energy com-

---

[1] LNG and LPG are treated as one in the statistics used, it is assumed a 50 - 50 % distribution

modities for heating, and it is expected to decrease in the period. Amount of waste incinerated to produce heat will double in the period, as a consequence of the expansion at Heimdal heating plant. In 2013 it is expected to constitute as much as 25 % of the total consumption. Waste and pellets consumption is the only ones that increases in the period, replacing heating oil for DH production, which in turn replaces electricity and fuel oils in buildings connecting to the DH grid. Most of the changes in the consumption in the period is listed in table 12. Consumption of both HFO industry, LFO private and LPG private are expected to decrease, but these constitutes very small amounts of the total consumption.

Table 12: Significant changes from 2004 to 2013 [%]

Energy commodity	**Change 2004 - 2013**	**Share of total 2004**	**Share of total 2013**
Electricity	- 11.30	59.12	51.49
Waste	+ 102.50	12.73	25.03
LFO industry	- 11.50	10.36	8.30
Wood private	- 24.30	6.64	4.88
LNG industry	- 15.11	3.46	2.85
LPG industry	- 15.11	3.46	2.85
Pellets industry	+ 51.50	1.98	2.91

The figure 9 shows the impact vectors relevant for the consumption in Trondheim 2004 and 2013. The DH impacts are calculated based on consumption for heat production in 2004, and includes the grid and transport services (calculation of these are given in 13. The energy commodities are stacked relative to amount consumed (in 2004), the commodity with highest consumption on the bottom.

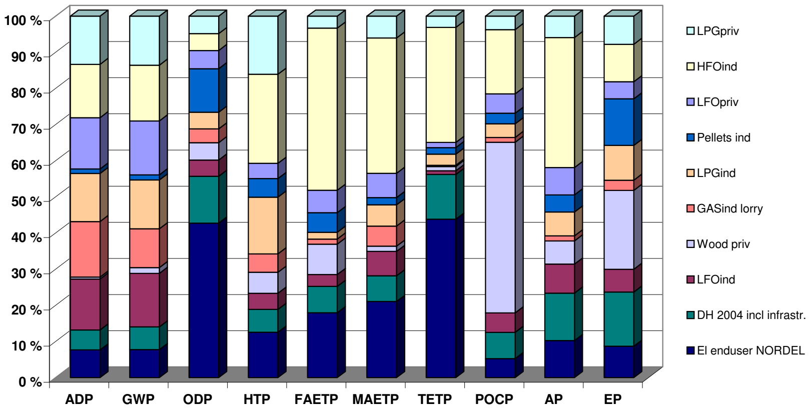


Figure 9: Impact results relevant for case study

6.2 Infrastructure consumption

DH Grid

The DH grid in Trondheim extended to approximately 105 km in 2004 [26]. 25 % of the grid consists of twin pipes and the rest is single pipes (laid in pairs) [23].

The DH grid consists of the following pipe dimensions [23];

DN25: 15%
DN32: 10%
DN40: 7,5%
DN50: 15%
DN65: 7,5%
DN80: 7,5%
DN100: 15%
DN125: 15%
DN150: 5%
DN200: 2,5%

These are further distributed to the four dimension there are available LCA data for. Twin pipes are not made in large dimensions [23], so these are all assigned to the dimension DN25.

DN25 twin: 25%
DN25 single: 22,5%
DN100 single: 52,5%
DN500 single: 0%

All the percentage distributions given above applies to length of grid, and as single pipes are laid in pairs, required length of these are twice as the length of the grid consisting of single pipes.

Number of pipe elements per dimension is then;

DN25 Twin:

$$\frac{0.25 \cdot 105\,km}{0.012\,km\,/\,pipe\ element} = 2187.5\,pipe\ elements \approx 2200\,pipe\ elements \tag{7}$$

DN25 Single:

$$\frac{0.225 \cdot 105\,km \cdot 2}{0.012\,km\,/\,pipe\ element} = 3937.5\,pipe\ elements \approx 4000\,pipe\ elements \tag{8}$$

DN100 Single:

$$\frac{0.525 \cdot\ 105 \cdot 2}{0.012\,km\,/\,pipe\ element} = 9187,5\,pipe\ elements \approx 9200\,pipe\ elements \tag{9}$$

Data for expansion of the DH grid from 2004 to 2013 are based on the impact study of the expansion of the Heimdal heating central [14], the energy review from 2005 [9] and information from TrondheimEnergi [23]. 32,7 km of pipes are being laid in this period (note that this is total *length of pipes* laid, and not the length of the grid. The same percentage distribution of pipe dimensions are assumed in the expansion of the grid [23] as for the existing grid, and the calculations of pipe elements per dimension is performed in the same manner as shown in equations 7 - 9.

Electricity Grid
Construction of new electricity grid is based on *Regional kraftsystemutredning for Sør-Trøndelag 2007 - 2022* [34]. New electricity grid is constructed partially to increase transmission capacity (Strinda - Storhaugen, 7 km cable) and to replace old cables (assumed 8 km cable). Both types are of high voltage transmission network.

Waste transport
Local waste transport for incineration in Trondheim (2003), includes household waste collection from the municipalities; Trondheim, Melhus, Klæbu, Midtre Gauldal and Tydal and trade waste [19]. Total transport service needed for the collection of this waste is not easily calculated. One would have to know the transport lengths within all these municipalities, and that is not easily accessible information as various companies are responsible for the collection of waste in these municipalities (as well as other municipalities too). One would also need to know the transport length of the trade waste. It is chosen to leave the local waste transport outside the study, as there is not obtained sufficient data to make any qualified assumptions regarding transport lengths. It is, however, assumed that local waste transport service per year are the same for year 2004 and 2013, as significant changes are not expected here [14]. Therefore the omittance of this transport service will not affect the comparison of the two scenarios.

Residues from the combustion of waste (filter cake and filter ash) are transported to Langøya, a special waste treatment plant in the southern Norway. Transport service needed for this, are taken from the master thesis by Kinzler [11] about waste treatment in Mid Norway, where transport service needed is given as 1 421 600 tkm in 2002 and 2 227 500 tkm in 2020. These numbers can be used for respectively 2004 and 2013, as they represents amounts of residue from before and after the expansion at Heimdal incineration plant.

As the new oven plant opens at Heimdal, waste from more remote places are collected and taken to HVS for incineration. Transport service needed for this waste is estimated in [14] to 400 000 km per year and an average load of 15 tons. This estimate is used as needed transport service for long waste transport in the 2013 scenario.

Total consumption of infrastructure in the two scenarios are listed in table 13

Table 13: Consumption of infrastructure in Trondheim 2004 and 2013

Infrastructure component	**Consumption 2004**	**Consumption 2013**	**Unit**
DN25 Twin	2 200	2 900	Segm. à 12 m
DN25 Single	4 000	4 615	Segm. à 12 m
DN100 Single	9 200	10 630	Segm. à 12 m
DN500 Single	0	0	Segm. à 16 m
El grid low voltage	0	0	km
El grid medium voltage	0	0	km
El grid high voltage	0	15	km
Long waste transport	0	6.00E+06	tkm
Special waste transport	1.42E+06	2.23E+06	tkm

6.3 Calculations

All impact vectors from the screening LCAs are listed in the Ecxel file *Impact vectors* (attached). These are read into Matlab and the relevant ones for the scenarios are gathered in one single impact matrix; I (with subscript a and b for NORDEL and Norwegian electricity mix respectively). The Matlab script file *Impacts* is attached. The consumption of energy commodities and infrastructure is listed in the Excel file *Scenarios* (attached). These are read into Matlab and gathered in one demand vector (y) for each scenario. Total impacts per category (total impact vector d) are calculated; $d = I \cdot y$.

$$\begin{pmatrix} d_a \\ d_b \\ d_c \\ \cdot \\ \cdot \\ \cdot \\ d_j \end{pmatrix} = \begin{pmatrix} i_{a1} & i_{a2} & i_{a3} & \cdot & \cdot & \cdot & \cdot & \cdot & i_{a20} \\ i_{b1} & i_{b2} & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & i_{b20} \\ i_{c1} & i_{c2} & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ i_{j1} & i_{j2} & i_{j3} & \cdot & \cdot & \cdot & \cdot & \cdot & i_{j20} \end{pmatrix} \cdot \begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ y_{19} \\ y_{20} \end{pmatrix}$$

The subscripts a, b, ... , j indicates the impact categories, and the subscripts 1, 2, ... , 20 indicates the energy commodities, infrastructure components and transport services.

The matrix for total impacts per energy commodity and infrastructure (D_{pro}) is calculated; $D_{pro} = I \cdot \hat{y}$.

This matrix is further aggregated, to obtain assembled results for the electricity grid, the DH grid and the waste transport services. Four figures are made; 1 and 2: comparison of the two electricity mix alternatives for each scenario, 3 and 4: comparison of the two scenarios for each electricity mix alternative. The figures are based on normalized versions of the total impact vectors (d), relative to the vector with the highest impacts. Results are exported to the Excel file *Dpro* (attached), where various graphical presentation of the results are made. Selected results and figures are given in paragraph 6.4.

6.3.1 Calculations in eTransport

Energy commodities
Calculation of fuel consumption in eTransport is done in the operational model, based on inserted information by the user on heat loads, fuel prices, boiler efficiencies and max effects. Fuel consumption in the boilers are calculated, but here, fuel type is not registered. Consumption of various fuels are calculated for supply nodes and for imports to the system [4]. If it is found feasible to separate between industrial and private end use, the fuel specific consumption should be linked to the boilers. In the boiler dialogue box, where efficiency and max effect (as well as emission coefficients and emission penalties) is defined by the user, there is already a place to insert type of fuel input. This might be developed to link the consumption of fuel type to the boiler (b) in order to get type of fuel consumption (F) and size of boiler linked. Consumption of one type of energy commodity (f) and size of boiler (s) should then in turn be multiplied by the relevant impact vector (i), to obtain the impact result (d);

$$d_{fs} = F^{Bo}_{btfs} \cdot i_{fs} \tag{10}$$

This d_{fs} would be the resulting impact for consumption of fuel for one particular boiler in one time step (usually one hour). Consumption for all time steps (n) for all segments over a whole year has to be summarized;

$$d_{fs} = \Sigma^{n}_{t=1}(F^{Bo}_{btfs} \cdot i_{fs}) \tag{11}$$

(Alternatively, the consumption of fuels calculated at the supply nodes could be connected to the relevant impact vectors in the same manner as shown above, if only one type of end use is applied)

Infrastructure and transport

DH grid

Currently, there is no option to insert length of DH pipes in eTransport. An option for the user to insert number of segments of each dimension must be obtained. Eventually lengths can be inserted per km, and the impact vectors be adjusted to be valid for 1 km instead of length of segment (before implementation). This data for length of DH grid (L^{DH}) and for each pipe dimension (k) shall in turn be multiplied by the relevant impact vector, for the years which the actual DH grid is part of any investment alternative (a);

$$d_k^{DH} = L_{ak}^{DH} \cdot i_k^{DH} \tag{12}$$

Electricity[1] Lengths of grid in km is inserted by the user in eTransport, but there is not an option to define voltage level. This must be obtained, if construction of new electricity grid is going to be included in the environmental impacts. Calculation as described for DH grid.

Discrete transport

There is one module for bulk transport implemented in eTransport currently, for biomass. Possible inputs to this is capacity and trip time. It should be developed bulk transport alternatives for other fuels and for waste as well, and the possibility to define transport length. In eTransport, the transport service needed will be calculated during optimization, relative to the calculated consumption of the energy commodity that needs transport. This means that transport service needed must be given as transport service per MWh used of the energy commodity (as input to boiler or sold to market). To manage this, the distance for the needed transport for the energy commodity must be defined, and the load capacities of the means of transport in MWh of the energy commodity.

For waste incinerated for heat production, the case is somewhat different. The consumption of waste is not a consequence of heat needed, but rather a consequence of waste available. This means that amount of waste collected and incinerated is known prior to the optimization, and transport service needed related to waste incineration could be calculated in a slightly easier way. One could perhaps have an additional dialogue box related to waste incineration, where amounts of local and long transport for waste (and special waste) needed are defined, in distance in km and amount in tons, in total for one year. This should in turn be multiplied to the relevant impact matrix, to obtain yearly impacts for the various waste transport services.

---

[1]

[1] Calculations for natural gas distribution network would be similar

Total impacts

Eventually, all impact vectors (d) for all energy commodities, infrastructure and transport for each year in every period (where they are part of a possible investment alternative) shall be summarized, to obtain total results for each investment alternative. To get this correct, it is very important that the consumptions used to calculate impacts are linked to modules that are clearly defined to be part of certain investment alternatives, that is defined to be an alternative for some (or all) periods.

6.4 Results

The total impacts for each impact category for the scenarios are given in table 14.

Table 14: Impacts per impact category for 2004 and 2013 scenario

Impact category	Unit	2004	2013
ADP	$kg\,Sb\,eq$	1.76E+06	1.55E+06
GWP	$kg\,CO_2\,eq$	2.73E+08	2.51E+08
ODP	$kg\,CFC-11\,eq$	1.01E+01	9.43E+00
HTP	$kg\,1,4-DB\,eq$	1.44E+08	1.31E+08
FAETP	$kg\,1,4-DB\,eq$	9.27E+06	8.69E+06
MAETP	$kg\,1,4-DB\,eq$	1.18E+11	1.07E+11
TETP	$kg\,1,4-DB\,eq$	1.02E+07	9.37E+06
POCP	$kg\,C_2H_4\,eq$	7.34E+04	7.43E+04
AP	$kg\,SO_2\,eq$	1.04E+06	1.18E+06
EP	$kg\,PO_4^{--}\,eq$	1.07E+05	1.25E+05

Figure 10 shows the same results, relative to the result for the base scenario.

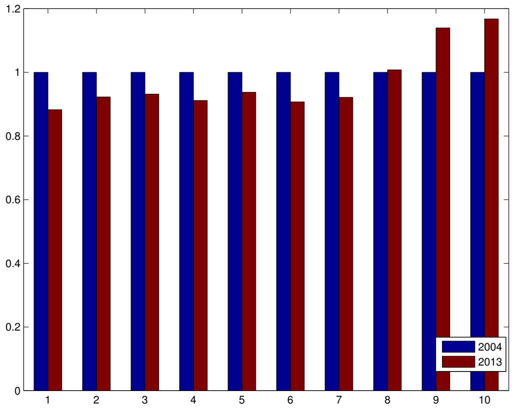


Figure 10: Comparison of the two scenarios[1]

The scenario for 2013 results in better environmental performance than the 2004 scenario for all the impact categories, except for POCP, AP and EP. The total consumption of energy commodities were increased by 3.04 %. The environmental performance increases as consumption of fossil fuels and electricity has been replaced by waste incineration and pellets. Waste incineration contributes little to most impact categories relative to the other energy commodities, except from AP and EP. For these categories, electricity (both mixes) have little impact, relative to waste incineration. This is the reason that the

---

[1] 1:ADP 2:GWP 3:ODP 4:HTP 5:FAETP 6:MAETP 7:TETP 8:POCP 9:AP 10:EP

impacts in these two categories increases from 2004 to 2013.

The figures 11 and 12 shows the relative impacts for each energy commodity and infrastructure for each category. Note that all waste transport is given in one, all DH grid components are given in one and all electricity grid components are given in one. Electricity grid and waste transport could be included in electricity for heat and waste incineration respectively, but are kept separate in order to be able to see their contribution to the overall impacts. The energy commodities are stacked relative to share of consumption (in 2004), the commodity with highest share at the bottom.

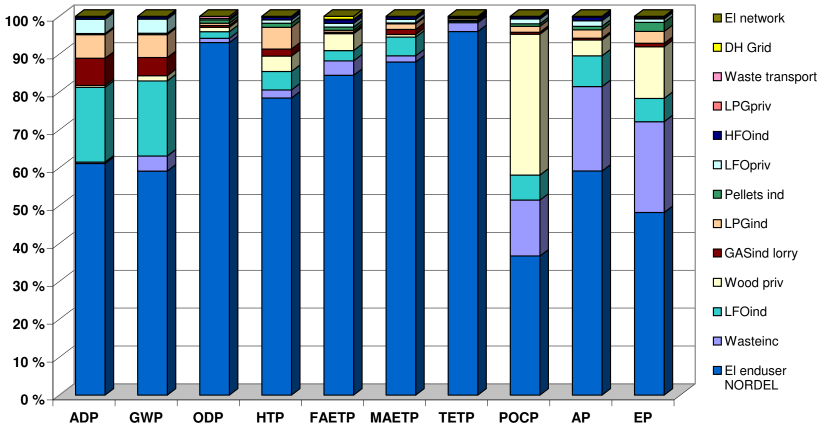


Figure 11: Impacts per category per energy commodity and infrastructure 2004

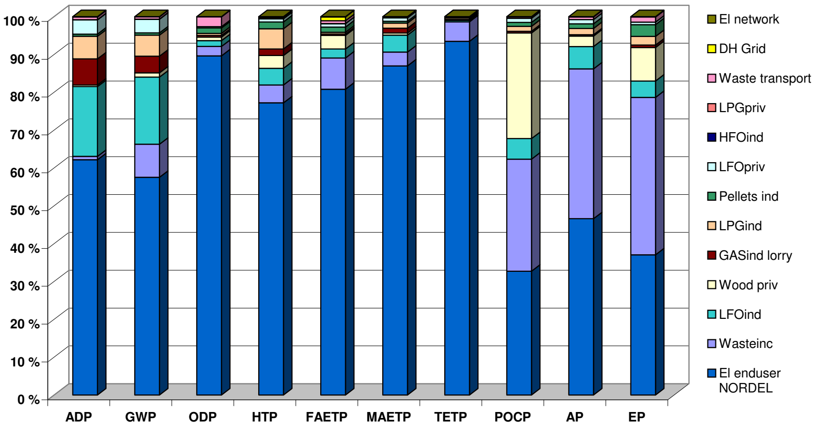


Figure 12: Impacts per category per energy commodity and infrastructure 2013

Electricity has both high impacts and large share of the consumption, it should be possible to replace some of this consumption with energy commodities with less impacts. Light fuel oil could be replaced by natural gas, LPG or ideally pellets or DH, as these has less impacts in most categories (shown in figure 9), and comprises about 10 % of the total consumption for heating purposes. Impacts from the new electricity grid in 2013 does not contribute much to the overall results for electricity use, but then, there was not much grid built (15 km). Waste transport are contributing most in the categories ODP and EP. For ODP, the waste transport impacts exceeds the impacts from the waste incineration.

6.4.1 Choice of electricity production mix

The two alternative choices for electricity production mixes are compared, and also the effect this choice will have on comparing the two scenarios. Figure 13 shows total environmental impacts in 2004 for the two electricity mix alternatives, set relative to the NORDEL electricity mix.

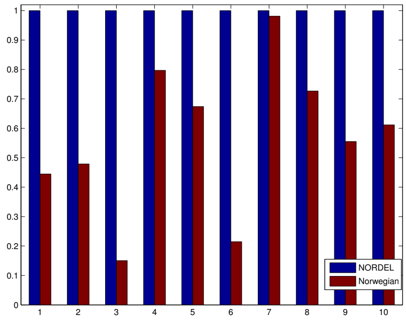


Figure 13: 2004 scenario, comparison of electricity mix alternatives

It is clear that the NORDEL electricity mix results in higher impacts for all impact categories. The differences varies from only 2 -3 % (TETP) to as much as about 85 % (ODP). In 2004, electricity amounts to as much as 59 % of the total energy commodity consumption for heating, this is why different electricity mixes can result in such high differences for the total results. The question is, will the choice of electricity mix affect any of the rankings between the two scenarios?

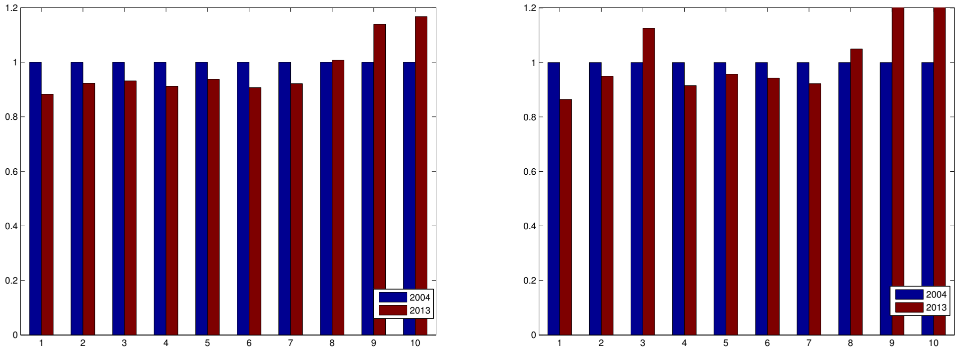


Figure 14: Comparison of the two scenarios applying NORDEL (left) and Norwegian electricity mix

The ranking of the two scenarios are, as seen in figure 14, affected by choice of electricity mixes. Here, it is especially pronounced for the categories ODP, POCP, AP and EP.

The size of the difference due to el mix choice in comparing two or more alternatives, depends on size of change in electricity consumption relative to other energy commodities. And to relative impact in the categories compared to the other energy commodities. It is not looked thoroughly into the actual causes of the differences here, as this comparison was done more as a curiosity.

6.4.2 Presentation of results in eTransport

The resulting impact vectors for each investment alternative should be normalized relative to the alternative with the highest overall impacts. This could be used to obtain bar charts, as seen in figure 14. This would provide the user a graphic intuitive picture of the environmental impacts results, and ease decision-making regarding this.

The results could be given in a separate tab in the *Operation and Investment Analysis Window.* Ideally, the results should be part of the optimization of investment alternatives, using multi-criteria optimization.

7 Discussion

The suitability of the chosen method of implementing pre-calculated LCAs for relevant commodities and services is not fully graspable before it is tested in practice. There are a lot of uncertainties, like whether it is possible to obtain results for all consumptions relevant for energy planning. It is uncertain how much of the results should be based on specific data, and how this would affect the workload on implementation and the user-friendliness. It is emphasized that the LCA results obtained in this project are coarse, and need a closer look, but are assumed to be good enough for test-implementation. If the method presented here is chosen for implementation of LCA in eTransport, the LCAs must be improved and ensured to apply to Norwegian conditions. Processes that requires specific data which differs between regions needs to be assessed separately, like for instance transport of fuel from production/refinig to end use, if this is found to have any significant influence to overall results.

Updating of the LCA results implemented in eTransport will require a lot of work, with fully or partially revision of the LCAs. It is, however not necessary to update very often, as such LCA data are fairly valid over time. It is recommended to use LCA expertise for the obtaining of new LCA results and for the updating procedures.

8 Conclusions

The presented method should be tested and further evaluated.

In this project the importance of user-friendliness has been stressed, as, assumably, the future use of eTransport for energy planners could be their first experience with calculations of environmental effects in a life cycle perspective. It is further assumed that the easier the LCA results are generated for the user through eTransport, the easier the methodology will be accepted and used, that is regarded in choice of investment alternative.

The presentation of the results are of great importance, and it should be easy to draw conclusions from the results. Here, a bar chart presenting the investment alternatives relative to the one with the highest impacts for most (or all) impact categories are suggested.

Ideally, eTransport should be modified to optimize both regarding economical and environmental aspects, and it is strongly recommended that this is a goal for future modifications of eTransport. A presentation of environmental effects in a separate tab beside the results from the economical optimization can easily be ignored, and end up having no function whatsoever.

References

[1] Naturgass, forbruk i norge. www.energilink.no.

[2] B. H. Bakken. email correspondence, march 2007.

[3] B. H. Bakken, M: Catrinu, I. Graabak, I. Steinsland, Ø. Vessia, and O. Wolfgang. Visjonsspesifikasjon etransport ii. Technical report, SINTEF, 2007.

[4] B. H. Bakken, H. I. Skjelbred, and O: Wolfgang. eTransport: Investment planning in energy. supply systems with multiple energy carriers. *To be published in: Energy*, 2007.

[5] H. Baumann and A-M. Tillmann. *The Hitch Hiker's Guide to LCA*. Studentlitteratur, 2004.

[6] H. Bergsdal. Integrerte strategier for regional avfallshåndtering og lokal energiforsyning i midt-norge. Master's thesis, NTNU, 2002.

[7] PRé consultans. Simapro 7.0, 2006.

[8] K. Ødegård, B. E. A. Bjørneby, R. Finnstun, and J. Heldal. Dokumentasjon av lastebilundersøkelsen. Notat, SSB, 2007.

[9] M. Vågsland (Entro Energi), O. Hårstad (TEV Grid), E. Sørheim (Trondheim municipality), and B. Storeng (TEV DH). Lokal Energiutredning 2005 Trondheim kommune.

[10] Trondheim Energi. Utvidelse av avfallsforbrenningsanlegget ved heimdal varmesentral - en kort orientering. online.

[11] B.-Y. K. Eriksen. Integrerte strategier for regional avfallsbehandlling i midt-norge og alternative behandllingsmetoder for aske. Master's thesis, NTNU, 2003.

[12] R. Frischknecht et. al. The ecoinvent database: Overview and methodological framework.

[13] K. Aasestad et.al. Energiforbruk i kommunene, june 2006.

[14] E. Evensen, B. Stålaker (TEV DH), E. Kjerschow (Kjelforeningen Norsk Energi), and A. Heie (Interconsult ASA). Konsekvensutredning om avfallsforbrenningsanlegget ved heimdal varmesentral. Technical report, TEV DH, 2002.

[15] A. Finstad, K. Flugsrud, G. Haakonsen, and K. Aasestad. Vedforbruk, fyringsvaner og svevestøv. Technical report, SSB, 2004.

[16] Centre for Environmental Studies. www.leidenuniv.nl. University of Leiden, 2001.

[17] M. Fröling and C. Holmgren. *Miljöbelastning från produktion av fjärrvärmerör*. PhD thesis, Chalmers tekniska högskola, 2002.

[18] G. Haakonsen and E. Kvingedal. Utslipp til luft for vedfyring i norge. Technical report, SSB, 2001.

[19] Aage Heie. email correspondence, june 2007.

[20] E. Hertwich. Lca introduction. Note, 2005.

[21] B. Hoem. The norwegian emission inventory 2006 - documentation of methodologies for estimation of emissions of greenhouse gases and long-range transboundary air pollutants. Technical report, Statistics Norway, 2006.

[22] Swiss Centre For Life Cycle Inventories. Ecoinvent database v1.3. Technical report, www.ecoinvent.org, 2000.

[23] Trondheim Energi Fjernvarme AS K. O. Lodgaard. email correspondence, may 2007.

[24] Ø. Moe (Tempero Energitjenester Ltd), O. Hårstad, A. Sylte, M. Aarstein (TEV Grid), S. Gismervik (Trondheim municipality), Bente Storeng (TEV DH), Rolf Hillestad, and Morten Moe (Smallworld Systems Ltd). Lokal Energiutredning 2004 Trondheim kommune, 2004.

[25] Miljødepartementet. Forskrift om gjenvinning og behandling av avfall, 2004.

[26] Ø. Moe, T. Larsen (Tempero Energitjenester), O. Hårstad (TEV Grid), B. Storeng, Amund Utne (TEV DH), Hans Einar Lundli, and Nils Jørgen Moltubakk (Trondheim municipality). Lokal Energiutredning 2006 trondheim kommune, 2006.

[27] NORDEL. Annual statistics, 2000.

[28] NVE. Statistics. www.nve.no, 2007.

[29] Nordel objective. www.nordel.org.

[30] OED. Lov om produksjon, omforming, overføring, omsetning, fordeling og bruk av energi m.m., June 1990.

[31] M. Reenaas, C. Solli, A. H. Strømman, and E. Hertwich. Life cycle assessment of wood based heating in norway. Technical report, NTNU, To be published.

[32] C. J. Rydh, M. Lindahl, and J. Thingstrøm. *Livscykelanalys*. Studentlitteratur AB, 2002.

[33] Stadler P. Tietje O. Spielmann M., Kägi T. Life cycle inventories of transport services. Technical Report ecoinvent report No. 14, Swiss Centre for Life Cycle Inventories, 2004.

[34] A. Sylte, L., and T. Szabo (TEN). Regional kraftsystemutredning for sør-trøndelag 2007 - 2022. Technical report, TrønderEnergi Nett AS and Trondheim Energi Nett, 2007.

[35] Environmental Production Agency USA. Compilation of air pollutant emission factors, 1995.

Appendix

Appendix 1: Nomenclature in eTransport

The nomenclature listed is from a paper describing eTransport [4], and it must be noticed that some of the nomenclature here does not agree with what is integrated in the eTransport code where more descriptive nomenclature is used, as for example EL_LINE_LOSS.

Parameters

A_{fkt} = Constraint coefficients for component k in timestep t
b_{ft} = Restrictions on resources/capacities in timestep t
c_{st}^{El} = Electricity prices or generation cost in timestep t at supply node s [USD/MWh]
c_d^{inv} = Investment cost for investment d [USD]
δ = Annual discount factor; $\delta = 1/(1 + \mathrm{r})$
ε_{be} = Emission coefficient for emission type e from boiler b
λ_d = Lifetime of investment alternative d [years]
L_{ij} = Length of power line from i to j [km]
L_{lt}^{El} = Electricity load at load node l in timestep t [MWh/h]
η_b^{Bo} = Boiler efficiency [%]
Pen_{be}^{Em} = Emission penalty for emission type e from boiler b [USD/kg]
Pen^{El} = Electricity deficit penalty [USD/MWh]
r = Interest rate [pu]
Π_{start} = The first year in the first timestep in the planning period
Π_{end} = The first year in the final timestep in the planning period
Π_{step} = The number of years in each timestep in the planning period
w_{ζ} = Weight factor for length of segments [days]
$Wmax_b^{Bo}$ = Maximum heat output from boiler b [MW]
X_k = Line reactance [Ω/km]; $k \, \epsilon \, El\_line\_types$

Variables

c_{kt} = Operating cost of component k in timestep t [USD]

C^p = Operating cost for different technologies [USD]; $p \, \epsilon \, Technologies$

$C^{ope}_{s\pi\varsigma}$ = Operating cost in a given state s, period π and segment ς [USD]

$c^{ope}_{s\pi}$ = Annual operating costs for state s in period π [USD]

c^{inv}_{π} = Total investment cost (expences) in period π [USD]

C^*_{π} = Minimum net present value for period π through $(\Pi_{end} + \Pi_{step})$ [USD]

$D^{El}_{lt} \geq 0$ = Electricity deficit in timestep t [MWh/h]

$DP(direction)_{ijt}$ = Losses calculated for all lines where power is flowing out from node i; 0 if power flows *into* the node [MWh/h]

$Emit_{ebt} \geq 0$ = Amount of emission type e from boiler b in node i; timestep t [kg/h]

F^{Bo}_{bt} = Fuel used by boiler b in timestep t [MWh/h]

ϕ_{it} = Phase angle at node i in timestep t [rad]

Φ = Rest value of investments [USD]

$I_{d\pi}$ = Binary variable that identifies investments. $I_{d\pi}$=1 if the investment $d \, \epsilon \, D$ has been carried out *in period* π, and $I_{d\pi} = 0$ otherwise

$I^{scrap}_{d\pi}$ = Binary variable that identifies the scrapping of equipment. $I_{d\pi}$=1 if the equipment from project $d \epsilon D$ has been scrapped *in period* π, and 0 otherwise

$Load\_flow_{ijt}$ = Energy flow from network load i to load node j in timestep t [MWh/h]

$Local\_flow_{ijt}$ = Energy flow from supply node i to load node j in timestep t [MWh/h]

$Net2net\_flow_{ijt}$ = Energy flow from network nodes i to j in timestep t [MWh/h]

P^{El}_{ijt} = Power flow from busbar i to j in timestep t[MWh/h]

P^{Ld}_{ijt} = Power flow in timestep t to load connected at node i [MWh/h]

P^{Loc}_{slt} = Power flow in timestep t to load l directly connected to supply s [MWh/h]

P^{N2N}_{nit} = Power flow in timestep t from/to other network modelsat node i (e.g. from local CHP model or to heat pump model) [MWh/h]

P^{Sup}_{sit} = Power flow in timestep t from market or local generator s (e.g. wind, hydro) connected at node i [MWh/h]

π = Identifier for investment periods given as first year in each period

S_π = State identifier; $S_\pi \,\epsilon\, States$

$S^{El}_{lt} \geq 0$ = Electricity sold at node l in timestep t [MWh/h]

$Supply\_flow_{ijt}$ = Energy flow from supply node i to network node j in timestep t [MWh/h]

t = Index for timesteps (hours) within operational model, $t \,\epsilon\, Time\_steps$

τ = Index for years within an investment period, $\tau \,\epsilon \{1, ..., \Pi_{step}\}$

U^{El}_{st} = Use of electricity at supply point s in timestep t [MWh/h]

W^{Bo}_{bt} = Heat output from boiler b in timestep t [MWh/h]

x_{kt} = Decision variable for component k in timestep t

$y_{d\pi}$ = Binary variable that identifies investment history.$y_{d\pi} = 1$ if the investment $d \,\epsilon\, D$ has been carried out *before or in period* π, and $y_{d\pi} = 0$ otherwise

ζ = Index for load segments within a year

Sets

$Boilers$ = Set of boilers

D = Set of investment alternatives

$El\_busbars$ = Set of electricity busbars (nodes)

El_line_types = Set of predefined and user specified line types

El_loads = Set of electricity loads

$El\_markets$ = Set of electricity markets; $El\_markets \subset El\_loads$

El_power_lines = Set of power lines

$Emissions$ = Set of (predefined) emission types; $Emissions = [CO_2, CO, NO_x, SO_x]$

$Load\_points$ = Set of load and market nodes

$Net2load$ = Set to define connections between network nodes and load nodes

$Net2net$ = Set to define connections between two different networks

$Network\_nodes$ = Set of network nodes

$Periods$ = Set of investment periods

$States$ = Set of system states (alternative system designs)

$Segments$ = Set of load levels within a year

$Supply2load$ = Set to define direct connections between supply nodes and load nodes

$Supply2net$ = Set to define connections between supply nodes and network nodes

$Supply\_points(El)$ = Supply points (for electricity)

$Technologies$ = Set of technology modules contributing to the object function;
$Technologies = [El\_sup, El\_load, Bo, \ ...]$

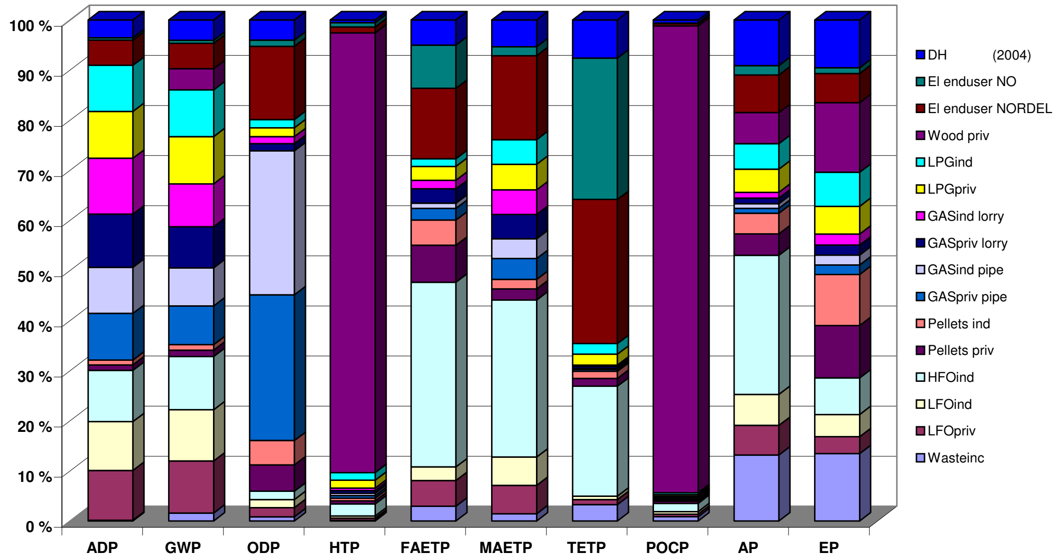
$Time\_steps$ = Set of hours in the operating model, typically [1, 2, 3, ... , 24]

Appendix 2: Electricity production mix Norway

Table 15: Production mix Norway 2000 in percent, as assessed in SimaPro

Conventional thermal	**0.24**
Hard coal	0.03
Heating oil and refinery gas	0.01
Natural gas	0.14
Coke and blast oven gas	0.08
Hydro power	**98.04**
Roll over-operated hydro power (wave power??)	**0.43**
New renewable energy	**0.17**
Wind power	0.02
Biomass and animal products	0.15
Waste	**0.08**
Municipal and industrial waste	0.08
Imports	**1.03**
Denmark	0.10
Finland	0.12
Sweden	0.64
Russia	0.16
TOTAL	**100**

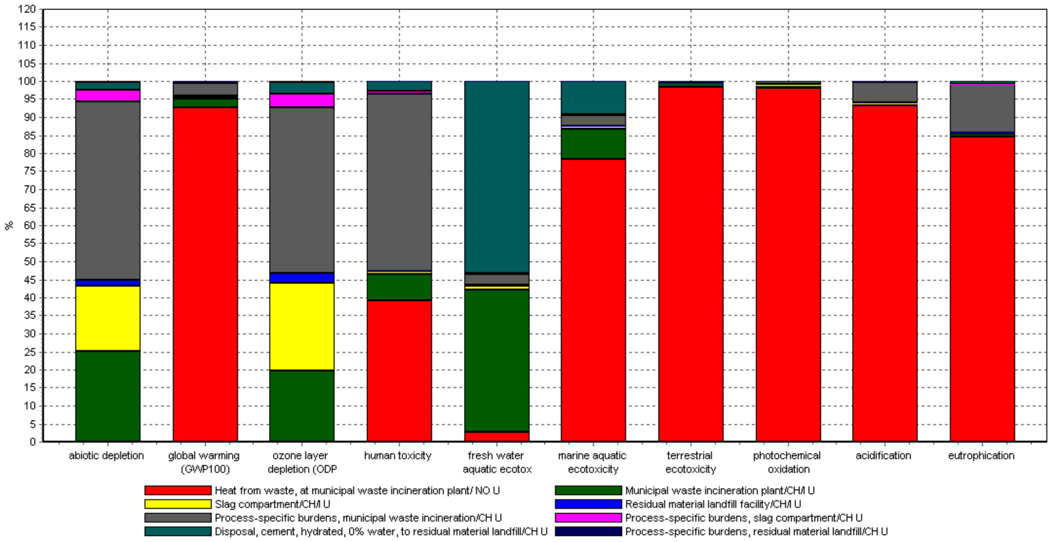
Appendix 3: Relative impacts for all energy commodities



Appendix 4: Inventory for production of DH pipes

		Unit	DN25 Single	DN25 Twin	DN100 Single	DN500 Single
Inputs	Steel pipe	kg	23.9	47.8	118	1247
	Polyethylene	kg	12.2	15.5	29.2	388
	Copper wire	kg	0.32	0.32	0.32	0.43
	Spacer	kg	0.29	0.49	0.91	13.85
	Polyuretan	kg	7.71	12.5	26.94	229.6
	Rubber band	p	14	12	12	0
	PVC-pipe	g	51.6	51.6	51.6	103.2
	End cap	g	6.8	13.6	59.4	1417.6
	Plug	p	1	1	1	1
	FOPS	p	1	1	1	1
	End cover	p	0	2	0	0
	Sprag (trekloss)	g	0	164	0	0
	Steel band	g	0	70	0	0
	Steel clip	g	0	29.5	0	0
Excessive material	Steel	g	15.2	30.9	64.4	684.1
	Copper	g	21.17	21.17	21.17	28.17
	Polyethylene, defect DH pipes	g	8.69	8.82	15.9	212.8
	Polyethylene, defect shells	g	0.24	0.3	0.57	7.57
	Polyuretan	g	5.49	9.03	14.7	126
Energy use	El	kWh	8.28	16.79	35	372.12
	Heat oil	MJ	11.19	22.7	47.32	503.01
	Diesel	MJ	2.53	5.14	10.71	113.87
Auxiliary chemical	Release agent	g	3.33	6.76	14.1	149.8
	Cleaning agent	g	1.51	3.07	6.4	68.1
	Glycol	ml	0.19	0.39	0.8	8.55
	Hydraulic oil	ml	0.84	1.7	3.54	37.6
	Motor oil	ml	0.76	1.54	3.22	34.2
	Various oils	ml	0.46	0.93	1.93	20.5
	Technical oils	MJ	0.07	0.15	0.31	3.3
Emissions and waste	MDI to air	mg	0.09	0.14	0.31	2.6
	Cyclopentane to air	g	12.1	19.7	42.6	362.9
	Ozone to air	g	0.17	0.22	0.42	5.53
	Waste to incineration	g	310	620	1300	13800
	Paper for recycling	g	24.7	50.2	104.6	1111
	Waste oil	g	2.3	4.6	9.7	103
	Other industrial waste	g	108	221	460	4891

Appendix 5: Process contributions for incineration of waste



Analyzing 1 MWh 'Heat from waste, at municipal waste incineration plant/ NO U'; Method: CML 2 baseline 2000_johanne V2.03 / World, 1990 / characterization

Appendix 6: Description of attached files

Scenarios - Excel file

This contains consumption of energy commodities, infrastructure components and transport services for the two scenarios for Trondheim municipality. This file serves as input for the demand vectors, y, in the Matlab script.

Impact vectors - Excel file

This contains the LCA results for the energy commodities, infrastructure components and transport services assessed. This file serves as input for the impact vectors in the Matlab script.

Impacts - Matlab script file

This is the script for the calculations performed to obtain total LCA results for the two scenarios. Selected results are exported to the Excel file *Dpro*.

Dpro - Excel file

Results from Matlab is exported to this file. These are further used to generate some bar charts.