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Environmental assessment of biomass-based decentralised polygeneration

The case of Swiss Residential buildings

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Abstract

Sustainability in the building sector demands remarkable efforts to increase energy efficiency and the share of renewable energies. Biomass-based micro cogeneration systems can help to improve the energy efficiency of residential buildings whiles reducing the over-dependence on fossil energy resources. In this study, the environmental performance of cleaned and upgraded biogas and natural gas in domestic fuel cell and internal combustion engine applications has been assessed. The systems were compared to European grid electricity mix and condensing gas boiler system as the reference. The use of biogas demonstrates clear advantages over natural gas and the reference in terms of climate change and resource depletion. Refined biogas reduces the impacts on resources by approximately 75% and even further with raw biogas. In comparison with the reference, the damage on ecosystems quality from biogas in terms of acidification and eutrophication is substantial, but considering the high global warming potential of methane, the conversion of biomass to biogas appears an opportunity cost. Refining biogas adds up to its cost and environmental burden. In spite of its likelihood to positively or negatively influence consumer behaviour, biomass-based micro CHP demonstrates the potential to create energy self-sufficiency, employment, and income within the society. Biomass digestion presents itself as an alternative waste management strategy.

Keywords: biomass-based; micro-cogeneration; energy efficiency; environmental

Executive Summary

In many industrialised countries, electricity is produced in large power stations. These power stations transmit electricity through high voltage transmission systems to substations where the voltage is reduced before distribution to consumers. In sharp contrast, decentralised energy (DE) generation produces power on the customer's site or at local power utilities. Examples of DE technologies include combustion engines, Stirling engines, fuel cells, photovoltaic, micro turbines, to mention just a few. These technological applications play a key role in ensuring reliable and secured energy supply and represent a suitable option for local network expansion. The development of DE system is backed by its potential to generate combined heat and power (CHP) and the use of renewable energy carriers or resources.

The implementation for small-scale distributed cogeneration is becoming widespread in some parts of Europe including Switzerland which is the main focus country of this study. The major parts of the Swiss energy policy as defined in the Swiss Energy Action Plan is energy efficiency in the buildings (residential and commercial), industrial and transportation sectors and the promotion of renewable energy.

This study assessed the performance of biomass-based micro CHP in the Swiss single-family and multi-family dwellings. The research is conducted in two phases. The first part gives a brief overview of the Swiss energy and some aspects of microchip applications. The second, and main, phase deals with life cycle modelling and analysis of integrated micro CHP applications for Swiss residential buildings. Cleaned and upgraded biogas *(herein called refined biogas)* and natural gas were used as fuels for a fuel cell and an internal combustion engine integrated into these buildings. Raw biogas is used for sensitivity analysis. The systems are compared to European grid electricity mix and condensing gas boiler as reference. The approach to the second phase consists mainly of three stages:

- estimation of thermal and electrical efficiencies for the different micro CHP applications based on results of previous energy simulations;
- estimation of annual delivered energy and annual net energy consumption of the domestic buildings;
- assessing the environmental burdens of the integrated micro CHP systems using Life cycle assessments (LCA).

Main findings

Compared to the reference in the Swiss average building stock, refined biogas achieved a reduction in total cumulative energy demand (CED) of about 440-600MJ-eq representing some 40-65% whiles natural gas achieved a maximum of 20 % reduction. Impacts from the use of non renewable fossil resources account for a larger share of the cumulative energy demand for natural gas. The energy invested in the on-shore and off- shore production of natural gas is found to be mainly responsible for the high demand in non-renewable fossil energy. Such huge impacts are avoided when biogas is used as fuel. Due to the type of electricity mix used at the processing plant facilities, the impacts from nuclear energy resources are considerable in the biogas results. Though the impacts from non renewable nuclear resources dominate the biogas results, their effects are not as high compared to natural gas.

More than 100% primary energy efficiency was achieved with refined biogas whiles a maximum of 80% was achieved with natural gas. The relatively high efficiencies from biogas are due to the fact that the energy content of the biomass is not taken into account by the inventory. The second reason is that the energy invested in the infrastructure for natural gas, for example long distance pipelines from exporting countries to Switzerland, is well avoided in the case of biogas because the production and transportation is within the confines of Switzerland. Consequently, a lower input to output energy ratio is obtained which shoots up the energetic efficiency.

With the impact category indicators, the refined biogas demonstrated clear advantages in terms of global warming potentials but considerable impacts from acidification and eutrophication. The endpoint indicators according to EI-99 also revealed that the use of biogas reduces the impact on resources by approximately 75%. Biomass acts as a CO_2 sink to mitigate climate change from this side. However, the emission of ammonia and sulphur dioxide into the atmosphere has damage on ecosystems quality through acidification and eutrophication potentials. Biogas production is a pragmatic way to avoid emissions of methane which would otherwise escape into the atmosphere if the biomass was land-filled hence presenting an opportunity cost.

Conclusions

Central to the question addressed in the research, is that integrated biomass-based micro CHPs are environmentally friendly. Indeed, even against the backdrop of some uncertainties in the qualitative results, the thesis sought to confirm the environmental and some social benefits from the use of bioenergy in support of indicators other than the chosen methodology. Compared to the grid electricity and gas boiler as the benchmark, the use of biogas in micro CHP applications greatly reduced impacts on energy resources and climate change. This is a step in the right direction and a point of departure for addressing energy and climate change issues. With respect acidification and eutrophication, the use of biogas demonstrated considerable negative impacts. However, the benefit from avoiding the decay of biomass in the field appears greater. Biogas also proved to have relatively higher primary energy performance factor than natural gas, representing a higher energetic efficiency.

Within the local and regional context, micro CHP and biogas development synergies have the tendency to ensure energy security and reduce the over-dependence on fossil resources thus creating “energy self-sufficiency”. In spite of its ability to positively or negatively influence consumer behaviour, biomass-based micro CHP exhibit the potential to create jobs and income in a local canton whiles more or less, creating pride and prestige among the pioneers of the technology adopters. In the short to medium term, biomass-based micro CHP may not have any authentic influence on fuel and electricity prices in Switzerland. However, if policy interventions in the form of tax and fiscal incentives are put in place, it could lead to a widespread adoption of biomass-based energy systems considering the high installation cost of micro CHP devices. Ultimately, the potentials exist to improve access to local information whiles strengthening inter-sectoral cooperation among different stakeholders if suitable policy tools are implemented.

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1 Introduction

Energy plays an important role in the development and welfare of human societies. Energy is needed for domestic, industrial, commercial and transport activities and its consumption is growing steadily at the global level (European commission, 2005). The current conventional ways of producing and using energy have the tendency to accelerate environmental damage, increase inequity and jeopardize global economic growth if certain changes are not pragmatically implemented (Goldemberg and Johannson, 2004). The world is plagued with local, national and global environmental problems associated with conventional energy systems (Goldemberg and Johannson, 2004). Other challenges that need equal attention are the security of supply and the high cost of energy prices in some countries, not to mention the two billion people in the world with no access to reliable electricity (Goldemberg and Johannson, 2004). Recent developments in the energy sectors are however changing the customary principles of ownership, operation, management and financing of energy utilities (Goldemberg and Johannson, 2004).

In many industrialized countries, electricity is traditionally produced by large centralised power plants. Centralised power production stations are usually sited near energy resources; chiefly coal, natural gas and oils from which fuels can be obtained- or hydro, and nuclear reactors. In this setting, the electricity generated is distributed via a central grid through transmission lines to the end-users. This traditional energy system is vulnerable to a wide range of failure in this era of attacks and natural catastrophes (Greenpeace UK, 2006). It greatly contributes to climate change as well as being highly inefficient. For instance centralised power distribution is associated with power losses through long distance transmission and a high cost in maintaining the power distribution networks- through the use of transformers[1]. The heat or thermal energy that is released during the production of electricity also often goes as waste although in some countries, for some parts of the year it is used for district heating in a combined heat and power system.

One way of ensuring efficient and reliable supply of energy is to decentralise its generation. Decentralised energy (DE) is however seen as a possible step towards sustainable energy future since it could help reduce greenhouse emissions, reduce grid loads and widen the scope for renewable energy utilisation (Pehnt et al., 2004). The emergence of small scale privately owned electric utility industries using biomass is one pathway that can allow power providers to produce electricity close to the end user rather than the source of fuel. The technical and economical feasibility of using renewable energy carriers coupled with the new developments and technologies have led to a shift in the economies of scale in recent years (Koeppel, 2003). Some of the technologies that are already available include fuel cell, photovoltaic, combustion engines, micro turbines to mention only a few. Decentralised energy supply play vital roles in increased power security and reliability and as a suitable option for local electricity network expansion.

On the supply side, a wide range of options do exit for the combined provision of home electricity and heat and the integration of renewable energies (Dorer, Weber et al. 2005). Economically CHP is attractive for decentralised energy generation. The attractiveness is manifested through the avoidance of cost for transmission and distribution. The ability to use waste heat improves the overall efficiency of the system. Again such systems have the advantage of being sited close to alternative fuel source such as biogas facilities. In view of this decentralised CHP systems could also be considered to have positive local and regional

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[1] Transformers are devices used to either step up or step down the voltage of electric current.

socioeconomic implications such as: (1) lowering consumers' energy cost, (2) creation of sustainable economic growth and jobs and (3) more importantly addressing climate change issues.

The implementation for small-scale distributed CHP is becoming widespread in some parts of Europe; e.g. the Netherlands, Germany and U.K (Cogen Europe, 2005). This is favoured by concrete governmental policies. Current EU regulations on energy promote the use of cogeneration as an effective means of achieving the Kyoto target (Uyterlinde et al., 2002). Other non EU member countries have redefined their energy policies to focus on energy efficiency and promote renewable energy utilisation. According to Van herle et al., (2004), green electricity is being promoted within the EU. With the emergence of decentralised generation, biogas presents itself as an attractive fuel source and demonstrates some advantages over natural gas (NG) (Van herle et al., 2004). Biogas production itself is seen as an environmentally friendly way of managing waste stream. The drawback of biogas form a systems' perspective is that the fresh gas contains impurities which could affect the performance of energy systems.

In relation to the goals of sustainable development, Switzerland has introduced stringent policies to reduce its energy consumption and per capita CO_2 emissions (Pfeiffer, Koschenz et al. 2005). The major parts of the Swiss energy policy as defined in the Swiss Energy Action Plan is energy efficiency in the building (residential and commercial), industrial and transportation sectors and the promotion of renewable (IEA, 2003)[2]. About 50% of the total primary energy in Switzerland is ascribed to all buildings; heating, air-conditioning and hot water constitutes 30%, electricity 14% and the remaining 6% is for construction and maintenance (SFOE, 2006). The fact that the buildings sector currently accounts for some 50% of overall gross energy consumption makes it necessary hub for energy-saving strategies (Pfeiffer, Koschenz et al. 2005). In this regard, and towards for a sustainable energy future, Switzerland has implemented a programme dubbed "energy and building technology for a 2000W[3] society" (Dorer, Weber et al. 2005; Pfeiffer, Koschenz et al. 2005). According to Spreng et al. (2002) a primary energy threshold equivalent to 2000 W per person, is suitable indicator for assessing sustainability.

Given the relevant positive effects associated with the emergence of decentralised CHP system coupled with the possibility to run on renewable sources of fuel, some important questions that can be raised are: "what is its performance in terms of efficiency? Does it really help to reduce environmental impacts? Is it really cost effective? What could be the socioeconomic advantages? Etc". While many questions can be raised they all cannot be covered at this time, or in a work of this size. However, in an attempt to assess the potentials of decentralised energy systems this study uses Swiss building stock as the main focus. Previous studies on the performance of fuel cell–based micro CHP with NG in Swiss residential buildings shows a reduction in non-renewable primary energy demand and CO_2 emission for all building types (Dorer et al. 2005). This paper therefore builds upon the performance assessment of micro CHP technologies and their integration into the Swiss residential building stock by refining the methodology of the previous study to include an internal combustion engine and biogas fuels and to a lesser extent outline its socioeconomic potentials micro CHPs in Switzerland.

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[2] Energy Policies of IEA countries, Switzerland. 2003 review.

[3] The 2000 Watt Society is a vision introduced by the Board of the Swiss Federal Institutes of Technology aiming at a sustainable society regarding ecological, economic as well as societal aspects. It postulates a total primary energy consumption limit of 63 GJ per capita and year, which equals an average power consumption of 2000 watts per capita. Currently, the average Swiss consumes about 6600 watts of primary energy.

1.1 Purpose and objective of the study

The purpose of this study is to assess the performance of biogas in decentralized micro-CHP system in residential facilities and outline the potentials for Switzerland. The biogas performance will be assessed in terms of efficiency and environmental impacts. The objective of this study is therefore to find out how micro-cogeneration units perform with biogas with respect to primary energy efficiency and environmental impacts.

The research questions to be answered are:

1. What is the performance (environmental and efficiency) of micro CHP units running on biogas fuel?

2. What are some of the socio-economic advantages and challenges at the regional and national levels for residential micro CHP systems?

1.2 Scope and limitations

A complete study of future energy scenarios demands thorough investigation into systems analyses and countrywide boundary conditions. However, this thesis cannot and will not cover the many topics. This thesis builds on a previous study on the performance assessment of fuel cell-based micro CHP applications. In order to establish a bottom- up approach for future analysis of the performance of biomass-based polygeneration in Switzerland, this study concentrates on energy decentralisation at the household level. The study is limited to a few possible scenarios for fuel cells and reciprocating internal combustion engines in micro CHP applications and their integration into residential family houses. Two out of the three building types in Switzerland are investigated. While desirable there will be no establishment of additional computer simulations due to time and resource availability within this project. The case scenarios are modelled based on existing data in the ecoinvent[4] database as well as the results on the performance assessment of fuel cell-based microchip application (Dorer et al. 2005). It must be acknowledged that while these micro CHP scenarios maybe indicative of the general characteristics to some extent, each technology has unique characteristics and therefore the cases under consideration may not necessarily be a representative of all decentralised micro CHP systems.

1.3 Research methodology

In presenting a theoretical basis for this thesis a literature review summarising the key aspects of Swiss energy and micro CHP applications was carried out to respectively identify the energy policies and consumption patterns as well as the energetic and environmental aspects of micro CHP applications.

The second phase of the thesis involved modelling of energy scenarios with biogas and NG for Swiss residential buildings using life cycle application software. Here a "cradle to grave" analysis for meeting household energy demands was performed. The purpose of this section is to provide an understanding of input and output energy flows and the impacts associated with the delivery of energy. Using the net household energy demand as the starting point, the dynamic simulation results from their previous study were transferred to new configurations whose delivered energy were then estimated. The share of the heat provided by the gas boiler was also estimated. The estimated delivered energies were used establish life cycle models for

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[4] Ecoinvent (2005) ecoinvent centre, ecoinvent v1.2, Swiss centre for Life Cycle inventories, Dubendorf, Switzerland, 2005. Online version: http://www.ecoinvent.ch

biogas and natural gas chains existing data in ecoinvent database. The environmental burdens associated with the delivery of energy were thus calculated. While it was not the intention of this study to conduct a socio-economic survey for decentralized energy systems (for example using structured questionnaires), a number of issues were examined in order to provide some idea of the relevance of such power supply changes in the social context (i.e. the context of the potential users and beneficiaries).

1.4 Outline of the thesis

Following this introduction, the thesis is arranged in six chapters covering the performance of biogas and natural gas in micro CHP applications. Chapter two gives the background of decentralised energy systems, energy consumption in Switzerland and a brief introduction to the various micro CHP technologies. Chapter three presents the problem formulation, the methodology for estimating the delivered energy for domestic buildings and the life cycle assessment methodology for natural gas and biogas. The results of the different impact categories from the life cycle assessment are presented in chapter 4. The next chapter discusses the energetic and environmental impacts of micro CHP applications based on the results. It outlines the aspects of biomass-based micro CHP from the socioeconomic perspective. A final chapter draws conclusions from the study and presents an outlook based on the authors' own reflections.

2 Background

Technological advancement in decentralised energy systems coupled with the fact that it is gaining recognition has led to the evolution of various publications in literature. As a result, a number of terminologies have been used to refer to decentralised energy generation; including distributed generation, embedded generation, micropower, small scale production, on-site generation, etc.(Dunn, 2000; Ackermann et al., 2001; Bruckner et al., 2005). These 'loose' terminologies are sometimes used interchangeably to mean different energy systems, hence a difficulty in assigning a single concise definition. Bruckner et al., (2005) confirms the difficulty to concur a single concise definition and proposes two approaches; to supply selection standards based on scale, placement, ownership and operational authority or to list representative examples based on engineering design and product stream. Although it is not the intension of the study to harmonise the definitions for decentralised energy systems, a working definition is needed in order to stay within the limits of the subject matter.

In essence, decentralised energy systems can be categorised as either thermal (wood pellets, solar thermal, and heat pumps) or electricity (photovoltaic, hydropower, wind) or CHP (fuel cells, Stirling engines, micro turbines). In this vein, Ackermann et al. (2001) defined decentralised generation as *"the installation and operation of electric power generation units connected directly to the distribution network or connected to the network on the customer side of the meter"*. Though the drive for this definition is based on the core idea of locating energy generation close to the end user, Koeppel, (2003) identified the lack of concrete information such as technology and power rating, environmental impacts and mode of operation. It is however difficult to give a concise definition that incorporates all these information.

Decentralized CHP applications can also be categorized according to their power ratings. Again, there are different views, though, as to the real power ratings of these categories. Different manufacturers give different categories to their products. This could be partly due to the fact that diverse terminologies that can be used to describe decentralized energy systems. A category used by Ackermann et al. (2001) and Koeppel, (2003) is as follows; "Micro generation: < 5 kW; Small- scale generation: 5 kW-5 MW; Medium generation: 5 MW-50 MW; Large generation: >50 MW".

Pehnt et al. (2005) also classified micro CHPs as units with less than 15 kWh power rating. Some categories put micro- and small- units together as domestic CHPs and merge medium- and large- as industrial CHPs. Within this thesis it is deemed that the working definition for decentralised energy systems will be considered to have power ratings of 1-2 kWel and less than 5 kWth connected to the customer side of the meter.

In order to get a clear picture of what this study is about and the different forms of decentralised energy system, a simplified model of decentralised energy systems will be presented in figure 2-1. The model presents decentralised systems as the core with three energy generating possibilities. The system can be power-driven, heat driven or both. For this thesis, decentralised micro CHP system is of particular interest.

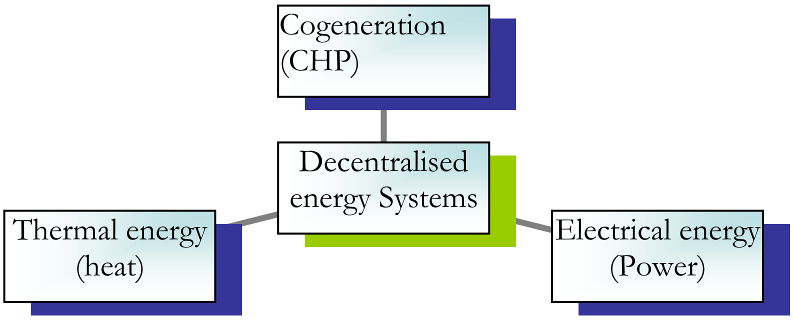

Figure 2-1 Simplified view of the basic forms of decentralised energy system[5]

At present, most of the existing decentralized energy systems in residential buildings are not entirely autonomous. In almost all cases, and at least for the current domestic decentralised applications, they are integrated to supplement the energy demand; particularly heat, in addition to gas boilers. Excess electricity can be fed into the grid system to give a load relief during peak demands. Figure 2-2 below depicts a simplified system of integrated micro CHP unit in a residential facility with centralized grid power. To date, most of these residential micro CHP energy systems are in the R&D phase in some parts of Europe, Japan and the US (Cogen Europe, 2005). For this thesis, decentralised energy will be deemed to consist of a micro CHP unit, fed with fuel gas distribution networks, and are sited at or close to the point of use.

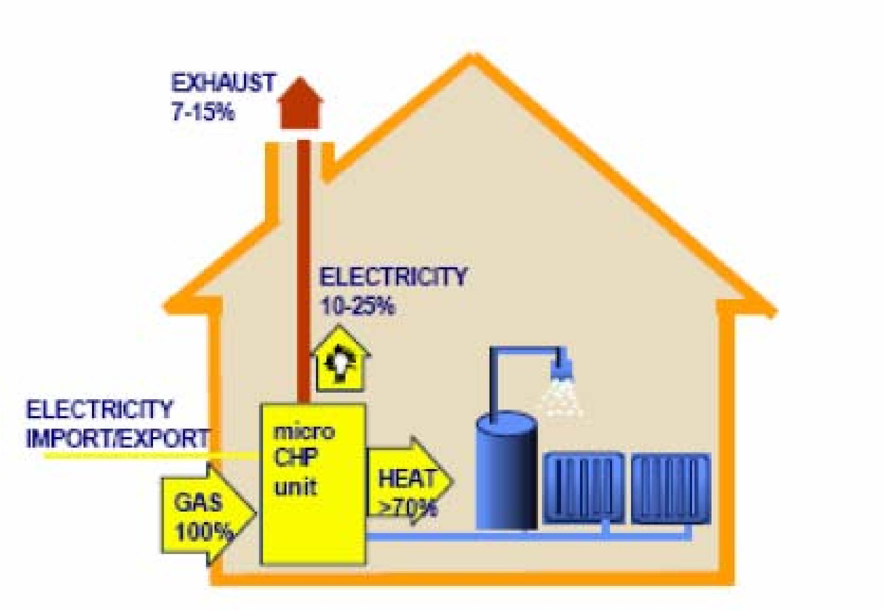

Figure 2-2 Conceptual visualisation of residential micro cogeneration energy system

(Source: MicroMap 2002)

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[5] Developed by author.

2.1 Micro-cogeneration systems

2.1.1 General

Micro-cogeneration is the concurrent production of small energy units of power (1 - 5 kWe) and heat in a unit building (Harrison and Redford, 2001). It is believed to be an efficient, clean and reliable method of generating electrical power and thermal energy from a single fuel source. The electricity produced is used within the building and the excess is fed into a central grid whereas the heat is for water and space heating. Nearly always, there will be a lack of heat demand during summer which reduces the overall efficiency down to the electrical efficiency. Thanks to the presence of absorption and electric chillers which can utilise this unwanted heat to produce cooling (polygeneration) - thus a potential displace air conditioners running on electricity.

Micro-cogeneration can be used in residential, commercial, institutional and industrial facilities. The diverse conversion technologies that have evolved for domestic settings include reciprocating internal combustion engines, Stirling engines, low- and high-temperature fuel cells and micro gas turbines (Pehnt et al., 2005). In CHP systems, the overall efficiency of energy conversion increases to over 80% as compared to an average of 30–35% in conventional fossil fuel-fired electricity generation systems (Onovwiona and Ugursal, 2006). This remarkable increase in efficiencies greatly reduces the consumption of fuel resources. Some models of micro CHP units for residential facilities have been developed. Fig. 2-3 (a and b) show some examples of micro CHP units that are used in domestic family dwellings.

(a) Combustion engine

(b) Fuel cell stack

Figure 2-3 (a and b) Examples of a micro CHP unit for single and multifamily houses

(Sources: www.micropower.co.uk, 2006; SFOE, 2006)

Demonstrating the ability to produce higher useful thermal and electrical energy from a single fuel source, micro CHP system are gaining widespread potential use in the residential sector (Onovwiona and Ugursal 2006). That said, the rationale for household cogeneration coupled with the integration of renewable energy sources has led to the recent development of diverse conversion technologies which is applicable to the domestic sector. In addition, the diffusion of micro CHP is defined by their techno-economic, environmental, and market prospects. The level of emergence of micro-CHP system is varied depending on the system and the boundary conditions (Pehnt et al., 2004). For example, while fuel cell-based technologies are in the R&D phase, reciprocating and Stirling engines are at the market threshold. Pehnt et al., (2004) compared the different conversion technologies based on some selected criteria. Table 2-1 displays the characteristics of some of the micro CHP technologies based on their techno-economic, environmental, and market prospects.

Table 2-1 Characteristics of some micro-cogeneration technologies

Conversion technology	Electrical efficiency	Total efficiency	Noise level	Pollutant emissions	Fuel flexibility	Market availability	Economic viability
Reciprocating engine	20-25	>85	Medium	High	Medium	Commercially available	Applications with high operational hours and electricity demand
Stirling engine	10-14	>85	Low	Low to medium	High	Near to market	-
Fuel cell	28-35	80-85	Low	Zero to almost zero	Medium	Pilot plants and R&D	High cost reduction necessary

Source: Pehnt et al., 2004

It is clear from table 2-1 above that fuel cell technology demonstrates superiority in terms of electrical efficiency and emissions but it is not economically viable. However, with a rather high environmental disadvantage, reciprocating engine exhibit better techno-economic and market prospects.

2.1.2 Benefits and barriers of micro CHP systems

Some questions that automatically arise is that "if micro CHPs have a great deal of potential in saving energy through improved efficiencies, why then is it still rare? Why are people still dependent on expensive and unreliable centralised power plants?" Just as any system, micro-cogeneration systems have some benefits and barriers (Dunn, 2000)[6]. Some of the benefits of micro-cogeneration systems are highlighted below;

1. Micro CHP greatly reduces the burden on the environment in terms of emission due to its improved efficiency compared to the separate production of heat and electricity.

2. Compared to larger centralised plant, micro CHP systems can be said to have a short lead time, thus the planning, positioning and building of small scale plants can be more rapid and reduce risk.

3. Micro CHP systems can utilise oil, natural gas, biogas among others as fuel. The diversity of its fuel mix lessens the demand and price fluctuation of fossil fuels.

4. They can be reliable because all the individual systems cannot fail at the same time, thus ensuring power security. They are easily maintained and widely dispersed making them suitable for hospitals, schools, hotels and other commercial buildings.

5. Micro-CHP allows individuals and the local community to select the type of energy system based on the type of fuel available locally. In the case where the feed-in-tariff is

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[6] For more information, refer to Dunn, S,. Research associate. Making way for micropower. World watch institute, DC

higher for electricity generated from renewable energy, individuals can make profit by selling their excess to the public grid.

6. The design and manufacture of micro CHP units makes them modular and easy to retrofit. It uses modules which can be interchanged as units without disassembly of the module. In that sense, the power rating can be adjusted through retrofitting to meet required energy demands (Dunn, 2000).

However, very significant barriers also must be recognized and help explain the drawbacks of development and diffusion of micro CHP technologies.

1. Micro CHP units are expensive to install and requires a high initial capital cost. The cost per kilowatt-hour for utility power from the grid is usually lower than the cost of installing micro CHP plant. Although there is a potential to reduce energy cost when installed, the initial set up cost may serve as a deterrent to potential home owners who would want to install such system in their homes.

2. There is little or no incentive for relieving peak loads in most cases. Rather, in countries like the US where a few micro CHPs already exist, customers are faced with unfair standby charges, exit fees and transitions costs. This does not serve as a drive for other potential customers (Dunn, 2000).

3. Micro CHP will not be economically viable and environmentally friendly in locations with high heat demand in comparison with a large district CHP (Pehnt et al., 2004). Reciprocating engines which are the only commercially available micro CHP are associated with high acidification and eutrophication potentials. Compared to centralised plants which produce localised point source pollution, the use of reciprocating engines for example, will imply distributing the emissions over the entire area.

4. The over-dependence of the current and future micro CHPs on NG as the source of fuel does not auger well for the sustained utilisation of fossil resource. The widespread use of micro CHP will put undue pressure on the finite fossil resources. The alternative use of renewable fuels is still in R&D stage and has not hitherto been fully established.

2.1.3 Who are the actors involved?

Technology development is inspired by the actions and interactions of the various societal actors (Pehnt et al., 2004). The major actors at the extremes are the manufacturers and the end-users. In between these two extremes falls the network of other actors. The end-users of a technology play a very vital role in the network of actors because their demand patterns have a great influence on the supply. The demand for micro CHP is determined by the level of comfort and affordability or purchasing power of the customers (Meijer, 2002). In the Netherlands for example, the social housing organisation, (the owners and building companies) decides which energy technology to apply (Meijer, 2002). Meijer, (2002) emphasizes that it is easier to stimulate the housing organisation to resort to the use of micro-CHP technologies more especially when the necessary policies are in place. This may however differ by country according to the pertaining legislative instruments. For example in Germany, the national government plays a leading role in the diffusion of micro CHP plants through the German legislation (Pehnt et al., 2004).

The actors who can influence the development and diffusion of micro CHP include tenants, energy companies, national and local governments, suppliers and manufactures of micro CHP systems, consultancies, contractors and electrical dealers. Figure 2-4 below displays the different actors in the diffusion and adoption of micro CHP technologies.

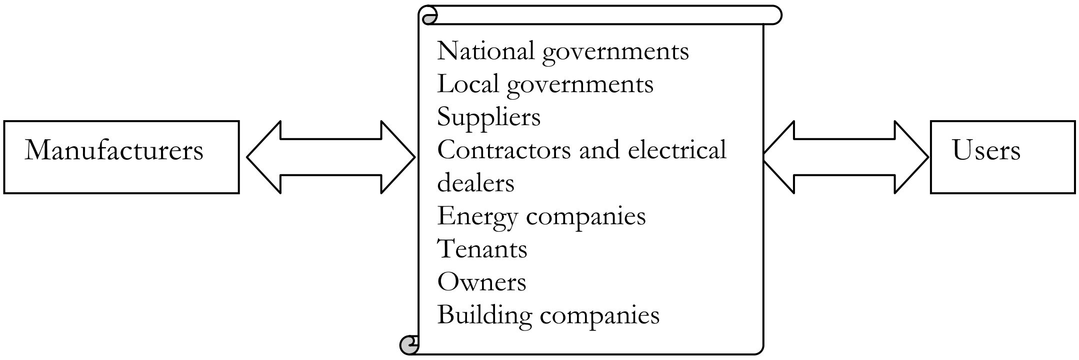

Figure 2-4 Different actors involved in the development and diffusion of micro CHP systems[7]

2.1.4 When could all this happen?

The current trends of innovations make the advent of micro CHPs inevitable. The transition from monopoly to competition in the energy market is becoming rapid and hence the liberalization of energy markets coupled with new profitable opportunities provide a drastic phenomenon to consider alternative forms energy production. For instance, Cogen Europe[8] (1999) has calculated that the technical potential of small scale engine is 3000 MWe on a total of 270 000 sites in the UK market. In a liberalized market, energy utility companies can maintain their existing customers and even gain new ones by way of switching to delivering micro-CHP products and services. This, of course will depend on how well information on micro-CHP systems is disseminated to the customers and how affordable the systems will be on the energy market. In Germany the general institutional framework for micro CHP has considerably improved after liberalising her energy market through the German legislation (Pehnt et al., 2004). Further, these technologies will go a long way to ensure secure and reliable supply of energy to urban, suburban and rural communities.

Secondly, there is an escalating ecological and environmental pressure to minimize CO_2 emissions. Some advanced countries are restructuring their energy polices in particular to meet their Kyoto targets. Cogeneration installations can result in CO_2 emissions reduction of up to 50% when compared to separate production of heat and electricity (Cogen Europe, 1999). In addition to the potential for energy savings in decentralized micro CHP applications, the negative environmental impacts of high-tension voltage transmission lines, which include visual pollution and radiation concerns can be addressed. According to Cogen Europe (1999), decentralized cogeneration is the most cost effective way to produce energy while reducing greenhouse gases.

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[7] Model developed by author

[8] Future Practice Report no. 32, Drummond Hislop, ESD under contract to ETSU on behalf of EEO of DOE, January 1993

In spite of the dynamisms in distributed energy technologies, society has its own pace with accepting such technologies. As it has always been the case, distributed energy technologies will only find its way to the society if it is backed by the right policy, informative and economic instruments. For example, as it is happening in Germany at the moment, the legislative instrument has enhanced the economic opportunities of micro CHP plants by introducing bonuses for electricity fed into the grid and electricity and natural gas tax exemptions (Pehnt et al., 2004). Since the current environmental policies are geared towards mitigating GHGs and conserving resources, micro-CHP applications can be said to be in its take- off stage.

2.2 The Switzerland case

Within the EU community and the member state level, there is an urgent need to actively promote energy efficiency in the light of Kyoto agreement to reduce CO_2 emissions. The expected benefits include positive environmental impacts, energy supply security and sustainable energy policies among others. The EU Kyoto commitment has aims to avoid 65 Mt CO_2/year by 2010 by doubling the use of cogeneration to 18% of EU electricity production by 2010 (Cogen Europe, 1999)[9]. Switzerland is not part of the EU member countries and does not automatically apply EU policies but some of its energy policies are in line with the development in the EU. According to the its energy action plan, Switzerland has a Kyoto target of 8% reduction in greenhouse gas emissions from 1990 levels in the first commitment period from 2008-2012 (SFOE, 2006).

There has been an anticipated gap in the Swiss electricity supply of 27 TWh by the 2030, due to the phase out of all Swiss nuclear power plants and the simultaneous expiring of contracts for the import of electricity from France (Verband Schweizerischer Elektizitätswerke[10] in Dones et al., 2006). The extended use of cogeneration and the widespread use of renewable energies have been proposed as one of the possible alternatives to achieve a 2000W society,[11] to cater for the anticipated future energy gap and improve ecological performance. Like many other European countries, market liberalisation of power systems is gaining political concern and customers will soon be allowed to choose their power utility suppliers (Wustenhagen, 1998).

In the light of the above scenarios coupled with the vision towards a 2000 W society, the attractiveness of biomass-based micro CHP integrated in the Swiss building stock is being investigated.

2.2.1 Swiss power system and energy policy

Switzerland has a population of about 7.4 million[12]. The country's electricity system is chiefly based on hydro and nuclear power generation. Electricity accounts for 22% of Swiss final energy consumption (Wustenhagen, Markard et al., 2003). With a per capita consumption of 7.380 kWh, fairly above the EU average of 6.063 kWh, the annual electricity production in 2000 was 65 TWh and the total domestic consumption was 56 TWh (BfE 2001 in (Wustenhagen, Markard et al., 2003). The Swiss electricity grid is part of the Union for the

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[9] European Cogeneration Review, July 1999.

[10] Verband Schweizerischer Elektizitätswerke (VSE), "Vorschau 1995 auf die Elektizitätsversorgung der Schweiz bis zum Jahr 2030", VSE, Zurich (September 1995)

[11] Basic energy per capita that is required to ensure continuous economic prosperity (Pfeiffer et al, 2005)

[12] Swiss Federal Statistics office. [Online]. Available: http://www.bfs.admin.ch/bfs/portal/en/index/themen/bevoelkerung/stand_u_struktur/blank/kennzahlen0/bevoelkerungsstand.html 2006-08-31

coordination and transmission of electricity (UCTE). Switzerland is strongly involved in international electricity trading with France, Germany, Italy and Austria. The Swiss electricity consumption has been growing since the 1990s. Figure 2-5 displays the growth pattern of the Swiss electricity consumption.

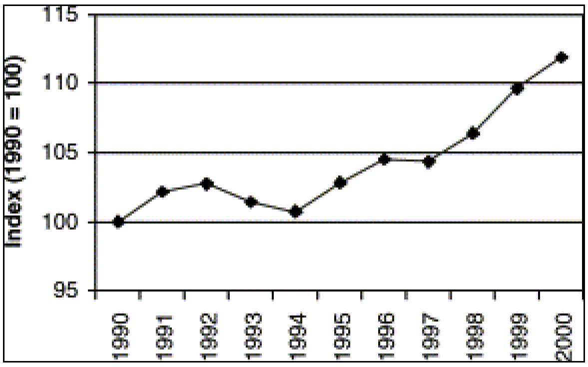

Figure 2-5 Growth in Swiss electricity consumption

Source: BfE 2001 in (Wustenhagen, Markard et al., 2003)

The "Swiss Energy 2000 Action Plan," whose aim is to stabilise electricity consumption and to reduce fossil fuel consumption and CO_2 emissions beyond 2000, is the core of Swiss energy policy (IEA 1998). The legal instrument binding the energy policy in Switzerland is defined by the integration of the energy article in the Swiss Federal Constitution, the Energy Act, the CO_2 Act, the Nuclear Energy Act and the drafts of the revised Electricity Act and the proposed new Electricity Supply Act (SFOE, 2006). Decisions on energy-related measures are however taken at the municipal, cantonal and federal levels, in that order. The requirements in the energy policy place much responsibility on the federal and cantonal levels as they are expected to use their capabilities to ensure economical and environmentally sound supply and efficient utilisation (SFOE, 2006). The drawing of energy legislations and regulations is the responsibility of the cantons. Coming into force in May 2000, the CO_2 Act in Switzerland requires companies and private individuals to take voluntary measures to achieve the targeted CO_2 reductions. The current energy policies are geared towards meeting Switzerland's energy and climate objectives, promote the use of new renewable forms of energy and lessen the degree of dependence on fossil fuels (SFOE, 2006).

2.2.2 Energy consumption

Energy is used for cooking, heating, cooling, lighting, transporting, machinery, to mention only a few. The different sectors that consume energy include transportation, residential, agricultural, industrial, commercial and public, and others. The sources of energy in Switzerland are nuclear, fossil fuels, hydroelectric power, and other renewable sources. The fossils include coal and coal products, natural gas, and crude oil. Fossil fuels constitutes about half of the total energy consumption followed by nuclear. The renewable sources include, primary solid biomass (includes fuel wood), biogas and liquid biomass, geothermal, solar and wind. Primary solid biomass constitutes about 80% of the total energy from renewable sources. Figure 2-6 below shows the energy consumption in Switzerland by source from 1971 to 1999.

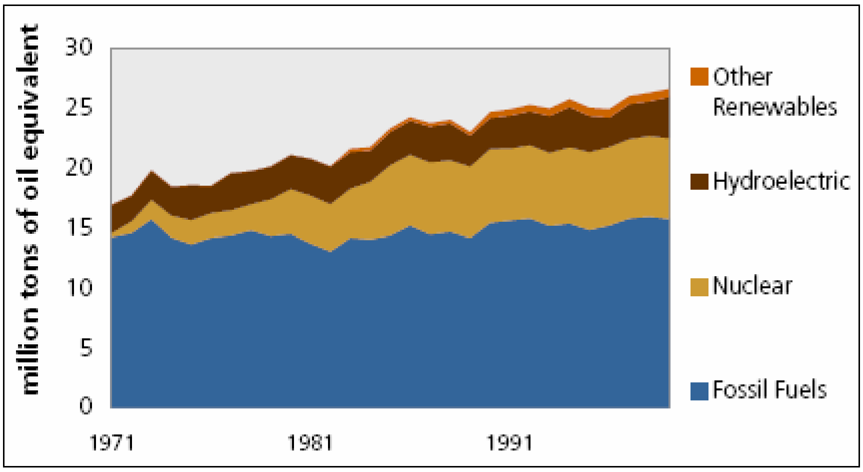

Figure 2-6 Energy consumption by source, Switzerland, 1971 to 1999

Source: Earthtrends, 2003

The share of renewable in the Swiss end energy consumption in 2004 was 16.52% out of the total of 877 290 TJ energy consumed (SFOE, 2006). More than two- thirds of the total renewable consumption is through electricity and this is due mainly to the relatively high proportion of hydropower in the Swiss electricity mix. The total consumption of renewable heat is less than a third of the total renewable energy consumption. Fig 2-7 below shows the breakdown of the 2004 Swiss end-energy consumption with the proportion of renewable energy.

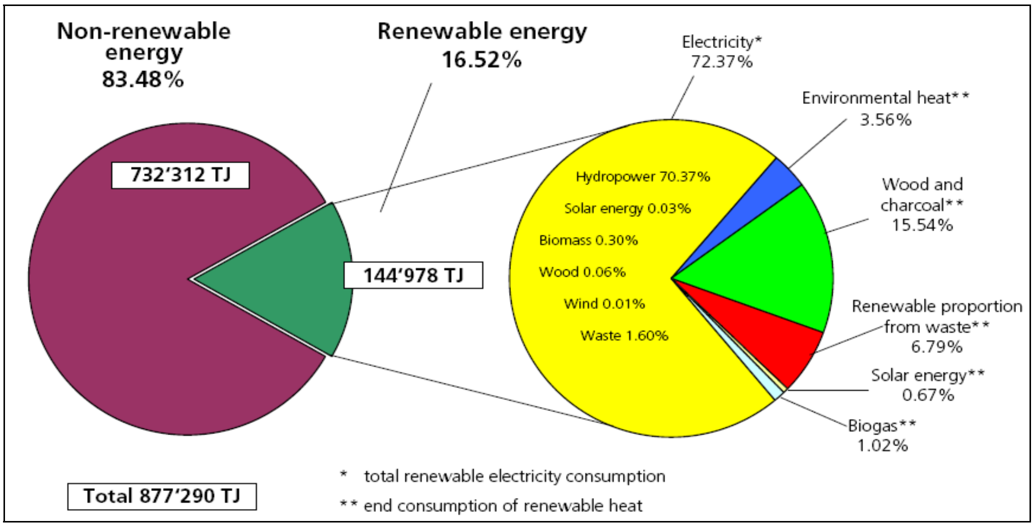

Figure 2-7 2004 Swiss end energy consumption with proportion of renewable energy

Source: SFOE 2006

Sector-wise, the transportation sector consumes about 33% of the total energy in Switzerland. This is followed closely by residential with 28% (Earthtrends 2003). Together, they constitute over 50% of the total final energy consumption of about 21 415 Mtoe. Domestic end-energy consumption raised to more than 56 TWh in 2004, with households, industry and the service sectors each accounting for one-third of this total. In 2004, the proportion of electricity to overall energy demand was approximately 23% (SFOE, 2006).

About 50% of the total primary energy in Switzerland is ascribed to all buildings. Heating, air-conditioning and hot water constitutes 30%, electricity 14% and the remaining 6% is for construction and maintenance (SFOE, 2006). The fact that the buildings sector currently accounts for some 50% of overall gross energy consumption makes it necessary hub for energy-saving strategies (Pfeiffer, Koschenz et al., 2005). The efficiencies in these sectors are key areas in the Swiss Energy Action Plan. Figure 2-8 shows the sector-wise distribution of the final energy consumption in Switzerland in 2003.

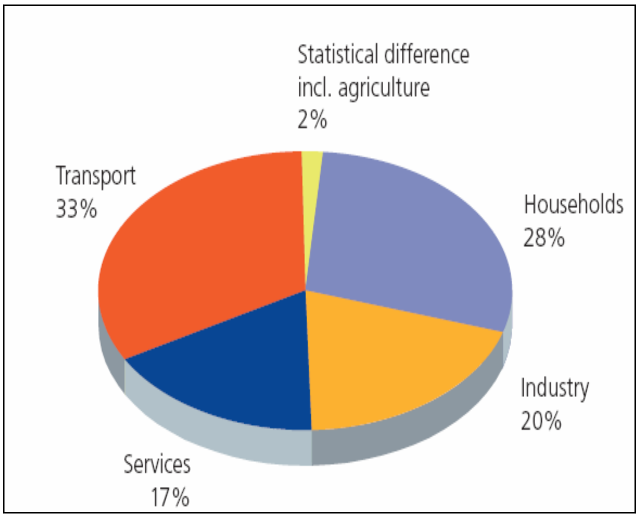

Figure 2-8 Final energy consumption in Switzerland in 2003 by consumer groups

Source: Swiss Energy Statistics 2003

2.2.3 Current situation of distributed energy in Switzerland

The overall electrical power production in Switzerland in 2002 was 65011 GWh. This is divided into 56.2% hydropower, 39.5% nuclear and 4.35 conventional and other renewable power plants (Koeppel 2003; Swiss energy statistics, 2003). 1.39 % of the total electrical energy is from renewable sources other than hydro. Though renewable, there is still a debate going on about the environmental subtleness of hydro power in Switzerland. Koeppel (2003) outlined the distribution of all renewably produced electrical energy apart from hydro and how their shares have increased from 1990 to 2002. Although hydro power is a renewable source of energy, it is not considered environmentally benign by all stakeholders and unlike new renewable (solar, wind, biomass), there is little room for new hydropower generation facilities in Switzerland (Wustenhagen, Markard et al., 2003). In the wake of ageing nuclear plants and the possibilities of terminating electricity purchasing agreement with France as emphasized in the Energy bulletin (2006), decentralised cogeneration seems to be an alternative option for Switzerland.

In the year 2002, about 1000 CHP facilities including biomass plants with rating capacities of 350kWe to 1MWe were in operation in Switzerland (Koeppel, 2003). The smaller installations operate mainly at waste water treatment plants whiles the larger CHPs are operated by industries. There is a clear evidence that the number of CHP installations, particularly below 1 MWe, have increased dramatically over the past decade. This could be due to the ease with which smaller installations could reach economies of scale. The reported data however focused on small and medium cogeneration (Koeppel, 2003). The share of micro-CHP at the residential building level has however not been outlined. Table 2-2 presents increment in electrical power produced from renewable sources in Switzerland from 1990 and 2002

Table 2-2 Electrical power produced from renewable sources in Switzerland in 1990 and 2002

Technology	1990 GWh	%	2002 GWh	%	Increment %
Total	438.9	100.00	900.7	100.00	105.2
Photovoltaic	1.1	0.25	13.8	1.53	1154.5
Biomass	7.2	1.64	27.6	3.06	283.3
Wind energy	0.0	0.0	5.4	0.6	-
Solid waste	372	84.76	745.6	82.79	100.4
Liquid waste	58.6	13.35	108.2	12.01	84.6

Source: Koeppel, 2003

2.3 Natural gas in Switzerland

Natural gas is a very important component in the Swiss energy mix. It contributes about 12% to the country's energy consumption with households representing the largest share of 40% (SFOE, 2006)[13]. According to 2003 estimates, Switzerland consumes about 3.2 billion cubic meters on natural gas annually (World Bank, 2006)[14]. Switzerland relies exclusively on imports to meet its natural gas requirements. The country currently imports 45% from Germany, 22% from the Netherlands, 16% from France, 13% from Russia and 4% from Italy (SFOE, 2006). Currently, natural gas is only being exploited for mainly heating and cooking. The use of natural gas in electricity generation is not being subjugated in Switzerland. The potential to use NG in the future for electricity production and the extent to which it will be used could determine its development in Switzerland. Among the fossils natural gas is considered to have the highest hydrogen and the least carbon which gives it the ability to reduce CO_2 emissions by a quarter to that of gasoline (Riva, D'Angelosante et al., 2006). Natural gas can therefore be seen as an alternative for countries to meet their Kyoto targets. It is in the agenda of the Swiss federal government to promote the use of natural gas and biogas as a motor fuel. The import and distribution of natural gas is summarized in table 2-3 below.

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[13] Swiss federal office of energy. [Online]. Available: http://www.bfe.admin.ch/themen/00486/00488/index.html?lang=en. July 5, 2006

[14] The World fact book. [Online]. Available: http://www.cia.gov/cia/publications/factbook/geos/sz.html. July 5, 2006

Table 2-3 Natural Gas in Switzerland in 2003

Unit: TJ - on a gross calorific value basis

Imports	122238
Domestic supply	122238
Total transformation	9622
CHP	9622
Distribution losses	852
Total final consumption	111764
Industry	36681
Commercial and public services	24835
Residential	44774
Other non-specified	5474

Source: adapted from the IEA Energy statistics[15]

2.4 Biogas in Switzerland

Biogas production in Switzerland started in the thirties where digesters were built to stabilise sewage sludge in wastewater treatment. Biogas has, over the past few years, achieved substantial recognition as a renewable energy carrier in decentralised CHP systems to meet local energy demand. The development of biogas technologies for the sake of energy production in Switzerland started in the 1970s with the installation of about 56 plants in the agricultural sector (Markard et al., 2005). Compared to Austria and Germany which started with the same technological idea, the diffusion of biogas in Switzerland has been confined to isolated experiments (Markard et al., 2005). The pursuit for profitability and efficiency has led to substantial improvement in the biogas technologies. A typical example is the development of the compact biogas plants by a company called Kompogas AG. Kompogas has at the moment installed 17 compact biogas plants and 13 larger, semi-industrial plants. The Kompogas plants, together with the agricultural biogas plant generate power amounting to 12 GWh per year (Markard et al., 2005). Van herle et al., (2004) pointed out that the different sources of biogas can potentially yield 57 PJ per year (6% of Switzerland's primary energy). The production and use of biogas in Switzerland demonstrates a rather high potential. Table 2-4 below presents the summary of the estimated theoretical biogas potential for Switzerland.

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[15] Full detailed time series are available from 1960 to 2003 for most OECD countries and from 1971 to 2003 for all other countries through our on-line data service at http://data.iea.org/ieastore/statslisting.asp

Table 2-4 Estimate of theoretical biogas potential for Switzerland

Source	Energy (PJ)	CH_4 (%)	Equivalent (m^3 per year)
Sewage	1.9	65	11
Industrial WW	2.3	65	13.5
Solids households	1.8	60	12.375
Solids other (industry and public)	1.1	60	7.65
Solids now incinerated	19.5	-	-
Solids in Landfills	0.5	55	-
Livestock	22.7	55	-
Solids agro residues	7.6	55	-
Total	57.4		44.5

Source: Van herle et al., 2004.

The realistic biogas potential is however associated with sewage waste water, solids (households, public and industrial) and agriculture (agro residues and liquid manure).

Markard et al., (2005) however identified that in spite of the high potential for biogas production in Switzerland, the rates of diffusion and adoption was however slow or constant. They proposed interventions that will positively affect the future diffusion of biogas in Switzerland. These include (1) the establishment of jointly owned and operated biogas plants; (2) the establishment of farm communities; and (3) the explicit inclusion of farmers in regional waste handling management systems.

Moreover, biogas producers are gradually infiltrating the political arena with support from the Swiss federal government. For example, in 2003, biogas producers and representatives of the gas industry signed a framework agreement according to which a volume of biogas equivalent to 10% of natural gas used in Switzerland as a motor fuel is to be purchased by gas suppliers and fed into the network (SFOE, 2006)[16]. Such favourable governmental policies will see a significant growth in biogas potentials.

2.4.1 Kompogas plant

Landfilling of combustible non-recyclable municipal solid waste (MSW) has been banned in Switzerland since January 2000[17]. All combustible non-recyclable MSW is therefore incinerated and the heat is recovered for district heating and electricity. Incineration is a cost to the waste generators (households and industries). The incinerating companies charge between 150 to 160 CHF per ton of all waste collected[18]. In a similar sense, the deposition of the slag in a residual-waste landfill is costly, since it contains environmentally damaging heavy metals[19].

Biogas production is essentially a friendly way to process waste streams of variable nature including (sewage sludge, liquid organic industrial effluents, farm residues, landfill, municipal

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[16] Swiss Federal Office of Energy (SFOE). Available at www.bfe.admin.ch/themn/00486/00488/index.html

[17] Federal administration, Department of the Environment, Transport, Energy and Communication, Federal office of the environment, Switzerland

[18] Personal communication with Rolf Wetter, Project manager at Kompogas AG.

[19] See 14

and industrial solid organic residues)(Van herle, Membrez et al., 2004). In spite of the negative aspects such as the potential for generating offensive odour and the high initial set up cost of the digester, the production of biogas can be beneficial from the environmental and socio-economic points of view. Biogas is produced for electricity, heat and fuel for vehicles and compost is obtained as a useful by-product which is a good source of fertilizer. Presently in Switzerland, a company called Kompogas AG is mainly responsible for commercial biogas production.

The Kompogas process was introduced in Switzerland over a decade ago. The process uses mechanical[20] and biological[21] methods to treat the biogenous portions of municipal solid waste (MSW).the systems are built on the basis of compact modular units which allow coverage of a large range of plant sizes and ensures high operational reliability. There are about 17 established Kompogas facilities at present. At a production capacity of 10 000 tons per year, the Kompogas plant produces surplus energy equivalent to about 660 000 litres of diesel fuel. One of such established Kompogas plants is the Otelfingen plant, situated in the eastern part of Switzerland. This plant collects wastes from agricultural waste mainly manure and organic waste from households, food industries and gastronomy for biogas production. In an effort to close the natural carbon cycle, the collection of biowaste is done by biogas powered trucks (picture shown in figure 2-9 below). Household waste constitutes about 30% of the total waste collected. The waste is sorted into different fractions (organics, plastics and metals) in the households but further sorting is done at the premises of the plant.

The biogas produced is used in a CHP system to produce heat and electricity. Additionally excess biogas is refined and used as fuel for vehicles. Part of the generated heat is sold to households within the vicinity of the plant whiles the remaining is used by the digester because the anaerobic digestion process is thermophilic[22]. The daily production of biogas is 6 000 m^3 which is equivalent to approximately 3500 litres of gasoline. The plant has a capacity of 30 tons per day. This yields 10m^3 of compost and 5m^3 of liquid fertilizer. It is estimated that 1 ton of input material yields an average of 110 m^3 of biogas. 30-40 kWh of electricity is used to process 1ton of biowaste which yields a total of approximately 240 kWh of electricity. In total, about 200 kWh of significant surplus energy is produced from 1 ton of biogenic input. The processing plant consumes about 20% of the electricity produced. The electricity produced from biogas is sold at CHF 0.15 per kWh (feed-in tariffs based on the “15-cent scheme[23]”).

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[20] The mechanical process consists of size reduction stage, the removal of ferrous metals and the separation of components that can be used for energy generation. The high thermal value fraction of the residual heat is separated from the biodegradable fractions.

[21] The biological treatment entails the fermentation process inside the fermenters based on anaerobic–thermophile dry fermentation for a period of 14 days.

[22] Requiring high temperatures for normal process development

[23] The ”15 cent scheme” is the average feed-in tariff for all independent power suppliers

Figure 2-9 Biogas powered truck for collection of waste at the Kompogas facility

Source: http://www.recyclenow.org/Report_IEA_Bioenergy_1MB.pdf

2.5 Brief summary of micro-CHP technologies

2.5.1 Reciprocating internal combustion engine

The reciprocating engine utilizes one or more pistons to convert internal pressure to rotating motion. In other words, a reciprocating engine converts chemical energy in fuel to mechanical power. The reciprocating engine applications are vigorous and well-built small scale CHP units similar to the ones in motor vehicles. The sizes of these reciprocating engines range from tens of kilowatts to about 10 MW and can accommodate a wide range of fuels (Orlando, 1996). The most common form of reciprocating engine is the reciprocating internal combustion (IC) engine. Reciprocating engines are classified according to their method of ignition: i.e. spark-ignition and compression-ignition as in Otto[24] and diesel engines respectively.

Diesel engines run on heavy oil or can be put on a dual fuel mode to accommodate natural gas and diesel simultaneously. They are suitable for large-scale CHP applications. The heat recovery potential for diesel engine is usually limited because the maximum attainable temperature is 85 ºC (the temperature of the engines' cooling system) (Onovwiona and Ugursal, 2006). Otto engines are well suited for small scale cogeneration units. They run mainly on natural gas although propane, gasoline and landfill gas can also be used. The heat recovery system produces about 160 ºC hot water (20 bar steam)[25]. Fundamentally, the

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[24] Otto engines are also called spark ignition engines and diesel engines, compression-ignition.

[25] Frangopoulos CA. EDUCOGEN, The European educational tools on cogeneration. European Commission. December 2001.

reciprocating IC engine-based CHP system is composed of the engine, generator, heat recovery system, exhaust system, controls and acoustic enclosure. The generator is driven by the engine, and the useful heat is recovered from the engine exhaust and cooling systems (Onovwiona and Ugursal 2006).

Again Onovwiona and Ugursal (2006) points out that reciprocating IC engines have efficiencies ranging from 25-40%. This is in essence the same as efficiencies from Otto and diesel engines for automobiles which are about 25% and 40% respectively. The difference in efficiencies is due to the fact that diesel engines have a higher compression ratio than Otto engines. Depending on the size of the engine, the electrical efficiency ranges from 28-39%, (Onovwiona and Ugursal 2006). Nevertheless, the size of the installation may not have a much wider impact on the overall efficiency of a reciprocating engine. The total efficiency however for reciprocating IC engine-based CHP application is in the range of 85–90% with little variation due to size (Major, 1995).

Currently there are several gas engines that are sited on biogas producing facilities to utilise the non-purified biogas to produce heat and electricity. The raw gas is transported over a condensation medium to take out the water which can affect the performance of the reciprocating engine.

2.5.2 Micro turbine

These are miniature versions of combustion turbines that supply reasonable electrical efficiency. They range from 25 to 80 kW in size and they are suitable for meeting heat and power requirements of multi-family houses (MFH) (Onovwiona and Ugursal 2006). Micro turbines run on natural gas, diesel, landfill gas, ethanol and other bio-based liquids and gases (Pilavachi 2002). The operating mechanism involves pressurizing air in a compressor and igniting in a combustion chamber. The hot combustion gas expands and turns a turbine and provides power by rotating the turbine shaft. The hot exhaust gas pre heat the air as it passes from the compressor to the combustion chamber with the help of a recuperator[26]. The presence of a recuperator that reduces fuel consumption also greatly increases efficiency. According to Pilavachi (2002), preheating of fuel by the hot exhaust gases can yield fuel savings of about 30-40%. Microturbines produces a reasonable electrical efficiency of around 30 % and an overall efficiency of 80% can be achieves when used for cogeneration application according to Onovwiona and Ugursal, (2006). The major pollutants from the use of micro-turbine systems are NOx, CO and non-combusted hydrocarbons, and minute amount of SO_2. The design of micro turbines has the potential to allow for low emissions even at full load. This makes it well suited for future energy systems.

2.5.3 Fuel cell

Fuel cell technology is a relatively new and environmentally designed technology. It has the advantages of generating low noise and emissions and the potential to achieve 85-90% total efficiency (Onovwiona and Ugursal, 2006). They are classified either as stationary fuels cells or automotive fuel cells. Although there are similar designs for all fuel cell systems, the difference lies in the type of electrolyte used. The various types of fuel cell technologies that are currently

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[26] A device that recovers heat from hot exhaust gas. A recuperator is a heat exchanger that helps boost the efficiency of some gas turbine engines. In such an engine, air is compressed, burned with fuel, and used to drive a turbine. The recuperator passes some of the heat of the exhaust gas back to the air as it comes through the compressor.

present include alkaline fuel cells (AFC), polymer electrolyte membranes (PEM), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and lately, direct methanol fuel cells (DMFC) (Onovwiona and Ugursal, 2006).

A fuel cell operates by chemically combining hydrogen and oxygen, from the atmosphere, to produce electricity, water and heat. The sources of the hydrogen fuel include electrolysis of water, natural gas, coal and propane. There is no point source pollution if fuelled on pure hydrogen, (Pehnt and Ramesohl, 2005). This is because purified hydrogen reacts with oxygen in the air to produce water. Purified hydrogen is usually produced through electrolysis of water which is expensive. Pehnt and Ramesolh (2005) further asserted that in the case where hydrocarbon fuel, e.g. natural gas is used, then a fuel processor (reformer) is needed to draw the hydrogen which leads to the emission of pollutants and greenhouse gases. However a fuel cell has the potential to reduce carbon dioxide emissions by up to 49%, nitrogen oxide (NOx) emissions by 91%, carbon monoxide by 68%, and volatile organic compounds by 93, % (Scott 1993; Onovwiona and Ugursal, 2006). The features of low emissions and noise levels make fuel cell based cogeneration suitable for residential dwellings.

It is possible to run the fuel cells on biogas, even at remarkably low levels of methane, at which conventional heat engines would not work. The power output varies with methane content, with maximum power production occurring at 45% methane; corresponding to maximal production of H_2 and CO through internal dry reforming (Staniforth and Ormerod, 2002). Currently, the major drawbacks of fuel cells however are the high production cost and the short lifespan (Dorer et al., 2005; Onovwiona and Ugursal, 2006).

2.5.4 Stirling engine

Just like the other micro-cogeneration technologies, Stirling engines demonstrate the ability to attain high efficiency, fuel flexibility, low emissions, low noise/vibration levels and good performance at partial load (Frangopoulos, 2001). Developed by a Scottish scientist, Stirling engine has been with us since the 19th century but its potential use in cogeneration applications has recently been discovered. Stirling engines run on a wide variety of energy sources including fossil fuels such as oil or gas, and renewable energy sources like solar or biomass (Onovwiona and Ugursal, 2006). Stirling engines operate on the Stirling cycle, which is similar to the Otto cycle, with the adiabatic processes of that cycle replaced with isothermal processes. Similar to other hot air engines stirling engines are well suited for micro-cogeneration applications because they are noiseless, and they require very low maintenance (Bonnet, Alaphilippe et al., 2005). Stirling engines are classified according to their spatial arrangement: Alpha, Beta and Gamma arrangements[27]. A dual power pulse per one revolution cycle and a continuous combustion make stirling engines operate smoothly and generate low emissions and noise levels than internal combustion engines (Frangopoulos, 2001). Onovwiona and Ugursal (2006) further assert that a wide variety of fuels can be used for stirling engines because of the external combustion process. To this end, the combustion process can also be controlled. The ability to control the combustion process leads to

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[27] An alpha Stirling contains two separate power pistons in separate cylinders, one "hot" piston and one "cold" piston. The hot piston cylinder is situated inside the higher temperature heat exchanger and the cold piston cylinder is situated inside the low temperature heat exchanger.

A beta Stirling has a single power piston arranged within the same cylinder on the same shaft as a displacer piston. The displacer piston is a loose fit and does not extract any power from the expanding gas but only serves to shuttle the working gas from the hot heat exchanger to the cold heat exchanger.

A gamma Stirling is simply a beta Stirling in which the power piston is mounted in a separate cylinder alongside the displacer piston cylinder, but is still connected to the same flywheel. The gas in the two cylinders can flow freely between them and remains a single body. (Credit: http://en.wikipedia.org/wiki/Stirling_engine 2006-10-18) relatively higher combustion efficiency than the IC engine. The electrical efficiency is about 40%, and the overall efficiency of a Stirling engine cogeneration system is 65–85%. Stirling engines also have good capability to operate under part-load conditions. It is expected that while the full load efficiency can be 35–50%, the efficiency at half load can be expected to be in the 34–39% range (Frangopoulos, 2001; Onovwiona and Ugursal, 2006).

Emissions from current Stirling burners can be much lower than that emitted from gas Otto engines with catalytic converter, making the emissions generated from stirling engines comparable with those from modern gas burner technology (Onovwiona and Ugursal, 2006). The internal exhaust gas from the recirculation systems, preheated air and fuel gas are combined to reduce the maximum temperature, thereby suppressing the formation of nitrogen oxide (Onovwiona and Ugursal, 2006). In comparison to conventional fired fossil fuel cogeneration units, continuous combustion considerably lowers the emission level. The emission level is low with only 80–120 mg/m^3 NOx and 40–60 mg/m^3 CO, and traceable hydrocarbon and soot emissions (Onovwiona and Ugursal, 2006).

2.6 Energetic aspects of cogeneration

The combined generation of heat and power from cogeneration units saves primary energy resources and emissions in comparison to separate production of heat and electricity with the conventional systems. CHPs can therefore be viewed as the means to achieving clean and efficient energy. Most of the current cogeneration units run on natural gas. Natural gas is believed to burn clean among the other fossils like oil and coal and has a higher heating value compared to biogas. The efficiency of CHP is measured in terms of electrical and overall (global efficiency). It is measured as the portion (percentage) of the input fuel that can usefully be recovered as power and heat. The Emphasis here is placed on the usable energy and not the delivered energy. The selection of CHP systems for particular applications depends on the power to heat ratio. The efficiency of a cogeneration system depends, among others, on the type of the prime mover, size, and the temperature at which the recovered heat can be utilized (Onovwiona and Ugursal 2006).

2.6.1 Energy performance

Energy efficiency performance is simply the ratio of the energy input to energy output. The energy performance factor is a criterion for evaluating energy efficiency in terns of primary energy or delivered energy. Energy efficiency is calculated either on the basis of energy required for the production of energy carriers or how efficient the fuels are utilised in systems. In the energy analysis of biogas production, Berglund and Börjesson (2003) concluded that the energy input typically corresponds to 15-40% of the energy content of the biogas produced. The energy input for the biogas production is however determined by the raw materials used, system boundaries and calculation method chosen. Higher ratio implies lower system efficiency and vice versa. Biogas from sewage sludge and MSW has the highest system efficiencies with ley crops having the lowest (Berglund and Börjesson, 2003). Extensive handling of raw materials usually yields higher ratios. On the basis of utilisation, Dorer et al., (2005) found out that natural gas achieved primary energy efficiencies of 60-80% in domestic dwellings equipped with gas boiler and a fuel cell system.

2.6.2 Primary energy savings (PES)

Efficiency improvements are important in energy utility systems on both the supply and demand sides. To the end user, energy saving implies cost savings and this can be traced back to savings on the resource from which the energy is coming from. Therefore, in order to compare different fuels required to meet the same energy load from a cogeneration system or to compare a cogeneration system to separate production of heat and electricity, the standard used is Primary energy saving (PES) (Camelia Worksop).

PES can be defined as a decisive factor that compares the fuel needed to meet given loads of energy demand in cogeneration systems to conventional plants. The PES index is used in the European directive on cogeneration to determine the energetic performance of cogeneration systems (Camelia Worksop). PES was formally called Fuel Energy Saving Ratio (FESR). FESR is defined as the ratio of the fuel difference to the fuel energy required in the reference (separate) units. The major difference is that FESR is used for estimating instantaneous energy savings whiles PES is used for calculating annual energy savings. Generally, higher efficiencies from the cogeneration systems result in savings in primary energy compared to the separate conventional generation.

2.7 Environmental aspects of Micro-cogeneration systems

Though cogeneration units almost always yield higher global efficiencies than conventional separate power and heat generation, their environmental impact is not always better. Environmental performance of energy systems are measured using life cycle assessments. For cogeneration systems other approaches such as the separate analysis of the various impacts e.g. global warming, and emission of air and water pollutants do exist (Meunier et al., 2005). LCA approach is however accepted worldwide of analysing the environmental impacts of products and unit processes.

All energy systems have impacts on the environment through their life cycles from production to end-users (Riva, D'Angelosante et al., 2006). However, the magnitudes of these impacts vary from one energy system to the other depending on many factors. In co- and tri-generation[28] systems, the optimisation of the global efficiencies ensures the efficient use of fuel and the subsequent conservation of energy resources by reducing wastefulness of fuel. As an added advantage, obnoxious emissions can also be reduced as a result. In the analysis of the life cycle of biogas powered co- and tri-generation systems using agricultural crop residues, (Chevalier and Meunier, 2005) concluded that the environmental impact depends on the fraction of heat (or cold) used, the distance for crops collection, the efficiencies of the unit and on the NOx, emissions. This could of course vary with different types of biomass. That said, environmental impacts from cogeneration can be viewed from two dimensions; impacts relating to technologies, and those relating to resources and climate. The impacts relating to resource and climate are categories into resource depletion, climate change, acidification and eutrophication. The rest are ecotoxicology, land use, ozone depletion and minerals.

In terms of the technologies, reciprocating engines give a rather high pollutant emission level depending on the catalyst/engine technology and the level of maintenance. The age of the engine and the operation features are also factors that determine the level of emissions. Depending on the burner type, Stirling engines will produce low to medium emissions where as Fuel cells generally produce zero to almost zero emissions depending on the fuel used (Pehnt et al., 2004). In comparison with efficient and state-of-the-art separate generation of electricity and heat, micro CHP demonstrates superiority in terms of GHG reduction (Pehnt, 2004). However, acidification may be considerably higher in small reciprocating engines compared to centralised gas power plants. This is essentially due to the high level of ammonia that is released from biomass. Ammonia content varies with different types of biomass; agricultural waste is known to release high levels of ammonia. With regards to resources and

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[28] Trigeneration is combined production of cooling, heating and power.

climate protection, the performance of micro CHP depends primarily on the total attainable efficiency. It is worth clarifying that primary energy savings only give information regarding the energetic efficiencies of the systems but not their environmental impacts (Meunier et al., 2005).

The ecological and environmental performance of micro CHP in comparison to other potential alternatives was investigated by Penht et al., (2005). Table 2-5 below shows the performances of the different systems. From the table it can be deduced that in terms of micro CHPS, Stirling engines and fuel cells are environmentally subtle with regards to NOx emissions. Fuel cell demonstrates the highest environmental superiority among the technologies compared. However, reciprocating engine in micro CHP applications appear less friendly to the environment with the highest recorded NOx emissions.

Table 2-5 Economic and environmental parameters of micro CHP technologies

	Reciprocating engine (3-6 kW lean burn)	Stirling engine (3 kW)	Fuel cell (SOFC)
Default capacity			
Electric (kWel)	5.5	3.0	1.0
Thermal (kW)	13.9	15.0	2.7
Default efficiency			
Electric (kWel)	25%	15%	32%
Thermal (kW)	88%	90%	85%
Minimum efficiency			
Electric (kWel)	25%	15%	28%
Thermal (kW)	84%	85%	80%
Maximum efficiency			
Electric (kWel)	25%	19%	32%
Thermal (kW)	95%	94%	90%
NOx Emissions (mg/Nm^3)	300	15	3

(Source: Penht et al., 2005)[29].

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[29] All efficiencies are seasonal and in some cases include hot standby and distributional losses.Based on Manufacturers' information, estimates based on operational experience with many installed systems as well as bibliographical review (ZSW, 2000; ASUE, 2003; ASUE/ Energiereferat der Stadt Frankfurt/Main, 2001).

3 Methodology

Nomenclature (*Abbreviations and indices)*

bg-raw	non-purified biogas
bg-ref	refined biogas
C5	case no. 5 (SFH PH)
C7	case no. 7 (SFH Swiss average)
C8	case no. 8 (MFH PH)
C10	case no. 10 (MFH Swiss average)
CH-mix	Swiss electricity mix
el	electrical
ICE	internal combustion engine
kW	kilowatt
MFH	multi-family house
MJ	mega joule
natgas	natural gas
PH	passive house
QC	heat supplied from micro cogeneration unit.
QG	heat supplied from gas boiler
SFH	single-family house
SOFC	solid oxide fuel cell
Swiss average	average for the Swiss building stock.
th	thermal
UCTE	Union for the Coordination of Transmission of Electricity

3.1 Problem Formulation

The case buildings are residential family houses with different insulation types. The design characteristics of the case buildings are based on the Swiss average construction (Dorer, Weber et al., 2005). The overall annual energy balance for the case buildings are estimated based on the results derived form the dynamic simulation of fuel cell- based micro cogeneration. The thermal load consists of space heating and domestic hot water and the electric load is the collective demand from lighting and miscellaneous electric equipment in the households. Heat from lighting and electrical appliances are partly taken into account as internal heat gains.

The domestic energy system considers two micro CHP units, state-of-the-art gas boiler and electricity from public grid. Natural gas and cleaned and upgraded biogas (refined biogas) are used as the primary fuel. The natural gas is imported from other countries and delivered at low pressure to the consumers. The refined biogas has a standard of 96 % methane by volume and it is delivered at low pressure to the consumer. Unrefined biogas from agricultural waste is used in one of the scenarios to test the sensitivity of different biogas fuels.

3.2 Scenario definition

Reference scenario: Residential family houses (SFH and MFH) heated with a state-of-the-art condensing gas boiler and Grid Electricity is supplied by the European mix, UCTE.

Case definitions

- SFH fitted with a fuel cell-based micro CHP unit running on purified biogas or natural gas and supplying additional heat and electricity.
- SFH fitted with an IC engine-based micro CHP unit running on purified biogas or natural gas and supplying additional heat and electricity.
- MFH fitted with a fuel cell-based micro CHP unit running on purified biogas or natural gas and supplying additional heat and electricity.
- MFH fitted with an IC engine-based micro CHP unit running on purified biogas or natural gas and supplying additional heat and electricity.

Each of the scenarios is tested on two building standards based on the insulation types. These standards are the Passive house and the Swiss average. This is because the type of insulation determines the level of energy demand. The passive house standard is defined by the German Passive house Institute, (Dorer, Weber et al., 2005) and the Swiss average is the energy level based on the average for the Swiss building stock. Table 3-1 below show the energy demands per m^2 energy reference floor area, heat transfer coefficients of exterior walls and glazing and solar heat gain coefficient of glazing of the different building types.

Table 3-1 Energy demands per m^2 energy reference floor area, heat transfer coefficients (U-values) of exterior walls and glazing and solar heat gain coefficient (G-value) of glazing of Swiss average buildings and passive house.

Building type	Swiss average building stock (Swiss av.)		Passive House (PH)	
	SFH	MFH	SFH	MFH
Space heat demand (MJ/(m2 a))	425	450	44	46.5
Electricity demand (MJ/(m2 a))	120	130	52.8	55.6
U-value exterior walls (W/(m2 K))	0.7	1.1	0.15	0.16
U-value roof (W/(m2 K))	0.35	0.58	0.11	0.15
U-value glazing (W/(m2 K))	2.8	2.8	0.7	0.7
G-value glazing	0.76	0.76	0.59	0.59

Source: (Dorer, Weber et al., 2005)

The major cases, from which the scenarios are developed are based on the building type and occupancy, are presented below:

1. c5: 4 person-occupancy SFH PH
2. c7: 4 person-occupancy SFH Swiss average
3. c8: 12 person-occupancy MFH PH
4. c10: 12 person-occupancy MFH Swiss average

After the different combinations with natural gas and refined biogas with fuel cell and internal combustion engine applications in different cases, 17 scenarios were obtained and these are used for the LCA modelling. The different scenarios are listed below.

1. Domestic energy demand c5, fc, bg-ref, ch-mix
2. Domestic energy demand c5, fc, natgas, ch-mix
3. Domestic energy demand c5, ICE, bg-ref, ch-mix
4. Domestic energy demand c5, ICE, natgas, ch-mix
5. Domestic energy demand c7, fc, bg-ref, ch-mix
6. Domestic energy demand c7, fc, natgas, ch-mix
7. Domestic energy demand c7, ICE, bg-ref, ch-mix
8. Domestic energy demand c7, ICE, natgas, ch-mix
9. Domestic energy demand c8, fc, bg-ref, ch-mix
10. Domestic energy demand c8, fc, natgas, ch-mix
11. Domestic energy demand c8, ICE, bg-ref, ch-mix
12. Domestic energy demand c8, ICE, natgas, ch-mix
13. Domestic energy demand c10, fc, bg-ref, ch-mix
14. Domestic energy demand c10, fc, natgas, ch-mix
15. Domestic energy demand c10, ICE, bg-ref, ch-mix
16. Domestic energy demand c10, ICE, natgas, ch-mix
17. Domestic energy demand c10, ICE, bg-raw, ch-mix

3.3 Approach

In order to consider the environmental performance of biomass-based micro CHP integration in Swiss building stock, life cycle energy assessment is carried out. The approach to the study consists mainly of three stages:

- estimation of thermal and electrical efficiencies for the different micro CHP applications based on energy simulations;
- estimation of annual delivered energy and annual net energy;
- evaluation of the environmental impacts of the energy carrier using life cycle assessments (LCA).

3.3.1 Brief description of LCA methodology

Life cycle assessment (LCA) is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14040, 2005). LCA is a process-oriented tool that is used to describe systems on a 'cradle to grave' basis; in this case, from the stage of acquiring raw materials from the environment through downstream process to satisfying the household energy demands (Dones et al., 1999). LCA is an iterative act in the sense that the different stages can be repeated until the goals are achieved.

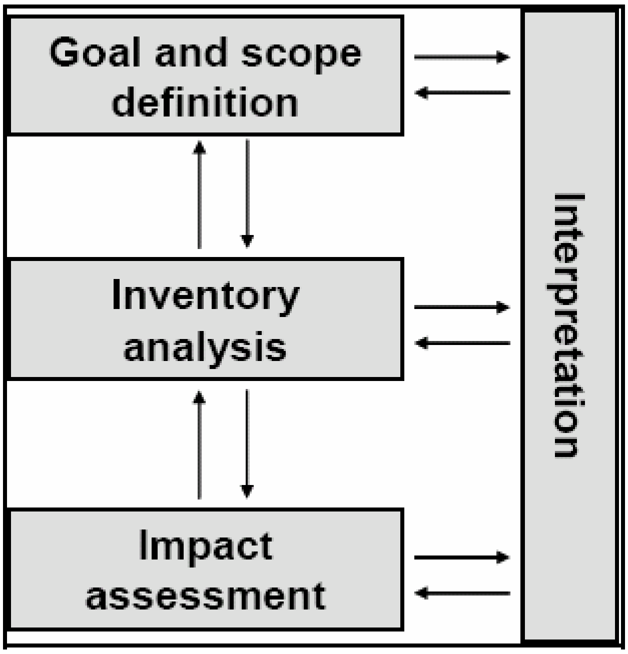

Figure 3-1 Phases of LCA methodology (ISO, 1997)

The LCA methodology framework consists of goal and scope definition, inventory, impact assessment and interpretation. Below is a brief description of the different stages:

1. Goal and scope definition: in this step, the purpose and boundaries of the product or process whose life cycle is to be assessed is defined.

2. Inventory: the inputs (raw materials) and the outputs (emissions) of the unit process flows are described in this step.
3. impact assessment: this step evaluate the effects of the emissions and raw materials on the environment
4. Interpretations step: basing on the previous steps, the processes are compared with similar ones to draw a valid conclusion.

3.3.2 Estimation of Energy simulation results

Energy simulation is used to determine the energy profile of a building. The simulation defines the building characteristics such as building geometry and floor plan, energy demand levels, heat distribution and ventilation, specific occupancy characteristics, domestic hot water demand, electricity demand and internal and external heat load. In this study the definitions[30] described by Dorer et al., (2005) will be applied. (See appendix 2 for the details).

Based on the results of the previous dynamic simulation on the "performance of fuel cell-based micro CHP system (Dorer, Weber et al., 2005), an empirical equation (formulae) was developed (See appendix 1). These formulae were used to estimate the ratio of heat supplied from the condensing and modulating gas boiler to the total amount of heat supplied from gas boiler and the micro CHP unit. Making this ratio (factor) constant, different efficiencies were used to estimate the biogas demand for the fuel cell and IC engine and the gas boiler in the new cases assuming the same net energy demand as in the related natural gas case. The residual electricity demand from the public grid and the total electricity from the micro CHP were also obtained as a result (see appendix 3). The simulation results takes care of the 10% grid losses which comes about when locally generated electricity is supplied to the public grid and re-supplied back to the household. These estimated parameters were used in the LCA modelling for the different scenarios.

The electrical and thermal efficiencies of the reciprocating internal combustion engines were obtained directly from manufacturers and literature whereas that of the fuel cell was derived from the simulation results. In order to maintain the dynamics in the simulation, the thermal and electrical efficiencies of the IC engine were re-estimated based on the efficiency ratios between SOFC and ICE. (See appendix 3).

Table 3-2 Electrical thermal and global efficiencies of the selected micro CHP units

Type	Electrical (%)	Thermal (%)	Global (%)
Reciprocating engine[a]	20.0	65.0	85.0
Fuel cell[b]	32.0	53.0	85.0

[a] based on manufactures information

[b] based on default efficiencies from literature.

Source: (Menag energie AG; Pehnt et al., 2004)

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[30] For further details on the building description and occupant driven demand see Dorer et al. 2005.

3.3.3 Life cycle assessment (LCA)

LCA methodology was used for developing the environmental inventories for the energy carriers and micro CHP units and the fuels that are used in meeting the domestic energy demand.

3.3.3.1 Goal and scope definitions

The goal of the study was to establish LCA models for micro CHP applications in the Swiss residential buildings and demonstrate the environmental benefits associated with satisfying the energy demand of these buildings. It is desired that the results will enable the author to generate a basis for comparison for biogas and natural gas that will allow the communication of their efficiency and environmental performances in residential micro CHP applications.

The scope covers grid electricity, condensing and modulating gas boiler and two different micro CHP units that are designed to deliver the thermal and electrical requirements of SFH and MFH. Described below are the components of the energy systems to be considered:

Grid electricity: the electricity mix considered for the study is the European average (UCTE)[31] for low voltage electricity supply (220 volts).

Gas boiler system: a state-of-the-art condensing and modulating gas boiler system with nominal net efficiency of 108% (LHV)[32] is assumed to supply the heating demand in the building. Condensing gas boilers can achieve up to 108% standard efficiency by gaining additional energy from flue gases (Dorer, Weber et al., 2005). In other words, the latent or hidden energy stored in the water vapour and the tangible energy from the exhaust gases are all converted into useful heat boosting the efficiency.

Solid oxide fuel cell (SOFC): this is an emerging micro-cogeneration technology and used as a standard for residential fuel cell-based micro CHP applications. The SOFC considered has a nominal rating of 1kW electric and 2.5kW thermal power output. Average efficiencies based on real case operation were estimated using the solver function in Microsoft Excel.

Internal combustion engine (ICE): the ICE considered for the studies is modelled as a 1 kW_{el} gas motor with electrical output of 1 kW_{el} and heat output of 3.25 kW_{th}. The system is considered to have a default global efficiency[33] of 85% with 20% electrical efficiency. All the heat is recovered for domestic hot water and space heating.

3.3.3.2 Assumptions

- The biogas used is upgraded to pipeline gas quality (Srivastava and Hill, 1993; Wikipedia 2006).

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[31] Union for the Coordination of Transmission of Electricity (UCTE), Brussels, Belgium. Annual reports see http://www.ucte.org/.

[32] The condensing gas boilers incorporate additional heat exchangers which utilizes the energy in the hot exhaust gas to pre-heat the water in the boiler system. Much of the water vapour produced by the combustion process condenses back into liquid releasing the latent heat. The captured heat adds to the overall efficiency of the boiler (Dorer, Weber et al., 2005).

[33] Global efficiency is the same as overall efficiency. This is the total sum of the achievable thermal and electrical efficiencies.

- The estimated thermal and electrical efficiencies follow the dynamic simulation and they are achievable.

- Solid oxide fuel cell is used to represent all domestic fuel cell-based micro CHP regarding the dynamic behaviour.

- The existing natural gas distribution infrastructure is also used for the distribution of refined biogas.

- The fuel cell unit is installed with an inbuilt methane steam reformer with an efficiency of 80%. CO_2 emissions from the production of H_2 in a NG steam reforming are considered (Koroneos, Dompros et al., 2004).

3.3.3.3 Functional unit

The functional unit is the total energy demand of a square meter of living floor space per year in the different buildings. The respective reference flow is the input of 1MJ of energy to fulfil this demand.

3.3.3.4 System boundaries

The system boundaries for this study are defined by all the elementary flows from the extraction of the primary energy resources to delivering the net energy to the household (cradle to grave). The system boundaries for the biogas system entails the handling and transport of raw materials for biogas production mix (biogenous waste, sewage sludge and agricultural waste), operation of the biogas plant, purification and upgrading and use of the biogas produced. The infrastructure for processing and distribution are taken in account in the study.

With respect to the upstream[34] stages, the system boundaries for biogas from agricultural waste are the pre-treatment of the biomass in the pit, the digestion process in addition to the emissions from manure storage and usage as fertilizer. Storage infrastructure is not accounted for. The system boundaries do not consider environmental interactions due to the production of manure are outside s of this study. The transport expenditures and "use and upgrading of biogas" the use of biogas in co-generation is inside the system boundaries (Spielmann, 2006 unpublished data).The system boundary for biogas from sewage sludge is the installation and operation of the anaerobic treatment the environmental burden of the pretreatment and treatment of the digested sludge is outside the boundaries (Spielmann, 2006 unpublished data). The boundaries for biogenous waste include transportation, and plant infrastructure (Spielmann, 2006 unpublished data).

In the case of natural gas, the boundaries include the onshore and offshore production in exporting countries and the long distance pipeline transportation into Switzerland.

The boundary for the grid electricity includes the shares of national electricity production of UCTE member countries. It does not include transformation, transport nor distribution losses (Ecoinvent data V1.2, 2005).

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[34] Upstream process refers to all the stages from the collection of biowaste to the production of crude unrefined biogas.

With regards the gas boiler, the database was created with the assumption that oil and gas boilers of comparable capacity have approximately the same material and energy uses for manufacturing. Thus, through the description of the infrastructure of the oil boiler, the module includes the most important materials used for production. It includes also the transport of these materials and the energy and water needed for production (Ecoinvent data V1.2, 2005).

The boundary for the micro CHP units includes the most important materials used for production. It includes also the transport of these materials and the energy and water needed for production (Ecoinvent data V1.2, 2005). Figure 3-2 below represents the system boundary of the entire study.

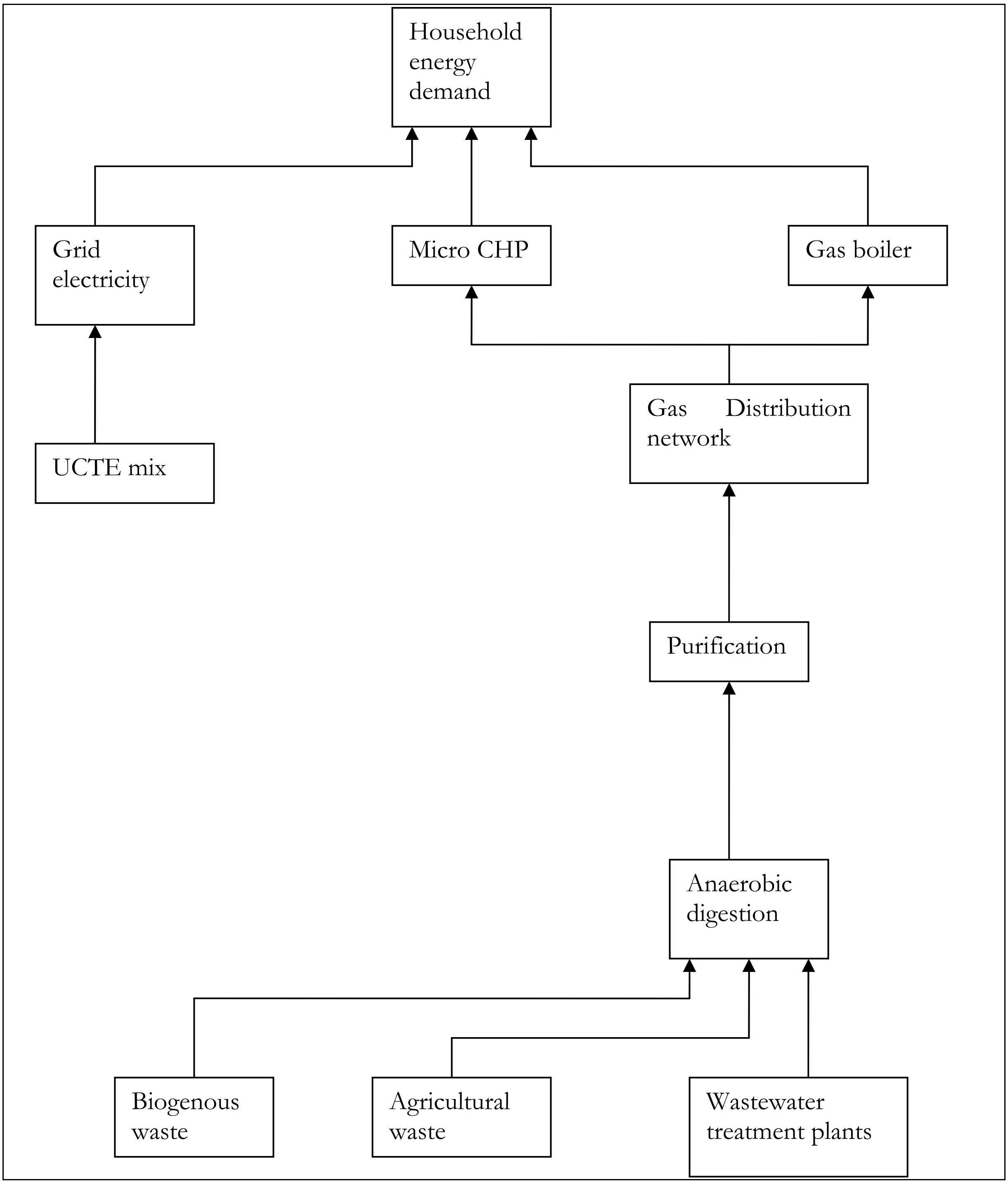

Figure 3-2 Schematic representation of the system boundary of the of the study ("Cradle to Grave")

3.3.3.5 Geographical boundary

The geographical reference boundary for the assessment of micro CHP systems in this study is Europe and Russia. The time boundary is in the near future. The latest data in ecoinvent database is used for the LCA models.

3.3.3.6 Allocation

The main difficulty with the allocation of emissions on in biogas production is the decision to consider the process as a production process or a waste treatment option. Considering the biogas process as performing three functions; disposal of biowaste, production of biogas, and production of press water and compost for agriculture, the upstream allocation was based on economic factors (Spielmann, 2006 unpublished data). The downstream allocation is based on the exergy content of the biogas (Spielmann, 2006 unpublished data). The inventory made allocations based on what the authors perceive to be the main product of the system. For example in the production of biogas from agricultural manure, emissions from the digestion process are exclusively allocated to biogas while the accumulation of heavy metals from the use of fertilizer is allocated to animal husbandry (Spielmann, 2006 unpublished data).

3.3.3.7 Life cycle inventory analysis

The life cycle inventory involves data collection and computations to quantify the flows of inputs and output of the product system (ANSI/ISO, 1997; Osman and Ries, 2006). A ‘cradle to grave’ inventory is made for the input fuel entering a unit process which in this case is the micro CHP unit and the gas boiler. The pre-chain process for the production of natural gas and refined biogas is included in the overall analysis as it is already documented in the database.

An LCA software package, SIMAPRO (Pre Consultants, 2006), was used to design the LCA models and generate impacts based on the emissions resulting from the production, transportation and use of energy in the residential building cases. The software tool gives the characteristics of the impact categories based on standardised normalisations sets that already defined in the data base. Normalization however becomes an optional step when this tool is used and the results can therefore be interpreted based on the characterisations.

3.3.3.8 Impact categories and impact assessment methods

There are a number of impact categories that are associated with the production and use of natural gas and biogas in CHP units. For the biogas CHP, the impacts result from the construction and decommissioning of the of the plant, emissions from the CHP units including the digestion process, CO_2 sequestration by biomass and avoided methane losses and the use of lubricating oils (Chevalier and Meunier 2005). In addition to the above, the onshore and offshore production of NG and the long distance pipeline transportation accounts for significant impacts. In relation to the goal of the study, a few pertinent environmental impacts have been selected for the sake of comparison. These include resource consumption, GHG emission, eutrophication and acidification.

Resource consumption relates to the extraction of fossil fuels and minerals. The characterisation factor is the cumulative energy demand (in MJ-eq); but this may differ according to the method used. For example, Eco Indicator 99 method uses abiotic depletion potential (in MJ) (Chevalier and Meunier 2005) as the characterisation factor.

Global warming/climate change is defined as the impact of GHG emissions on the radiative forcing on the atmosphere leading to a rise in the earth's temperature (Chevalier and Meunier 2005). Methane and CO_2 are typical examples of GHG. With a characterisation factor of global warming potential (GWP for 100- year time duration), the results are expressed in kg CO_2 eq. The impact is determined over an integral horizon of 100 years because GHGs has different atmospheric residence times.

Acidification relates to the build up of acidifying emission in the atmosphere causing widespread effects on the environment. The characterisation factor is acidification potential and it is expressed in kg SO_2 eq. Acidification may lead to local and regional impacts on soils, waters biological organisms or materials (Chevalier and Meunier 2005).

Eutrophication relates to the impacts from nitrogen and phosphorus build-up in the environment which inadvertently leads to nutrient enrichment (Chevalier and Meunier 2005). The characterisation factor is the eutrophication potential expressed in kg PO_4 eq.

These categories are based on the results of the inventory assessment. The characterisation factors based on the impact categories, parameters and reference units in a simplified LCA are shown in table 3-3 below.

Table 3-3 Impact categories and characterization factors in simplified LCA

Impact category	Inventory parameter	Classification factor U	Reference	Value U (kg/kg ref)
Energy resources		Cumulated energy demand	MJ	
Global warming	CO_2	Global warming potential	CO_2 equiv.	1
	CH_4		CO_2 equiv.	21
	N_2O		CO_2 equiv.	310
Acidification	SO_2	Acidification potential	SO_2 equiv.	1
	NO_X		SO_2 equiv.	0.7
	NH_3		SO_2 equiv.	1.88
	HCl		SO_2 equiv.	0.88
Eutrophication	NO_X	Eutrophication potential	PO_4^{3-} equiv.	0.13
	NH_3		PO_4^{3-} equiv.	0.33

Source: (Pehnt 2006)

For this study, three impact assessment methods were used to quantify the impact categories. These were Cumulative energy demand (CED), CML 2 baseline 2000 method and West Europe 1995 (CML) and eco-indicator 99 (H) V2.03 method with Europe EI 99 H/A normalisation (EI 99). Although these methods cover a wide range of impact categories, global warming, energy resources, acidification and eutrophication will only be considered.

CED method was chosen exclusively for energy resources because it has the advantage of separating the total energy demand into fractions of non renewable sources and renewable sources. The impact categories from the different energy sources are expressed in terms of MJ equivalence.

CML method was used for the midpoint assessment where impact categories are chosen relatively close to the inventory results. The impact categories are expressed in equivalency factors. For example the unit for global warming is kg CO_2 equivalence and that of acidification is kg SO_2 equivalence. These equivalence units are rather abstract and do not permit comparison between different impact categories.

Finally, EI 99 was chosen as the appropriate method for the endpoint damage assessment. EI 99 is a global damage oriented-approach that links impacts categories to its damage. The damage types include damage to human health, ecosystems quality and resources.

3.3.3.9 Limitations

1. In general, model scenarios are hypothetical and as such real world applications might register some complex differences.
2. Concrete data on stationary fuel cell-based applications are difficult to obtain since these technologies are only at the market threshold.

In view of the above limitations, it is worth noting that the validity of the findings is subject to the all uncertainties that might exist in the ecoinvent database.

4 Results

The results from the life cycle results are systematically presented using three different LCA methods as justified in the previous chapter.; Cumulative energy demand (CED), CML 2 baseline 2000 method (CML) and eco- indicator (EI 99).

The emissions from the inventory were classified into the various impact categories by the SIMAPro software. The results are therefore compared according to selected impact categories which are primary energy consumption, climate change/ global warming, acidification and eutrophication. In total, 17 different scenarios were modelled and analysed based on the diverse combinations of micro CHP technology, fuel type and the building standard (chapter 3). The types of insulations also play a significant role since the level of insulation determines the building energy demand.

4.1 Characterisation

The characterisation factors were used to reveal the comparative involvement of the life cycle inventories to the impact category indicators.

4.1.1 Energy resources

The characterisation results of the primary energy resources from the LCA studies are presented using the cumulative energy demand approach. This method is used to quantify the effects of resource depletion resulting from the extraction of materials for energy production. Natural gas and refined biogas in micro-CHP applications are compared to the reference conventional case. Figure 4-1 presents the comparison between natural gas and refined biogas for the different scenarios considered.

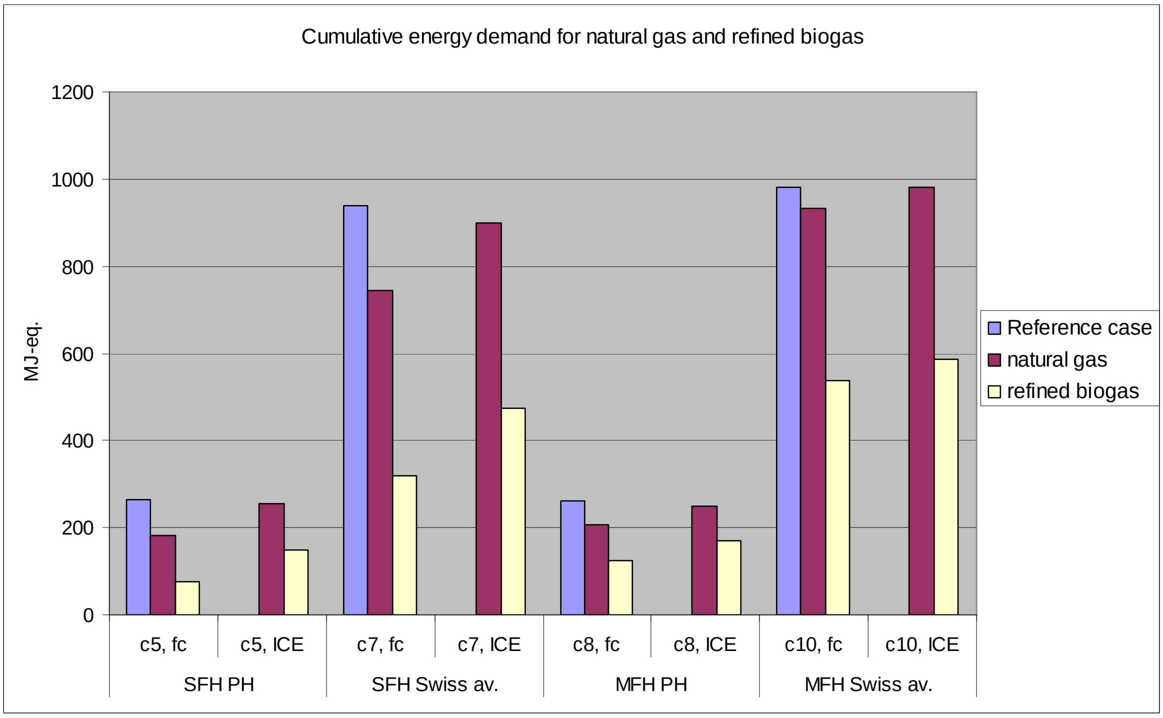

Figure 4-1 Comparing the total cumulative energy demand from natural gas and refined biogas for satisfying domestic energy needs to the reference case (CED Method)

From figure 4-1, it can be seen that there are no much differences between the total cumulative energy demand for the natural gas cases and the reference case. It can generally be observed from the results that the total CED for natural gas in I C engine based micro CHP system is almost the same as than of the reference case whereas the FC registered slightly lower MJ-eq than the reference cases. This trend is true for all the scenarios investigated. With respect to refined biogas however, a considerable difference can be seen. The total cumulative energy demand for refined biogas is significantly lower than the reference scenario. Again, on the level of the micro CHP units, IC engine recorded slightly higher impacts than the FC. Compared to the reference in Swiss average buildings, refined biogas achieved a reduction in the total cumulative energy demand of about 440-600 MJ-eq representing 40-65%. NG achieved a maximum of 20% reduction.

When it comes to the individual impacts from the energy resources, it can be seen from figure 4-2 that non-renewable fossils gave the highest resource depletion impact from the use of natural gas. The impacts resulting from nuclear energy resources on the other hand, are higher for refined biogas than natural gas. With regards to renewable energy resources, the impacts resulting from using biomass, wind, solar and geothermal resources are largely insignificant. This is not the case however, for water (hydro) which recorded higher quantitative impact values among all the renewable energy resources due to the relatively high distribution of hydro electricity in Switzerland.

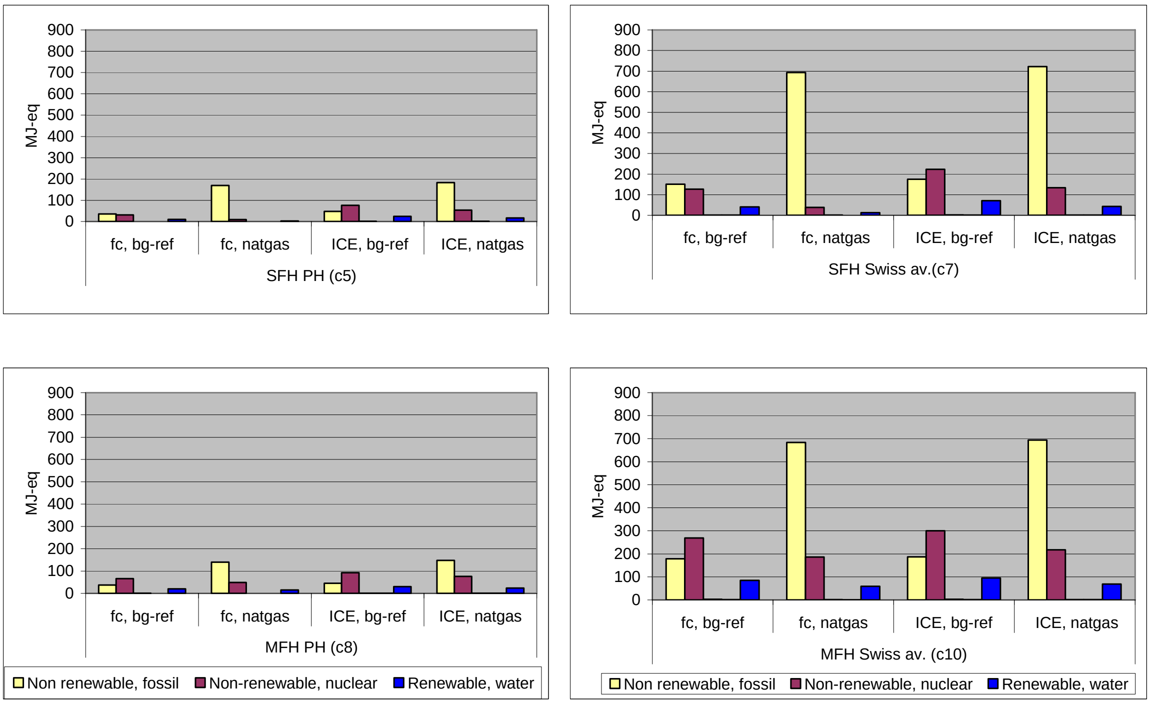

Figure 4-2 Cumulative energy demand [in MJ] for satisfying the energy needs of 1 m² of living floor space per year for the four different cases(CED Method)

The results on the cumulative energy demand (fig 4-1 and 4-2) showed that the depletion of non- renewable fossil resources is significantly higher natural gas for compared to refined biogas. The vast majority of the impact is attributable to the onshore and offshore production of natural gas. In the case of non renewable nuclear resources which dominated the refined biogas scenarios, majority of the impacts are due to underground naturally occurring uranium and open pit mining of uranium. Uranium is used to produce electricity through nuclear chain reactions and this forms part of the electricity mix that is needed for biogas production. The biogas facility uses the electricity mix including nuclear energy resources because the plants are situated in Switzerland. In the case of the renewable resources, the results showed quite a significant impact arising from water (hydro power). This can be traced to the use of electricity from hydropower at the reservoir or run-off-river power plant. With the refined biogas scenarios, additional impacts are attributed to low and medium voltage electricity grid.

4.1.2 Primary energy efficiency / Energy performance factor

The energy performance factor is used to assess the efficiency of energy systems in utilising primary energy to meet the annual energy (electricity and heat) demand in the domestic building. In other words, it is the ratio of the net energy output to the primary energy. In this study the primary energy efficiency is calculated using the net energy demand from the estimated simulation results (see appendix 3) and the total cumulative energy demand from the LCA results.

The results of the primary energy efficiency for the studied cases are graphically presented in figure 4-3 below. From the graph, it can be seen that with the exception of one scenario, all cases with refined biogas fuel have efficiencies > 1, whiles the natural gas cases are < 1. However, the natural gas cases show quite a steady efficiency irrespective of the type of micro CHP unit used. This is however not the same for the refined biogas cases.

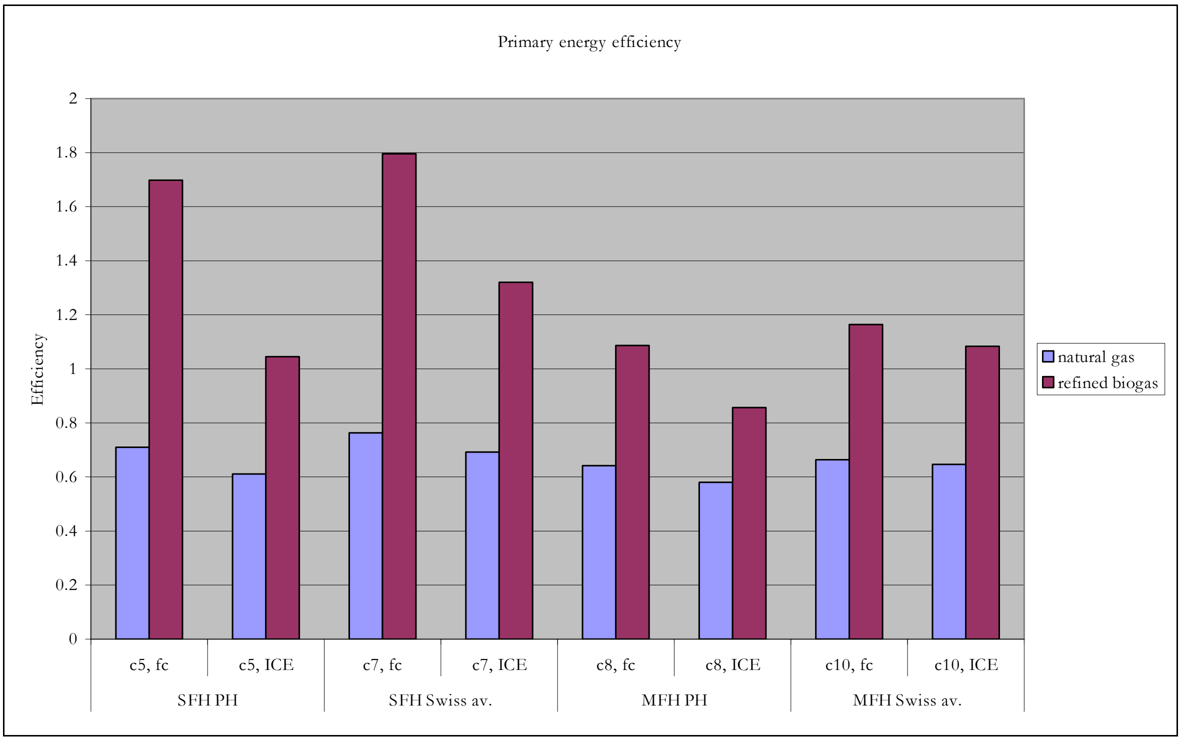

Figure 4-3 Comparing the primary energy efficiency for natural gas and refined biogas

The results interestingly show some suspected data gaps in the refined biogas cases. Thermodynamically, more than 100 per cent efficiencies are not feasible to achieve. It is however suspected that the energy content of the biomass input was not taken into account in the inventory database. This can offset the energy balance of the biogas system and could possibly explain the extremely high efficiencies in the refined biogas cases. The exceptionally high efficiencies in the biogas scenarios could also be due to the fact that the embodied energy (energy content) in the biomass was not considered in the ecoinvent database. Another reason could be that energy is mostly invested for production and long-distance pipeline transportation of natural gas from the exporting countries whereas such energy investments are avoided in the case of biogas due to its localised production.

4.1.3 Global warming / climate change

The global warming potential is characterised using CML 2 baseline 2000 method with West Europe 1995 normalization set. The potential impacts from global warming are analysed based on an integral time horizon of 100 years basically due to the different residence times of GHGs. Methane and CO_2 emissions are identified to be the major contributors to the global warming menace with methane having a higher potential (GWP = 21) than CO_2.

It can be seen from figure 4-4 that the global warming potentials from natural gas are noticeably higher than the conventional reference cases with fuel cell applications but slightly lower with the IC engine applications. In the case of the refined biogas, the global warming potentials are generally lower than that of the reference case irrespective of the type of micro CHP used. Compared to the reference case in the current Swiss average buildings, refined biogas achieves a 20-40% reduction in global warming potential.

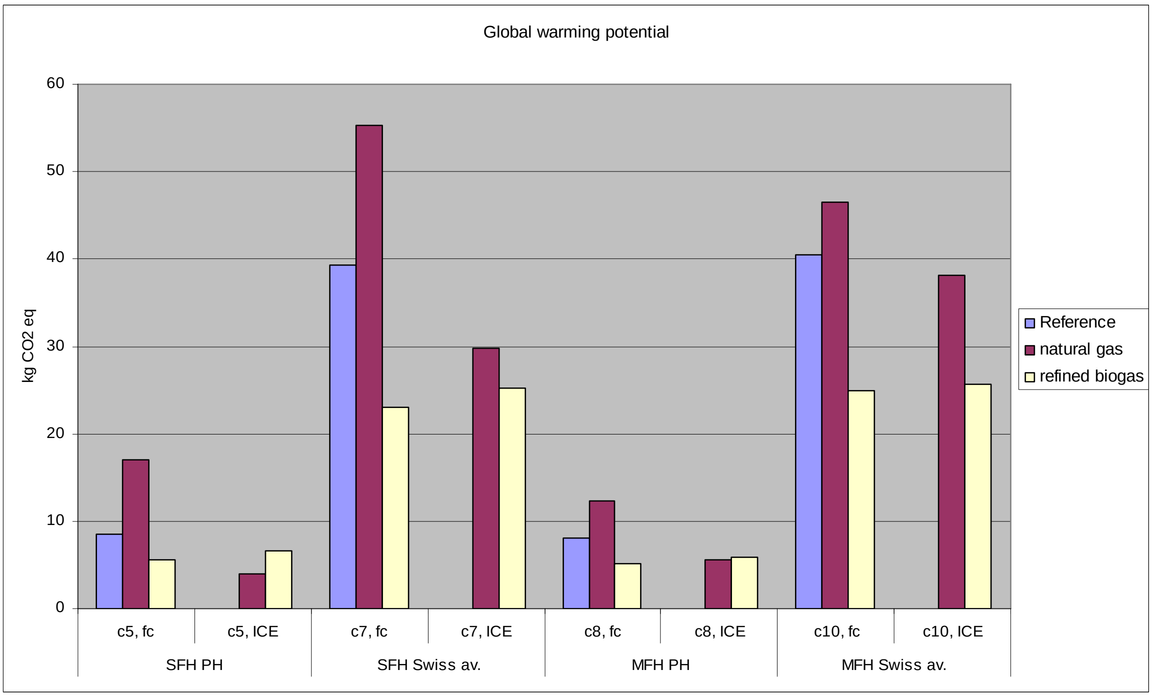

Figure 4-4 Comparing the global warming potentials from the use of natural gas and refined biogas to the reference case (CML 2 baseline 2000 method)

As seen in fig 4-4, the climate change impacts are significantly higher for natural gas than refined biogas. CH_4 and CO_2 emissions are fossil or biogenic based depending on whether it is coming from natural gas or biogas respectively. In the case of modelled natural gas scenarios, fugitive methane (fossil) losses were identified in the low pressure distribution networks to the consumers and long distance pipeline transportation. With respect to CO_2 the majority of the impacts were generated from the exhaust gas from the gas boiler. The micro CHP units also released considerable amount CO_2 emissions through reforming and combustion for FC and IC engine respectively. Considerable CO_2 emissions were also attributed to the use of gas turbine at compressor stations and the burning of lignite on power plants during natural gas production.

In the case of the refined biogas, the impacts are mainly due to emissions of biogenic methane through fugitive loses. The purification process accounted for over 50% of the total biogenic methane losses. Considerable losses are also attributed to low pressure distribution to consumers, the micro CHP unit and the production of biogas from biowaste and sewage sludge. Biogenic CO_2 is not accounted for because it is not considered as a CO_2 load - having come from the atmosphere anyway. The production of biogas is however associated with the release of CO_2 (fossil) resulting from the use of industrial gas boilers (> 100 kWh) to provide heat for the digestion process.

4.1.4 Acidification

The impacts from acidification was also compared using CML 2 baseline 2000 method with West Europe 1995 normalization set. Acidification is potentially caused by the emission of NH_4, NOx and SO_2.

It can be seen from figure 4-5 the acidification potentials for both natural gas and refined biogas are noticeably lower than the reference case in FC applications. With the IC engine however, the acidification potentials both natural gas and refined biogas are almost the same as that of the reference case. There is however no significant difference between the impacts from natural gas and refined biogas in all the scenarios investigated.

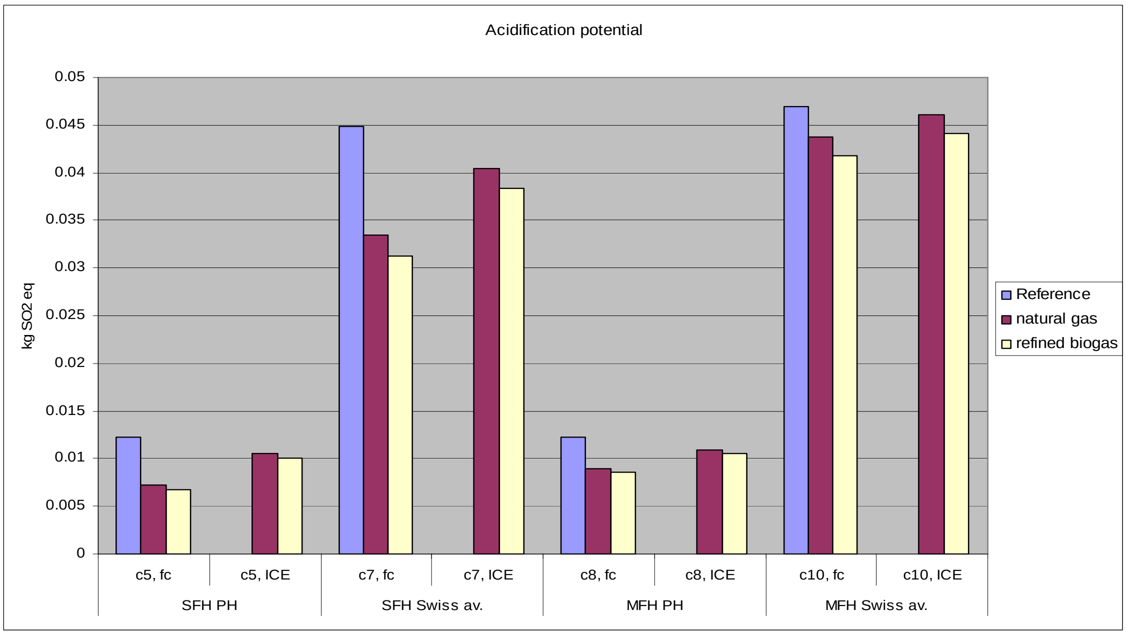

Figure 4-5 Comparing natural gas and refined biogas in terms of acidification potential, (CML 2 baseline 2000 method)

According figure 4-5, the results show that the acidification potentials of natural gas and refined biogas were almost quantitatively similar for each scenario pair. In comparison to the reference case, the FC applications show noticeably lower values than the corresponding IC engine counterparts. The similarity is not very surprising because both refined biogas and natural gas contains only traceable amount of SO_2 which is the main agent for acidification. However, the inventory shows that with regard to natural gas, the burning of sour gas in gas turbines during the production process accounts for most of the SO_2 emissions. In contrast, the purification of biogas is the main source of SO_2 emissions. Ammonia from biogas from agricultural digestion from storage is also a partial contributor to this impact. The difference between the micro CHP units could be basically due to the emissions from the different conversion processes (Pehnt 2001; Chevalier and Meunier 2005).

4.1.5 Eutrophication

The CML 2 baseline 2000 method with West Europe 1995 normalization set is again used here to quantify this impact category. According to the CML method, eutrophication is caused mainly by the emission of nitrogen and phosphorus compounds.

As depicted in figure 4-6 below, the pattern of potential impact from eutrophication is similar to that of acidification. It can be observed that, in comparison with the reference case, the potential impacts from natural gas and refined biogas are considerably lower with FC-based applications. On the other hand, scenarios with IC engine-based applications are almost the same as the reference cases.

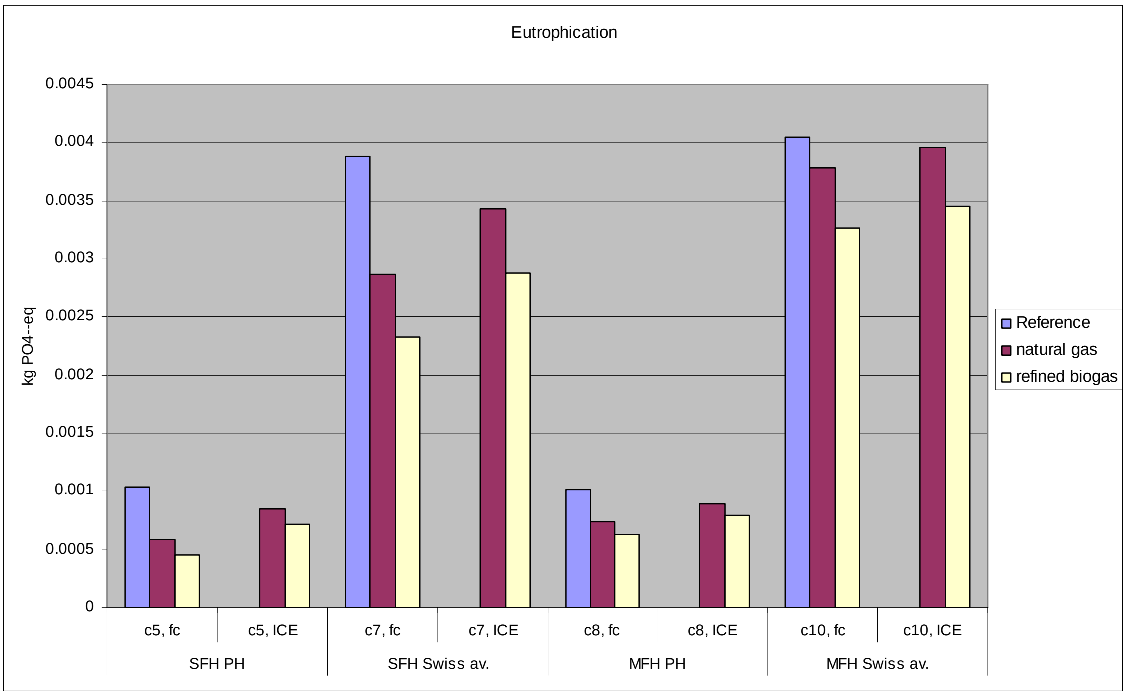

Figure 4-6 Comparing characterization results of natural gas and refined biogas in terms of eutrophication potential, CML 2 baseline 2000 method

According to the inventory, eutrophication in the refined biogas case is caused mainly by emission of ammonia and nitrous oxides as a result of the fugitive losses of biogas during storage. In the case of natural gas, the inventory revealed that the disposal of basic oxygen furnace slag (BOF)[35] into residual material landfills during the production is responsible for eutrophication. The considerable difference between the IC engine and the FC is basically due to the different exhaust emissions from their respective energy conversion processes.

4.2 Normalisation

No normalisation was performed for the studies.

4.3 Damage assessment

In order to verify the robustness of the results, damage assessment/valuation stage comes in handy. The damage assessment step means that the impact categories from the classification step are grouped to form damage categories. Damage assessment method identifies the impact category indicators in relation to one of the three endpoints[36] which include human health, ecosystem quality and resources (Eco-Indicator 99, Methodology report, 2001). Since all impact categories that refer to same damage type have the same unit, it is justified to exclude weighting.

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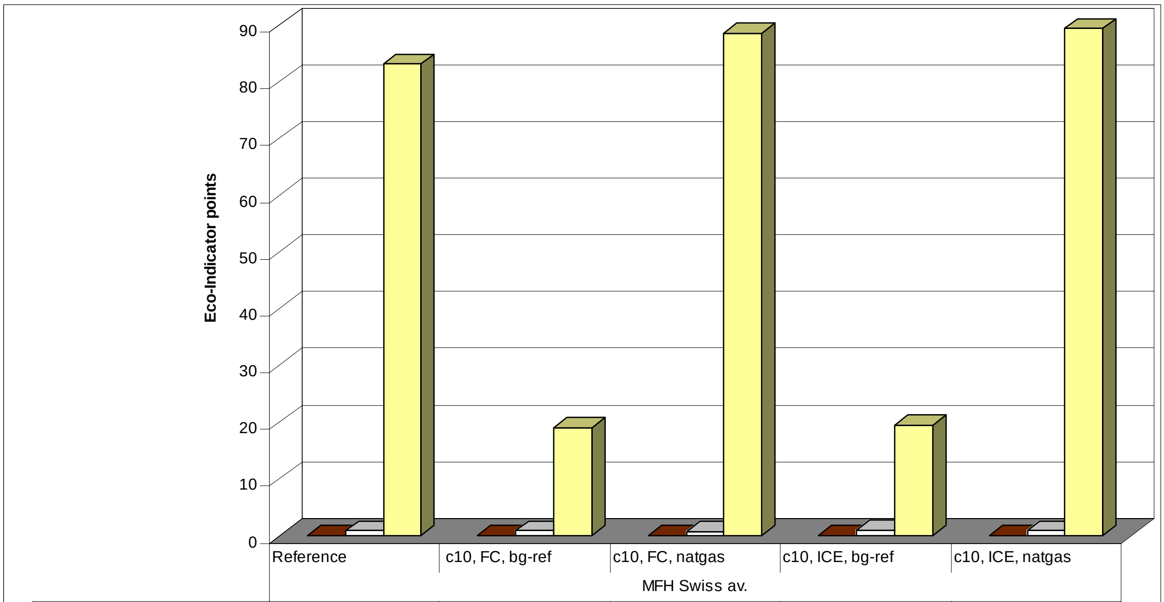
[35] Basic oxygen furnace slag (BOF slag) is a solid waste generated from the steel-making process. The slag contains a mixture of metal oxides, metal sulphides and metal atoms in their elemental form.

[36] Endpoints are aggregated impact categories where impacts with similar effects are grouped as one indicator. They are classified as damage assessment on resources (MJ-Surplus), human health (DALY) and ecosystems quality (PDF*m2yr).

Eco-Indicator 99 (EI 99), a damage-oriented method is used to classify the impact categories from the system flow into the various endpoints (Goedkoop and Spriensma, 1999). In dealing with the model uncertainties, the SimaPro software separates the three damage categories based on a Hierarchists perspective. This perspective embraces an agreement among a panel of scientists as the determining factor for the inclusion of effects (Eco-Indicator 99, Methodology report, 2001).

The case with MFH Swiss average was selected for the damage assessment analysis because it registered the highest values of all the investigated parameters. The chart below illustrates the damage assessment from the LCA.



	Reference	c10, FC, bg-ref	c10, FC, natgas	c10, ICE, bg-ref	c10, ICE, natgas
■ Human Health DALY	0.0000161	0.0000126	0.0000164	0.0000113	0.0000152
□ Ecosystem Quality PDF*m2yr	0.902	0.884	0.759	0.962	0.836
□ Resources MJ surplus	83.1	19	88.6	19.5	89.4

Figure 4-7 Comparing the damage assessment impacts of natural gas and refined biogas to the reference case in the Swiss average cases (Eco-Indicator 99)

It can be seen from the figure 4-8 above that the damage on resources from the use of natural gas is almost the same as that of the reference case. In the case of refined biogas scenarios however, the damage on resources is about 4 times lower compared to the reference case. When it comes to the damage on ecosystems quality, the results showed no noticeable differences between both natural gas and biogas and the reference case. This predilection follows through for the impacts on human health as well.

4.4 Sensitivity analysis

The most important assumption in the LCA study is the use of purified biogas with comparable quality standards to that of natural gas. In order to assess the influence of this assumption on the results, a sensitivity analysis is carried out. A modelled scenario is investigated with a micro IC engine unit running on unrefined biogas from agricultural digestion in an MFH Swiss average. This scenario best fits a farm house that uses the biomass from agricultural waste to produce heat and electricity. The new scenario is compared with refined biogas and natural gas under similar conditions using CML 2 baseline 2000 method. The characterised results are displayed in the figure 4-9 below.

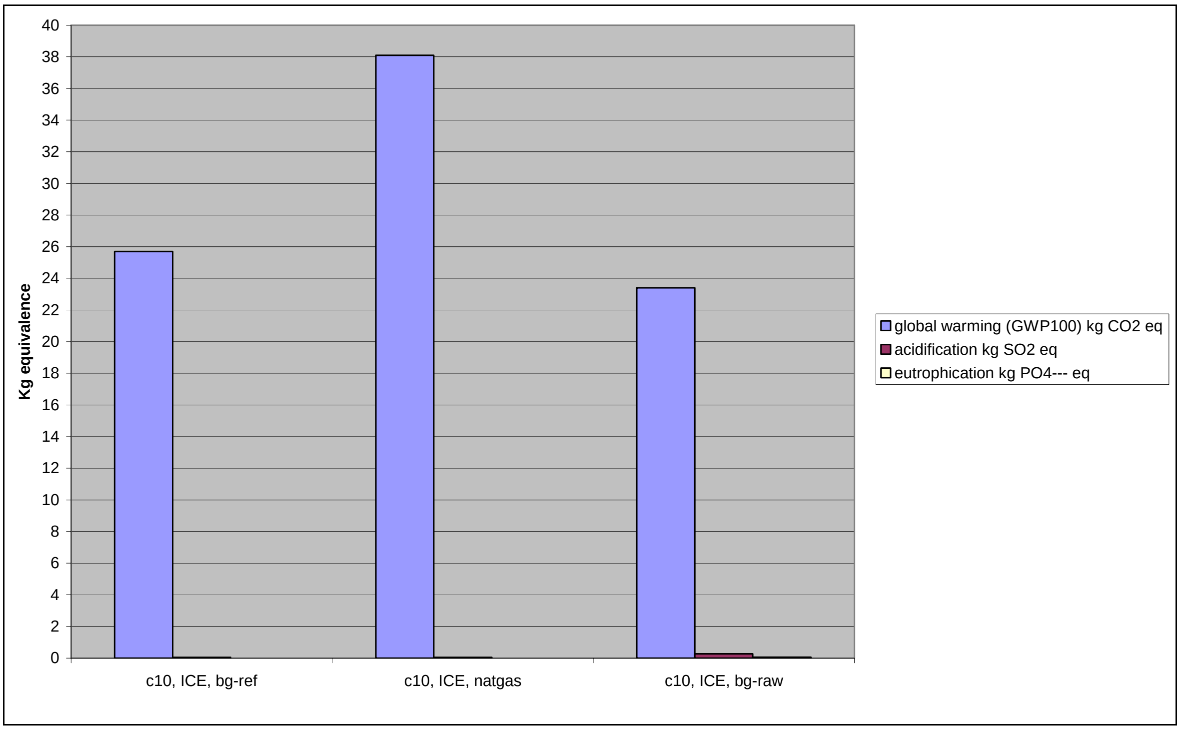
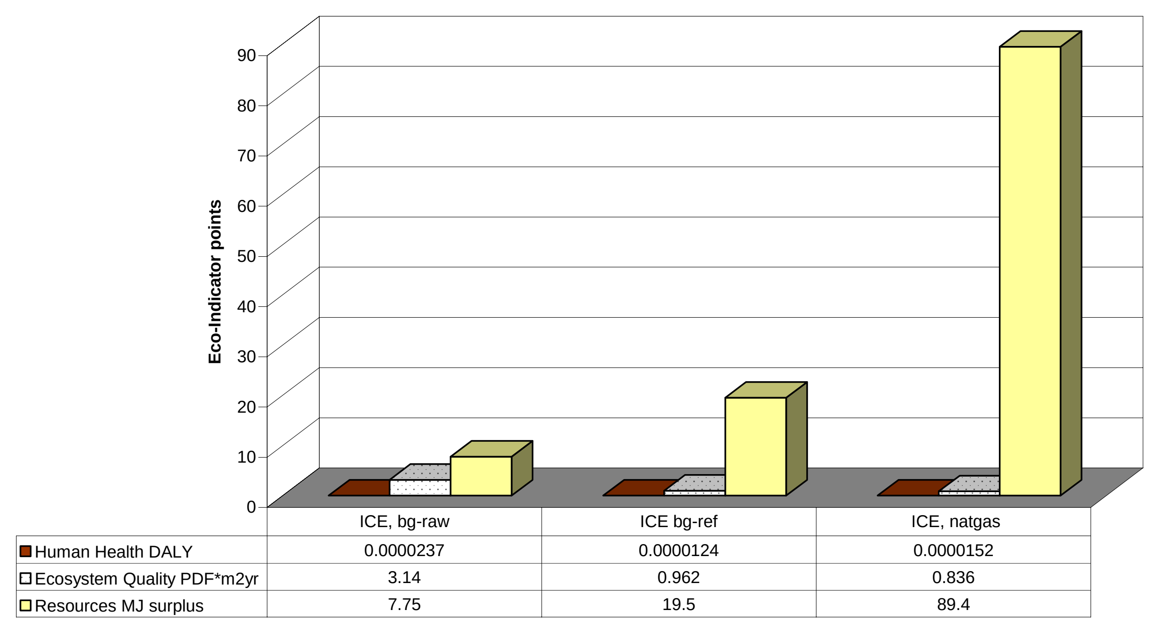


Figure 4-8 Comparing the characterisation results of refined biogas, natural gas and unrefined biogas (CML Method)

With regards to GWP, IC engine with natural gas fuel gives visibly high impacts of 38 kg CO_2 eq. This is mainly due to the emission of fossil CO_2. The raw biogas gives the least impact of about 23 kg CO_2 eq. The impacts from biogas are mainly due to emission of biogenic methane through biogas losses. Since methane is 21 times more potent than CO_2, the least amount of loses can yield higher impact potentials (Edelmann and Schleiss, 1999; Chevalier and Meunier 2005). Considerable fossil-based CO_2 emissions were seen in the use of industrial condensing boilers to provide heat for the digestion process and the materials for the infrastructure such as steel and concrete. The difference between the refined and unrefined biogas could be due to additional methane losses during the refining and distribution stages. With respect to acidification and eutrophication, the raw biogas has much potential impacts compared to refined biogas and natural gas. This is principally due to emissions of ammonia from biogas from agricultural digestion. However, the benefit from avoiding the rotting of biomass on the field outweighs the ammonia emission from the agricultural digestion and hence creating an opportunity cost.

4.4.1 Damage assessment for the sensitivity analysis

The potential damage was assessed using eco indicator 99 method. The results are presented in figure 4-11 below.



	ICE, bg-raw	ICE bg-ref	ICE, natgas
■ Human Health DALY	0.0000237	0.0000124	0.0000152
☐ Ecosystem Quality PDF*m2yr	3.14	0.962	0.836
☐ Resources MJ surplus	7.75	19.5	89.4

Figure 4-9 Comparing the damage assessment impacts from raw biogas with refined biogas and natural gas in a Swiss average cases (Eco-Indicator 99)

It can be seen from the chart above that with respect to damage on resources, natural gas recorded the highest impact of about 90 MJ-surplus. This is over 10 times higher than that from raw biogas. This is fundamentally due to the fact that the production and transportation of natural gas have magnificent impacts on minerals and fossil resources.

However, with respect to ecosystems quality, the raw biogas is the major contributor to the impact as a result of the relatively high levels of acidification and eutrophication. When it comes to refined biogas, it can be seen that the refinery lowers the impacts on ecosystem quality but increases the impacts on resources.

5 Discussions

In the previous chapter, the results from the LCA studies were presented. The aim of this chapter is to analyze the LCA results in comparison to existing literature. In an attempt to make a fair comparison, the study paid much attention to the results life cycles assessments of natural gas and refined biogas. It has to be emphasised that the results apply only to the energy systems studies and under the assumptions and conditions described. Indeed, the occupant-driven factors, the level of building insulation of the household and specifications of the micro CHP unit will, to a larger extent, determine the pattern of the energy demand profile of different domestic buildings. This section will analyse the environmental and energy performance with some general discussion and remarks on the LCA methodology and then finish off with some descriptive socio-economic implications.

5.1 Environmental performance

Looking at the entire result, two things become clear. Firstly, it can be inferred that in comparison with natural gas and the reference case, there are clear advantages in terms of climate change/global warming and consumption of finite energy resources when biogas is used for micro CHP units. Reindhardt and Gartner, (2003) proved that in most cases, biomass-based fuel save fossil energy resources and GHGs compared to conventional fuels. This also concur with the findings from (Chevalier and Meunier 2005; Pehnt 2006). Secondly, there are no clear trends revealed for the other environmental impacts especially when refined biogas is used. In terms of acidification and eutrophication, there is almost no difference between natural gas and refined biogas. These findings are valid only in the situation where the biogas is refined. However, as shown by the sensitivity analysis, unrefined biogas has undoubtedly considerable damage on the ecosystems quality due to impacts from acidification and eutrophication. Contrary to the findings from Chevalier and Meunier (2005) the damage with respect to acidification from biogas is rather higher. This could be due to the emission of higher quantities of NH_4 and SO_2 the use of agricultural biogas. All things being equal, the combustion of biogas will lead to emissions of NOx and SO_2. This probably explains why the results showed considerable differences between IC engine and the FC. According to Chevalier and Meunier (2005) this damage can be avoided if air cleaning process is used to reduce NOx emission in the exhaust gas or the use of low NOx emission-rated IC engine unit. Refining biogas can considerably reduce the impacts on ecosystems quality but it is expensive.

The high climate change impacts from the fuel cell units are basically due to emissions of CO_2 from the reforming process. The CO_2 emission from the methane reforming which was used as a proxy for the LCA modelling might have dominated in the results of the fuel cell-based applications. In this regard, Riva et al., (2006) confirms that in international databases there is an overestimate of the emissions in comparison with data collected by the gas industry. The use of biogas in IC engine proves to have positive environmental impacts with respect to climate change and resource depletion. considering on-site and distributed production as a potential source for reducing the network peak load coupled with environmental restrains to minimise CO_2 emissions and to reduce primary energy consumption, can assist the micro CHP diffusion (Dentice, rsquo et al., 2003).

5.2 Energy performance

The energy performance factors of biogas can be affected by the entire life cycle of the biogas production include the type of raw materials used, the system boundaries and the methods for allocation (Berglund and Börjesson, 2003).When dealing with materials such as fuels and combustion products in LCA, energy fluxes become a vital issue in the quantitative comparisons. It is worth noting that the net or cumulative energy is defined by the energy consumed in the entire life cycle including the heat content of the fuel. In this case the energy quality (exergy is unconditionally taken into consideration. LCIs are modelled based on the net energy which is the cradle-to-grave energy.

Energy demand in household is driven by a cross-section of factors including building type, level of insulation and occupancy (Dorer, Weber et al., 2005). Indeed better insulation decreases the energy demand in the Swiss residential building stock. For all the building standards considered, the total cumulative energy for biogas tends to be significantly lower than the reference case. The results also showed that the use of biogas is very efficient in terms of primary energy. However there is a flip side. This result will only hold valid if the process energy requirements for biogas production mix was not covered by external energy resources. The energetic efficiency of biogas is a function of the ratio of the input energy to the energy content of the biogas (Berglund and Börjesson, 2003). Low ratios correspond to high energetic efficiencies and vice versa. Certainly, if all the input energy is not accounted for by the inventory, lower ratios will obviously be recorded. The inventory report shows that the process energy for biogas production was either totally or partly covered by conventional energy resources (Spielmann, 2006 unpublished data). For instance, in a case where the digestion process sought to optimize biogas recovery, the required process heat was obtained from combusting natural gas (Spielmann, 2006 unpublished data). This assumption invalidates the relatively high energy performance factors for the biogas to some extent. Such assumptions are common in international databases. In this regard, Ayres (1995) pointed out that existing theoretical data on fuel and combustion products in LCA may differ in practice.

The credibility of LCA results are influenced by the allocation procedures used. This is an important issue that needs to be considered in the inventory modelling of multi-output processes in LCIs. Allocation procedures are needed to distribute the environmental burden among co-products. The systems investigated under the framework of this thesis are compared based on the main function of providing energy. Nevertheless, in the anaerobic digestion of biomass can fulfil other secondary functions and processes. For example in the production of biogas, organic fertiliser is also produced as a co-product. It has been stated in ISO 14041 that allocation should be avoided wherever possible. If for some reasons allocation cannot be avoided, there should be divisions between the systems' inflows and outflows in order to show the fundamental linkages between them. Biased allocation procedures can lead to a trivial comparison of results.

The valuation method used for damage assessment is EI 99. The practical goal of this method is the calculation of single scores by limiting the information of the entire system. According to the EI methodology report (Eco-Indicator 99, 2000) such scores should be used with extreme care and if possible only for internal purposes due to lack of transparency. The results obtained from the damage assessment cannot therefore be used for the environmental marketing/labelling of biogas nor to prove to the public that biogas is better than natural gas.

5.3 Socio economic perspective

According to Whites Law, "culture evolves as the amount of energy harnessed per capita per year is increased, or as the efficiency of the instrumental means of putting the energy to work is increased" (White, 1959). In this case, the use of energy has social and economic implications on a society. Goldemberg and Johansson (2004) showed a relationship between gross energy consumption and Human Development Index[37] (HDI). It is argued that 2000 W per capita primary energy is the basic amount required to ensure continuing economic prosperity (Pfeiffer, Koschenz et al., 2005). Further increase in the per capita of primary energy consumptions does not have significant effects on the HDI but rather create social, economic and environmental tension. Parallels can be drawn to the good old "Law of diminishing returns". Since the idea of distributed energy system and renewable energy generation is entrenched into the sustainability concept, this section will attempt to take a quick look at the socioeconomic impacts that could be associated with the use of biomass-based micro CHPs in the local and regional context. It is worth noting that the information presented here is only descriptive and not on an in-depth socio-economic survey.

5.3.1 Local and regional implications

In this section, the implications of micro CHP and biogas will be looked at from a synergistic point of view. The factors presented here are not really quantifiable but they could go a long way in deciding the rate of diffusion of biomass based CHP systems.

Security of energy supply: the implications of decentralised energy generation in energy security issues are specifically on the reliability of power supply and the diversification of primary energy supplies. According to Pehnt et al., (2004), onsite generation of energy with micro CHPs can be a solution to realizing local and regional energy supply security which has been a crucial issue in recent times. This achievement is even far more possible if decentralised energy systems run on locally derived fuels such as biogas. Biogas systems can utilise local resources which is often waste. Locally or regionally derived fuels contribute immensely to not only local or regional but national energy security. In the light of future energy uncertainties about decommissioning of nuclear power plants in Switzerland and the predicted gap in future electricity supply, extensive biogas energy systems can however supplement the existing hydropower and ensure reliable and secured supply of energy. Energy supply security will render the municipalities and cantons self-sufficient. Additionally, in summer for example where heating is not needed, the excess gas productions can be utilised in local transportation fleets. Indeed decentralised generation, and in particular combined heat and power plants, are regarded as a step in the right direction to alleviate the risks of energy supply security (Casten 2003).

Prestige and pride: The installation of micro CHP systems may boast the pride and wellbeing of home owners. Decentralised energy systems may be regarded as fashionable or as an element of an integrated lifestyle concept or both (Gustavsson et al., 2005). Even within the micro CHP. Eventually, some degree of competition will be created between the different decentralised energy systems. Within the micro CHP users, the type of technology has been found to determine the social class of the user. A study conducted by Penht et al., (2004) showed that among the pioneers of this new technology, fuel-cell based applications appealed mostly to the academic high-income groups whereas manual skilled workers were most likely to use I C engines.

Waste management option: anaerobic digestion can be viewed as a waste management option for the organic fraction of MSW. Presently in Switzerland, the anaerobic digestion of humid biogenic waste has become more relevant due to the legal restrictions on the separate collection of waste and their appropriate treatment and recycling (Edelmann and Schleiss, 2001). In this regard, methane which would otherwise escape into the atmosphere if this waste was landfilled can be

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[37] HDI shows a country's' relative wellbeing in social and economic terms.

trapped and used for energy production. The digestion process helps to reduce waste volumes that go into incineration.

Win-win scenario: anaerobic digestion of waste fits into a win-win situation in industrial symbiosis. Biogas and compost are obtained as co-products whiles offering an alternative waste management strategy. The compost is used as an alternative to agricultural fertiliser whiles the biogas generates energy. For example at the Kompogas plant in Otelfingen, whilst the residents in the locality collect the digestion residues free of charge for their farms and gardens, the press water from the digestion process is aquaculture experiments to educate students. In this way, a platform is set where information can be given to local inhabitants in order to promote public sector participation in for example efficient source-separation of waste.

Employment and income: The setting up of anaerobic digestion facilities has the potential to create localised jobs in a community through waste upgrading, thus creating new occupational sectors and new organisational networks within local communities. This is an economic venture with the possibility to create jobs and revenue. Local farmers are more likely to combine business and industry if micro CHP proves to be profitable. In this regard, human labour is needed for the collection and transportation of waste to the production facility and for the manning of the digestion facilities. However, for an industrialised country like Switzerland the potential for job creation is not always great. Most processing facilities rely much on automation and less on human power. For example, the digestion plant at Otelfingen with a daily production capacity of 6 000 m^3 of biogas is manned by only three employees that work on a shift basis. Additionally looking at the low unemployment[38] rate of about 4%, the value of job creation from biogas production is not a major issue in Switzerland.

In a nutshell, biomass-based micro CHP has the potential to improve access to information whiles strengthening intersectoral cooperation among the different stakeholders. In addition it can promote the use of clean energy technology, reduce energy consumption and promote energy self-sufficiency.

5.3.2 Influence on electricity and fuel prices

Generally, the liberalisation of electricity markets is expected to significantly decrease electricity prices due to increased competition. This has been the case in Sweden for example, since 1996 when the electricity market was liberalised (Sundberg and Henning, 2002). Currently, electricity prices differ from canton to canton and from utility to utility in Switzerland. According to Wusterhagen, (1998), the pricing of Swiss green electricity ranges between 90 and 700% based on the price premium[39] of the product. The variation in price depends on the production cost. The price of green electricity is Switzerland is generally higher compared to Germany and the US, due to the apparent difficulty in establishing product and price differentiation for green electricity and hydropower. Moreover, hydro power is not considered environmentally benign by all stake holders in Switzerland (Truffer et al., in Wusterhagen, 1998).

The Energie-Spiegel (2005) reports that price of natural gas have experienced strong increase in recent times in Switzerland in line with global fossil fuel trends[40]. Such drastic increases in

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[38] The unemployment rate reached 4.4% of the working population in 2005 (2004: 4.3%).

[39] The price premium is the difference between green- and ordinary electricity expressed as a percentage of the original price.

[40] Energie-Spiegel No 14/October 2005. Facts for the energy decisions of tomorrow, PSI

price can pave the way for biogas and other biomass fuels. Again, with the goal of generating 10% of the current level of electricity from renewable by the year 2035, the price increase of natural gas has the tendency to promote renewable energy generation.

From the perspective of time, the potential for efficient use of energy is higher and cheaper in the short to medium term. However, politically-based market subsidies do have much influence on the implementation and developments of renewable energy systems. For example, currently in Germany for instance, solar power is paid up to 93 Rp./kWh feed-in tariffs depending on the installation as opposed to 15 Rp./kWh in Switzerland (Energie-Spiegel, 2005)[41]. This means that if the incentives are raised for domestic home owners in Switzerland, many of them could invest in micro CHP installation for their homes and relieve energy loads with their excess. In the case of industries, the price of input fuels and electricity from the grid exerts considerable influence on their profitability and the adoption of CHP systems[42].

5.3.3 Consumer behaviour

Pehnt (2006) argued that the application of distributed energy sources could modify consumer behaviour especially when the systems are installed at the customers' premises. The main argument was the ability to partially offset the positive environmental aspects of renewable energy systems with a rebound effect. A *Rebound effect* (also called a *Takeback Effect* or *Offsetting Behavior*) refers to increased consumption resulting from actions that increase efficiency and reduce consumer costs (Musters, 1995; Alexander, 1997; Herring, 1998). Studies done by the UK Energy Research Centre[43] proved that rebound effects have deep implications on a country's energy and climate policies. For example, if the development of biomass-based micro CHPs is cheap and efficient to the consumers, then in the macro perspective, lower energy cost would imply more money available for say holidays. These services can eventually offset the achieved energy savings.

That said there can be a positive outcome on the other hand; the use of biomass based micro CHP could inspire consumers' involvement in energy and environmental issues. Although these are intangible values, they can in a sense go a long way to reduce environmental impacts and increased energy independence. However, in this respect, Pehnt (2006) concluded that these positive effect, to a great extent depend on the specific form, timing and details of feedback, and on the presence of price-based incentives and ecological motives.

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[41] 1CFH = 100 Rp.

[42] In Reinhard Madlener and Marcel Wickart. Diffusion of cogeneration in Swiss industries: economics, technical change, field of application and framework conditions. [Online]. Available http://www.cepe.ch/download/staff/reinhard/madlener_wickart_ee15_2_p223.pdf 2006-08-31

[43] Centre that deals with energy policies and climate change issues. Available from http://www.ukerc.ac.uk/content/view/130/187

5.3.4 Potential barriers in Switzerland

5.3.4.1 Infrastructure

The widespread use of domestic micro CHP applications in Switzerland can be affected by the initial cost of the device and installation, access to biogas grid and space requirements. Although the analysis of real manufacturing and market prices of micro CHP devices is outside the scope of this thesis, it is perceived that the relatively high cost of the devices and the direct and indirect cost of installation could serve as a deterrent to home owners. The distance between the biogas facility and residential buildings could serve as a limitation. Normally, biogas facilities are sited in the outskirts of towns and villages because of odour. Further, for potential users living in multi-family dwellings with common basements, space requirements could be a restriction. According to Pehnt et al., (2006), these uncertainties could be overcome not only by reliable information but by the introduction of support schemes such as investment subsidies and feed-in-tariffs.

5.3.4.2 Support scheme for Biogas diffusion

Although there is a high potential for biogas production in Switzerland, the diffusion of biogas plants is not rapid due to limited support of solid innovation networks. According to Markard et al., (2005), support polices in Switzerland are dependent on national framework conditions. In comparison with Austria and Germany, the lack of guaranteed feed-in tariffs for electricity generated from biogas and information support hinders the growth of biogas in Switzerland. These limited support policies on biogas innovation networks are to prevent the threat of establishing market biases (Markard et al., 2005). Policy-wise, Switzerland has the chance to learn from countries like Germany that has lots of experience in high feed-in tariffs, or Sweden, the guru in quota regulation and tradable permits (Energie-Spiegel, 2005). One area where the Swiss energy policy could focus on is the introduction of incentives to encourage the investment in micro-scale energy units. In this regard, economic instruments in the form of tax and fiscal incentives can be the most effective way to promote local micro-scale energy systems on the household level.

6 Conclusions

The backdrop of some uncertainties in the qualitative results not withstanding, the thesis sought to confirm the environmental and some social benefits from the use of bioenergy in support of indicators other than the chosen methodology. However, the findings of this study is only suited for internal purposes and cannot be relied on for environmental marketing and labelling for biogas.

Two research questions were posed:

1. *What is the performance (environmental and efficiency) of micro CHP units running on biogas fuel?*

The performance assessment of biomass-based micro CHP in the Swiss residential building stock has been established. Biogas demonstrated a seemingly higher primary energy performance factor than natural gas. The validity of the finding is subject to further confirmation on the energy balance of the biogas systems. Compared to the grid electricity and gas boiler as the benchmark, the use of biogas in micro CHP applications greatly reduced impacts from energy resources and climate change. In satisfying the same energy need, biogas reduced the impact on resources by approximately 75%. The use of biogas however confirmed considerable negative impacts on ecosystems quality in terms of acidification and eutrophication. However, the benefit from avoiding biomass to decompose in the fields appears greater. Compared to the unrefined counterpart, refined biogas somewhat reduces the impacts on ecosystems quality.

2. *What are some of the socio-economic advantages and challenges at the regional and national levels for residential micro CHP systems?*

Within the local and regional context, micro CHP and biogas development synergies have the tendency to ensure energy security and reduce the over-dependence on fossil resources thus creating “energy self-sufficiency”. In spite of its ability to positively or negatively influence consumer behaviour, biomass-based micro CHP exhibit the potential to create jobs and income in a local canton whiles more or less, creating pride and prestige among the pioneers of the technology adopters. In the short to medium term, biomass-based micro CHP may not have any authentic influence on fuel and electricity prices in Switzerland. However, if policy interventions in the form of tax and fiscal incentives are put in place, it could lead to a widespread adoption of biomass-based energy systems considering the high installation cost of micro CHP devices. Ultimately, the potentials exist to improve access to local information whiles strengthening inter-sectoral cooperation among different stakeholders if suitable policy tools are implemented.

6.1 Outlook and further research

In the previous section, an attempt was made to answer the research questions in order to fulfil the objectives of this research. Whiles the main task of this research has been achieved, the author would like to contemplate on some issues that are of relevance in milieu of the case under investigation which can also be areas of further research.

On a wider note, the initial idea of the forgoing study is to initiate a bottom-up approach for the environmental assessment of biomass-based decentralised energy systems for Switzerland. The household level is the grassroots where results achieved here can be extrapolated to the local, regional and national levels. If a clearly defined methodology is established, then it can be used as a universal approach by other countries to evaluate emission savings at local, regional and national levels.

As shown in chapter 4, the LCA results demonstrate a relatively high energy performance factor. Such quantitative results are easily influenced by the choice of allocation procedures and system boundaries. It is recommended that the LCA modelling is repeated in future studies with due consideration to the allocation procedures in order to ascertain the real performance of integrated biogas energy systems. In addition, the same methodology should be extended to other micro CHP units like Stirling engines and micro turbines in order to add to the limited data currently available.

The socioeconomic aspect of decentralised energy generation requires a real survey using for example, interviews and structured questionnaire. Social impacts include the impacts emanating from the use of biomass-based micro CHP products and services and impacts from energy end-use conversion. Social impacts can be positive or negative. In order to assess the impacts for a socio-economic point of view, surveys should be performed in the Swiss contexts in order to assess the real implications of decentralised generation.

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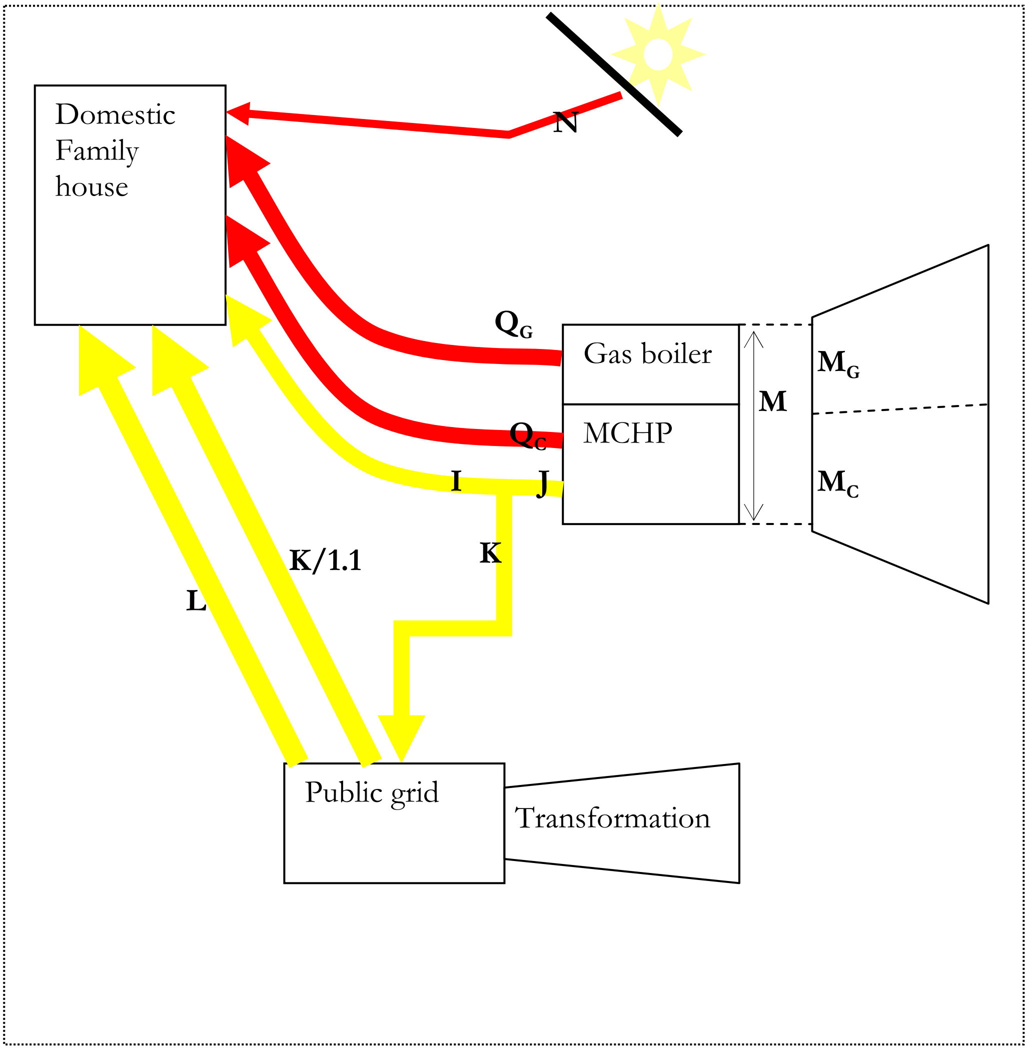
Abbreviations (if required)

BFE	Bundesamt für Energie
CHP	Combined heat and power
CO_2	Carbon (IV) oxide
EI	Eco-Indicator
FESR	Fuel energy saving ratio
FOEN	Federal Office for the Environment
GHGs	Greenhouse gases
ISO	International Standard Organisation
LCA	Life Cycle Assessment
LCI	Life cycle inventory
MSW	Municipal Solid Wastes
NG	Natural gas
NOx	Nitrogen oxide
PES	Primary energy saving
R&D	Research and design
SFOE	Swiss Federal Office of Energy
TRNSYS	the Transient Energy System Simulation Program

Appendices

Appendix 1: Deriving an empirical equation for the estimation of net energy demand for domestic dwellings



Where,

Q_G = quantity of heat supplied from gas boiler

Q_C = quantity of heat supplied from micro CHP unit

N = heat from solar collector

M = total gas demand in MJ

M_G = gas demand by boiler in MJ

M_C = gas demand by micro CHP in MJ

J = total electricity generated by micro CHP

K = generated electricity delivered to and re-supplied from public grid

I = generated electricity used directly by the household

L = residual electricity demand from public grid

K/1.1 = grid losses

Empirical formulae for the estimation of net energy demands based on TRNSYS simulation results.

$$(1)\ \text{Heat}: \quad F + G = Qg + Qc + N$$

$$(2)\ \text{Electricity}: H = I + K\,{}^{1}\!/_{1.1} + L = I + (1 - \frac{1}{11})K + L = J - \frac{1}{11}K + L$$

$$(3) \qquad \eta_{th} = \frac{Q_C}{M_C}, \eta_{el} = \frac{J}{M_C}, \eta_G = \frac{Q_G}{M_G}$$

$$(4): (3)\ in\ (1) \quad F + G = \eta_G.M_G + \eta_{th}.M_C + N$$

$$(5): (3)\ \text{in}\ (2) \quad H = \eta_{el}.M_C + L - \frac{1}{11}K$$

$$(6): (3)\ \text{with} \quad a = \frac{Q_G}{Q_C + Q_G} = \frac{Q_G}{Q_T}: \qquad \eta_G = \frac{aQ_T}{M_G} \to M_G = \frac{aQ_T}{\eta_G} = \frac{a(F + G - N)}{\eta_G}$$

$$(7): (6)\ \text{in}\ (4) \quad F + G = aQ_T + \eta_{th}.M_C + N$$

$$(8) \qquad H = \eta_{el}.M_C + L - \frac{1}{11}K$$

$$(9): (7)\ \text{Solved for}\ M_C, \qquad M_C = \frac{F + G - aQ_T - N}{\eta_{th}} = \frac{(1-a)(F + G - N)}{\eta_{th}}$$

$$(10): (9)\ \text{in}\ (8) \quad L = H - \frac{\eta_{el}}{\eta_{th}}(1-a)(F + G - N) + \frac{1}{11}K = H + \frac{\eta_{el}}{\eta_{th}}(a-1)(F + G - N) + \frac{1}{11}K$$

$$\text{Estimation of a}: a = \frac{Q_G}{Q_C + Q_G} = \frac{\eta_G.M_G}{\eta_G.M_G + \eta_{th}\frac{J}{\eta_{el}}} = \frac{\eta_G.\frac{aQ_T}{\eta_G}}{\eta_G.\frac{aQ_T}{\eta_G} + \frac{\eta_{th}}{\eta_{el}}J} = \frac{aQ_T}{aQ_T + \frac{\eta_{th}}{\eta_{el}}J} = \frac{\eta_{el}.a.Q_T}{a.\eta_{el}Q_T + \eta_{th}J}$$

$$a(a.\eta_{el}Q_T + \eta_{th}J) = \eta_{el}.a.Q_T$$

$$a = \frac{\eta_{el}Q_T - \eta_{th}J}{\eta_{el}Q_T} = 1 - \frac{\eta_{th}J}{\eta_{el}Q_T} = 1 - \frac{\eta_{th}J}{\eta_{el}(F + G - N)}$$

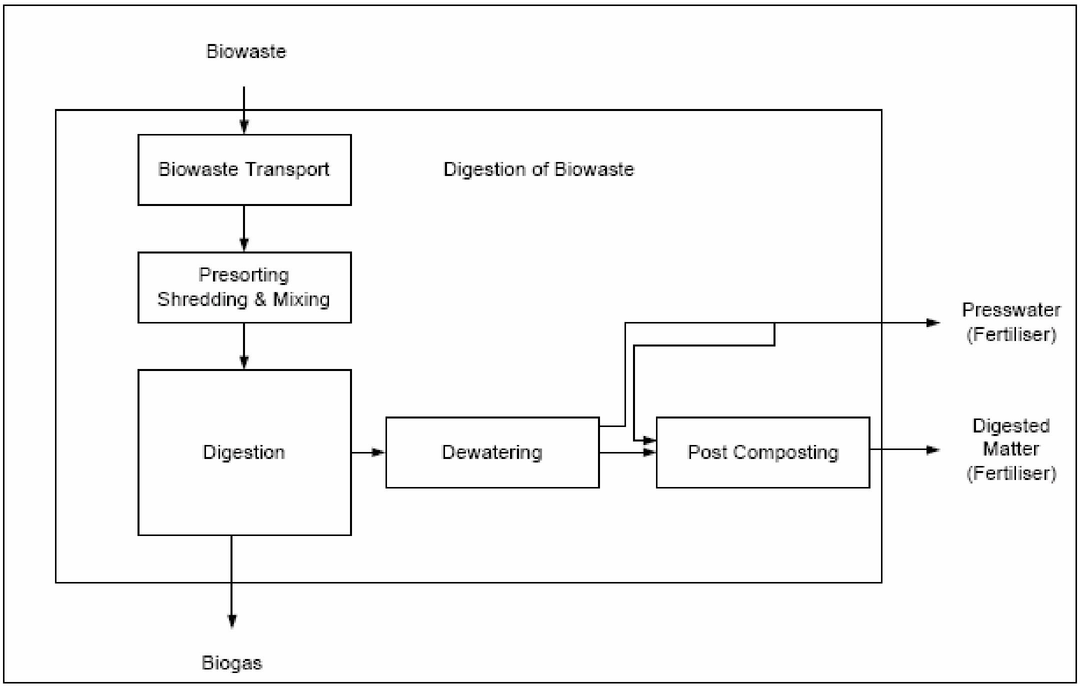
<u>Legend</u>

η_{el} = electrical efficiency

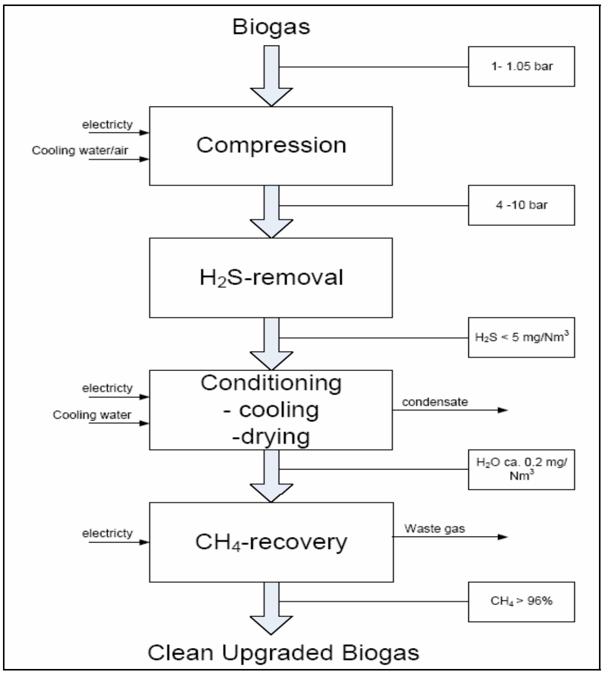
η_{th} = thermal efficiency

F, G and H = Introduced variables based on their respective columns on the excel sheet in appendices 2 and 3.

Schematic process flow of the anaerobic digestion of biowaste



Process flow for the use and upgrading of biogas production mix



Appendix 2: simulations results on the performance of fuel-cell based micro-cogeneration systems

Building type	Energy system	Occupants (No)	Storage size (m3)	Solar collektor (m2)	Domestic hot water demand	Space heating demand	Electricity demand	Generated electricity directly used	Generated electricity total	Generated electricity delivered to / re-supplied from	(Residual) Electricity demand from grid	Natural gas demand (end energy)	Heat supply collector	Electricity demand hot water storage	Heat losses hot water storage
									Fuel cell						
SFH PH	SOFC	4.00	0.70	0.00	47.08	43.71	52.56	28.52	49.80	21.28	4.69	171.53	0.00	0.00	10.64
SFH SIA ta	SOFC	4.00	0.70	0.00	52.29	154.57	78.14	46.61	89.83	43.22	-7.77	333.38	0.00	0.00	11.74
SFH Swiss	SOFC	4.00	0.70	0.00	60.49	424.39	119.12	60.20	106.29	46.09	17.02	629.26	0.00	0.00	15.11
MFH PH	SOFC	12.00	2.80	0.00	35.70	46.52	55.57	21.64	30.14	8.50	26.21	122.05	0.00	0.00	6.29
MFH SIA t	SOFC	12.00	2.80	0.00	37.66	130.89	99.37	22.71	32.67	9.96	67.61	206.18	0.00	0.00	6.54
MFH Swiss	SOFC	12.00	2.80	0.00	46.53	448.57	130.09	25.74	34.26	8.52	96.60	548.97	0.00	0.00	9.36
SFH PH	Gas boiler	4.00	0.70	0.00	46.89	43.41	52.56	0.00	0.00	0.00	52.56	102.98	0.00	0.00	11.79
SFH SIA ta	Gas boiler	4.00	0.70	0.00	52.06	153.59	78.14	0.00	0.00	0.00	78.14	207.62	0.00	0.00	14.31
SFH Swiss	Gas boiler	4.00	0.70	0.00	61.01	423.74	119.12	0.00	0.00	0.00	119.12	503.37	0.00	0.00	16.50
MFH PH	Gas boiler	12.00	2.80	0.00	35.97	45.90	55.57	0.00	0.00	0.00	55.57	88.26	0.00	0.00	6.97
MFH SIA t	Gas boiler	12.00	2.80	0.00	37.69	130.26	99.35	0.00	0.00	0.00	99.35	163.21	0.00	0.00	7.45
MFH Swiss	Gas boiler	12.00	2.80	0.00	47.55	446.32	130.09	0.00	0.00	0.00	130.09	506.28	0.00	0.00	10.06
									reciprocating internal combustion engine						
SFH PH	SOFC	4.00	0.70	0.00	47.08	43.71	52.56	28.52	49.80	21.28	4.69	171.53	0.00	0.00	10.64
SFH SIA ta	SOFC	4.00	0.70	0.00	52.29	154.57	78.14	46.61	89.83	43.22	-7.77	333.38	0.00	0.00	11.74
SFH Swiss	SOFC	4.00	0.70	0.00	60.49	424.39	119.12	60.20	106.29	46.09	17.02	629.26	0.00	0.00	15.11
MFH PH	SOFC	12.00	2.80	0.00	35.70	46.52	55.57	21.64	30.14	8.50	26.21	122.05	0.00	0.00	6.29
MFH SIA t	SOFC	12.00	2.80	0.00	37.66	130.89	99.37	22.71	32.67	9.96	67.61	206.18	0.00	0.00	6.54
MFH Swiss	SOFC	12.00	2.80	0.00	46.53	448.57	130.09	25.74	34.26	8.52	96.60	548.97	0.00	0.00	9.36
SFH PH	Gas boiler	4.00	0.70	0.00	46.89	43.41	52.56	0.00	0.00	0.00	52.56	102.98	0.00	0.00	11.79
SFH SIA ta	Gas boiler	4.00	0.70	0.00	52.06	153.59	78.14	0.00	0.00	0.00	78.14	207.62	0.00	0.00	14.31
SFH Swiss	Gas boiler	4.00	0.70	0.00	61.01	423.74	119.12	0.00	0.00	0.00	119.12	503.37	0.00	0.00	16.50
MFH PH	Gas boiler	12.00	2.80	0.00	35.97	45.90	55.57	0.00	0.00	0.00	55.57	88.26	0.00	0.00	6.97
MFH SIA t	Gas boiler	12.00	2.80	0.00	37.69	130.26	99.35	0.00	0.00	0.00	99.35	163.21	0.00	0.00	7.45
MFH Swiss	Gas boiler	12.00	2.80	0.00	47.55	446.32	130.09	0.00	0.00	0.00	130.09	506.28	0.00	0.00	10.06

Appendix 3: Estimated net energy demand for the various building types based on simulation results.

		Eff th	Eff el.	Eff total	Eff gb	Factor a [QG / (QC + QG)]	QC Supplied heat from cogen unit	QG Supplied heat from gas boiler	MC Natural gas demand of cogen. Unit	MG Natural gas demand of gas boiler	MT Natural gas demand	L (Residual) Electricity demand	J Electricity total from cogeneration [eff el * MC]	M Difference [%] to simulated value M	M Difference [MJ/m2/a] to simulated value M	L Difference [%] to simulated value L	L Difference [MJ/m2/a] to simulated value L
						[estimat	[estimat	[estimat	[estimat	[estimat	[estimat	[estimat	[estimat	[calculat	[calculat	[calculat	[calculat
							fuel cell										
SFH PH	SOFC	0.56	0.31	0.87	1.00	0.12	88.84	12.58	158.95	12.58	171.53	4.69	49.80	0.00	0.00	0.00	0.00
SFH SIA ta	SOFC	0.57	0.34	0.91	1.00	0.30	152.67	65.93	267.45	65.93	333.38	-7.77	89.83	0.00	0.00	0.00	0.00
SFH Swiss	SOFC	0.58	0.35	0.93	1.00	0.64	177.81	322.18	307.08	322.18	629.26	17.02	106.29	0.00	0.00	0.00	0.00
MFH PH	SOFC	0.59	0.36	0.95	1.03	0.44	49.16	39.35	83.84	38.20	122.04	26.21	30.14	0.00	0.00	0.00	0.00
MFH SIA t	SOFC	0.59	0.36	0.95	1.05	0.70	52.72	122.37	89.63	116.55	206.18	67.61	32.67	0.00	0.00	0.00	0.00
MFH Swiss	SOFC	0.57	0.33	0.90	1.00	0.88	58.74	445.72	103.25	445.72	548.97	96.60	34.26	0.00	0.00	0.00	0.00
SFH PH	Gas boiler	0.56	0.36	0.92	0.99	1.00	0.00	102.09	0.00	102.98	102.98	52.56	0.00	0.00	0.00	0.00	0.00
SFH SIA ta	Gas boiler	0.56	0.31	0.87	1.06	1.00	0.00	219.95	0.00	207.62	207.62	78.14	0.00	0.00	0.00	0.00	0.00
SFH Swiss	Gas boiler	0.56	0.31	0.87	1.00	1.00	0.00	501.26	0.00	503.37	503.37	119.12	0.00	0.00	0.00	0.00	0.00
MFH PH	Gas boiler	0.56	0.31	0.87	1.01	1.00	0.00	88.84	0.00	88.26	88.26	55.57	0.00	0.00	0.00	0.00	0.00
MFH SIA t	Gas boiler	0.56	0.25	0.81	1.07	1.00	0.00	175.40	0.00	163.21	163.21	99.35	0.00	0.00	0.00	0.00	0.00
MFH Swiss	Gas boiler	0.56	0.31	0.87	1.00	1.00	0.00	503.93	0.00	506.28	506.28	130.09	0.00	0.00	0.00	0.00	0.00
							reciprocating internal combustion engine										
SFH PH	ICE	0.69	0.20	0.88	1.00	0.12	88.84	12.58	129.65	12.58	142.22	29.10	25.39	-17.08	-29.30	520.24	24.41
SFH SIA ta	ICE	0.70	0.21	0.91	1.00	0.30	152.67	65.93	218.15	65.93	284.08	36.27	45.79	-14.79	-49.30	-567.08	44.04
SFH Swiss	ICE	0.71	0.22	0.93	1.00	0.64	177.81	322.18	250.47	322.18	572.65	69.13	54.19	-9.00	-56.61	306.11	52.11
MFH PH	ICE	0.72	0.22	0.94	1.03	0.44	49.16	39.35	68.39	38.20	106.59	40.98	15.36	-12.66	-15.46	56.38	14.77
MFH SIA t	ICE	0.72	0.23	0.95	1.05	0.70	52.72	122.37	73.11	116.55	189.66	83.62	16.65	-8.01	-16.52	23.69	16.01
MFH Swiss	ICE	0.70	0.21	0.90	1.00	0.88	58.74	445.72	84.22	445.72	529.94	113.39	17.47	-3.47	-19.03	17.39	16.80
SFH PH	Gas boiler	0.56	0.36	0.92	0.99	1.00	0.00	102.09	0.00	102.98	102.98	52.56	0.00	0.00	0.00	0.00	0.00
SFH SIA ta	Gas boiler	0.56	0.31	0.87	1.06	1.00	0.00	219.95	0.00	207.62	207.62	78.14	0.00	0.00	0.00	0.00	0.00
SFH Swiss	Gas boiler	0.56	0.31	0.87	1.00	1.00	0.00	501.26	0.00	503.37	503.37	119.12	0.00	0.00	0.00	0.00	0.00
MFH PH	Gas boiler	0.56	0.31	0.87	1.01	1.00	0.00	88.84	0.00	88.26	88.26	55.57	0.00	0.00	0.00	0.00	0.00
MFH SIA t	Gas boiler	0.56	0.25	0.81	1.07	1.00	0.00	175.40	0.00	163.21	163.21	99.35	0.00	0.00	0.00	0.00	0.00
MFH Swiss	Gas boiler	0.56	0.31	0.87	1.00	1.00	0.00	503.93	0.00	506.28	506.28	130.09	0.00	0.00	0.00	0.00	0.00

Appendix 4: Cumulative energy demand

SimaPro 7.0 Impact ass Date: 22.08.200 Time: 19:39:26

Title: Comparing processes
Method: Cumulative Energy Demand V1.03 / Cumulative energy demand
Value: Characterization
Per impact category: Yes
Skip unused: Never
Relative mode: Non

Impact category	Unit	fc, bg-ref	fc, natgas	ICE, bg-ref	ICE, natgas	fc, bg-ref	fc, natgas	ICE, bg-ref	ICE, natga	fc, bg-ref	fc, natgas	ICE, bg-ref	ICE, natga	fc, bg-ref	fc, natgas	ICE, bg-ref	ICE, natga
Non renewable, fossil	MJ-Eq	35.9	169	47.5	183	151	693	175	722	38.1	140	45.1	148	179	684	187	694
Non-renewable, nuclear	MJ-Eq	31.1	9.19	76.3	54	127	37.8	223	134	65.7	49	93	76.2	269	186	300	217
Renewable, biomass	MJ-Eq	0.272	0.124	0.61	0.458	1.17	0.57	1.89	1.28	0.527	0.414	0.731	0.616	2.25	1.69	2.48	1.92
Renewable, wind, solar, geothe	MJ-Eq	0.186	0.0639	0.442	0.318	0.842	0.345	1.39	0.888	0.389	0.296	0.544	0.45	1.68	1.22	1.86	1.39
Renewable, water	MJ-Eq	9.93	3.08	24.4	17.5	39.8	12	70.7	42.7	21	15.7	29.7	24.4	85	59.1	94.9	68.9

SimaPro 7.0 Impact ass Date: 22.08.200 Time: 19:39:59

Title: Comparing processes
Method: Cumulative Energy Demand V1.03 / Cumulative energy demand
Value: Single score
Per impact category: Yes
Skip unused: Never
Relative mode: Non

Impact category	Unit	fc, bg-ref	fc, natgas	ICE, bg-ref	ICE, natgas	fc, bg-ref	fc, natgas	ICE, bg-ref	ICE, natga	fc, bg-ref	fc, natgas	ICE, bg-ref	ICE, natga	fc, bg-ref	fc, natgas	ICE, bg-ref	ICE, natga
Non renewable, fossil	Pt	35.9	169	47.5	183	151	693	175	722	38.1	140	45.1	148	179	684	187	694
Non-renewable, nuclear	Pt	31.1	9.19	76.3	54	127	37.8	223	134	65.7	49	93	76.2	269	186	300	217
Renewable, biomass	Pt	0.272	0.124	0.61	0.458	1.17	0.57	1.89	1.28	0.527	0.414	0.731	0.616	2.25	1.69	2.48	1.92
Renewable, wind, solar, geothe	Pt	0.186	0.0639	0.442	0.318	0.842	0.345	1.39	0.888	0.389	0.296	0.544	0.45	1.68	1.22	1.86	1.39
Renewable, water	Pt	9.93	3.08	24.4	17.5	39.8	12	70.7	42.7	21	15.7	29.7	24.4	85	59.1	94.9	68.9
Total		77.388	181.4579	149.252	255.276	319.812	743.715	471.98	900.868	125.716	205.41	169.075	249.666	536.93	932.01	586.24	983.21

Characterisation and Normalisation (CML)

SimaPro 7. Impact ass Date: 05.09.2006 Time: 14:32:00

Title: Comparing processes
Method: * CML 2 baseline 2000 (Revised) V2.04 / West Europe, 1995
Value: Characterization
Per impact Yes
Skip unuse Never
Relative m Non

Impact cat	Unit	c5, fc, bg-ref	c5, fc, natgas	c5, ICE, bg-ref	c5, ICE, natga	c7, fc, bg-ref	c7, fc, natgas	c7, ICE, bg-re	c7, ICE, natga	c8, fc, bg-ref	c8, fc, natgas	c8, ICE, bg-ref	c8, ICE, natga	c10, fc, bg-ref	c10, fc, natga	c10, ICE, bg-r
abiotic dep	kg Sb eq	0.0185	0.083	0.0256	0.0912	0.0781	0.34	0.0931	0.357	0.0207	0.0699	0.025	0.0747	0.0968	0.341	0.102
global warr	kg CO2 eq	5.57	17	6.64	4.02	23.1	55.3	25.3	29.8	5.2	12.3	5.84	5.54	25	46.5	25.7
acidificatio	kg SO2 eq	0.00675	0.00727	0.01	0.0106	0.0313	0.0334	0.0383	0.0404	0.00853	0.00892	0.0105	0.0109	0.0418	0.0438	0.0441
eutrophicat	kg PO4---	0.000452	0.000586	0.000713	0.00085	0.00233	0.00287	0.00288	0.00343	0.000633	0.000735	0.000793	0.000895	0.00327	0.00378	0.00345

SimaPro 7. Impact ass Date: 05.09.2006 Time: 14:32:57

Title: Comparing processes
Method: * CML 2 baseline 2000 (Revised) V2.04 / West Europe, 1995
Value: Normalization
Per impact Yes
Skip unuse Never
Relative m Non

Impact cat	Unit	c5, fc, bg-ref	c5, fc, natgas	c5, ICE, bg-ref	c5, ICE, natga	c7, fc, bg-ref	c7, fc, natgas	c7, ICE, bg-re	c7, ICE, natga	c8, fc, bg-ref	c8, fc, natgas	c8, ICE, bg-ref	c8, ICE, natga	c10, fc, bg-ref	c10, fc, natga	c10, ICE, bg-r
abiotic dep		1.25E-12	5.6E-12	1.73E-12	6.15E-12	5.26E-12	2.29E-11	6.28E-12	2.41E-11	1.4E-12	4.71E-12	1.69E-12	5.04E-12	6.53E-12	2.3E-11	6.85E-12
global warr		1.16E-12	3.54E-12	1.38E-12	8.36E-13	4.8E-12	1.15E-11	5.27E-12	6.2E-12	1.08E-12	2.57E-12	1.21E-12	1.15E-12	5.19E-12	9.68E-12	5.34E-12

Damage assessment (EI 99)

Human He	DALY	0.00000341	0.00000442	0.00000142	2.5E-06	0.0000116	0.0000157	0.00000781	0.000012	0.00000323	0.000004	0.00000226	0.00000304	0.0000126	0.0000164	0.0000113	0.0000152
Ecosystem	PDF*m2yr	0.117	0.0834	0.229	0.195	0.523	0.388	0.763	0.627	0.198	0.173	0.266	0.24	0.884	0.759	0.962	0.836
Resources	MJ surplus	4.24	22.7	5.02	23.8	17.6	92.5	19.3	94.8	3.93	18	4.4	18.6	19	88.6	19.5	89.4

SimaPro 7. Impact ass Date: 06.09.2006 Time: 09:46:24

Title: Comparing processes
Method: * Eco-indicator 99 (H) (revised) V2.04 / Europe EI 99 H/A
Value: Damage assessment
Per impact No
Skip unuse Never
Relative m Non

Damage ca	Unit	Ref Domestic	Ref Domestic	Ref Domestic	Ref Domestic energy demand, MFH PH,Gas boiler, UCTE-mix
Human He	DALY	0.0000161	0.00000407	0.0000154	4E-06
Ecosystem	PDF*m2yr	0.902	0.296	0.849	0.304
Resources	MJ surplus	83.1	16	81	14.8

damage assessment

Impact category		SFH PH					SFH Swiss av.					MFH PH					MFH Swiss av.				
	Unit	Reference	c5, fc, bg-ref	c5, fc, natgas	c5, ICE, b	c5, ICE, natga	Reference	c7, fc, bg-ref	c7, fc, natga	c7, ICE, bg-re	c7, ICE, nat	Reference	c8, fc, bg-ref	c8, fc, natga	c8, ICE, bg-re	c8, ICE, natga	Reference	c10, FC, bg-	c10, FC, nat	c10, ICE, bg-	c10, ICE, nat
Human He	DALY	0.00000407	0.00000341	0.00000442	1.4E-06	0.00000245	0.0000154	0.0000116	0.0000157	0.00000781	0.000012	0.00000399	0.00000323	0.000004	0.00000226	0.00000304	0.0000161	0.0000126	0.0000164	0.0000113	0.0000152
Ecosystem	PDF*m2yr	0.296	0.117	0.0834	0.229	0.195	0.849	0.523	0.388	0.763	0.627	0.304	0.198	0.173	0.266	0.24	0.902	0.884	0.759	0.962	0.836
Resources	MJ surplus	16	4.24	22.7	5.02	23.8	81	17.6	92.5	19.3	94.8	14.8	3.93	18	4.4	18.6	83.1	19	88.6	19.5	89.4

Damage assessment for sensitivity analysis

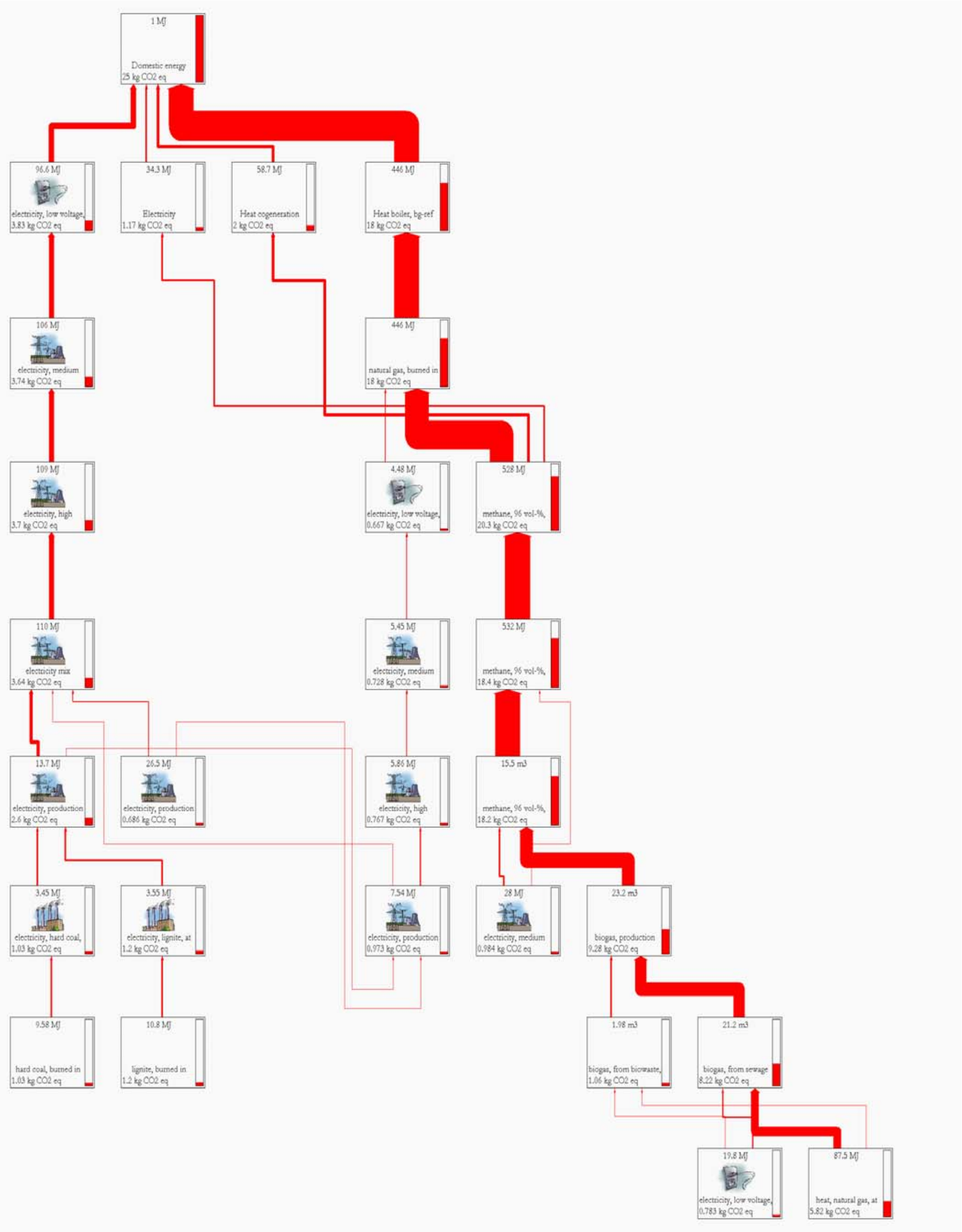
SimaPro 7. Wirkungsa Datum: 08.09.2006 Zeit:

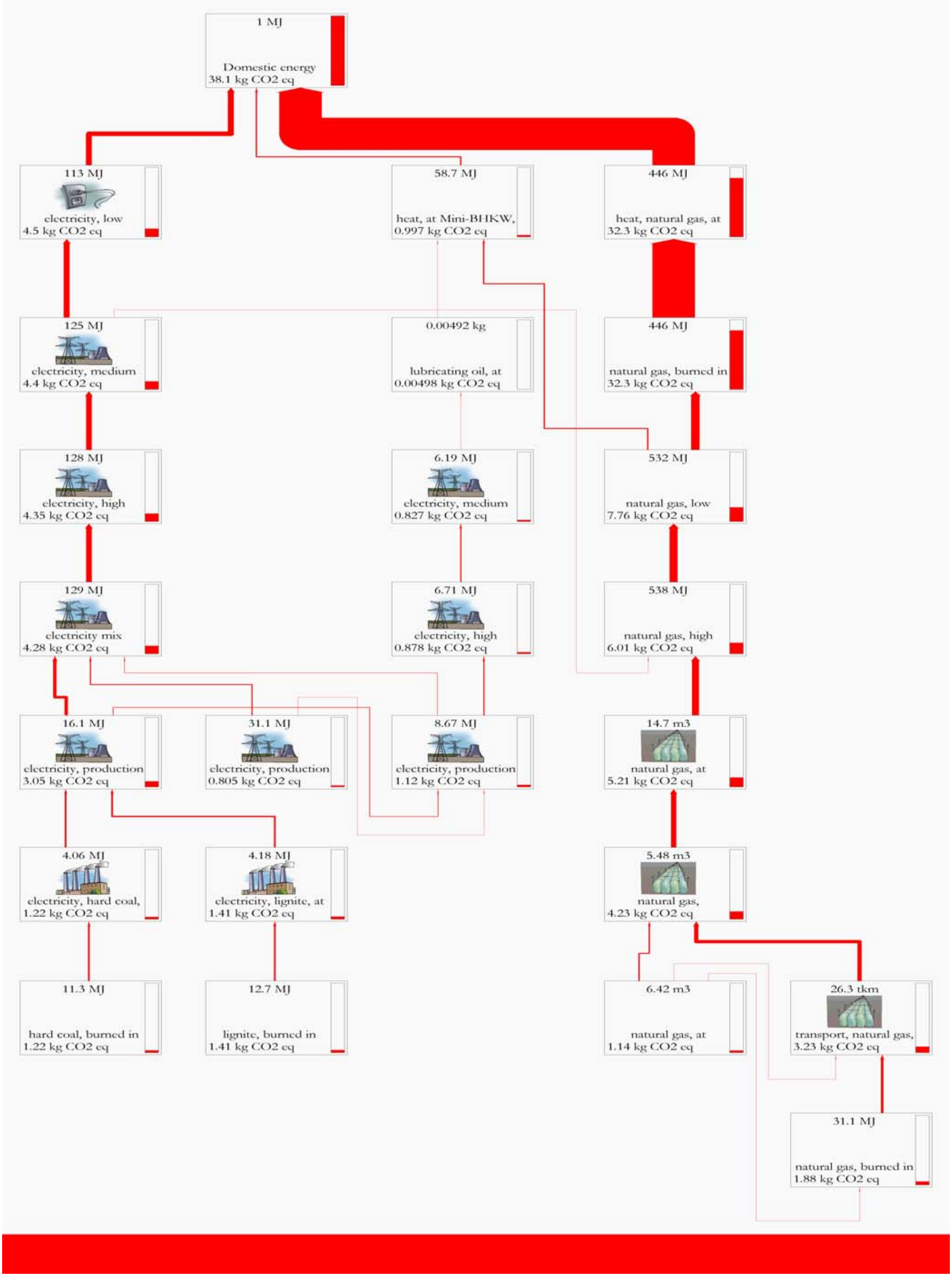
Titel: 1 MJ Energie 'Domestic energy demand c10, ICE, bg-raw, UCTE-mix' mit 1 MJ Energie 'Domestic energy demand c10, ICE, bg-ref, UCTE-mix' und mit 1 MJ Energie 'Domestic energy demand c10, ICE, natgas, UCTE-mix' vergleichen
Methode: * Eco-indicator 99 (H) (revised) V2.05 / Europe EI 99 H/A
Wert: Schadensabschätzung
Pro Wirkur Nr
Ungenutzte Nie
Relativer M Nicht

Impact cat	Unit	Domestic ene	Domestic ene	Domestic energy demand c10, ICE, natgas, UCTE-mix
Human He	DALY	0.0000237	0.0000124	0.0000152
Ecosystem	PDF*m2yr	3.14	0.962	0.836

		Domestic energy demand c10, UCTE Mix		
Impact categ	Unit	ICE, bg-raw	ICE bg-ref	ICE, natgas
Human Heal	DALY	0.0000237	0.0000124	0.0000152

Samples of network flow charts for multi-family Swiss average buildings




1 MJ
Domestic energy
38.1 kg CO2 eq
113 MJ
electricity, low
4.5 kg CO2 eq
58.7 MJ
heat, at Mini-BHKW,
0.997 kg CO2 eq
446 MJ
heat, natural gas, at
32.3 kg CO2 eq
125 MJ
electricity, medium
4.4 kg CO2 eq
0.00492 kg
lubricating oil, at
0.00498 kg CO2 eq
446 MJ
natural gas, burned in
32.3 kg CO2 eq
128 MJ
electricity, high
4.35 kg CO2 eq
6.19 MJ
electricity, medium
0.827 kg CO2 eq
532 MJ
natural gas, low
7.76 kg CO2 eq
129 MJ
electricity mix
4.28 kg CO2 eq
6.71 MJ
electricity, high
0.878 kg CO2 eq
538 MJ
natural gas, high
6.01 kg CO2 eq
16.1 MJ
electricity, production
3.05 kg CO2 eq
31.1 MJ
electricity, production
0.805 kg CO2 eq
8.67 MJ
electricity, production
1.12 kg CO2 eq
14.7 m3
natural gas, at
5.21 kg CO2 eq
4.06 MJ
electricity, hard coal,
1.22 kg CO2 eq
4.18 MJ
electricity, lignite, at
1.41 kg CO2 eq
5.48 m3
natural gas,
4.23 kg CO2 eq
11.3 MJ
hard coal, burned in
1.22 kg CO2 eq
12.7 MJ
lignite, burned in
1.41 kg CO2 eq
6.42 m3
natural gas, at
1.14 kg CO2 eq
26.3 tkm
transport, natural gas,
3.23 kg CO2 eq
31.1 MJ
natural gas, burned in
1.88 kg CO2 eq