RES | THE SCHOOL for RENEWABLE ENERGY SCIENCE

Renewable heat and electricity supply to residential settlements

Gas versus heat transport for low-energy housing

Tomasz Sasin

UNIVERSITY OF ICELAND

University of Akureyri

RENEWABLE HEAT AND ELECTRICITY SUPPLY TO RESIDENTIAL SETTLEMENTS

Gas versus heat transport for low-energy housing

Tomasz Sasin

A 30 credit units Master's thesis

Supervisor:
Dr. Robert Steinberger-Wilckens

A Master's thesis done at
RES │ the School for Renewable Energy Science
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RES │ the School for Renewable Energy Science
Solborg at Nordurslod
IS600 Akureyri, Iceland
telephone: + 354 464 0100
www.res.is

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ABSTRACT

The use of energy in the residential sector is among the most significant causes of global warming and greenhouse gas emissions. The majority of energy consumed in households accounts for space heating and the preparation of warm water. The key to decreasing energy consumption is increasing energy efficiency. The most progress in energy efficiency in the residential sector is expected to be made by improving the insulation of buildings and using low-energy equipment. However, in settlements with very high insulation standards, transport of heat becomes senseless as heat losses may be higher than delivered energy. The easiest way to eliminate losses in this case is generating heat directly at the consumer's location. In the thesis seven ideas are proposed which eliminate heat transport and involve a switch to gas transport or direct electrical energy delivery. In the presented scenarios, all the energy delivered to the settlement comes from renewable energy sources. Four of the concepts were taken into further consideration and an energy efficiency analysis was performed for them. The thesis also presents an up-to-date overview of concepts regarding district heating, efficiency standards for buildings and statistics of renewable energy resources in Germany and the European Union.

The main conclusion reached from this research is that energy distribution by electricity and gases is more efficient than heat distribution and with the use of distributed generation it is possible to completely avoid losses that are present in heat delivery. The biggest problem concerning switching to renewable energy sources is storage of energy during periods of lack of energy delivery from primary sources. In terms of energy efficiency and environmental impacts, the use of biogas reformed in solid oxide fuel cells seems to have the least environmental footprint.

PREFACE

This thesis work was carried out in the Institute for Energy Research in Forschungszentrum Jülich, Germany and supported by the School for Renewable Energy Science in Akureyri, Iceland, which I gratefully acknowledge.

Forschungszentrum Jülich is one of the largest interdisciplinary research centres in Europe. Research at Jülich is divided into four research areas: health, information, environment, and energy.

The School for Renewable Energy Science in Akureyri is a private institution of higher learning offering an intensive one-year Master of Science program in renewable energy science. The graduate program is offered in cooperation with the University of Iceland and the University of Akureyri.

The subject was originally proposed by Dr. Robert Steinberger-Wilckens and the objective was to compare alternatives in which renewable energy is provided for residential settlements. Questions which arose were associated with energy efficiency, needs of storage of energy and environmental impacts.

I would like to thank Dr. Robert Steinberger-Wilckens, the head of the Solid Oxide Fuel Cell department for his advices and guidelines during this project. I would like to thank also Ms. Manuela Hackbarth for her administrative assistance during my stay in Germany and Mr. Thomas Feck for his support with GEMIS software.

Last but not least I am grateful to the whole RES School administration and faculty staff: Dr. Björn Gunnarson, the Academic Director of RES; Dr. Thorsteinn Ingi Sigfusson, Dr. David Dvorak, the Academic Coordinators for the Fuel Cell Systems and Hydrogen concentration; Ms. Sigrun Loa Kristjansdottir, Chief of the RES office; and Mr. Arnbjorn Olafsson, the Director of International Affairs, all of whom gave me this marvellous opportunity to study for a year in Iceland which enlighted me and changed my outlook regarding the world's most important energy issues.

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1 INTRODUCTION

Millions of year ago, the sun's energy, which was harnessed by plants, created huge areas of forests and biomass. With time, and under the impact of various processes, these changed into the hydrocarbon fuels which we know today as coal, oil and natural gas. These materials lay deep underground, unused until humans discovered their presence and energy properties. The solar energy "frozen" as hydrocarbons became vastly used and contributed enormously to the vast development of human society. However, carbon bonded in the fuel was out of the earth's circulation for so much time that releasing it from the fossil fuels disturbed the present, natural balance of the earth's atmosphere.

This disturbance refers mostly to changes in the earth's climate, and is considered by many people to be the greatest environmental, social and economic threat faced by the planet. Additional emissions of the main product of burning fossil fuels – carbon dioxide, which is the main greenhouse gas responsible for climate change, causes so-called global warming. Global warming is the increase of Earth's average temperature, which has influence on droughts, floods and other forms of extreme weather. Higher temperature causes glacial and snow melting which results in rising of sea levels, forcing hundreds of thousands of people in coastal zones to migrate. Before the Industrial Revolution, the concentration of carbon dioxide in the atmosphere was 280 parts per million (ppm), while today it is 390 parts per million and it is predicted to rise to 450 or even 500 parts per million by the end of the century.

The recognition of the reality of climate change caused people to exert serious efforts to counteract this threat. These are performed in three areas: politics, technology and economics. While governments, international organizations and unions are responsible for political and economical decisions, engineers, scientist and research centers are responsible for technical development. Most of the political actions are oriented toward decreasing emissions of greenhouse gasses, mostly by increasing the energy efficiency of different processes as well as eliminating fossil fuel plants and switching into cleaner, renewable energy. Switching to renewable energy sources is also happening because of one more, very important reason – fuel depletion.

Since deposits of crude oil, coal and natural gas are limited, humankind faces a future that lacks a supply of these resources. Many experts claim that right now we are at the peak of oil extraction and production, which means, after 2010 we will enter the phase of oil depletion. Coal is predicted to last for at least 200 years, however its mining and extraction is becoming more difficult as well as more dangerous for people working under ground because of the exhaustion of the deposits with the easiest access. To overcome these problems, humankind must turn to the most basic energy source: the sun; only this time with efficient techniques for harnessing its energy. The Sun delivers in one hour more energy than the world would use in a whole year (Lewis, Nocera, 2006) and it is almost an unlimited supply of energy. Most of the renewable energy sources have their origin in the radiation of sun. Renewable energy sources which are expected to increase their share the most in the future (solar photovoltaic and wind) will have to be able to satisfy peoples' demand for energy.

From the individual consumer's point of view, one of the most important power generation purposes is to provide energy to homes. This means electricity for different electrical devices as well as heating functions. Heating is the most energy consuming activity in the residential sector, responsible for about 80% of greenhouse gas emissions. To reduce this significant environmental impact, one main response is expected by the improvement of the energy efficiency of buildings, mostly their insulation, which translates into smaller demand for heating energy. Another option which will decrease greenhouse gas emissions from the residential sector is to switch to renewable energy sources. This thesis presents solutions which entirely utilize renewable energy, providing electricity and heating energy for a small community of 30 households.

The thesis describes present energy use, the potential of renewable energy sources, European Union policies on energy, building codes and standards, techniques and ideas for new methods of residential heating as well as the technical approach to the storage of energy (whether battery or hydrogen) and distribution aspects (hydrogen and biogas). In the second part, the application of specific district heating alternatives is shown. This part involves energy efficiency calculations as well as storage capacity optimalization in order to determine the most energy efficient solution. As the project was performed in *Forschungszentrum Jülich* in Germany and most of the data are relevant for Germany, special attention is given to this country.

The most interesting part from the RES Fuel Cell and Hydrogen point of view is the generation of renewable electricity and storing it as hydrogen with a hydrogen distribution network and utilization in fuel cells.

2 PROBLEM DESCRIPTION

The use of energy in the residential sector is among the most significant causes of global warming and greenhouse gas emission. The majority of energy consumed in households accounts for space heating and the preparation of warm water. In contrast to Iceland, Germany does not have almost unlimited access to cheap and abundant heat. On the other hand, Germany is Europe's leader in renewable energy technologies as well as hydrogen economy implementation.

The key to decreasing the consumption of energy is energy efficiency. Cogeneration of electricity and heat together is a well known option that diametrically increases efficiency. Heat is transported via pipeline network to the consumers and used for space heating and preparing warm water. Applying renewable energy sources to provide power for households will open a new period of history in power generation. Production of electricity from sources like wind power and solar can be made on a local scale and big, fossil-fuelled cogeneration plants are, in this case, not required.

The most progress in energy efficiency in the residential sector is expected to be made by improving the insulation of buildings and using low-energy equipment. However, in settlements with very high insulation standards, the transport of heat becomes senseless as the amount of heat lost may be higher than the energy delivered. The easiest way to eliminate losses is generating heat directly at the consumer's home. In this thesis, ideas are proposed which eliminate heat transport and switch to gas transport or direct electrical energy delivery. All the energy delivered to the settlement comes from renewable energy sources. As there are few options, in order to choose the best one in terms of environment protection, environmental impacts as well as energy efficiency must be compared. A conventional gas-fired district heating network will serve as a reference. Wind resource analysis and the application of different storage options will give insight to the size of storage units, as the described settlements are not connected to the national grid. The amount of energy in the storage units must be sufficient in long periods of limited renewable electricity supply.

The conclusions in this thesis will be based on which of the four proposed options has the highest efficiency and likelihood of being applied in similar projects.

2.1 District heating facts

District heating is a system for distributing heat that is generated in a centralized location for residential and commercial heating requirements such as space and water heating. The heat can be provided from a variety of sources, including geothermal, cogeneration plants, waste heat from industry and purpose-built heating plants.

In Germany, district heating has a market share of around 14% in the residential buildings sector which is one of the lowest figures in the EU (In Iceland it is 95%) (Wikipedia, term: *District heating*).

Moreover, almost no growth is observed in providing energy by district heating in Germany, France, and United Kingdom – three important countries with respect to the overall European energy balance. The figure below shows total heat production in 27 members of EU. As data comes from 2006 (when EU had 25 members) shares are estimated for the two new members who joined the EU on the 1st of January, 2007.

Table 2.1 Total heat production in UE 27 (Eurostat, 2008a, provisional data).

Total heat production (1000 toe)	**49 266**
among which: in heating plants	15 865
Heat consumption	41 293
of which: in households and services	29 799
of which: in households	20 282

One way to increase the share of district heating is cogeneration with electricity. This method significantly increases total efficiency as heat is used and not wasted.

2.1.1 European Union Directive on cogeneration

The Directive of the European Parliament and the Council on the promotion of cogeneration, based on useful heat demand in the internal energy market, was approved in 2004. The Cogeneration Directive attempts to promote cogeneration through a systematic identification and progressive realization of the national potential for high efficiency cogeneration by creating a common definition and removing barriers (The International Network for Sustainable Energy, 2008).

Cogeneration refers to heat and electricity produced simultaneously in one process. The main advantage lies in thermal efficiency: whereas the conversion efficiency of electricity generation alone (i.e. the proportion of the calorific potential of the fuel that is actually used) is between 35-55% (LHV), the overall efficiency of CHP plants can be as high as 80-90%. This shows the potential of CHP in saving energy and in reducing greenhouse gas emissions (Eurostat, 2007).

The purpose of this Directive was to increase energy efficiency and improve the security of supply by creating a framework for the promotion and development of high efficiency cogeneration of heat and power based on useful heat demand and primary energy savings in the internal energy market (EU Directive 2004/8/EC).

2.1.2 German district heating and electricity market basic facts

In Germany, district heating has a market share of around 14% in the residential buildings sector together with 1 335 water and 91 steam networks which supply buildings and industrial customers with steam and heat through over 310 000 "house" substations (German heat and power association, 2005).

The heat comes mainly from cogeneration plants (83%). Heat-only boilers supply 16% and 1% is surplus heat from industry. The cogeneration plants use natural gas (42%), coal (39%), lignite (12%) and waste/others (7%) as fuel (Wikipedia, term: *District heating*). The share of cogenerated heat and electricity is very similar to the Danish one (where district heating networks reach 60% of houses) where 81.9% of total district heating was produced in combination with electricity (Danish energy authority, 2007).

The connected heat load in the country is around 57 000 MW (German heat and power association, 2005) and the total electricity generation in 2006 was 636 600 GWh (Vattenfall, 2006).

Pipeline length for the distribution of district heating was 18 702 km in 2003 (German heat and power association, 2005) while in Denmark total length of pipes is around 50 000 km (Danish energy agency, 2008).

Typical heat delivery costs for district heating networks lie between 2 and 3 € Cents/kWh, while the cost of one kWh of electricity for the final consumer (households) in 2007 was 14.3 € cents and the average for EU 27 was 8.2 € cents (Eurostat, 2008b, BMU, 2006a).

2.2 Energy efficiency of building standards and codes

Energy efficiency is the key to a sustainable energy future. The use of energy in buildings accounts for a large share of the total end use of energy (figure 2.1). In sectors such as residential and commercial the major part of the energy consumption takes place in buildings. This includes energy used for controlling the climate in buildings and for the buildings themselves, but also energy used for appliances, lighting and other installed equipment.

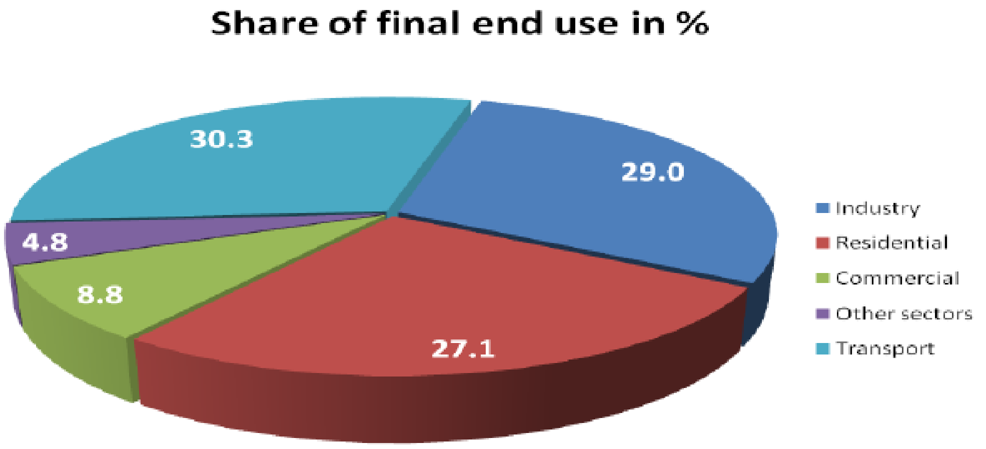


Figure 2.1 Share of final energy use in the world (International Energy Agency, 2008).

Energy efficiency requirements in building codes or energy standards for new buildings are among the most important single measures for building energy efficiency. This is particularly the case in times of high construction activity or in fast developing countries.

Energy is used in buildings for various purposes: heating and cooling, ventilation, lighting and the preparation of hot sanitary water. In residences and commercial buildings, installed equipment and appliances require energy, as do removable devices like mobile phone chargers and portable computers (figure 2.2).

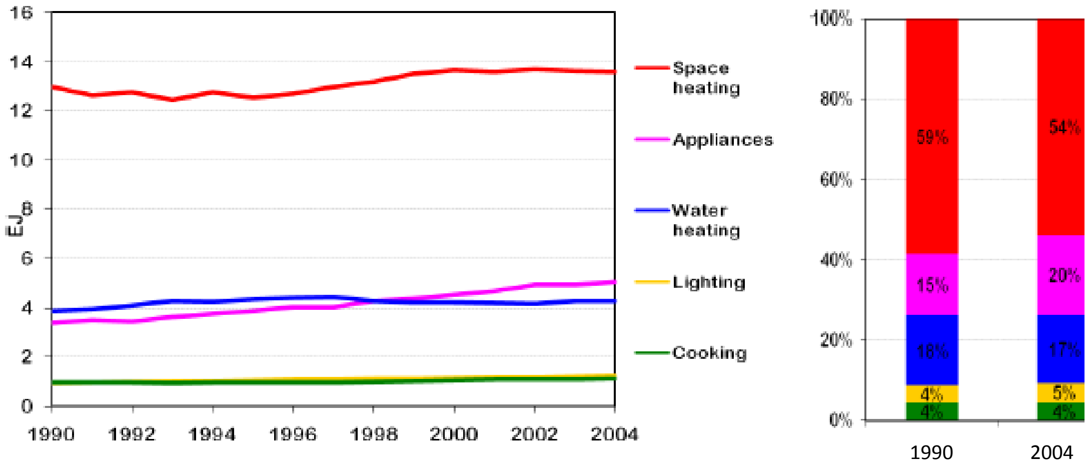


Figure 2.2 Energy use in buildings in IEA countries (International Energy Agency, 2008).

Energy efficiency requirements in building codes can ensure that concern is given to energy efficiency at the design phase and can help to realize the large potential for energy efficiency in new buildings. Energy efficiency requirements for new buildings are set in different ways. Based on national or local traditions they can either be integrated in the general building codes or standards for new buildings, or they can be set as separate standards for energy efficiency.

The terms “building codes” or “energy standards” for new buildings generally refer to energy efficiency requirements for new buildings whether they are set in building codes, specific standards or other ways, unless otherwise stated (International Energy Agency, 2008).

2.2.1 European Union Energy Performance in Buildings Directive (EPBD)

The European Directive on Energy Performance of Buildings (EPBD), which came into force 16 December 2002 to be implemented in the legislation of Member States in 2006, aims to improve the overall energy efficiency of new buildings and large existing buildings during significant renovation. Because the building sector is responsible for about 40% of Europe’s total energy consumption, the EPBD was an important step for the European Union to reach in order to achieve the level of saving required by the Kyoto Agreement; the EU is committed to reduce CO_2 emissions by 8% by 2010 relative to the base year of 1990 (Boermans, Petersdorf, 2007).

According to this directive, all member states have to set standards for energy efficiency in new buildings based on the energy performance of the building. The performance has to take into account the building shell including air-tightness, heating and cooling installations, ventilation, the orientation and position of the building, passive solar systems and solar protection, and the indoor climate according to the annex to the directive. For non residential buildings, built-in lighting systems also have to be included. The positive influence of active solar systems and other renewable energy systems, CHP, district heating or cooling and natural light are also taken into account (International Energy Agency, 2008).

The principal objective of the Directive is to promote improvements in the energy performance of buildings within the EU through cost-effective measures. There are four main aspects of the Directive (Anderson, 2007):

1. Establishment of a calculation methodology: Member states must implement a methodology for the calculation of the energy performance of buildings, taking account of all factors that influence energy use.
2. Minimum energy performance requirements: there must be regulations that set minimum energy performance requirements for new buildings and for large existing buildings when they are refurbished.
3. Energy performance certificate: there must be an energy performance certificate made available whenever buildings are constructed, sold or rented out.
4. Inspection of boilers and air-conditioning: there must be regulations to require inspections of boilers, heating systems and air conditioning systems.

Implementation of the EPBD Directive in Germany

In Germany most aspects of the EPBD have already been implemented by the Energy Saving Ordinance in 2002. A calculation method for the energy performance has therefore been put in place, requirements for new buildings have been based on that method, energy performance certificates have been made compulsory for new buildings and in case of certain major refurbishments, requirements for nearly all cases of modernization of fabric elements have been in place since 1984 without any threshold concerning the buildings size. Boilers have needed to be inspected regularly since 1978 and must be replaced if necessary. All the missing aspects of the directive have been implemented by the Energy Saving Ordinance 2007. Since this ordinance did not change the level of requirements, the requirements are going to be enforced gradually by the Energy Saving Ordinance 2009 (Horst, Schettler-Köhler, 2008). Figure 2.3 presents the scale of reference values of energy demand for residential buildings. Table 2.2 presents more detailed reference values of energy demand for a few of the building standards in Germany.

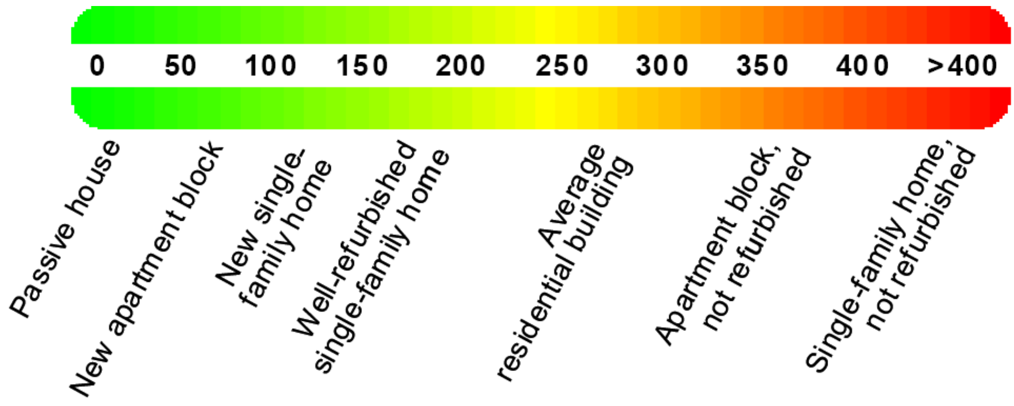


Figure 2.3 Scale of reference values [kWh/m^2•a] for residential buildings (heating & hot water) (Horst, Schettler-Köhler, 2008).

In Iceland, according to *Orkuspárnefnd* (the Energy Authority) demand for typical Icelandic house is at the level of 60 kWh/m^2•a, however *Rarik*, which is an electrical distributor says that heat demand is at the level of 70 – 90 kWh/m^2•a. Peak power is estimated as 18 W/m^3 and an average 55% of the peak power.

2.2.2 Heating degree days

Heating degree days express the severity of the cold over a specific time period, taking into consideration outdoor temperature and room temperature (Boermans, Petersdorf, 2007).

The number of heating degrees in a day is defined as the difference between a reference value (i.e. 18^{o}C) and the average outside temperature for that day.

The figure below shows relative heating degree-days during a period of 25 years. A general observation from this figure is that relative number of days in which heat is needed is decreasing. This may be caused by climate warming and milder winters.

Figure 2.5 presents a map of Europe with colors representing the number of heating degree days. For Germany this number is between 2000 and 3000.

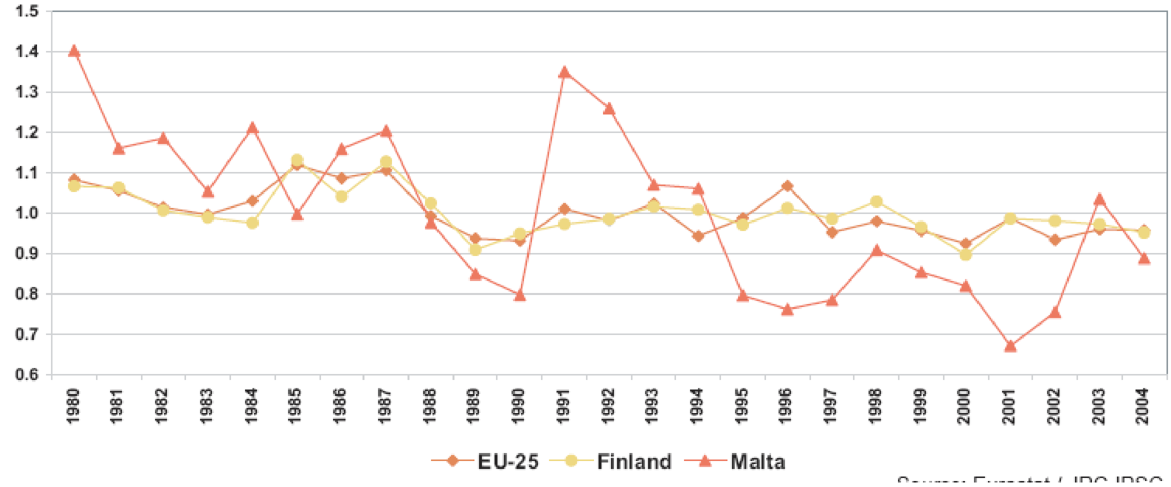


Figure 2.4 Relative heating degree-days 1980-2004, EU-25, Finland and Malta (Eurostat, 2007).

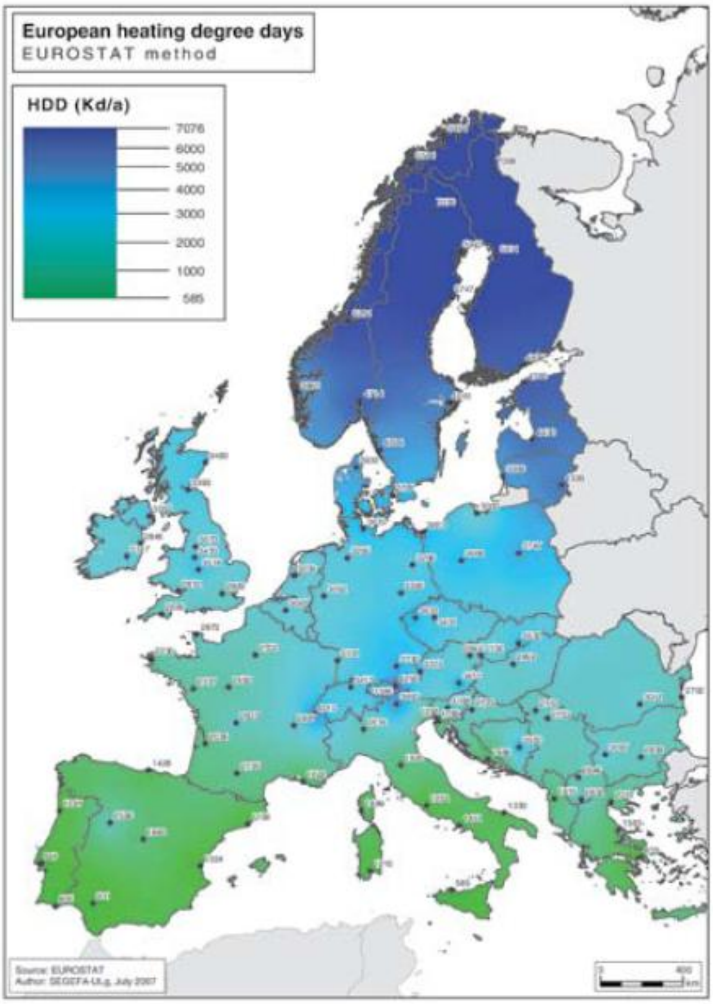


Figure 2.5 Map of European heating degree days (Boermans, Petersdorf, 2007).

2.2.3 Energy consumption, building standards and codes in Germany

Energy consumption in households

In the private households in Germany 80% of the energy consumed is used for space heating, the energy consumed for other purposes plays a secondary role (figure 2.6). The increase in energy use in the year 2005, compared to 1990 was caused mostly by the change to higher living standards and larger area of living space per capita.

Moreover, the consumption of final energy in the residential sector (figure 2.7 *Others sectors* scope) has been at a rather constant level through many years.

Finally, the last data shows that energy consumption in households has the biggest share of all sectors in the country (figure 2.8). This share contributed to the emission of 122.4 million tonnes of CO_2 in 2003 (Sustainable Energy Technology at Work, 2007).

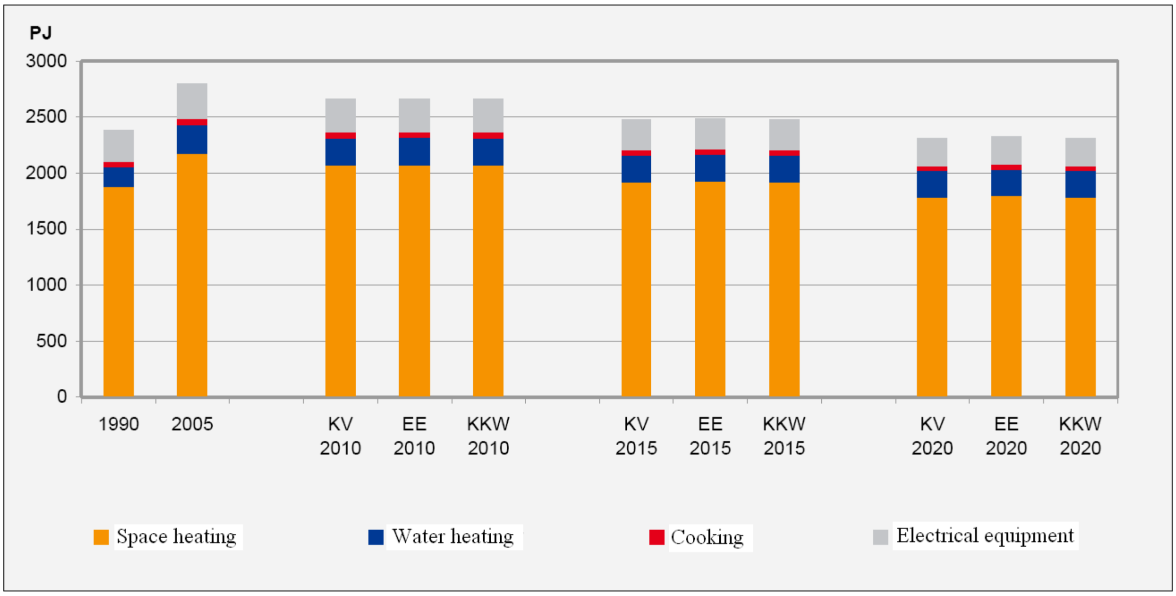


Figure 2.6 Energy use in private households by purpose from 1990 to 2020 (Prognos AG, 2007).

Case KV – a doubling of the energy productivity between 1990 and 2020 is assumed, meaning annual growth of 3% between 2005 and 2020. Case EE – in addition to the previous assumption, here the faster development of renewables is predicted. Case KKW – the use of nuclear power plants will be lengthened for an additional 20 years.

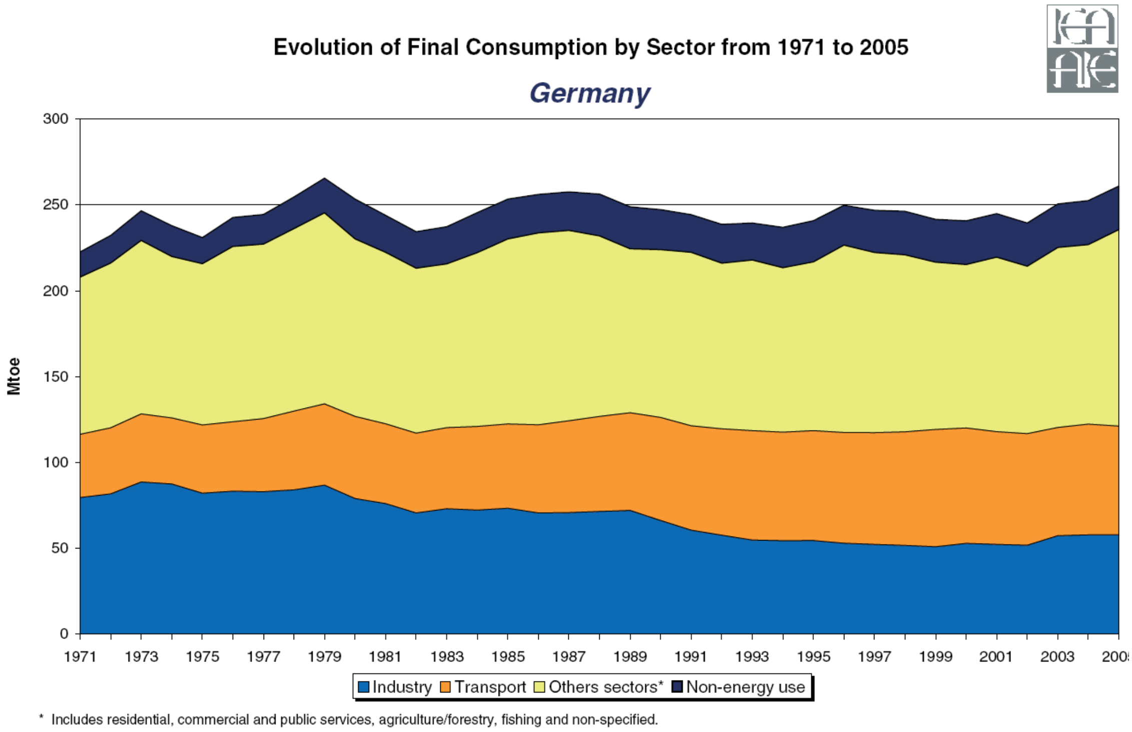


Figure 2.7 Evolution of Final Consumption of Energy by Sector in Germany from 1971 to 2005 (International Energy Agency Statistic, 2005).

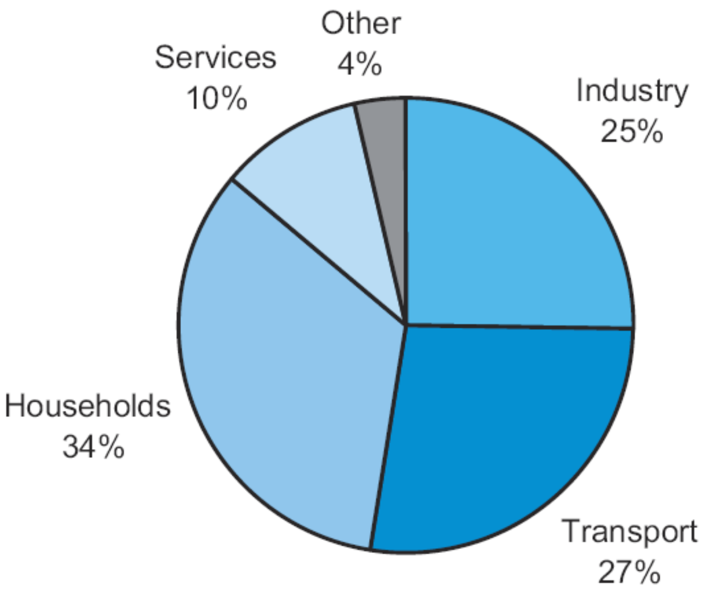


Figure 2.8 Energy Consumption by Sector in Germany in 2007 (Eurostat, 2007).

Building standards and codes in Germany

Energy saving acts have been setting the maximum allowable heating energy demand of a single family house for the last 30 years. The figure below shows changes of standards over time as well as development of the technology which causes a decrease of energy demand.

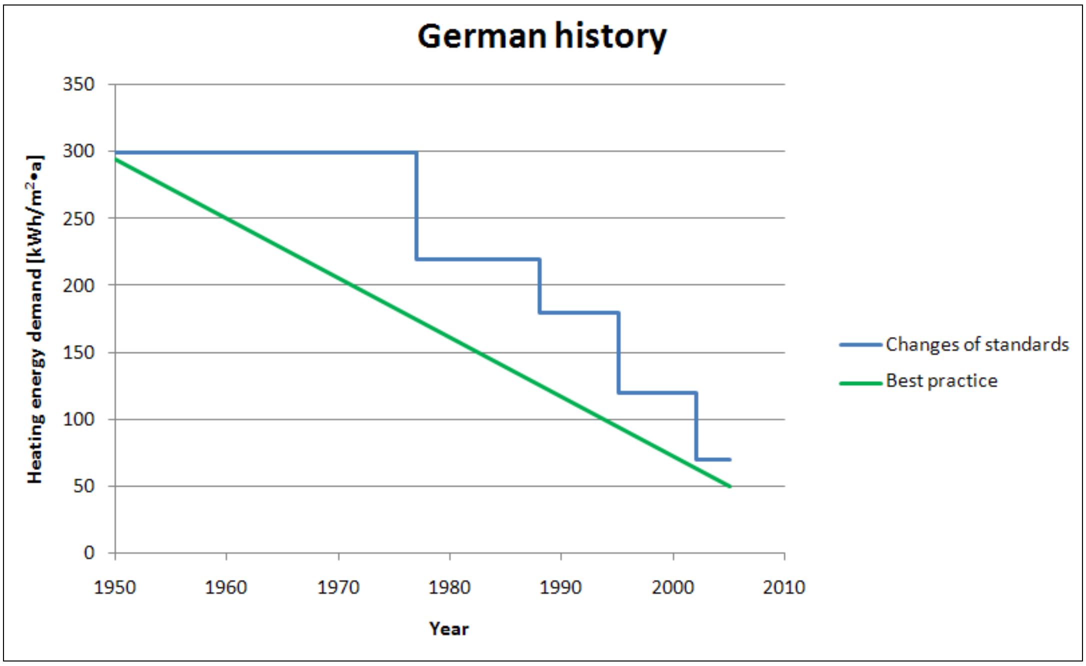


Figure 2.9 Reduction of heating energy demand of a German single family house due to increased national thermal and energy performance requirements (Erhorn, Erhorn-Kluttig, 2006).

Table 2.2 gives more detailed information about reference values of building standards. The recent standard for a typical house sets the limit at 70 kWh/m^2•a.

Table 2.2 Values of heat energy demand in kWh/m2•a for different standards of buildings.

Standard	**Heat Demand**
Old building standard	100 kWh/m^2•a for heating and warm water
New building standard	70 kWh/m^2•a for heating and warm water
Ultra low energy buildings	40 kWh/m^2•a for heating and warm water
Passive buildings	40 kWh/m^2•a; 15 kWh/m^2•a for heating alone

A low energy building is generally considered to be one that uses around half of the German and Swiss energy standards for buildings. Ultra low energy buildings usually use less than half of the energy needed in low energy building (Wikipedia, term: *Low-energy house*).

A passive house is a building that requires little energy for space heating or cooling. It is achieved by an excellent thermal insulation, gaining heat from internal appliances, residents, solar heat and heat recuperation from ventilation. Heating energy consumption including hot water should not be more than 40 kWh/m^2•a, and heating energy alone should not be more than 15 kWh/m^2•a.

Beyond passive and ultra low energy buildings there are also *zero energy buildings*, which refers to buildings with a net energy consumption of zero over a typical year (Wikipedia, term: *Zero-energy building*).

Heat demand for different insulation standards

Four examples below show how different heat demand standards improvements change power duration curves in households.

The power duration curve characterizes power demand during time. The horizontal axis represents time (in hours) and is set up from the highest heat demand to the lowest. Demand for heat follows the outside temperature. Therefore it decreases while moving, over time, to higher temperature values.

The warm water load (together with losses related to it) has a constant value, as warm water with the same quantity is needed all year long.

A combined heat and power unit follows the heat and warm water demand, and when its line covers with the line of heat demand, the line then generates more losses. Warm water load is showed together with grid losses and their share is equal (50%).

Figure 2.10 shows the reference power duration curve for a building with heat demand of 100 kWh/m^2 per year.

Figure 2.11 shows the power duration curve for a building with heat demand of 70 kWh/m^2 per year, which is the new building standard in Germany for single houses.

Figure 2.12 shows the power duration curve for a building with heat demand of 40 kWh/m^2 per year, which is the ultra low energy building standard in Germany for single houses.

Figure 2.13 shows the power duration curve for a building with heat demand of 15 kWh/m^2 per year, which is the passive house standard in Germany.

The following figures are based on data coming from one of the projects carried out in Germany (see section 4.2).

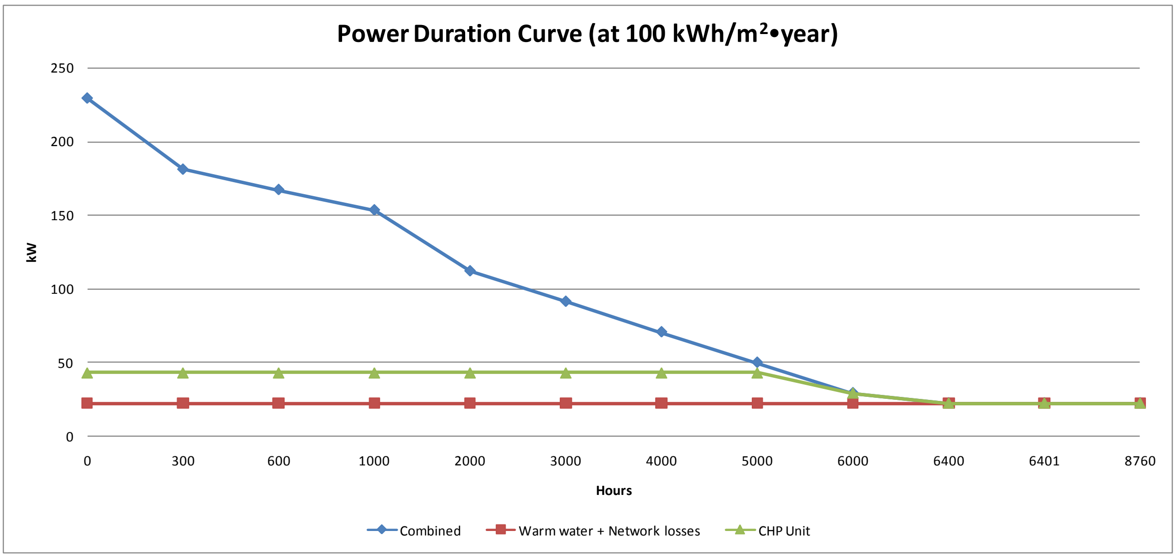


Figure 2.10 Power duration curve for one building at 100 kWh/m2•a.

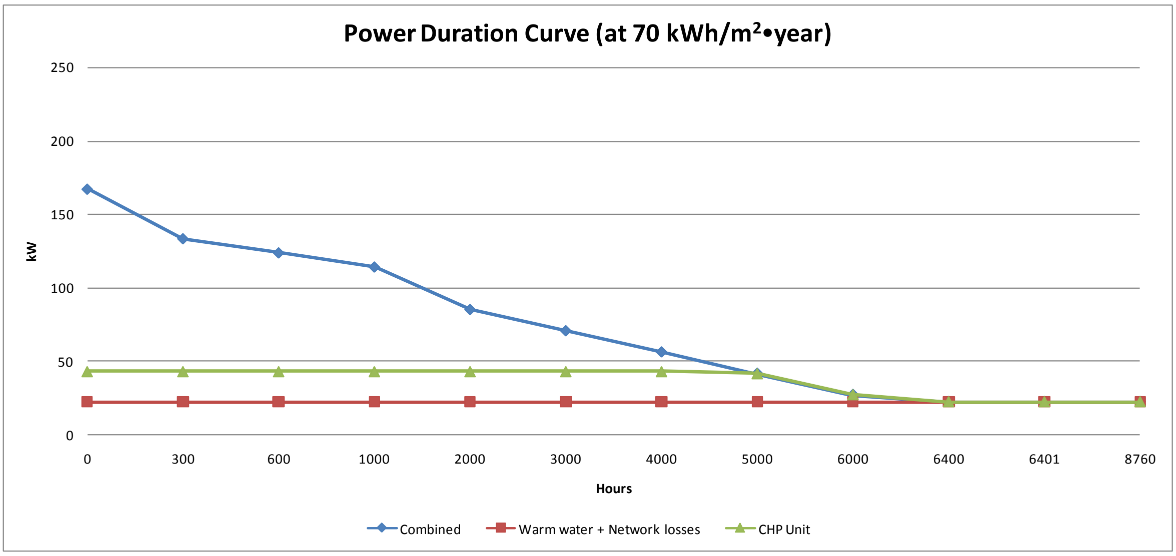


Figure 2.11 Power duration curve for one building at 70 kWh/m2•a.

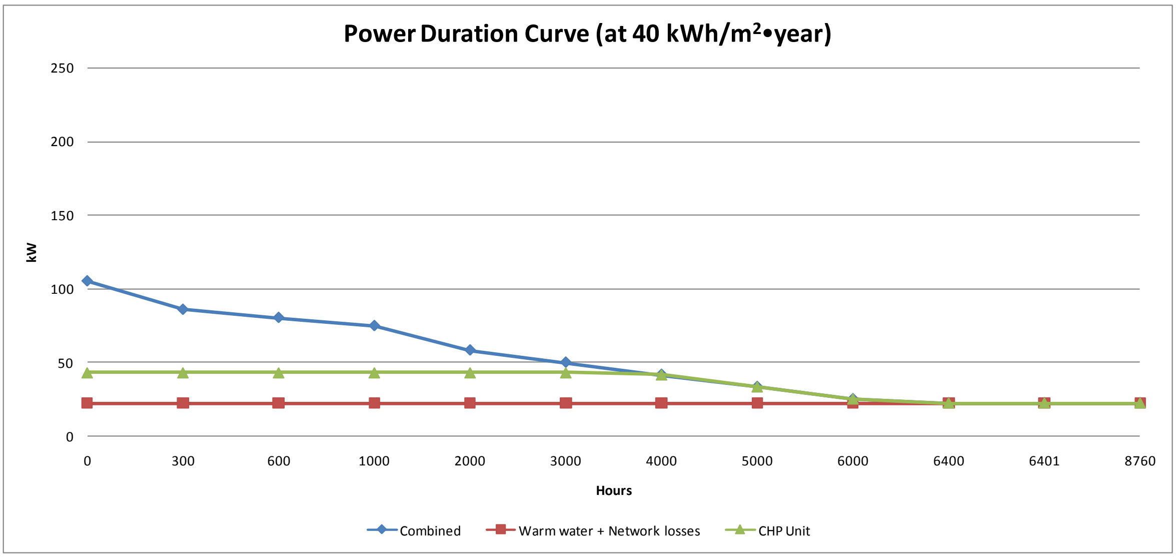


Figure 2.12 Power duration curve for one building at 40 kWh/m2•a.

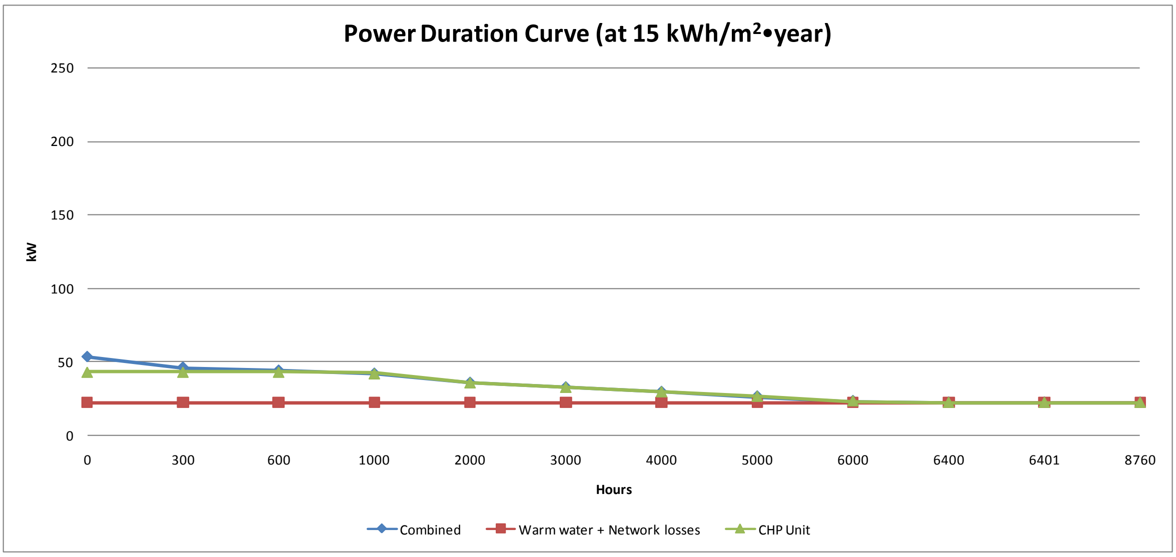


Figure 2.13 Power duration curve for one building at 15 kWh/m2•a.

In the last case, when the CHP unit duration curve covers rapid warm water load demand, heat delivery becomes very inefficient, as 50% of the energy is continuously lost. This effect will become more and more important when making insulation standards progress and decreasing heat demand by households. That is the reason central heat generation should be replaced by distributed units, which produce heat directly in the consumer's home, avoiding transmission and losses.

2.2.4 Heat losses in the pipeline systems

All of the pipes used in district heating systems are insulated. Insulation prevents heat loss from pipes, saves energy and improves the effectiveness of the thermal systems (Wikipedia, term: *Pipe insulation*).

Figure 2.14 shows general heat loss in the pipes in relation to fluid temperature, transmission length and the velocity of the fluid.

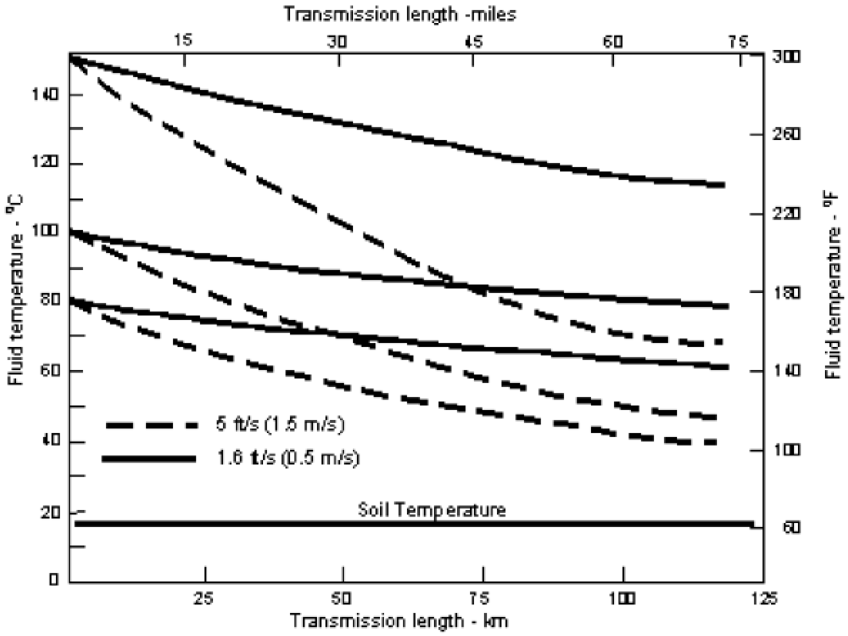


Figure 2.14 Pipe heat loss (Valdimarsson, 2008).

The heat losses depend on (Zirngibl, 2008):

- the thickness and the material of the insulation,
- the piping material,
- the surface of the whole piping system,
- the load of the substation,
- the difference between the heating media temperatures and the ambient temperature.

Heat loss in the pipe depends on the insulation and its conductivity, but heat loss also increases in pipes with smaller diameter (like local pipes or distribution pipes in building).

An example from one of the manufacturers – Logstor A/S – illustrates how good quality insulation can change the properties of heat flow and loss in the pipes.

Figure 2.15 shows the ageing course of the insulation foam and consequently the heat loss of *FlexPipes,* with and without a diffusion barrier. One can see that most of the degradation takes place in the first 5 years.

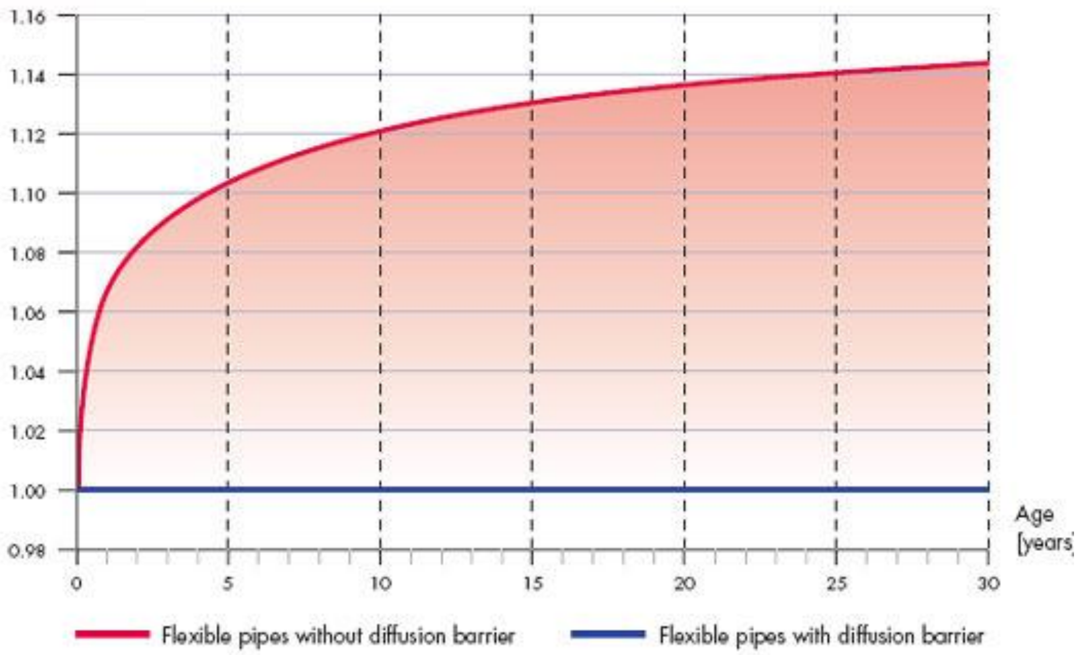


Figure 2.15 Relative ageing over time (Logstor, 2008).

Heat losses in the older systems might be very significant and responsible for much of the energy waste, therefore it is highly important to avoid these losses by all means. In the thesis, there are options presented which completely reduce heat losses by eliminating the heating grid and moving heat generation directly to the final user.

3 FUTURE ENERGY SUPPLY SOLUTIONS

Energy plays a crucial role in the life of human beings and with certainty it will continue to do so in the future. Before the industrial revolution and intense exploitation of fossil fuels, humans depended on solar energy. Solar energy is found in different forms, such as biomass (wood, turf) or wind power (windmills), and its resources have determined the population of nations. This period in history can be described as the *first solar energy civilization.* After this period the industrial revolution brought massive use of fossil fuels and incredibly rapid improvement in many aspects of everyday life. There are, however, many secondary effects concerning this development. Enormous changes to the environment cause its constant degradation and influence all life forms, including people. Extensive emissions of greenhouse gases cause global warming, melting glaciers and a rising sea level. The mining of coal and minerals causes landscape degradation and destroys the underground water regime. People must be more cautious and participate in more sustainable activities, as the planet cannot afford further degradation. Our activities have to be sustainable so that future generations can meet their needs as easily as we do. Within three centuries, the human race has consumed extensive resources which took millions of years to create. One issue of the highest priority is that fossil fuel resources are not unlimited and one day they will be entirely depleted. As fossil fuels are the motor of today's global economy we should use them to develop technologies that harness energy when they are gone. All these activities lead people to the future *second solar energy civilization.* With the use of efficient photovoltaic panels, wind turbines and novel techniques, human beings will be able to satisfy their energy needs with less harm to the surrounding environment and global climate.

3.1 European Union policy on energy

Today's European Union evolved from the European Coal and Steel Community founded in 1951 by the Treaty of Paris. Coal was then the primary and nearly the only source of energy. This confirms that sufficient energy supply was one of the most important areas of interest of every kind of authorities on different levels of power sixty years ago and still is today.

It is not surprising that today, energy matters are one of the most often discussed issues in the EU among politicians as well as wide panels of experts, scientists, environmentalists and engineers. France, which now (second half of 2008) holds the presidency of the European Union and has made a common energy and environment policy a top priority of its leadership. The European Union's administration and information division on energy themes presents a very broad spectrum of subjects, starting from basic cover of the energy demand, through environmental issues to the future of energy supply.

The key aspects of the energy policy include (EurActiv, 2007, European Commission, 2008):

- Cut of 20% of greenhouse gas emissions from primary energy sources by 2020 (compared to 1990 levels).

- Cut of up to 50% of carbon emissions from primary energy sources by 2050 (compared to 1990 levels).
- Minimum share of renewable energy sources of 20% by 2020.
- Minimum share of 10% for the use of biofuels in transport fuel by 2020.
- Development of a common external energy policy to actively pursue Europe’s interests on the international scene with supplier, consumer and transit countries.
- Focus on research and development efforts on renewable energy, energy conservation, low-energy buildings and low carbon technologies with support for clean coal technology using carbon capture and storage.
- Improved oil and gas stocks and crisis response mechanisms.

It is clearly visible that most of the efforts are oriented toward a clean and more efficient energy supply. As will be further discussed in chapter 3.4, fuel cells and hydrogen will become very important links in the energy supply chain. Figure 3.1 presents a timetable of the most important EU laws enacted in the field of energy as well as fuel cells and hydrogen.

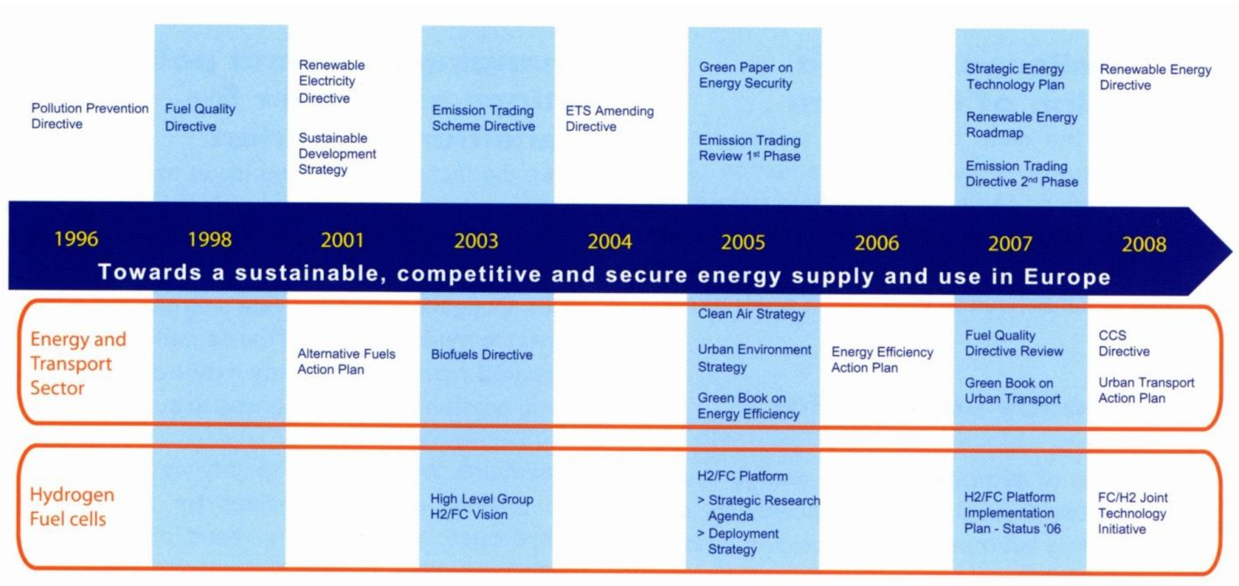


Figure 3.1 Timetable of EU’s energy-related acts (Schindler, Würster et al. 2008).

3.2 Transition phase

Limitations in the availability of fossil energy resources as well as the threat of climate change to mankind and the biosphere have led to the formulation of political goals with regard to the security of energy supply and the reduction of greenhouse gas emissions. All the underlying issues can be addressed in an efficient and sustainable way by energy conservation, by the increased use of renewable energy sources and by the use of hydrogen and fuel cells (Schindler, Würster et al. 2008).

A transition policy involves three main aspects (Lysen, 2002):

- improving efficiency of power plants,
- development of renewable energy sources,
- development of clean fossil fuels.

These aspects cover what the European Union energy policy described in the section before. It means, in fact, that the EU energy policy is strongly oriented around a transition and release from the environmental burden of combusting fossil fuels. In the long term, renewable energies will be able to provide more energy than fossil fuels. On a global level, solar energy and wind power can become the major pillars of the energy system.

Figure 3.2 presents the predicted development of energy sources up to the year 2100.

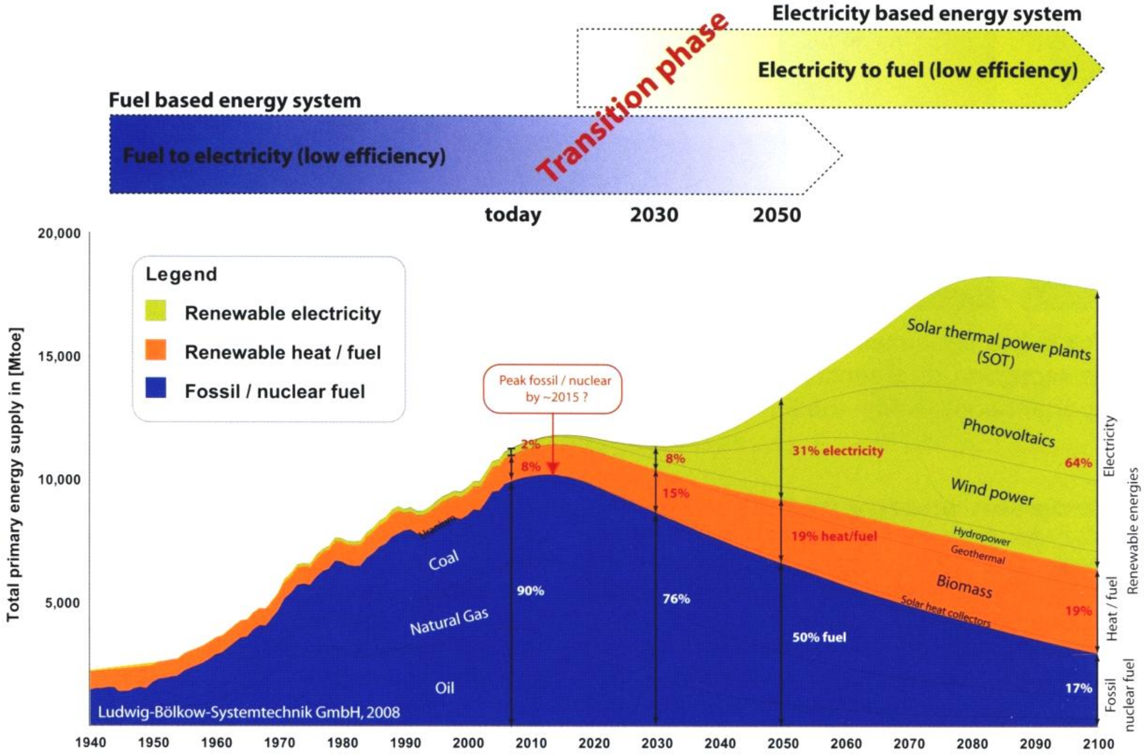


Figure 3.2 Future energy sources (Schindler, Würster et al. 2008).

From the graph, one can see that the peak use of fossil and nuclear fuels is forecast by 2015, and then the share of these sources should decrease to 17% in 2100.

In the long term, the primary energy system will be dominated by electricity as a result of the transition from a fuel based energy system to an electricity-based one. An important issue concerning this change will be the storage of electricity. Here, hydrogen is predicted to play a main role as a universal energy carrier, which can be easily produced from water by electricity.

Another transformation that will have to take place is switching from centralized power generation in multi-megawatt power plants to distributed generation. This will happen due to the use of local renewable resources, which will be able to provide limited power to the consumers in the "neighbourhood" of the power source.

3.2.1 Distributed generation

Distributed generation (DG) refers to the power generated from many small (local) energy sources. The main advantage of distributed generation is decreasing the amount of the energy lost in transmitting electricity or heat, because units are situated close to the destination places or even in the same buildings. Furthermore, DG units can utilize local renewable resources. Wind turbines, PV solar or micro hydro power are examples of distributed generation units that are fully renewable energy resources. Distributed generation is characterized by the small generation size, the proximity to the loads, and its connection to distribution networks. The main purpose of this equipment is to generate the active power required by the loads, so no energy is overproduced and lost when demand is low (Ramirez et al. 2008).

3.2.2 Examples of fully renewable energy supply

There are plenty of existing examples of using renewable energy as a support for conventional sources of energy. Mostly these are thermal solar power, photovoltaic, wind power and biomass co-firing. Thermal solar power is especially popular at places with high and long solar radiation (Southern Europe, Australia, California, Florida, etc.), while biomass is popular in developing countries (India, China). Despite the high interest in renewables, projects that utilize a fully renewable energy supply are still novel and rare.

One of the best examples of existing, fully renewable systems is the energy system in Iceland. In Iceland 100% of electric energy comes from renewable sources (geothermal and hydro) and around 90% of houses are connected to the district heating networks which use geothermal heat. Electricity is generated in power plants and then distributed to the users. Distributed generation is almost non-existant (except in few remote places). Therefore, from the consumer’s point of view, the system scheme is almost the same as in Western Europe.

As the nature of the renewable sources which are expected to grow the most in the future (wind, photovoltaic) does not assure constant power output, a storage medium is needed. Hydrogen, as a future energy carrier that is produced by electricity coming from, for example, wind energy has a very low environmental impact. Most of the installations that use hydrogen are so called “wind-to-hydrogen” projects. They are quite popular in places with low population density where distributed generation is sometimes the only way to provide electricity.

A very interesting “wind-to-hydrogen” project of fully renewable electricity was carried out on a small island off the western coast of Norway. Project *Utsira* started in 2004 and finished in spring of 2008. Two wind turbines at the combined wind and hydrogen plant on Utsira produced power for 10 households. Surplus electricity was stored as chemical energy in the form of hydrogen. The hydrogen that ensured a stable power supply was produced from water and electricity from one of the two 600-kilowatt wind turbines (figure 3.3), by means of an electrolyser. The excess power from the turbines was sold on the electricity market (StatoilHydro, 2008)

3.3 Two wind turbines at the island of Utsira (Utsira community, 2006).

When the wind did not blow, a hydrogen motor and fuel cell converted the stored hydrogen back into electricity. This way the two wind turbines could function as a stable and secure source of power to the island community, even when it was not windy (NorskHydro, 2005).

Another recent (November 2008) project on “wind-to-hydrogen” technology started in Yorkshire, in the UK. One of the business parks in Yorkshire will use a hydrogen Mini-Grid System as a primary power source to the building (IT PRO, 2008). Electricity will be generated by a 225 kW wind turbine attached to an electrolysis unit which will convert some of the wind energy into hydrogen. Hydrogen will then be stored in tanks and fed to a 30 kW fuel cell, when required, to provide electricity to the building during the day and potentially to supply the National Grid with surplus power. The whole system will also consist of a 240 Ah batteries and supervisory software to control and regulate the system. The building will be attached to traditional electricity supplies in case of emergency but it is expected that this building will be fully self-sufficient (The Advanced Manufacturing Park, 2008).

An interesting project in Krefeld, Germany, was developed by the electric utility *RWE AG* and district heating supplier *Fernwärmeversorgung Niederrhein*. Since December 2004, a molten carbonate fuel cell (MCFC) has been supplying electricity and heat to a residential area in Krefeld-Fischeln. Designed as a CHP system, the fuel cell generates electricity and heat simultaneously. The fuel cell in Krefeld generates approx. 225 kW of electrical power and has a thermal output of around 160 kW.

The characteristic feature of this project is that the fuel cell does not supply an individual selected customer, but an entire residential area with houses and apartment buildings as well as small retail business. The power generated by the fuel cell is fed into the electricity grid of the Krefeld municipal utility and consumed directly by local residents. The waste heat is used to produce district heat which is distributed to surrounding buildings via the district heating network of *Fernwärmeversorgung Niederrhein.* In winter some 40 homes can be supplied with heat for space heating or hot water. In summer, the waste heat is used to supply approx. 300 homes with hot water (RWE AG, 2008). Although the fuel cell is supplied by natural gas and that makes the project incompatible with basic requirements of renewable energy supply, its idea is very close to one of the ideas presented in this thesis (biogas instead of natural gas) and therefore a note about this project is presented.

3.3 Renewable energy in Germany

Germany is the world's 4th largest coal consumer, but is, on the other hand, a good example of how a country with a moderate climate can develop a variety of renewable energy sources.

The potential for the use of renewable energy sources within Germany amounts to 5200 PJ (or 1444 TWh) per year, which corresponds to 37% of the present-day primary energy consumption. The potential is always assessed, considering restrictions on the areas which could be used for solar cells, wind sites or for energy crop cultivation (BMU, 2006a).

Figure 3.4 shows the development of electricity generation from renewable energy sources. The highest increase is predicted in wind resources as well as biomass. According to the authors, solar power will increase its share very slowly, gaining 6% in 2020.

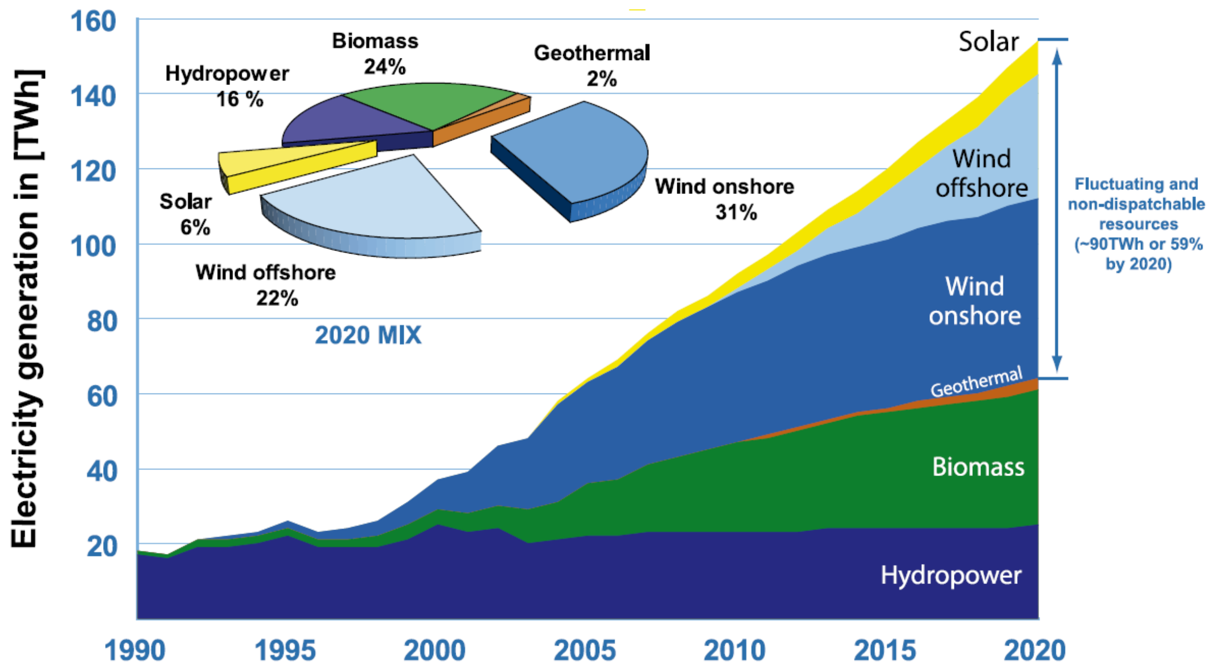


Figure 3.4 Electricity generation from renewable sources in Germany (Schindler, Wurster et al. 2008).

3.3.1 Energy related policies

Germany has adopted policy measures to actively exploit the potential of renewable energy sources. The government considers renewables to be an important source of energy and anticipates that they will be vital for replacing phased-out nuclear power and contributing to climate change mitigation. The government is therefore promoting renewables through a significant amount of financial support and active R&D, which also plays an important role in the promotion of renewable energy (International Energy Agency, 2002).

Main focuses of the research aids (BMU, 2006b):

- decreasing the costs for renewable energy systems,
- resource saving production methods,
- optimization of net integration,
- quick transfer of technology to the market,
- system oriented resolution methods (insulation combinations, household appliances),
- projects and technologies across national borders,
- cross-sector research.

The table below presents a number of projects in different renewable energy sectors as well as financial support provided for them. Photovoltaics are the main area of interest with the highest number of new projects and allocated money.

Table 3.1 Approved, ongoing and finished projects in 2006 (BMU, 2006b).

	New approved projects		**Ongoing projects**		**Finished projects**	
	number	1000 EUR	number	1000 EUR	number	1000 EUR
PV	39	43 367	118	135 398	34	24 502
Wind	29	16 083	122	55 518	48	7 925
Geothermal	11	23 718	36	51 724	5	995
Low-temp. solar thermal	13	5 058	45	24 125	10	6 298
Solar thermal electricity production	16	6 875	53	23 111	28	9 726
Cross sector research and other	10	3 716	28	20 295	4	1 052
Total	**118**	**98 818**	**402**	**310 166**	**129**	**50 498**

To make renewables more attractive, new installations are being subsidised by the government. The average compensation for electricity produced by renewables was 9.5 € cent/kWh in 2005. The compensations differ by sector, capacity of the installation, by the biomass used and, in wind energy, by the location of the installation. The amount of subsidy is being regularly revised in order to ensure appropriate regulation. The feed-ins and compensation system is being regulated by the *Erneubare-Energie-Gesetz* (Renewable Energy Act). This act gives the investors a planning security for a relatively long period of time. The transmission system operators are obliged to purchase and feed into their grids, on a priority basis, electricity that is generated from renewable sources.

In the field of district heating the most optimal heating system and technology should be used in order to minimize the amount of water and air for heating purposes. The system can be automated so that the outdoor and indoor conditions will be taken into account in order to choose the optimal working regime. For heating purposes energy from solar collectors could be used, as the prices of these installations have been decreasing (BMU, 2006b).

A major contribution to energy efficiency is expected from a better insulation of buildings. Using new insulation materials with better characteristics and implementing new air-conditioning and heating systems with proper standards is expected to decrease household energy demands.

3.3.2 Renewable energy potentials

For the European Union the largest technical potentials for renewable electricity generation are identified in wind and solar energy. The technical potential in Europe 27 is estimated at 3 500 to 4 000 TWh per year for wind energy and 1 500 to 2 000 TWh per year for electricity from solar thermal power stations and more than 1 000 TWh per year for electricity from photovoltaic plants (see figure below). In Germany the largest potentials are identified in wind, offshore and photovoltaic as well.

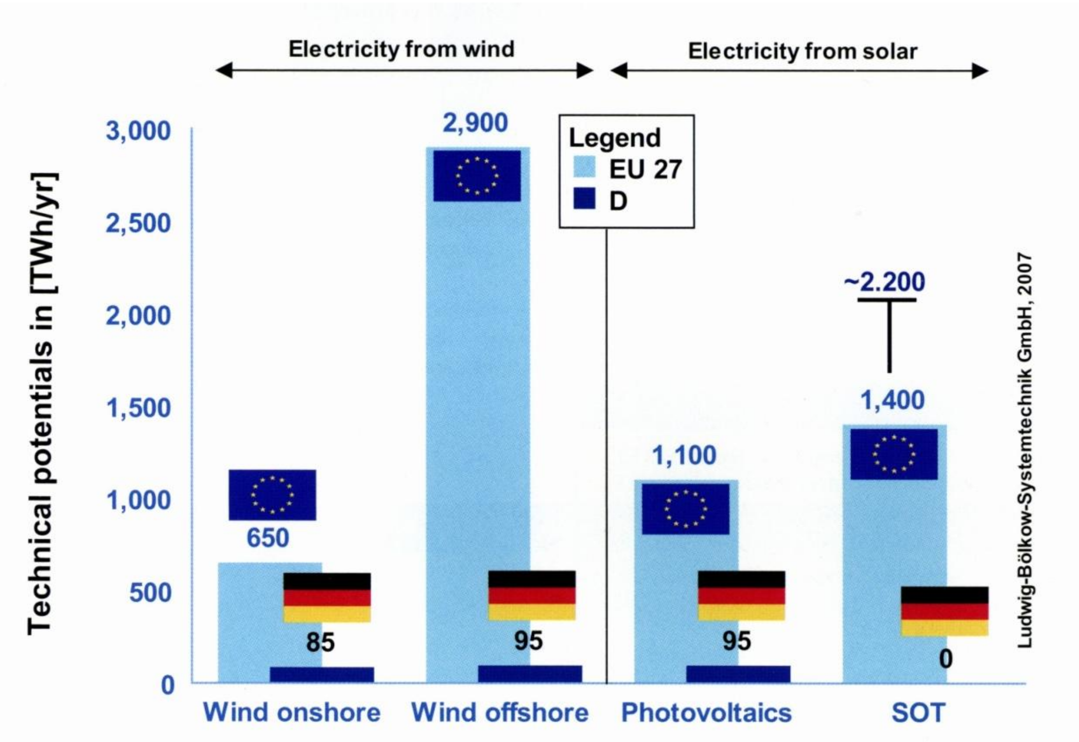


Figure 3.5 Technical potential of electricity production from wind and solar energy – European Union and Germany (Schindler, Würster et al. 2008).

In the long term it is possible to cover the major part of Germany's current demand for energy with renewables. This increase can come from using more biomass, solar energy, wind energy and geothermal. Almost all the available hydro resources have already been developed. A further increase in hydro production can be achieved by upgrading and refurbishing the current installations.

Table 3.2 presents the long-term usage potential of renewable energies for electricity, heat, and fuel production in Germany and renewable energies in 2005 (end use energy), compared to total energy consumption in 2005.

The following table presents the predicted development of capacity and generation of energy from different renewable sources. The most important source of energy in this comparison is wind power, the generation of which is supposed to increase by a factor of 3 by the year 2020.

Table 3.2 Long term potential for renewable energy (BMU, 2006b)

	Electricity production		Heat production		Fuel production	
	Usage 2005 TWh	Potential TWh/a	Usage 2005 TWh	Potential TWh/a	Usage 2005 TWh	Potential TWh/a
Hydro	21.5	24	-	-	-	-
Wind energy (on land and offshore)	26.5	165	-	-	-	-
Biomass	13.1	60	76.5	200	20.7	60
Photovoltaic	1.0	105	-	-	-	-
Geothermal	0.0002	200	1.6	330	-	-
Direct solar	-	-	3.0	290	-	-
Renewables in total	**62.1**	**554**	**81.1**	**820**	**20.7**	**60**
Total consumption	**611**		**1 499**		**610***	

* *fuel consumption in transportation sector*

Table 3.3 Development of capacity and energy generation from renewable sources (BMU, 2006b).

	2005		2010		2015		2020	
	Capacity [MW]	Generation [TWh]	Capacity [MW]	Generation [TWh]	Capacity [MW]	Generation [TWh]	Capacity [MW]	Generation [TWh]
Hydropower	4 660	21.5	4 858	22.7	5 089	23.8	5 237	24.5
Wind	18 428	26.5	24 100	41.4	28 600	56.9	35 600	81.8
Photovoltaic	1 458	1.0	4 136	3.4	7 070	6.3	9 973	9.3
Biomass	2 400	13.1	2 636	17.4	3 548	23.7	4 493	30.1
Geothermal	0.2	0.0002	55	0.3	230	1.5	530	3.5
Import	0.0	0.0	0	0.0	0	0.0	535	2.3
TOTAL	26 946	62.1	35 785	85.2	44 537	112.1	56 368	151.4

The most relevant renewable energy sources for this thesis are wind, photovoltaic and biomass, as they are quite common and easily available to deploy.

Wind and Offshore

Utilizing wind power has a long history in human civilizations. Before the steam engine, sea travel was possible only by means of sailing vessels. Windmills ground grain and drove water pumps for irrigation and drainage purposes. Today's principal application of wind power is the generation of electricity and this sector is the fastest growing renewable energy source in Germany (BMU, 2006a).

19 460 wind turbines, with a total capacity of 22 247 MW, were installed in Germany by the end of 2007, and 39.5 TWh of wind electricity were generated during 2007, which is over 7% of Germany's electricity consumption (German wind energy association, 2008).

Figure 3.6 presents the resources of wind energy (as an average wind speed at 10m height) in Germany. Because good sites are often already occupied by old turbines from the 1980s and 1990s, old systems can be replaced by larger and more efficient ones. This kind of action releases even more possible resources and energy to harness in the future.

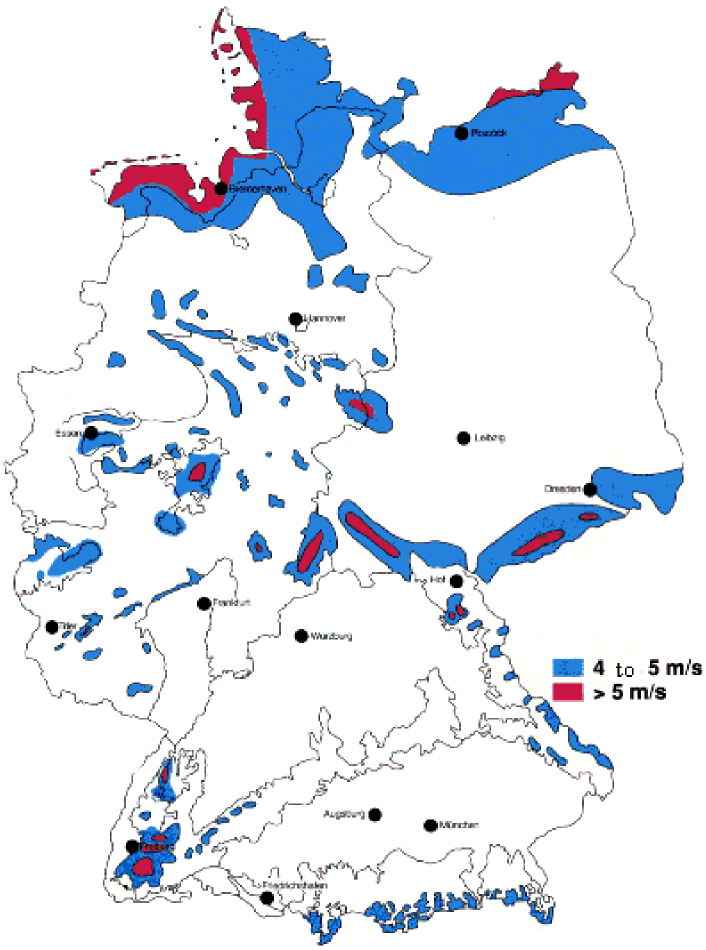


Figure 3.6 Wind speed at 10m height in Germany (TU Berlin, 1998).

The wind is stronger offshore and it blows more constant than on land. The capacity factor is about 40% higher than for the installations on land. That is why the possibility of the installation of offshore-wind parks should be investigated.

In Germany 40 projects have been submitted in the North- and Baltic Sea, 21 of which have already been approved (see figure 3.7). At this point two test installations have been built. The costs of offshore wind turbines is higher than on land (the water is at some places 40 meter deep), but this way less land will be used and the energy efficiency is higher. In addition, new work places are being created.

The compensation for offshore electricity stated in the Renewable Energy Act (EEG) is 9.1 € cent/kWh. In the Netherlands and in the UK the compensations are 15 € Cent/kWh. The aim of the federal government is to build offshore wind farms with a total capacity of 20 000 to 25 000 MW by the year 2030 (BMU, 2006b).

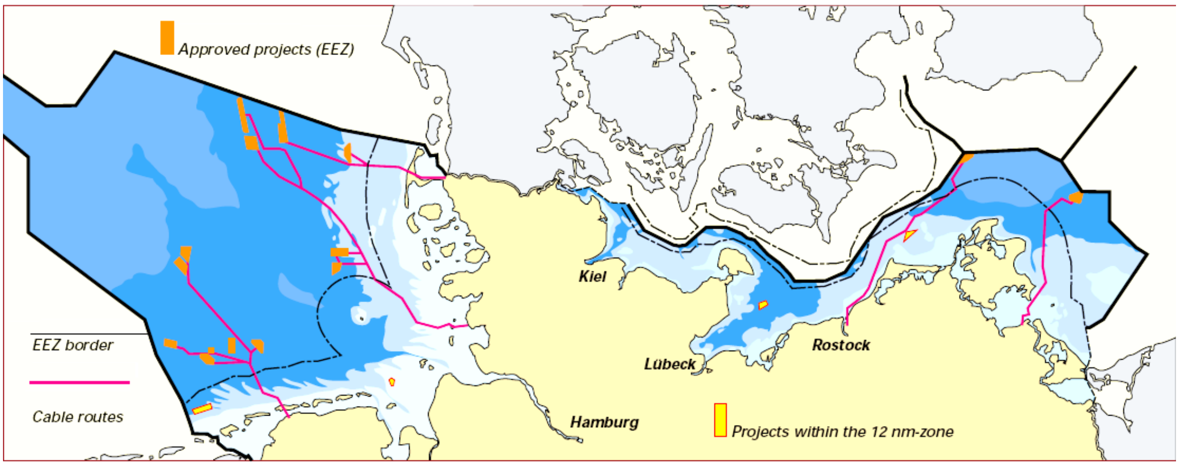


Figure 3.7 Licensed offshore wind farms in the North and Baltic Seas as of August 2006 (BMU, 2007).

In order to keep up the development of wind energy in Germany it is necessary to expand wind energy to new suitable locations (also offshore) and replace older devices with newer, higher capacity and better energy quality devices.

Photovoltaics

Solar cells directly convert sunlight into electrical power without any mechanical, thermal or chemical intermediate steps. Solar cells utilize the photovoltaic effect – for certain arrangements of super-imposed semiconductor layers, free positive and negative charges are generated under the influence of light (photons). These charges can then be separated by an electrical field and flow as electrons through an electrical conductor (BMU, 2006a).

Solar cells can easily be sizeable from few milliwatts, through the kilowatt range up to megawatt range. Another advantage of solar cells is that they convert and diffuse solar radiation so they can have a good load factor.

Germany has the highest installed solar electric capacity in Europe. Installed PV capacity has risen from 100 MW in 2000 to approximately 4 150 MW at the end of 2007 (BMU, 2008).

The map below (figure 3.8) presents the yearly sum of global radiation on horizontal surface (in kWh/m^2), i.e. possible solar resources in the country.

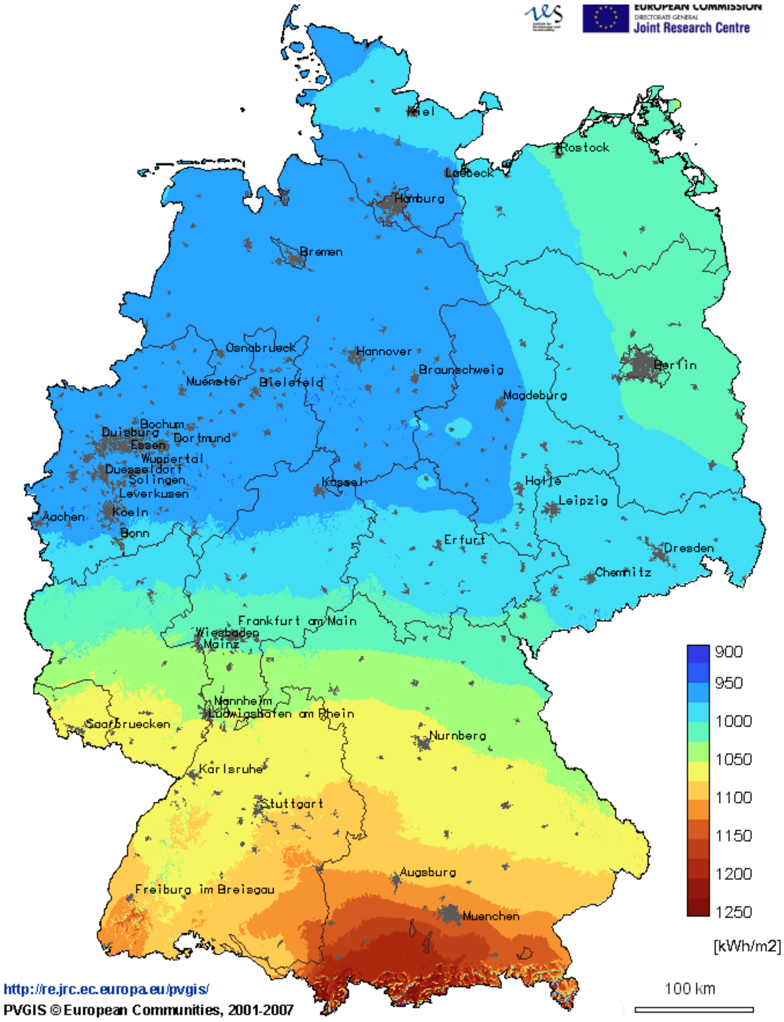


Figure 3.8 Yearly sum of global irradiation (in kWh/m^2) on horizontal surface in Germany (PVGIS, 2008)

Use of solar energy is being promoted by the market-stimulation programme of the German environment ministry. Producers of renewable energy get 43 € cents for each kWh of solar power generated and 7 € cents per kWh of wind energy generated. In many places photovoltaic systems are already successfully powering individual houses, supplying villages with power or being used for pumping systems (BMU, 2006b)

Biomass

The use of biomass for generating electricity and heat is a particularly attractive form of energy conversion from the climate point of view. When growing, the biomass removes CO_2 from the atmosphere and binds the carbon in the biomass. Although fossil fuels have their origin in ancient biomass, they are not considered biomass because they contain carbon that has not been taking part in the carbon cycle for a very long time. Their combustion therefore disturbs the carbon dioxide content in the atmosphere (Wikipedia, term: *Biomass*).

Organic leftovers are also suitable energy sources. Liquid manure, bio-waste, sewage sludge, municipal sewage and food leftovers can be converted into biogas and further combusted in boilers or reformed for use in fuel cells.

The table below presents detailed data about the share of biomass use in energy production in Germany with distinction for electricity, heat and fuel production.

Table 3.4 Share of biomass energy use (BMU, 2006b).

		End energy	Primary energy equivalent			Share in site energy consumption	Share in total primary energy consumption	
		[GWh]	In efficiency method [PJ]	In substitution method [PJ]		[%]	In efficiency method [%]	In substitution method [%]
ELECTRICITY PRODUCTION	Hydropower	21 524	77.5	211.7	**SHARE IN TOTAL ELECTRICITY PRODUCTION**	3.5	0.5	0.5
	Wind energy	27 229	98.0	258.4		4.5	0.7	1.8
	PV	1 282	4.6	11.4		0.2	0.03	0.1
	Biogenous solid fuels	4 647	38.6	38.6		0.8	0.3	0.3
	Biogenous liquid fuels	1 140	9.5	9.5		0.2	0.1	0.1
	Biogas	2 770	23.0	23.0		0.5	0.2	0.2
	Sewage gas	888	7.4	7.4		0.1	0.1	0.1
	Landfill gas	1 050	8.7	8.7		0.2	0.1	0.1
	Biogenous part of the waste	3 039	25.3	25.3		0.5	0.2	0.2
	Geothermal	0.2	0.0	0.0		0.0	0.0	0.0
	TOTAL	**63 569**	**292.6**	**594.0**		**10.4**	**2.1**	**4.1**
HEAT PRODUCTION	Biogenous solid fuels (household)	56 000	201.6		**SHARE IN TOTAL HEAT PRODUCTION**	3.7	1.4	1.4
	Biogenous solid fuels (industry)	9 300	33.5			0.6	0.2	0.2
	Biogenous solid fuels Cogeneration- and heat plants	1 575	5.7			0.1	0.04	0.04
	Biogenous liquid fuels	1 000	3.6			0.1	0.03	0.03
	Biogenous gaseous fuels	3 750	13.5			0.2	0.1	0.1
	Biogenous part of the waste	4 692	16.9			0.3	0.1	0.1
	Solar thermal	2 960	10.7			0.2	0.1	0.1
	Deep geothermal	129	0.5			0.01	0.003	0.003
	Near surface geothermal	1 472	5.3			0.1	0.04	0.04
	TOTAL	**80 878**	**291.3**			**5.3**	**2.0**	**2.0**
FUEL	Biodiesel	18 600	67.0		**% IN TOTAL FUEL CONS.**	3.1	0.5	0.5
	Vegetable oil	2 047	7.4			0.4	0.1	0.1
	Bioethanol	1 936	7.0			0.3	0.05	0.05
	TOTAL	**22 583**	**81.4**			**3.8**	**0.6**	**0.6**
	TOTAL	**167 030**	**665.3**	**966.7**	**EEU***	**6.6**	**4.7**	**6.6**

** End energy use*

Another opportunity to gain energy from biomass comes from biofuels. They offer an occasion to partially substitute petroleum as an energy carrier in the transport sector. Best known among liquid biofuels are the vegetable oils from rapeseed and sunflower seeds, and the processed form of rapeseed oil – biodiesel (BMU, 2006a).

Germany is the world's largest producer of biodiesel, with production at an estimated level of 33 000 barrels per day of biodiesel in 2005, or half of the total biodiesel production in the EU. Germany's biodiesel industry association expects that production in the country will grown by 20 to 30 percent a year. One of the principle drivers of biodiesel demand in Germany is the fact that it is exempt from excise taxes based on conventional diesel sales. However, in 2006, the German government enacted a 9 € cent per litre tax on biodiesel fuels, which led to a decline in biodiesel production from 2007, and planned to eventually increase the tax to the same level applied to conventional diesel by 2012 (BMU, 2006b).

3.4 Fuel cells and hydrogen as partners of renewable energy systems

Renewable energy sources like wind and photovoltaic are increasing their share in the total electricity generation. However these sources are not fully reliable, as no one can guarantee that a constant wind flow or solar radiation will be fully available all day long. This causes fluctuations in electricity production and possible shortages of energy supply.

To solve this problem, better methods of energy storage are needed. One option for efficient electricity storage is the production of hydrogen. Hydrogen can be produced from water using electricity, therefore it is an energy carrier, not a source of energy. Hydrogen is produced in the process of electrolysis in devices called electrolysers. The advantage of this device lies in its ability to operate with different electricity loads (although efficiency is lower if operating below the design point), so it is well situated for the changing power output from renewable resources. Hydrogen manufactured this way is pure and is ready to store and use in fuel cells.

The Fuel Cell is an electrochemical device which produces electricity from fuel and an oxidant. The principal components of a fuel cell are catalytically activated electrodes for the fuel, the oxidant and an electrolyte to conduct ions between the two electrodes (Sigfusson, 2008). The reactants flow into the cell, and the reaction products flow out of it while the electrolyte remains within. Fuel cells can operate virtually continuously as long as the necessary flows are maintained (Wikipedia, term: *Fuel Cell*). Many fuels are possible for powering fuel cells, but the most important is hydrogen. Natural gas and biogas are also potential fuels but need to be reformed to release hydrogen, which is further used. The power produced by a fuel cell depends on several factors, including the fuel cell type, size, temperature at which it operates and pressure at which gases are supplied to the cell.

Basically, in this thesis, the use of one of two kinds of fuel cells is considered – Proton Exchange Membrane Fuel Cell (PEFC) (see chapter 3.4.3 below) and Solid Oxide Fuel Cell (SOFC) (see chapter 3.4.4 below). The main difference between them is the operating temperature. The difference is almost 700°C, therefore it has a significant meaning for heating purposes.

3.4.1 Advantages of fuel cells

Because fuel cells produce electricity directly from chemical energy they are more efficient than combustion engines (they do not obey the Carnot limitation). Fuel cells have no moving parts; therefore they have the potential to be highly reliable. Moreover, there are no direct emissions of NOx, SO_2 and particulates.

Fuel cells can easily be scaled for demanded power and capacity and can be applied in various stationary applications, ranging from one kW_{el} systems for domestic heating, combined heat and power production for district heating or large buildings, up to megawatts applications for industrial cogeneration and electricity production without cogeneration (O'Hayre et al. 2006). What is more, the efficiency of fuel cells is independent from their capacity; therefore small, portable units as well as big, industrial fuel cells will have comparable performance.

3.4.2 Disadvantages of fuel cells

A major barrier to fuel cell implementation is the availability and storage of hydrogen. Fuel cells work best on hydrogen gas, which is not widely available. It has a low volumetric density and is difficult to store. Alternative fuels (methanol, gasoline) are difficult to use directly and require reforming, which can reduce fuel cell performance and increase requirements for ancillary equipment

Another big issue is the cost of fuel cells. It is still a developing technology, and is only economically competitive in highly specialized applications. Cost reduction is a must if fuel cells aim to revolutionize future energy supply (O'Hayre et al. 2006).

3.4.3 Proton Exchange Membrane Fuel Cell

The Proton Exchange Membrane fuel cell is one of the most popular fuel cells among researchers as well as industry manufacturers. The PEFC fuel cell has a quick startup, operates at a low temperature (typically $80^{o}C$) and has high energy density (exceeding 2 kW/l), making it the primary candidate for the automobile industry (Sigfusson, 2008).

Proton exchange fuel cells use electrolytes made of polymer (like the popular *Nafion*) that is permeable to protons and porous carbon electrodes containing a platinum catalyst. To operate, they require hydrogen, oxygen and water. Hydrogen is typically supplied from storage tanks and oxygen is drawn from the air (Hydrogen Technology Explained, 2008). Water is used to humidify the membrane, because only then can the membrane conduct protons.

Figure 3.9 shows a schematic PEFC marked with two electrodes separated by a membrane. The anode, which is porous so that hydrogen can pass through it, is composed of platinum (catalyst) particles supported on carbon particles and surrounded by a thin layer of proton-conducting ionomer. Hydrogen on the anode side moves through the electrode and encounters the platinum catalyst, which causes the hydrogen molecules to separate into protons and electrons. The membrane allows only the protons to pass through. While the protons are conducted through the ionomer and PEM to the other side of the cell, the stream of negatively-charged electrons follows an external circuit to the cathode. This flow of electrons through the external circuit is electricity that can be used to do work.

On the other side of the cell, oxygen gas flows to the cathode, which is made with platinum particles, to the anode, where a reduction reaction involving the gain of electrons takes place. When the electrons return from doing work, they react with oxygen and hydrogen protons at the cathode to form water. Most of the water is collected and reused within the system, but some amount is released in the exhaust as a water vapor (Hydrogen Technology Explained, 2008).

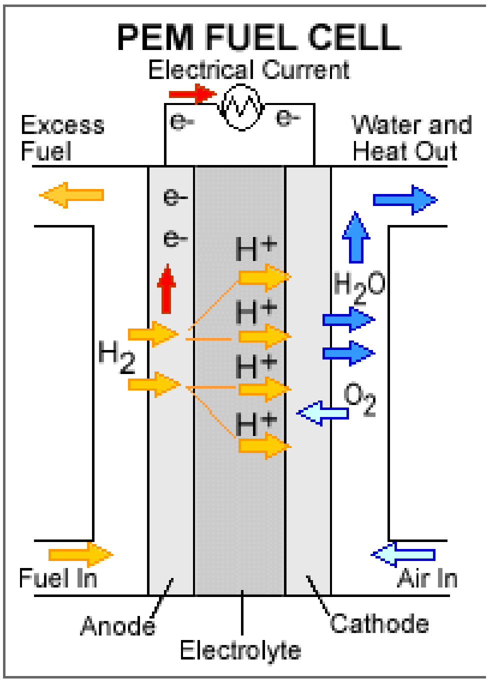


Figure 3.9 Scheme of a Proton Exchange Membrane fuel cell (Wikipedia, term: Proton exchange membrane fuel cell).

Problems related to this kind of fuel cell are water management, the need for cooling and control systems and the use of an expensive platinum catalyst. Moreover, PEFC only work on very pure hydrogen gas and are intolerant of other compounds, especially CO. The presence of a control and water management system causes parasitic losses of energy which decrease the overall performance and efficiency.

3.4.4 Solid Oxide Fuel Cell

Solid oxide fuel cells (SOFC) utilize a ceramic, solid, non-porous material as the electrolyte. The operating temperature is the highest among the fuel cells and can reach 1000^{o}C, but typically is around 700 – 800^{o}C. This high temperature allows the SOFC to operate directly on carbon-based fuels (especially methane, for instance from natural gas or biogas) which are reformed internally. Moreover they have no need for an expensive catalyst, as is used in low temperature fuel cells. Internal reforming leads to a decrease in the balance of plant costs in designing a full system.

Figure 3.10 shows the schematic of a solid oxide fuel cell. This kind of fuel cell is made up of four layers, three of which are ceramics. The reduction of oxygen into oxygen ions occurs at the cathode. Ions then diffuse through the solid oxide electrolyte to the anode where they electrochemically oxidize the fuel. In this reaction a water byproduct is given off, as well as two electrons. These electrons flow through an external circuit where they do work (like in a proton exchange fuel cell) (Wikipedia, term: *Solid oxide fuel cell*).

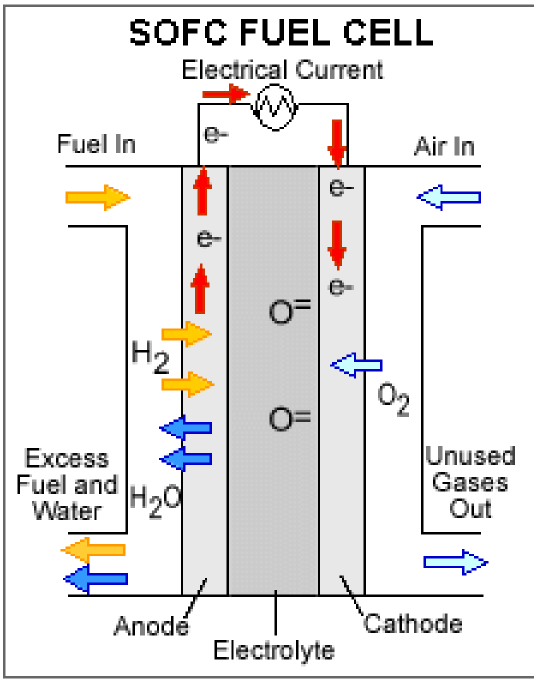


Figure 3.10 Scheme of a Solid Oxide fuel cell (Wikipedia, term: Solid oxide fuel cell).

A general disadvantage of SOFC is the long process of startup. Startup can take from 15 minutes up to 8 hours or more in different systems. The high operating temperature makes the stack hardware, sealing, materials requirements, mechanical issues, reliability concerns and thermal expansion matching tasks more difficult.

3.5 New ways of district heating

In order to avoid distribution losses in the grid, increase the efficiency of the power supply and decrease emissions of greenhouse gasses new solutions for heating have to be implemented. These solutions mostly change the source of power from a separated unit serving many customers to smaller, personal units that are installed in each home. In this case, the heat generated by the device is used directly in the same building and the distribution losses are virtually zero.

There are, however, technical issues concerning the resizing of heat engines. Small gas engines become very inefficient and it is hardly possible to install such a unit in a household. In this field, fuel cells are in the highest interest, as they can be easily sized to the demanded capacity, keeping their high efficiency.

Further, in this thesis there are presented seven ideas for new methods of district heating, all of them utilizing fully renewable energy for more efficient and cleaner heating in low energy houses. Basically, there can be specified few energy flow chains:

- electricity to H_2, H_2 distribution, decentralized fuel cell units,
- electricity to H_2, central fuel cell unit, heat and electricity distribution,
- electricity to decentralized battery systems,
- biogas distribution, decentralized fuel cell units with internal reforming,
- electricity to decentralized battery systems, biogas distribution, heating boilers
- electricity to decentralized battery systems and H_2, H_2 distribution, decentralized fuel cell units and batteries.

In all cases (except one) heat distribution is replaced by electricity and/or gas transport. This form of energy transfer is much more efficient as losses while transmitting are lower. Presented options are:

- reference grid,
- distributed generation using Proton Exchange Membrane Fuel Cells, hydrogen distribution network and central electrolyser,
- distributed generation using Solid Oxide Fuel Cells, hydrogen distribution network and central electrolyser,
- distributed generation using Solid Oxide Fuel Cell Plant, hydrogen pipeline and central electrolyser,
- biogas distribution network and Solid Oxide Fuel Cells with internal reforming,
- renewable electricity with storage in batteries,
- biogas distribution network and renewable electricity with storage in batteries,
- renewable electricity with complex storage in batteries, hydrogen production, storage and use in fuel cells.

3.5.1 Reference grid

The reference grid consists of a Combined Heat and Power (CHP) plant and a distribution network for district heating, hot water and electricity to the settlement. The heat is distributed to the consumers through a closed loop network, where the hot water is piped to each consumer in the supply network, cooled down by the consumer, piped back to the boiler in the return network and re-heated. Figure 3.11 presents the schematic plan of a small grid, which will be used as a reference in this project.

The CHP plant is a gas engine working entirely on natural gas. Natural gas is combusted to acquire heat and then electricity. The exhaust heat is used for district heating and warm water preparation (see figure 3.12) with temperatures ranging from approximately 80 to 130^{o}C. By capturing the excess heat, CHP uses heat that would be wasted in a conventional power plant. Efficiency of the gas engine is 35% for electricity, 45% for heat production and 80% combined.

The combined efficiency is high and satisfactory but, as was mentioned earlier in the thesis, low energy houses have a low heat demand during the year, therefore most of the heat just circulates in the grid causing heat transfer to the surrounding ground. Since the insulation standards will be getting tighter, the losses will be even more significant. Another issue concerning heat delivery is the problem of hot water preparation in summer. Customers expect that after opening the valve, hot water will appear immediately; therefore it circulates all around the grid. However, as there is no demand for space heating at this time of year, warm water delivery generates 50% of all losses. In the proposed ideas warm water is prepared directly at the consumers’ home, therefore distribution losses are avoided.

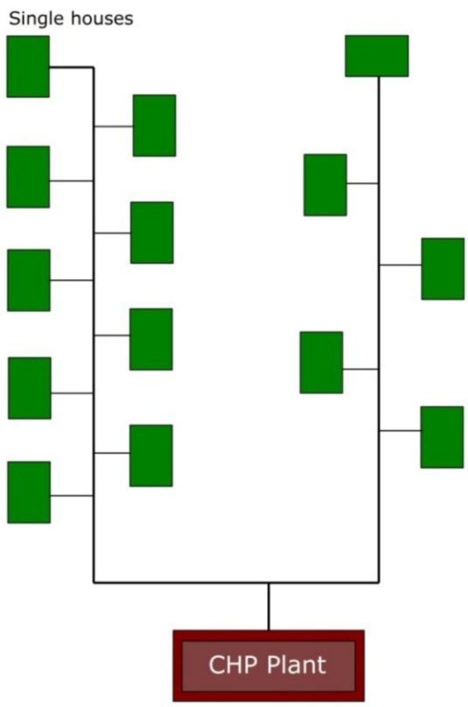


Figure 3.11 Schematic plan of the reference grid.

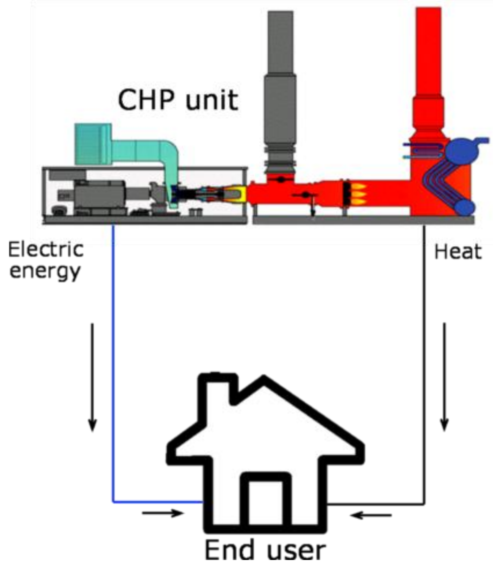


Figure 3.12 Scheme of reference units.

3.5.2 Distributed generation using Proton Exchange Membrane Fuel Cells, hydrogen distribution network and central electrolyser

This is the case in which heat and electricity delivery is changed to hydrogen transport. Each house owns a proton exchange fuel cell and is connected to the hydrogen supply network. The fuel cell produces electricity as well as heat (low temperature, up to 60^{o}C) to provide energy for space heating and water heating. The efficiency of the fuel cell is 45% electrical, 45% heat and 90% when combined.

Hydrogen is pumped through a pipe network similar to city/natural gas pipe networks (see figure 3.13). It would be possible to use the existing natural gas pipelines with some modifications. For hydrogen pipelines, it is necessary to use steel, which is less prone to embrittlement by hydrogen under pressure. Reciprocating compressors used for natural gas can be used for hydrogen without major design modifications. However, special attention must be given to sealing in order to avoid hydrogen leaks, and to materials selection for the parts subject to fatigue stress. As a rule, hydrogen transmission through pipelines requires larger diameter piping and more compression power than natural gas for the same energy throughput. However, due to lower pressure losses in the case of hydrogen, the recompression stations could be spaced twice as far apart (although not necessarily in the case presented in the thesis). In economic terms, most of the studies found that the cost of large-scale transmission of hydrogen is about 1.5–1.8 times higher than that of natural gas transmission (Sherif et al. 2005).

A central electrolyser produces hydrogen using renewable energy (wind power and photovoltaic energy) in quantities securing the demand of hydrogen in peak seasons. The electrolyser may be sized to receive all the power generated from a wind turbine and PV, but it would operate with the same capacity factor as these sources. The capacity factor is a coefficient of the utilization of installed capital, and therefore it is an important factor in determining the economics of any power generating or energy conversion device. A more economical option may be to size the electrolyser at a power lower than the renewable energy sources' maximum power output. In that case some of the power from the wind would be fed directly into the maintenance grid or remain unused, but the electrolyser would operate with a higher capacity factor. The economics of wind hydrogen systems greatly depend on the configuration of the system and its application, in addition to the available wind and solar resources (Sherif et al. 2005).

To ensure a continuous supply of hydrogen a storage unit must be installed. The nature of the proposed sources of renewable energy (wind, solar) does not guarantee constant power output, therefore a storage unit will serve as a "buffer tank" (see figure 3.14). The Storage unit will operate at a maximum pressure of 200 bars; therefore the use of a standard compressor is possible. The system is designed to cover all energy needs for the settlement; therefore a connection to the national grid is not foreseen.

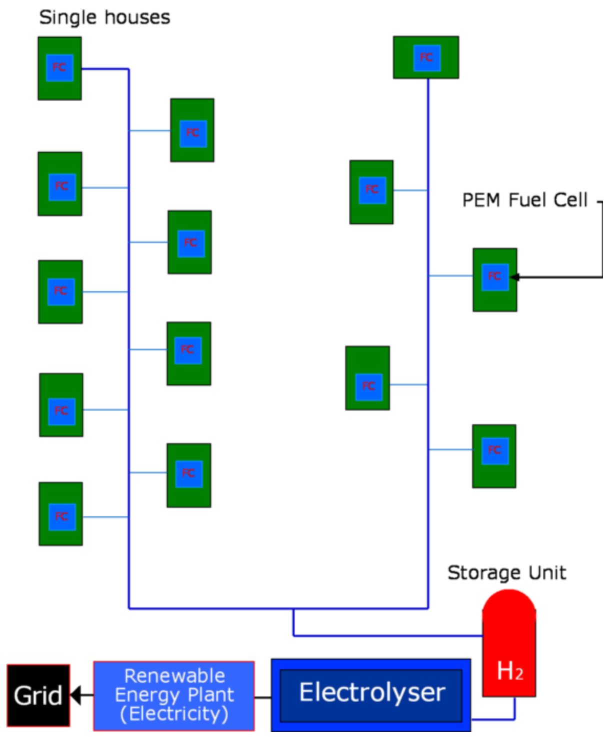


Figure 3.13 Schematic plan of the local grid with Proton Exchange Membrane Fuel Cells, hydrogen distribution network and central electrolyser.

The figure below shows the scheme of the system with basic devices and connections between them.

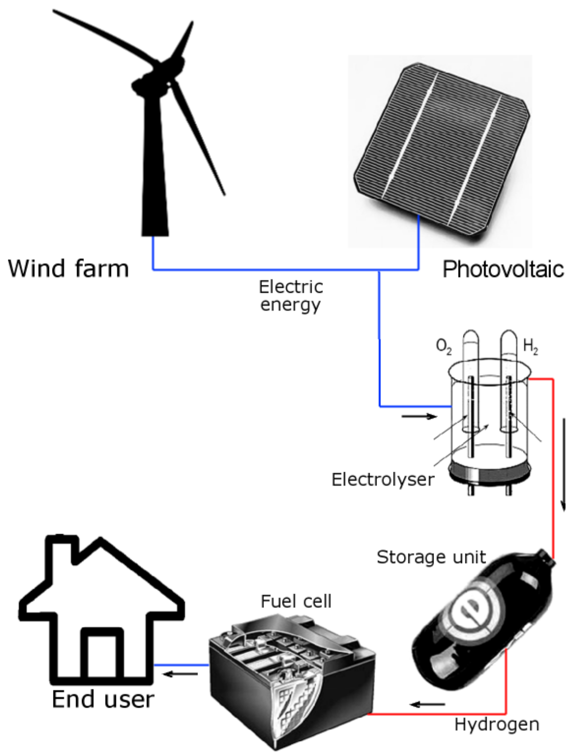


Figure 3.14 Scheme of the system with Fuel Cell, hydrogen distribution network and central electrolyser.

3.5.3 Distributed generation using Solid Oxide Fuel Cells, hydrogen distribution network and central electrolyser

The idea is the same as in the previously described alternative. In this case each house owns a Solid Oxide Fuel Cell which operates at much higher temperature (700 – 800°C). The efficiency of the fuel cell is 55% electrical, 25% heat and 80% as combined.

Electricity and heat is produced similar to the PEFC (figure 3.14) and the difference is in the balance of electricity and heat production, as this fuel cell has a generally slower response for rapid load demands. The rest of the distribution system is unchanged (figure below).

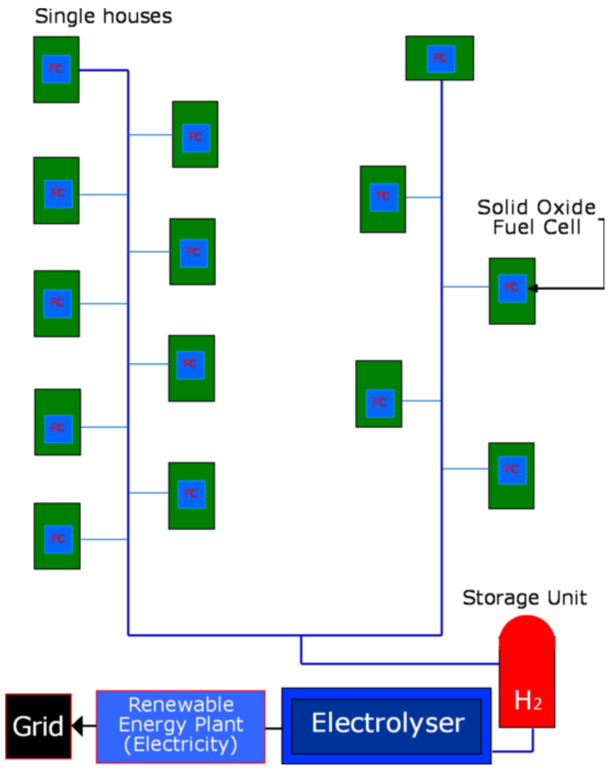


Figure 3.15 Schematic plan of the local grid with Solid Oxide Fuel Cells, hydrogen distribution network and central electrolyser.

3.5.4 Distributed generation using Solid Oxide Fuel Cell Plant, hydrogen pipeline and central electrolyser

In this case, instead of the CHP natural gas fired plant in the 3.5.1 section (reference case), a Solid Oxide Fuel Cell is responsible for producing heat and electricity. A distinction from the previous alternative is that one big SOFC unit serves the whole community. There are still heat losses as a result of using district heating pipelines; however the SOFC unit is more efficient in terms of electricity generation (55% instead of 35% in gas engine unit) and generally has a lower carbon emission impact, because of not using carbon-based fossil fuels.

The nature of the Solid Oxide Fuel Cell does not allow its use as an instant source of power. Start up of SOFC can take hours, but on the other hand an SOFC is more durable, reliable and cheaper than PE fuel cells. Therefore SOFC are preferred for use in residential applications and one central unit should have better performance, as the variation in the energy demand of many users is lower than for single user.

The hydrogen distribution network is not necessary in this case; only one pipeline is needed between the storage unit and the solid oxide fuel cell.

The figure below presents the plan of the local grid with one SOFC unit. This unit can be situated close to the settlements, because it does not emit noise and air pollutants.

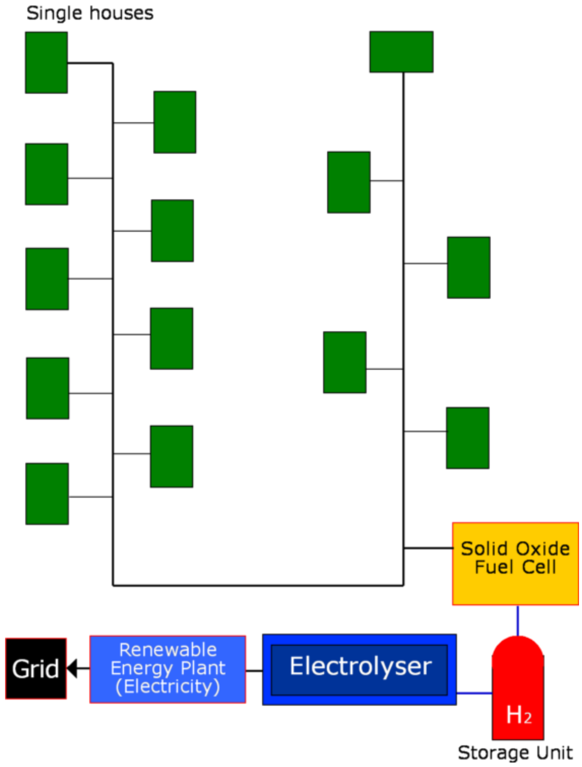


Figure 3.16 Schematic plan of the local grid with Solid Oxide Fuel Cell Plant, hydrogen pipeline and central electrolyser.

3.5.5 Biogas distribution network and Solid Oxide Fuel Cells with internal reforming

In this case heat and electricity delivery is changed to biogas delivery. Biogas can be supplied from local biomass sources and then can be burned in the boilers producing heat in the quantity needed by homes, or can be internally reformed in a high temperature Solid Oxide Fuel Cell to hydrogen used then by SOFC to generate heat and electricity.

Similar to the two previous alternatives, biogas can be supplied to each house, then reformed and used in "personal" SOFC or can be piped to the main SOFC unit which will produce heat and electricity distributed to the community. In figure 3.17 the first option is presented, as there are no heat losses while distributing biogas.

A standard natural gas distribution network may be used to distribute biogas. In fact, the properties of natural gas and biogas are similar, only the source of origin is different. Also, a storage unit for biogas can be as simple as a rubber gasholder (like in figure 3.18).

The most important factor in this alternative is the elimination of a hydrogen storage and distribution system. Implementing hydrogen still has some technical and safety problems due to the properties of hydrogen. Biogas is easier to handle, is cheaper and its infrastructure is more developed.

Figure 3.17 and 3.18 present a plan and a scheme of the system with a biogas plant, biogas storage and distribution chain.

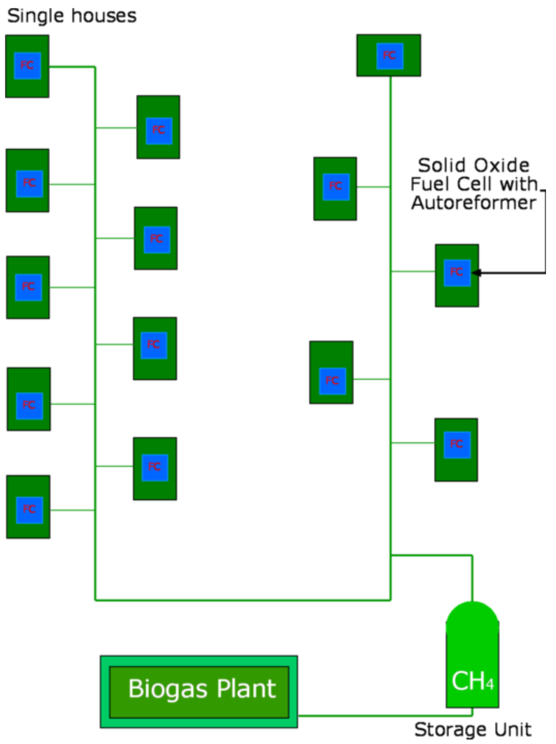


Figure 3.17 Schematic plan of the biogas distribution network and Solid Oxide Fuel Cells with internal reformer.

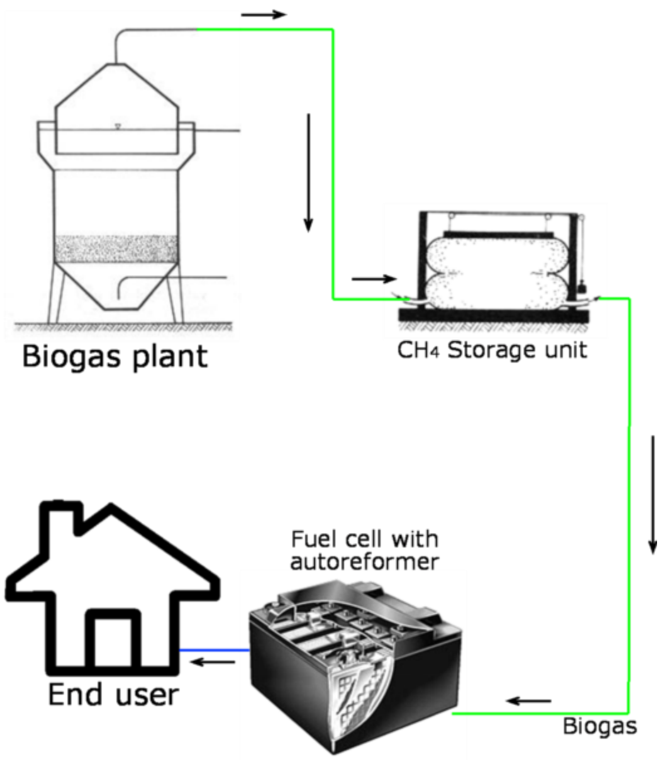


Figure 3.18 Scheme of the biogas plant, storage and Solid Oxide Fuel Cell with internal reformer.

3.5.6 Renewable electricity with storage in batteries

In this alternative, the heating and electrical power connections are based only on the electricity generated in renewable sources and stored in batteries (figure 3.19). The battery system must be sized properly to serve electricity demand as well as heat demand (heat generated in electric radiators and electric boilers). This requires high reliability as well as durability from the battery system. On the other hand it is a very efficient, safe and easy system to deploy because the final user needs only some space for batteries, control unit and standard grid connection.

Main problems arising in this alternative are the cost of batteries, their lifetime and capacity. On the other hand batteries are highly efficient in terms of energy storage (compared, for example, to hydrogen production, storage and distribution) with an efficiency exceeding 90%.

Another issue that should be considered is the self-discharging of batteries. All batteries suffer from self-discharge, for which nickel-based batteries have among the highest occurrence. The loss is asymptotical, meaning that the self-discharge is highest right after charge and then levels off. Lithium-ion batteries (which will be proposed in further application) self-discharge about 5% in the first 24 hours and 1-2% afterwards. Adding the protection circuit increases the discharge by another 3% per month. The protection circuit assures that the voltage and current on each cell does not exceed a safe limit. The self-discharge on all battery chemistries increase at higher temperatures. Typically, the rate doubles with every 10°C (Battery University, 2005).

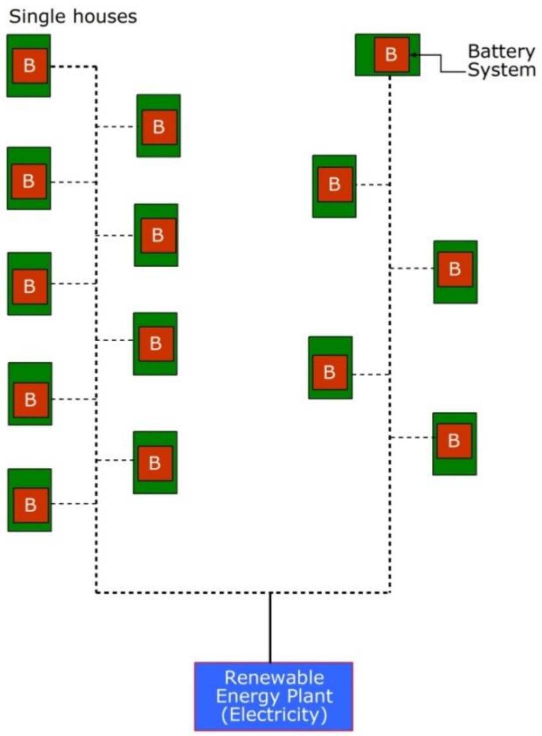


Figure 3.19 Schematic plan of renewable electricity grid with storage of the energy in the batteries.

The figure below presents plan of the simple system with a renewable energy plant, batteries and the connection between them.

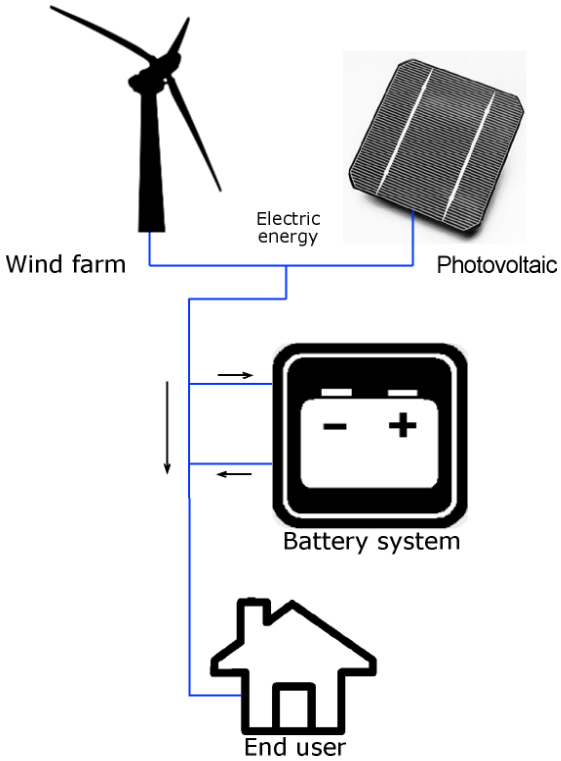


Figure 3.20 Scheme of renewable electricity system with storage of the energy in the batteries.

3.5.7 Biogas distribution network and renewable electricity with storage in batteries

In this case biogas is distributed by pipeline network in quantities covering heat and warm water preparation demand. Only heat energy is generated by the combustion of biogas in boilers, therefore a source of electrical energy is needed. This will be provided by connection to the renewable energy sources.

The idea is similar to the previous alternative, but in this case acquiring heat by combustion of biogas significantly decreases the need for electricity that would be used in electrical radiators. That allows considerably down-sizing battery system, which now serves only electrical appliances.

The figure below presents the schematic plan of biogas distribution network, renewable electricity grid and the battery systems.

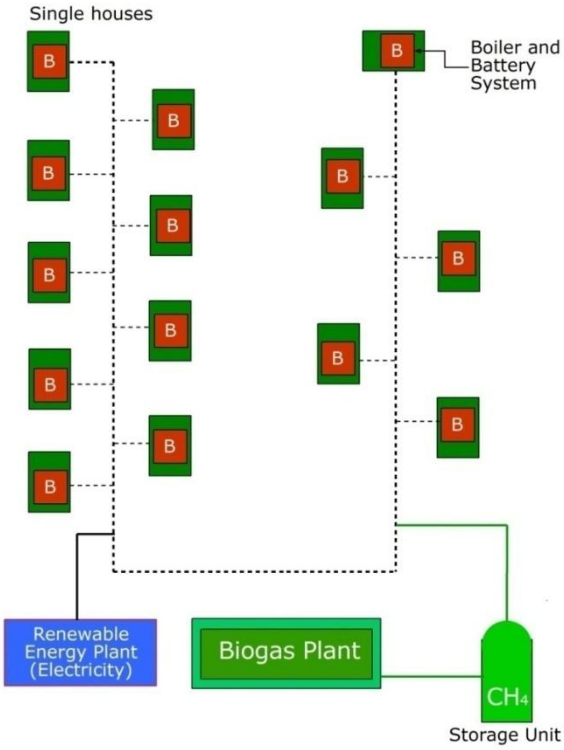


Figure 3.21 Schematic plan of biogas distribution network and renewable electricity with storage in the batteries.

The figure below portrays the plan of the system with renewable energy plant, biogas plant, electricity grid, biogas storage and distribution chain.

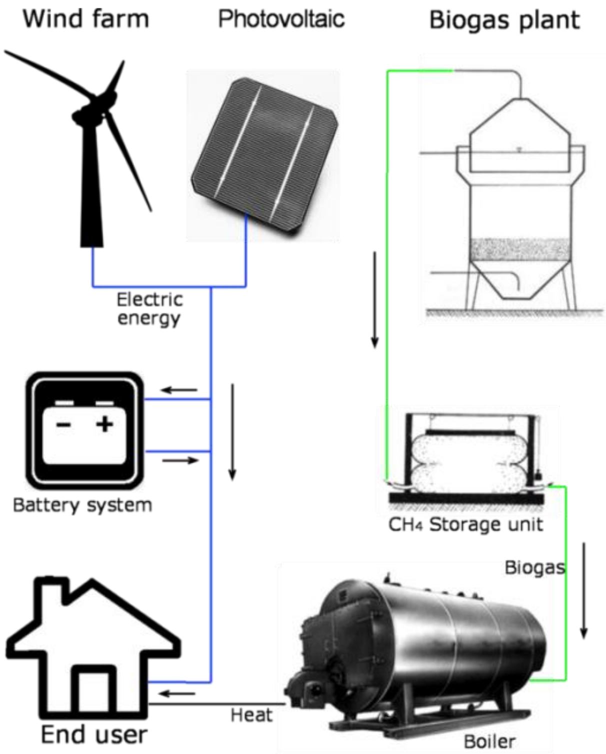


Figure 3.22 Scheme of the biogas distribution network and renewable electricity with storage in the batteries.

3.5.8 Renewable electricity with complex storage in batteries, hydrogen production, storage, distribution and use in fuel cells

This alternative combines the use of batteries as well as fuel cells into a hybrid system. Electricity is produced by renewable energy sources and distributed by the grid to the houses, which can store some of the energy in batteries. Surplus electrical energy (above that which can be absorbed by the grid in that particular moment) is used by an electrolyser to generate hydrogen, which is stored in the tank and distributed by pipeline system to houses and used in fuel cells (figure 3.23 and figure 3.24).

The battery in this case works as a small buffer allowing the use of electricity in short periods of limited proper power delivery from the renewable energy sources. In longer periods of limited electric energy from renewable sources, energy stored as hydrogen is used in fuel cells. Fuel cells serve as a heat source while generating electricity. This configuration also results in the need for a much smaller size of the battery system.

Most of the wind-to-hydrogen installations are based on this solution because a battery is, in fact, essential to minimize short term fluctuations in power output from the wind turbines. A battery is much more efficient and responds faster than a fuel cell, while the fuel cell is better adapted to longer and more constant operation. Moreover, this arrangement allows the fuel cell to operate on the low load (when the efficiency of fuel cell is the highest), covering basic power needs and using electricity from batteries during peak hours. Generally this is one of the most comprehensive solutions, and there are many system modifications depending on the designed capacities, sizes of the devices and fuel cells used.

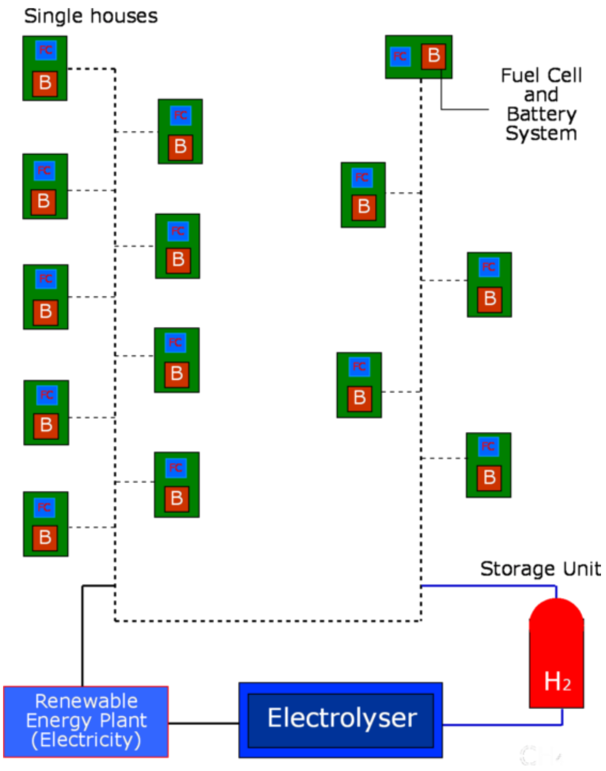


Figure 3.23 Schematic plan of renewable electricity grid with complex storage in batteries, hydrogen production, storage, distribution and use in fuel cells.

The figure below presents a plan of the complex system with renewable energy plant, batteries, electrolyser, hydrogen storage unit, distribution network, fuel cells and connection between them.

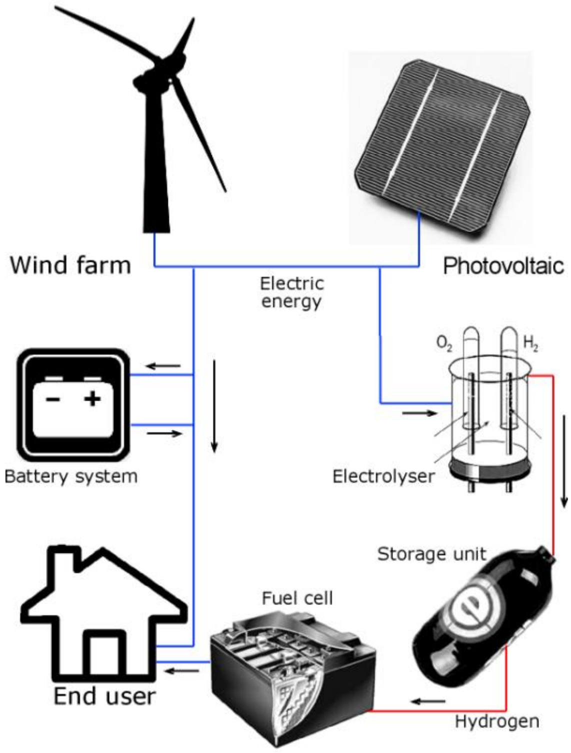


Figure 3.24 Scheme of renewable electricity with complex storage in batteries, hydrogen production, storage, distribution and use in fuel cells.

4 DATA PREPARATION

For the correct calculation and result, it is essential to base the analysis on proper data, well recognized and described limitations and assumptions. This chapter gives insights into the data sources, assumed parameters, proposed solutions, chosen alternatives as well as information about the project.

4.1 Information about the area

The area in which the project is performed is situated in central Germany, with temperate, seasonal climate moderated by the North Atlantic drift. Winters are mild and summer tends to be cool with changing to more continental climate in the east. Annual average temperature for the area in 2000 was 8.6^{o}C with values varying from -14^{o}C to 32^{o}C.

The figure below shows the duration curve of hourly temperature values through the year, sorted from the highest to the lowest value.

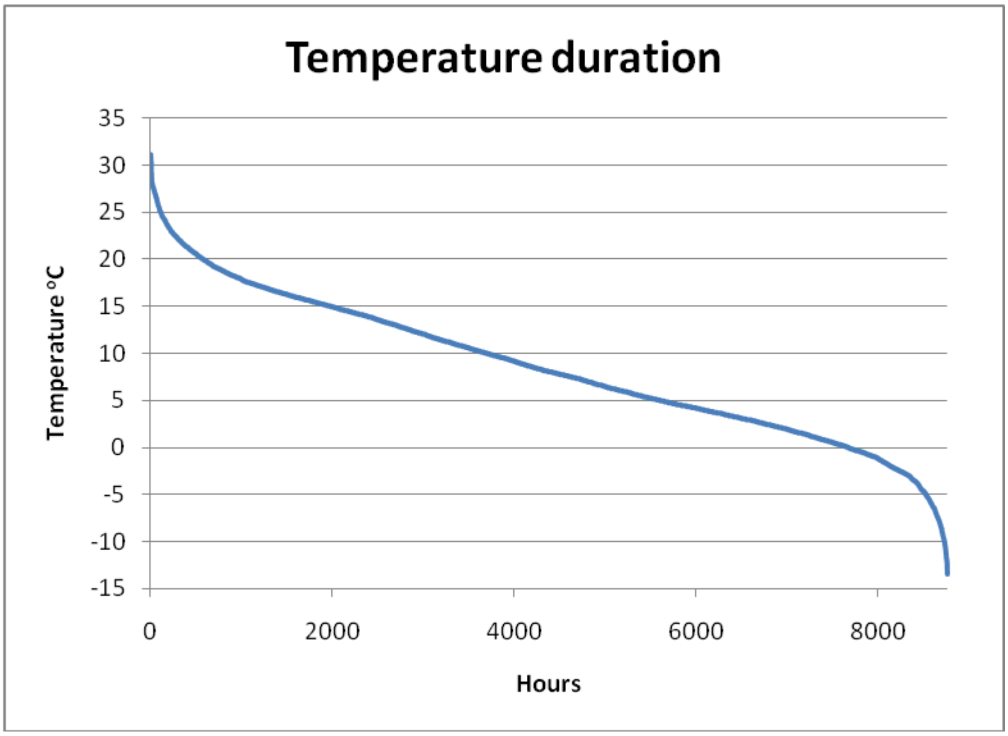


Figure 4.1 Hourly temperature values.

All the metrological data which were used for presenting statistics and calculations come from the German meteorological office for the city of Hannover (central Germany) for the year 2000.

4.1.1 Wind energy resources

Wind resources are not very significant, as the average wind speed at 10m is around 4 m/s. Wind is directed mostly south-west with around 8500 hours available a year. The figure below shows the wind distribution for the area.

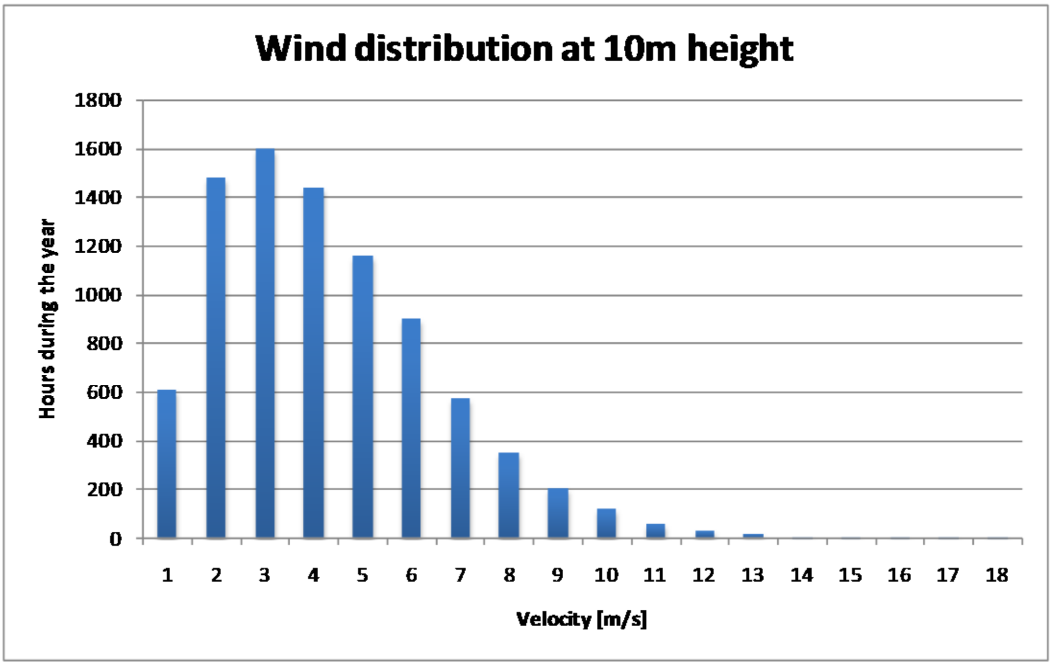


Figure 4.2 Wind distribution at 10m height for the area.

To get the data for further calculations of wind production a wind speed at heights of 30m and 50m was calculated using the equation:

Equation 4.1

$$v = \frac{v_{ref} \ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

where:

v – wind speed at height z above ground level

v_{ref} – reference speed

z – height above ground level for the desired velocity v

z_0 – roughness length in the current wind direction

z_{ref} – reference height

Assumed roughness for the area is 2, which represents: *agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of approx. 250 meters* (Troen, Petersen, 1991).

The figures below show the estimated distribution of the wind speed at heights of 30m, 50m and average wind speed in relation to height.

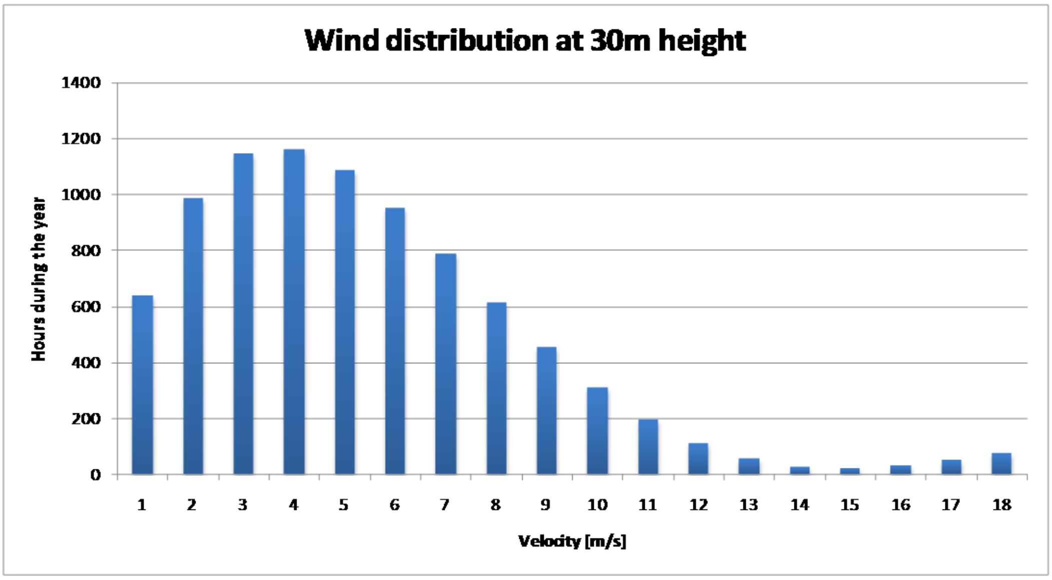


Figure 4.3 Wind distribution at 30m height for the area.

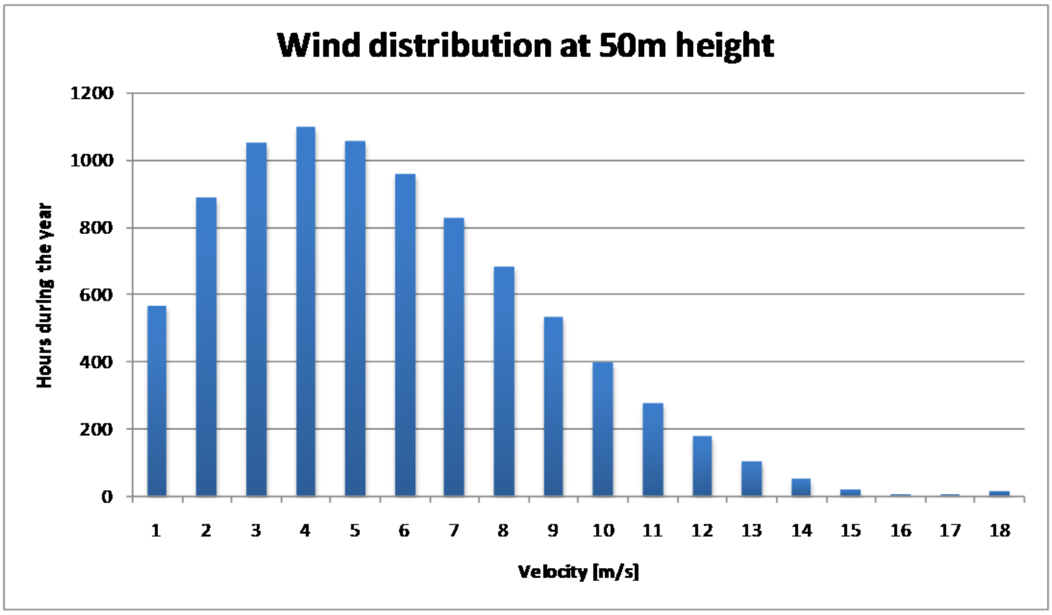


Figure 4.4 Wind distribution at 50m height for the area.

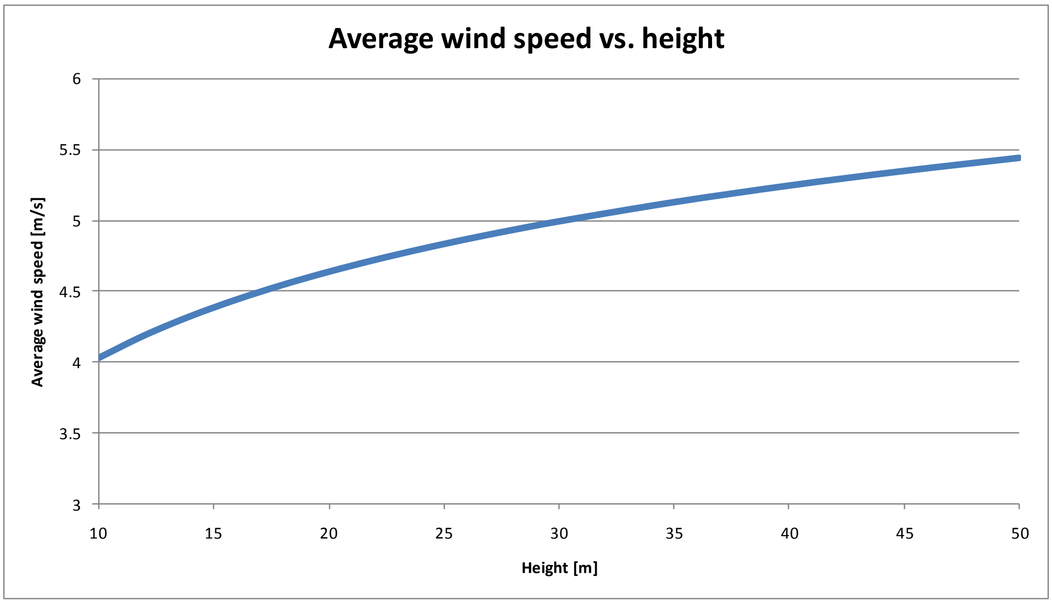


Figure 4.5 Average wind speed versus height for the area.

It should be mentioned that in the professional development of wind farms, data from the longer period should be achieved. Also, for predicting power production from the given wind resources, more specialized models should be used.

4.1.2 Solar energy resources

Solar resources are at the level of around 1 MWh per year per square meter (horizontal, global radiation) and the availability is 4700 hours in the investigated year, which is a promising result. The average radiation for the whole planet is around 1.36 MWh per year per square meter.

Using photovoltaic panels to harness the solar energy, the possible energy output is calculated using equation:

Equation 4.2

$$E = \eta \times P_{rad}$$

where:

η – efficiency of the photovoltaic panel (assumed 12%)

P_{rad} – value of the solar radiation during the year per one square meter

For the discussed area, energy output from the one square meter during the year is:

Equation 4.3

$$E = 12\% \times 928.15 \frac{kWh}{m^2 \times year} = 111.38 \frac{kWh}{m^2 \times year}$$

4.2 Information about the project

The reference system consists of 29 houses, each covering 150 square meters of area. four people live in each house. The table below gives basic data about the reference house and its consumption.

Table 4.1 Basic data about the reference system.

Factor	**Value**
Number of houses	29
Area of the single house	150 m^2
Heat demand of the house (assum. partial heating factor of 0.8)	70 $kWh/m^2 \bullet a$
Number of people in the house	4 (116 total)
Hot water usage	50 litres/person/day
Demand of electricity	4 000 kWh/a/house
Demand of heat (space heating and warm water)	12 000 kWh/a/house

Total energy demand for a single house per year is 16 000 kWh (electricity, heating and warm water) and for the whole settlement it is 464 000 kWh or 464 MWh.

All the figures concerning houses, grid, population, energy demand, etc. come from data concerning the year 2000 in Germany.

4.2.1 Daily energy demand by households

The energy demand of households follows the general power consumption characteristics of developed countries in Europe. The highest usage of electricity occurs in the evening between 18 and 22 hour, while the highest consumption of warm water occurs in the morning between 6 and 8 hour.

The following figure presents a typical yearly average load curve for a single house with marked maximum demand of electricity in the periods as stated. As the chart presents average values, these values will be used as a representation for the whole settlement (29 single houses).

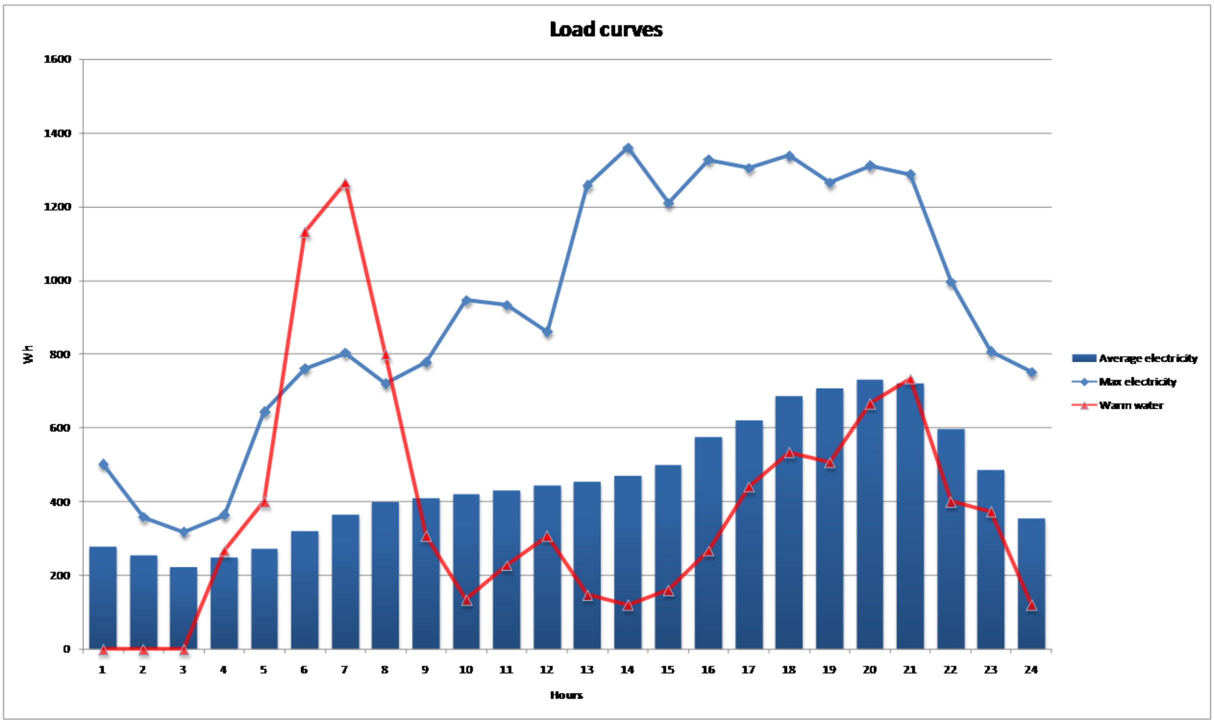


Figure 4.6 Typical daily load curves for electricity and warm water (Paatero, Lund, 2002).

The demand for space heating energy depends on the outside temperature. The system is designed for -12^{o}C at minimum, and the point when heating turns on or off is set at 15^{o}C. The figure below presents the hourly temperature values (coming from the meteorological office) and corresponding heating demand for the whole settlement.

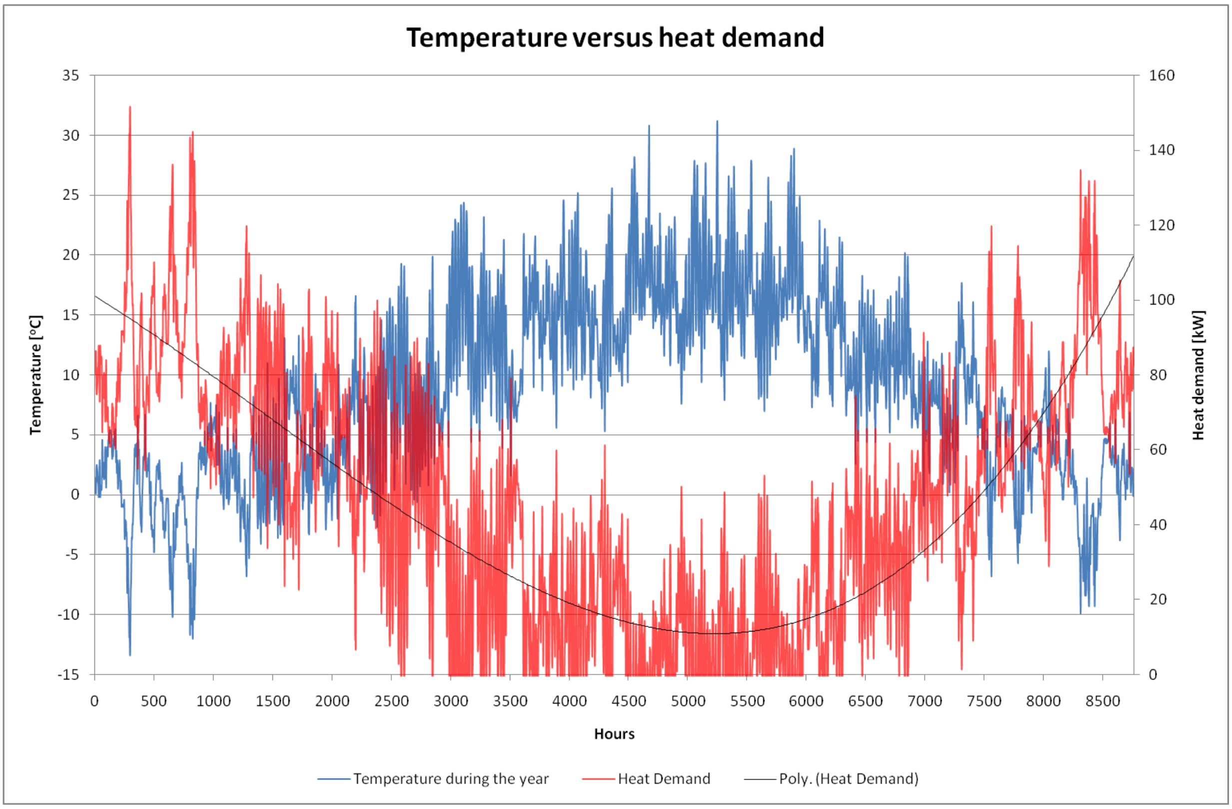


Figure 4.7 Temperature versus heating demand and trend line for heating demand.

4.3 Chosen alternatives

Not all of the options presented in chapter 3.5 are going to be calculated for their energy efficiency chain. The chosen alternatives represent either the basic energy flow schemes (like storage of electricity only in batteries) or complex solutions, which are usually applied in similar systems (cooperation between batteries, electrolyser and fuel cells). Cases chosen for further analysis are:

- reference system (section 3.5.1),
- distributed generation with PEFC in each house (section 3.5.2),
- biogas distribution network with SOFC in each house (section 3.5.5),
- renewable electricity with storage in the batteries (section 3.5.6),
- renewable electricity with storage in the batteries and distributed generation with a fuel cell in each house (section 3.5.8).

This distinction allows the comparison of efficiency chains as well as needs for storage units on different levels of complexity, including systems which exist only in theory.

4.3.1 Reference system

Power for the reference system (electricity and heat) is generated in a gas-fired combined heat and power unit with the life time of 15 years. This unit has a high efficiency of 80% (35% electrical and 45% thermal), however heat losses during distribution to the final users are so high that in some cases they can exceed heat consumption. This happens due to the fact that houses are so energy efficient that they do not need so much heat energy to maintain proper conditions inside. Therefore, hot water stays in the grid and transfers heat to the surrounding ground. That makes the system economically and environmentally not feasible.

The reference distribution grid has a length of 916 meters in total. The grid has a specific loss of 12W per meter and operates 8760 hours per year in order to supply hot water services.

The total loss of the heat in the grid is:

Equation 4.4

$$0.012\frac{kW}{m} \times 916m \times 8760h = 96\ 290\ kWh$$

Heat and warm water demand is 12 000 kWh per year per house, so total demand by the housing estate is:

Equation 4.5

$$12\ 000kWh \times 29 = 348\ 000kWh.$$

According to these values, losses in the grid correspond to 28% of the heat demand.

Using GEMIS software to calculate environmental impacts, it is obtained that the production of 1 kWh_{el} by the reference unit is responsible for the emission of 660 grams of CO_2, equivalent to the atmosphere.

GEMIS (Global Emission Model for Integrated Systems) is a life-cycle analysis program and database for energy, material, and transport systems. Calculations are performed using the lower heating value (LHV), and the parameter database for evaluating the environmental impact is provided by the manufacturer. The software takes into account the total life-cycle in its calculation of impacts - i.e. fuel delivery, materials used for construction, waste treatment, transports and auxiliaries. The heat losses of the heat distribution piping system are also included in the balance, in addition to all other energy used for extraction, preparation, refining, processing and transportation of fuels related to heat production.

The main unit used in these calculations is the carbon dioxide equivalent ($CO_{2\ eqiuv.}$). The CO_2 equivalent measures how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide as the reference (Wikipedia, term: *Carbon dioxide equivalent*).

4.3.2 Distributed generation with PEFC in each house

This alternative consists of renewable energy sources, electrolyser, storage unit, hydrogen distribution system and a 2 kW_{el} Proton Exchange Membrane fuel cell in each house (figure 3.13 and 3.14). The system does not have a battery or other kind of device for buffering energy fluctuations from wind/PV sources, which is very unlikely to happen in reality, but the idea is to show the energy efficiency of the basic energy flow, without disturbance from the storage system.

Two different wind turbines are proposed to provide enough power in two assumed cases (in the same alternative, the first assumption is that electricity in the PE fuel cell is generated with 26% of total efficiency and the second assumption is the cogeneration of heat and electricity in PE fuel cell with 52% of total efficiency, see chapter 6.1.2), with capacities of 850 kW and 330 kW. Wind turbines have an approximate life time of 30 years for moving parts and 50 years for the foundations and tower.

The 850 kW turbine could be the popular and common Vestas V52 model with a hub at 50m height and rotor diameter of 52m. The figure below presents the power curve of this product with cut-in wind speed of 4m/s and cut-off wind speed of 25m/s.

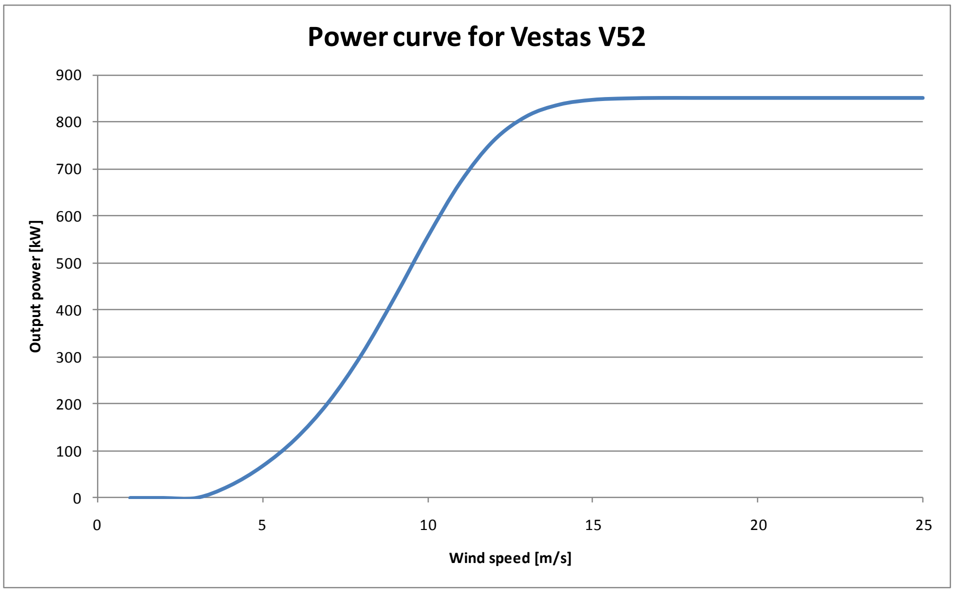


Figure 4.8 Power curve for Vestas V52 wind turbine.

The annual energy output of the turbine at the given wind distribution conditions is 1487 MWh, which is equivalent to 83% of the total yearly consumption by the settlement (see chapter 6.1.2).

The remaining energy demand will be acquired from the photovoltaic panels. With the calculated power output it will be necessary to install 2806 square meters of PV panels.

The capacity of the renewable energy sources is calculated to give, in the final balance (together with storage), a little bit higher than zero. However, there are periods of time when there is no wind or solar power, and energy must be taken from the storage unit. The longest period of given weather conditions in the analyzed year, with no energy supply from renewables is 250 hours, and the highest energy demand is 20 MWh. The storage unit (quantity of hydrogen stored) must supply energy for these periods.

For the second case a 330 kW turbine was chosen. This can be the Enercon E-33 turbine with its hub at 50m height and a rotor diameter of 33m. The figure below presents the power curve of this product with a cut-in wind speed of 3m/s and a cut-off wind speed of 25m/s.

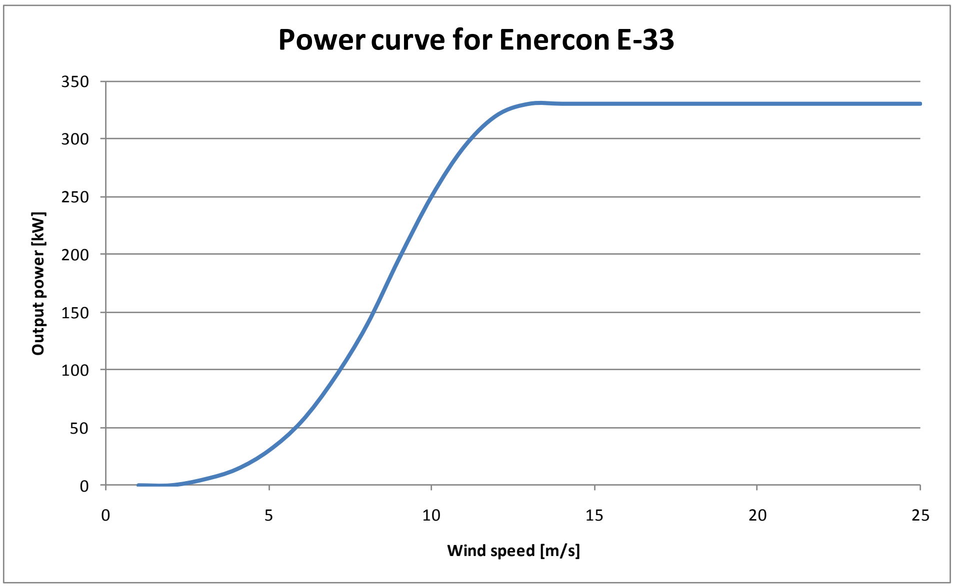


Figure 4.9 Power curve for Enercon E-33 wind turbine.

The annual energy output of the turbine at the given wind distribution conditions is 661 MWh, which is equivalent to 73% of the total yearly consumption by the settlement (see chapter 6.1.2).

The remaining energy demand will be acquired from the photovoltaic panels. With the calculated power output it will be necessary to install 2144 square meters of PV panels.

In this case the longest period with given weather conditions, with no energy supply from renewables is 283 hours and the highest energy demand is 22 MWh.

Connecting renewable energy sources

There are two options for connecting power from renewable energy sources. Electricity can be fed directly to the grid and the surplus power used to produce hydrogen. In this case, efficiency is very high because the main power chain consists of only a supplier – receiver with the electric grid between. On the other hand, this configuration requires big storage capacities, because every shortage in the power output from the renewable sources is noticed very quickly by the consumers.

Instead of connecting to the grid, a renewable energy source may be connected to an electrolyser to produce hydrogen, which then may be used in a variety of applications as discussed earlier. This system circumvents the problems related to the grid connection and generation imbalance charges.

Direct coupling of an electrolyser with a wind turbine implies intermittent operation with a highly variable power output. The problem, particularly with alkaline electrolysers, is that at very low loads the rate at which hydrogen and oxygen are produced (which is proportional to the current density) may be lower than the rate at which these gases permeate through the electrolyte and mix with each other. This may create hazardous conditions inside the electrolyser. Another problem related to operation with a highly variable power source is thermal management. The electrolyser takes time to reach its normal operating temperature, but due to intermittent operation it may operate most of the time at a temperature below nominal, which results in a lower efficiency (Sherif et al. 2005).

4.3.3 Biogas distribution network with SOFC in each house

This alternative is very different from the other cases, because it is the only one in which no electricity is generated. This process produces biogas, which is then used to generate electricity. There is no need to produce and store hydrogen, as energy already exists in the chemical bonds of methane.

This option is similar to the systems in which a fuel cell is fed by natural gas from the grid (like described project in Krefeld in chapter 3.2.2), but in this case methane from the produced biogas is used. Biogas is produced by anaerobic digestion of biomass, sewage, municipal waste, energy crops or similar materials. The main feature of biogas is the fact that carbon released during the reformation or combustion of biogas was previously absorbed and bonded by its source; therefore it is considered to be renewable and CO_2 neutral.

A solid oxide fuel cell (SOFC), due to its high operating temperature, can internally reform the fuel (methane) and use hydrogen to produce electricity. Because of the carbon content in the fuel, one of the products is also carbon dioxide. The combined efficiency of an internal reforming fuel cell does not differ much from one operating on pure hydrogen, and in this thesis it is assumed that both of the solid oxide fuel cells have the same efficiency (80%).

Storage and distribution of biogas is much easier than hydrogen. Methane has a higher volumetric energy density; therefore it is not necessary to compress it to high pressures (200 bars) like hydrogen. Moreover there are no problems with the embrittlement of steel due to hydrogen diffusion.

4.3.4 Renewable electricity with storage in batteries

This alternative assumes that all the energy used in the household is electricity and is stored in batteries. Households have electrical radiators as well as electrical boilers for preparing hot water. Batteries therefore have to be sized for serving these requests in case of a lack of energy delivery from the primary sources (wind, PV).

Batteries have excellent storage efficiency, exceeding 95%. The most common and best performing batteries are lithium-ion and metal-hydrate batteries. One of these types would be recommended to be used in the household. Although batteries are highly efficient, in order to store enough electricity, battery size must be enormous. This causes technical problems when connecting battery units and putting them to work. There are also safety issues to consider. If one of the battery units gets damaged and stops working, operation of the rest of the units may become unstable and potentially hazardous. To receive useful energy from the battery a DC/AC current converter with efficiency of 90% is also needed, which slightly decreases the total efficiency of the battery system.

Another issue concerning batteries is that their capacity decreases over time and with each charge and discharge cycle. Therefore, their lifetime dependability may be a serious problem, especially in residential applications where devices are expected to operate for many years. A short lifetime means that batteries will have to be replaced more often than other parts of the system, which significantly increases costs and the environmental impact. Also, the self-discharge will limit the long-term storage of electricity in batteries.

Because battery systems are highly efficient (81%, see chapter 6.1.4), the capacity of renewable energy sources was adjusted in order to avoid overproducing energy. To provide enough power, a 225 kW wind turbine is proposed. Turbine can be Vestas V29 model with hub at 31m height and rotor diameter of 29m. The figure below presents the power curve of this product with cut-in wind speed of 3.5m/s and cut-off wind speed of 25m/s.

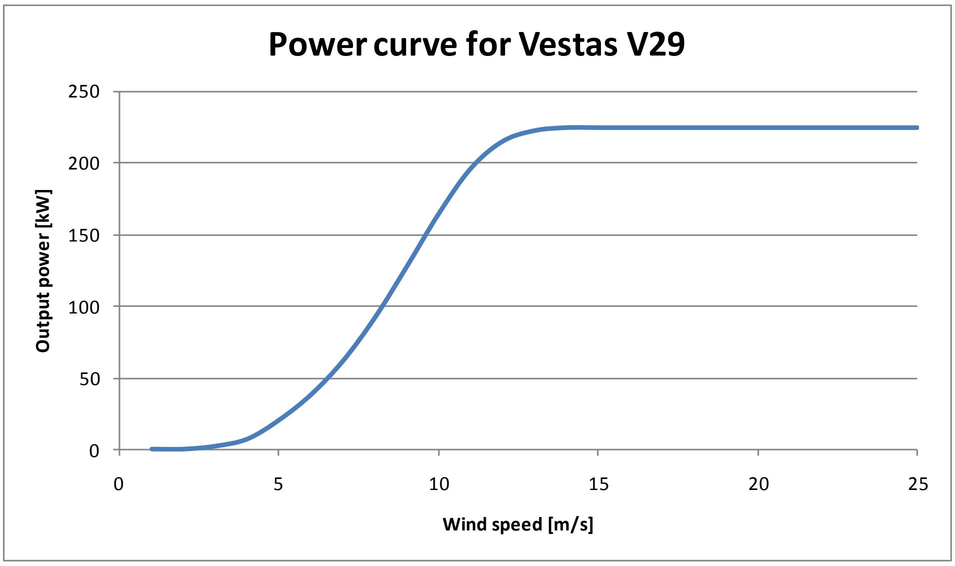


Figure 4.10 Power curve for Vestas V29 wind turbine.

The annual energy output of the turbine at the given wind distribution conditions is 365 MWh, which is equivalent to 64% of the total yearly consumption by the settlement (see chapter 6.1.4).

The remaining energy demand will be acquired from the photovoltaic panels. With the calculated power output it will be necessary to install 1843 square meters of PV panels.

Because of the wind turbine, which is now at a 30m height, the longest period with no energy supply from renewables increases (comparing to wind turbines at 50m height from the chapter 4.3.2) to 284 hours and the highest energy demand is 23 MWh. The battery storage will have to meet these requirements.

4.3.5 Renewable electricity with storage in batteries and distributed generation with fuel cell in each house

Most of the existing solutions in real projects are based on the cooperation between batteries, storage of energy in hydrogen, fuel cells and direct connection of electricity to the customers. This allows keeping the battery system to a practical size and optimized operation of the fuel cells in short periods of limited primary electricity.

Similar to the first alternative (section 4.3.2), the system may be very efficient in cases when most of the electricity goes directly to the customers, or less efficient when most of the electricity is used to produce hydrogen. Efficiency is therefore controlled by the size of the storage unit and the storage unit is sized by the energy demand and energy supply at a particular moment. To optimize the system, detailed information about energy demand by the household and statistical data about possible energy output from the renewable sources is needed.

In this case it is assumed that the battery and fuel cell system shares are equal. This means that the battery system is half the size of the system with only battery storage. And hydrogen production is smaller due to the contribution from the batteries. The presence of the batteries increases total efficiency to 66% (see chapter 6.1.5), compared to 52% in the fuel-cell-only system.

Due to higher efficiency, the installed capacity of the renewable energy sources was adjusted and it is proposed to build a 300 kW wind turbine. This wind turbine can be the Bonus 300/33.4 Mk III model with its hub at a 30m height and a rotor diameter of 33.4m. The figure below presents the power curve of this product with cut-in wind speed of 3m/s and cut-off wind speed of 25m/s.

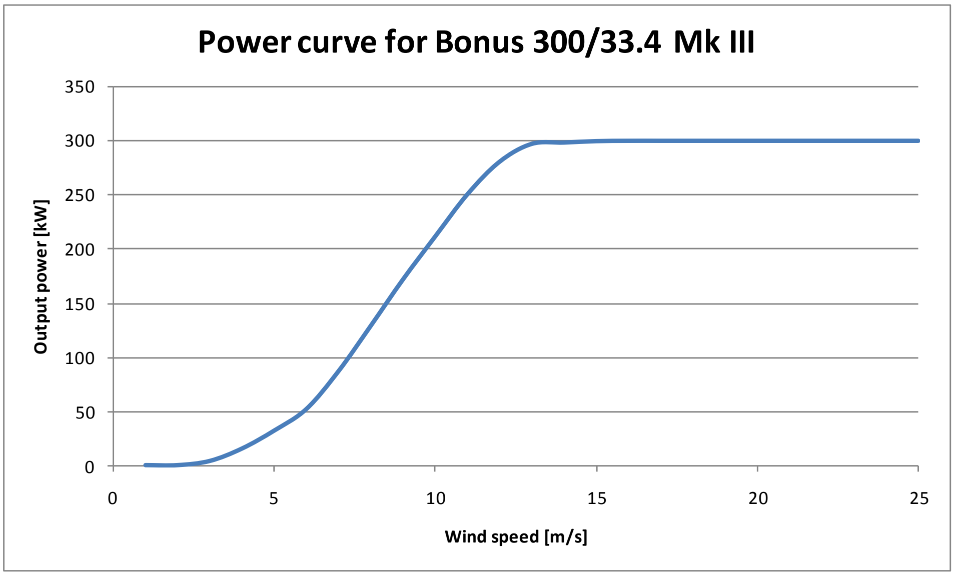


Figure 4.11 Power curve for Bonus 300/33.4 Mk III wind turbine.

The annual energy output of the turbine at the given wind distribution conditions is 503 MWh, which is equivalent to 72% of the total yearly consumption by the settlement (see chapter 6.1.5).

The remaining energy demand will be acquired from the photovoltaic panels. With the calculated power output it will be necessary to install 1776 square meters of PV panels.

In this case the longest period when energy has to be delivered from the storage unit is 284 hours and the highest energy demand is 22.3 MWh.

5 STORAGE SYSTEM CHARACTERISTICS

The described settlements are fully independent in the energy supply and not connected to the national grid or other kind of energy providing utilities. As households obtain their energy only from the local renewable energy sources, storage units have to be able to store enough energy in periods of limited energy delivery from renewables (up to even 300 hours). That makes the task of energy storage very challenging as well as interesting.

Below is a list of specified needs for the size of storage units, which are mostly dependent on the wind power production and assumed energy efficiency chain. Demand for storage was calculated using an Excel spreadsheet with hourly data referencing to wind and solar resources on the one side and energy demand for space heating and electricity on the other.

5.1.1 Distributed generation with PEFC in each house

The system is built up to the information given in sections 3.5.2 (Fig. 3.13 and 3.14) and 4.3.2. Each household will own a Proton Exchange Membrane fuel cell (PEFC) with a capacity of 2 kW_{el} and 500 W_{th} useful heat power.

The table below gives insights into basic hydrogen properties:

Table 5.1 Hydrogen properties.

Hydrogen energy data (LHV)	**Value**
Energy density - volumetric	3 kWh/Nm^3
Energy density - gravimetric	33.33 kWh/kg
Compressibility factor at 200 bars	1.132

The table below presents information about storage unit capacity assuming 52% total energy chain efficiency (combined heat and power operation):

Table 5.2 Storage unit properties.

Parameter	**Value**
Energy needed	22 000 kWh
Mass of stored H_2	660 kg
Volume of stored H_2	7333.3 Nm^3
Volume of stored H_2 at 200 bars	41.5 m^3

Typical energy demand by electrolyser is 4 to 5 kWh for 1 Nm^3 of hydrogen. With assumed demand of 5 kWh/1 Nm^3, a 300 kW electrolyser could produce 60 Nm^3 / hour. To fill the storage unit, working with a full load, the electrolyser would need 122 hours. Stored hydrogen should be sufficient for around 280 hours of continuous fuel cells operation.

The table below presents information about storage unit capacity assuming 26% total energy chain efficiency (the case with electricity production only, see section 4.3.2):

Table 5.3 Storage unit properties.

Parameter	**Value**
Energy needed	20 000 kWh
Mass of stored H_2	600 kg
Volume of stored H_2	6666.6 Nm^3
Volume of stored H_2 at 200 bars	37.7 m^3

Due to the higher capacity of renewable energy sources (850 kW wind turbine) it is possible to install a bigger electrolyser. A 500 kW unit should produce 100 Nm^3 / hour and to fill the storage unit, it would need 67 hours.

5.1.2 Biogas distribution network with SOFC in each house

The biogas plant is expected to produce constant quantities of biogas; therefore the proposed storage unit will serve as a buffer tank providing pressure leveling. The table below gives information about methane and biogas energy properties.

Table 5.4 Biogas properties.

Biogas energy data (LHV)	**Value**
Pure methane energy density - volumetric	9.97 kWh/m^3
Pure methane energy density - gravimetric	13.9 kWh/kg
Biogas (60% CH4) energy density - volumetric	5.98 kWh/m^3
Biogas (60% CH4) energy density - gravimetric	8.34 kWh/kg

Energy demand in this alternative is 696 MWh (total energy, including energy chain efficiency, see section 6.1.3), therefore the biogas plant has to be sized to meet this requirement. That means that the biogas plant should produce 116 388 cubic meters of biogas during the year.

Assuming constant operation of the biogas plant, all year long (8760 hours), a capacity of 80 kW should be sufficient to meet the energy demand.

5.1.3 Renewable electricity with storage in batteries

In this alternative each house owns a battery system. This battery could be a lithium battery Li-MnO_2. It is the most common consumer grade battery among lithium types, with about an 80% share in the market. It uses inexpensive materials and is suitable for low-drain, long life, low-cost applications. This battery can deliver high pulse currents and operates in a wide temperature range. Energy density is 280 Wh/kg gravimetric and 580 Wh/dm^3 volumetric (Wikipedia, term: *Lithium battery*).

For longest life, sealed maintenance-free batteries should not be discharged to greater than 50% of their total capacity rating. As a rule-of-thumb, assumed battery capacity is equal to the three-fold (3x) the highest energy demand during the year, which should assure a long life time of the system.

The table below gives information about the battery storage system properties:

Table 5.5 Battery system properties.

Factor	**Value**
Battery energy density – volumetric	580 Wh/dm^3
Battery energy density – gravimetric	280 Wh/kg
Energy needed	23 000 kWh
Energy needed per house	793 kWh
Volume of the battery system (3x) per house	4102 dm^3
Mass of the battery system (3x) per house	8500 kg

Calculated battery size should provide enough power for the household even for a period of 300 hours with no renewable energy production.

The figure below presents the size of storage systems in three cases:

- distributed generation with PEFC and 52% efficiency (combined heat and power operation, hydrogen compressed to 200 bars),
- distributed generation with PEFC and 26% efficiency (electricity production only, hydrogen compressed to 200 bars),
- renewable elctricity stored in the batteries.

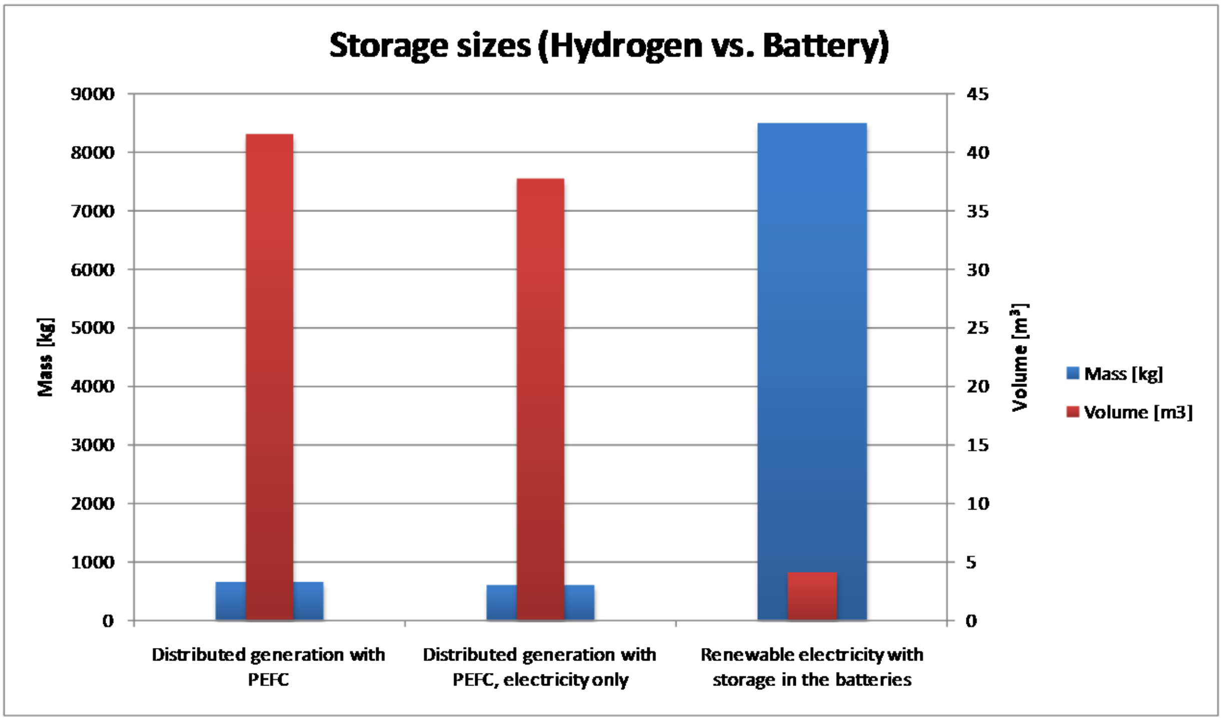


Figure 5.1 Sizes of storage systems in three cases.

It is clearly visible that the low volumetric energy density of hydrogen causes the need for very large storage in terms of volume, while the low gravimetric density of the battery causes the mass of the battery system to reach 8500 kg, compared to around 600 kg of hydrogen.

5.1.4 Renewable electricity with storage in batteries and distributed generation with fuel cell in each house

Cooperation between the fuel cell and batteries allows keeping quite high efficiency as well as downsizing the battery system. The presented three cases with different shares of energy delivery from batteries and hydrogen changes the requirements concerning storage unit sizes.

The tables below give information about the storage unit capacities depending on different share of batteries and hydrogen storage.

Table 5.6 Battery and hydrogen storage unit capacities (25% share of battery, 75% share of hydrogen).

Factor	**Value**
Energy needed	22 280 kWh
Volume of the battery system (3x) per house	993 dm^3
Mass of the battery system (3x) per house	2058 kg
Mass of stored H_2	501 kg
Volume of stored H_2	5570 Nm^3
Volume of stored H_2 at 200 bars	27.8 m^3

Table 5.7 Battery and hydrogen storage unit capacities (75% share of battery, 25% share of hydrogen).

Factor	**Value**
Energy needed	22 280 kWh
Volume of the battery system (3x) per house	2980 dm^3
Mass of the battery system (3x) per house	6173 kg
Mass of stored H_2	84 kg
Volume of stored H_2	928 Nm^3
Volume of stored H_2 at 200 bars	4.6 m^3

Table 5.8 Battery and hydrogen storage unit capacities (equal share).

Factor	**Value**
Energy needed	22 280 kWh
Volume of the battery system (3x) per house	1987 dm^3
Mass of the battery system (3x) per house	4115 kg
Mass of stored H_2	334 kg
Volume of stored H_2	3713 Nm^3
Volume of stored H_2 at 200 bars	21 m^3

In the last case a 160 kW electrolyser could produce 32 Nm^3 / hour. To fill the storage unit, working with a full load, the electrolyser would need 116 hours. The rest of the power from renewable sources can be directed to the battery for charging and directly for use in the households.

6 ENERGY EFFICIENCY CALCULATIONS AND LIFE CYCLE ASSESSMENT ANALYSIS

Energy efficiency calculations can give basic information about the amounts of energy needed as an input and possible environmental impacts related to the processes. Nevertheless, to get the full and comprehensive view of environmental impacts a proper life cycle assessment should be performed. Due to the time intended for the thesis as well as data availability this kind of analysis could not be carried out. However, a literature review concerning life cycle assessment will give insights into performed life cycle assessment studies and related environmental burdens.

6.1 Energy efficiency calculations

Energy efficiency calculations were performed as a product of the individual efficiencies of the devices and processes they represent. The assumed final outcome from the process chain was one energy unit (1 EU). One energy unit represents delivered energy to the final user. The final user is defined as a household consisting of four people, the building and electrical equipment within.

The calculations were performed upwards the process chain, therefore the result represents how many energy units are required as an input to get one energy unit for the final consumer. The equations below present formula used in calculating energy units.

Equation 6.1

$$Device\ efficiency_{(1)}\,[\%] \times Device\ efficiency_{(2)}\,[\%] \times Device\ efficiency_{(n)}\,[\%] = Total\ chain\ efficiency\ [\%]$$

Equation 6.2

$$Energy\ untis = \frac{1}{Total\ chain\ efficiency\ [\%]}$$

6.1.1 Reference system

The table below presents the energy efficiency chain for the reference system. Efficiency of the pipeline system comes from the section 4.3.1 and represents losses of heat in the grid. These values are relevant only when the CHP unit supplies warm water and heat for space heating. In warm periods when district heating is not used and the pipeline system distributes only warm water, the efficiency of the grid drops to 50%.

Table 6.1 Energy efficiency chain for reference system.

Device	Efficiency
CHP Unit	80%
Pipeline system	72%

Total	57.6%
Energy Units	**1.74**

The table below shows the energy efficiency chain in the reference system for the case when only electricity is produced (no heat production). This is unlikely to happen as there is constant demand for warm water, although this balance gives insights into basic energy efficiencies.

Table 6.2 Energy efficiency chain for reference system, electricity production only.

Device	Efficiency
CHP Unit electricity only	35%
Total	35%
Energy Units	**2.86**

6.1.2 Distributed generation with PEFC in each house

The specification below presents the energy efficiency chain for distributed generation with a proton exchange membrane fuel cell. In this case the PEFC operates in the cogeneration mode. Electricity to run the compressor comes directly from the renewable energy sources.

Table 6.3 Energy efficiency chain for PEFC.

Device	Efficiency
Electrolyser	65%
Compressor	90%
Storage unit	100%
Pipeline system	98%
Fuel Cell	90%
Total	52%
Energy Units	**1.94**

Using the result of the energy units to predict the capacity of the renewable sources, it is calculated:

Equation 6.3

$$RES\ energy\ output = Energy\ demand\ by\ settlement\ \times Energy\ Units$$

Equation 6.4

$$RES\ energy\ output = 464\ MWh \times 1.94 = 900\ MWh$$

assuming the above case in the capacity calculation should guarantee enough energy supply with 52% of total energy chain efficiency.

The following table shows the same scheme as the one above, but in this case the PEFC produces only electricity (no useful heat production). Electricity to run the compressor comes directly from the renewable energy sources.

Table 6.4 Energy efficiency chain for PEFC, electricity production only.

Device	**Efficiency**
Electrolyser	65%
Compressor	90%
Storage unit	100%
Pipieline system	98%
Fuel Cell electricity only	45%
Total	26%
Energy Units	**3.88**

Using the outcome of energy units to predict the capacity of the renewable sources, it is calculated:

Equation 6.5

$$RES\ energy\ output = 464\ MWh \times 3.88 = 1800\ MWh$$

Assuming the above (worst) case in the capacity calculation, this layout should guarantee enough energy supply, even with 26% of total energy chain efficiency.

6.1.3 Biogas distribution network with SOFC in each house

In this case, a biogas plant serves as a source of fuel for further utilization and is not a process itself; therefore it has 100% efficiency. The solid oxide fuel cell, due to internal reforming, has a different combined efficiency than a PEM fuel cell running on pure hydrogen.

Table 6.5 Energy efficiency chain for biogas distribution network and SOFC.

Device	**Efficiency**
Biogas plant	100%
Compressor	85%
Storage unit	100%
Pipeline system	98%
Fuel Cell with internal reformer	80%
Total	67%
Energy Units	**1.50**

Using the outcome of energy units to predict capacity of the biogas plant, it is calculated:

Equation 6.6

$$Biogas\ plant\ energy\ output = 464\ MWh \times 1.5 = 696\ MWh$$

with which rating the system should guarantee enough energy supply from the biogas plant.

The table below presents the same energy efficiency chain as above, but with the fuel cell producing only electricity

Table 6.6 Energy efficiency chain for biogas distribution network and SOFC, electricity production only.

Device	**Efficiency**
Biogas plant	100%
Compressor	85%
Storage unit	100%
Pipeline system	98%
Fuel Cell electricity only	55%
Total	46%
Energy Units	**2.18**

Using the outcome of the energy units to predict the capacity of the biogas plant, it is calculated:

Equation 6.7

$$Biogas\ plant\ energy\ output = 464\ MWh \times 2.18 = 1011.52\ MWh$$

6.1.4 Renewable electricity with storage in batteries

The specification below presents a short energy efficiency chain for battery the system, consisting of two devices.

Table 6.7 Energy efficiency chain for batteries.

Device	**Efficiency**
Battery	90%
DC/AC Converter	90%
Total	81%
Energy Units	**1.23**

Using the outcome of the energy units calculation to predict the capacity of the renewable sources, it is calculated:

Equation 6.8

$$RES\ energy\ output = 464\ MWh \times 1.23 = 570.72\ MWh$$

assuming the above case in the capacity calculation should guarantee enough energy supply with 81% of total energy chain efficiency.

6.1.5 Renewable electricity with storage in batteries and distributed generation with a fuel cell in each house

The table below shows the energy efficiency chain for the complex storage of electricity in batteries as well as hydrogen production, distribution and utilization in fuel cells. Efficiency of the fuel cell system comes from the section 6.1.2. It is assumed that the battery system and fuel cell system have the same share (50%) in power delivery in case of lack of supply from the primary energy source (renewable sources).

Table 6.8 Energy efficiency chain for batteries and fuel cell.

Device	Efficiency
Battery	81%
Fuel Cell system	52%
Average efficiency (50 - 50)	66%
Energy Units	**1.51**

Using the result of the energy units calculation to predict the capacity of the renewable sources, it is calculated:

Equation 6.9

$$RES\ energy\ output = 464\ MWh \times 1.51 = 701\ MWh$$

assuming the above case in the capacity calculation should guarantee enough energy supply, with 66% of total energy chain efficiency.

The following table shows the same energy efficiency chain as the one above but with the fuel cell generating only electricity. The share of power delivery is assumed to be equal between batteries and fuel cell.

Table 6.9 Energy efficiency chain for batteries and fuel cell, electricity production only.

Device	Efficiency
Battery	81%
Fuel Cell system electricity only	26%
Average efficiency (50 - 50)	53%
Energy Units	**1.87**

Using the result of the energy units calculation to predict the capacity of the renewable sources, it is calculated:

Equation 6.10

$$RES\ energy\ output = 464\ MWh \times 1.87 = 867.68\ MWh$$

6.1.6 Comparison of energy efficiency chains

The table and figure below present an overview of energy unit requirements in the discussed and presented alternatives.

Table 6.10 Overview of energy efficiency chains.

System setup	Energy Units
Reference system	1.74
Reference system, electricity only	2.86
Distributed generation with PEM fuel cell	1.94
Distributed generation with PEM fuel cell, electricity only	3.88
Biogas distribution network with SOFC	1.5
Biogas distribution network with SOFC, electricity only	2.18
Renewable electricity with storage in the batteries	1.23
Storage in batteries and DG with fuel cells	1.51
Storage in batteries and DG with fuel cells, electricity only	1.87

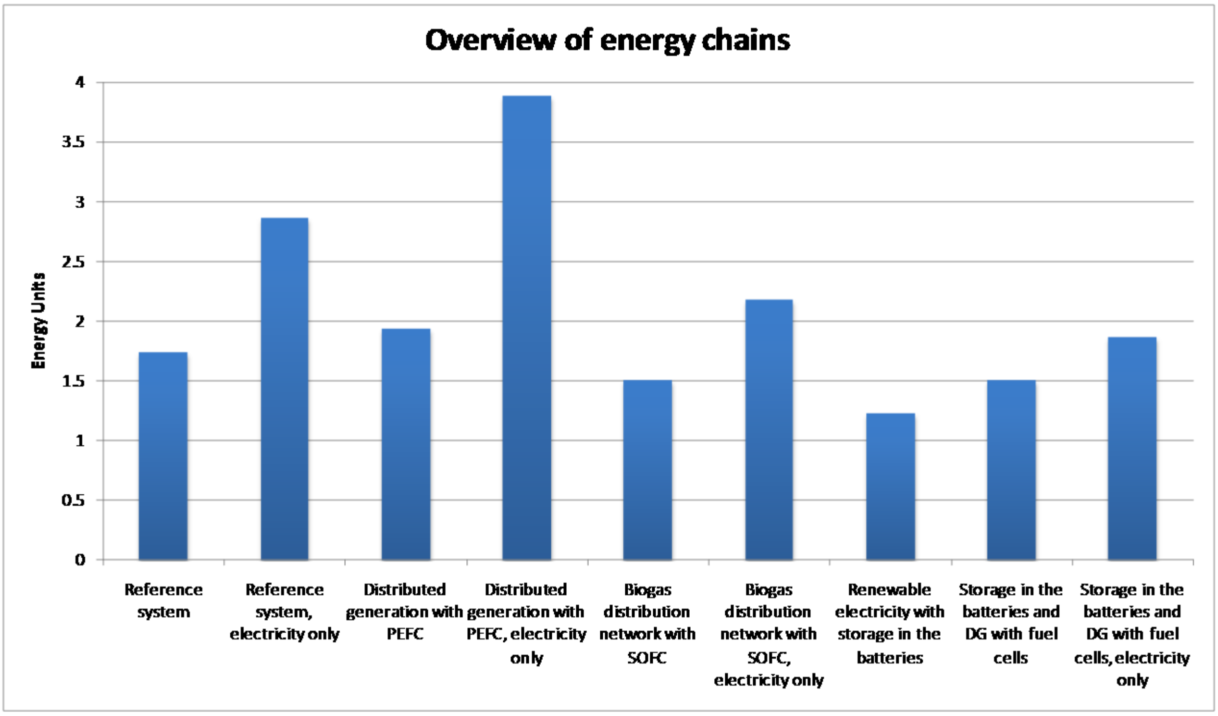


Figure 6.1 Overview of energy efficiency chains.

It is clearly visible that the highest efficiency lies with the battery system with only 1.23 energy units needed as input to receive 1 energy unit at the final consumer.

What is interesting, is the fact that generating electricity with classic burning of fossil fuels in gas turbine is more efficient (2.86 EU) than generating electricity in a fuel cell (3.88 EU) with use of hydrogen. This means that solutions for residential applications using fuel cell systems should always be considered in terms of combined heat and power operation.

Satisfactory outcomes were obtained for the biogas distribution network with the solid-oxide internal-reforming fuel cell. In combined operation this system setup requires 1.5 energy units as an input, which is a very promising result. This is mostly due to the lack of an electrolyser, which is in fact the weakest link in the process of producing and utilizing hydrogen.

Common operation of fuel cell and battery gives very good results. In this case the efficiency is dependent on the balance of these two devices. For example, sizing down the battery system to 25% and increasing the energy stored as hydrogen to 75% causes a decrease of the total chain efficiency to 59% (from 66%) and increases the number of energy units to 1.69 (from 1.51).

6.2 Life cycle assessment of future energy systems

Assessing future energy systems is important for providing information for decision makers, especially in the case of fuel cells, which are often portrayed as attractive options for power plants and automotive applications. The production of fuel cell stacks leads to environmental impacts which cannot be neglected, therefore the assessment of fuel cells as environmentally friendly energy conversion systems must consider the production, operation and disposal of the systems compared to conventional competitors (Pehnt, 2003).

Examining the resource consumption, energy requirements and emissions from a life cycle point of view gives a complete picture of the environmental burdens associated with the use of devices and the related processes. Life Cycle Assessment (LCA) is a systematic analytical method that helps identify and evaluate the environmental impacts of a specified process and its competing alternatives (Spath, Mann, 2004). The main unit used in LCA is the carbon dioxide equivalent.

Below, a literature review of different energy system components gives insight into performed LCA studies and their outcomes.

6.2.1 Wind turbines

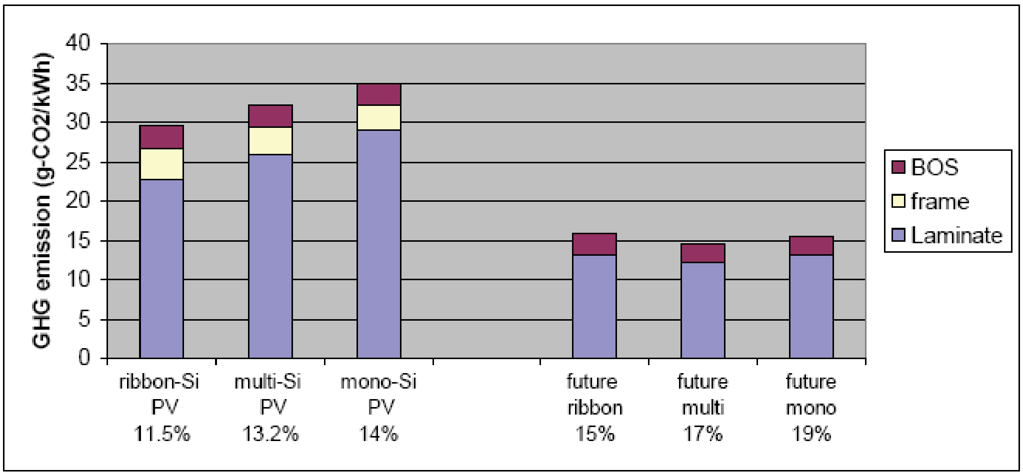
Wind power consumes no fuel for continuing operation, and has no emissions directly related to electricity production. Operation of wind turbines does not produce carbon dioxide, sulphur dioxide, mercury, particulates, or any other type of air pollution, as do fossil fuel power sources; however, leaking lubricating oil or hydraulic fluid running down turbine blades may be scattered over the surrounding area, in some cases contaminating drinking water sources. Wind power plants consume resources in manufacturing and construction. During the manufacturing process of the wind turbine, steel, concrete, aluminium and other materials will have to be made and transported using energy-intensive processes, generally using fossil energy sources (Wikipedia, term: *Environmental effects of wind power*).

According to a report by Jungbluth (Jungbluth et al, 2004), the absolute values of CO_2 equivalent emissions are about 11 g/kWh_{el} for an onshore turbine, which is a very low value. Only electricity coming from nuclear power plants has a similar CO_2 equivalent, but there are many waste disposal issues concerning nuclear plants. The highest burden for the environment is presented by the foundation and tower construction. The foundation is responsible for 55% of the greenhouse gas emissions, mostly due to the use of cement, the production of which is highly energy consuming (Hassing, Varming, 2001).

6.2.2 Photovoltaic panels

Unlike fossil fuel based technologies, solar power does not lead to any harmful emissions during operation, but the production of the panels leads to some amount of pollution. According to a report by Alsema (Alsema et al, 2006), PV systems have life cycle greenhouse gas emissions in the range of 25 to 35 g/kWh$_{el}$.

The figure 6.1 presents greenhouse gas emissions from present and future PV systems.



**BOS – Balance of System*

Figure 6.2 Greenhouse gas emissions of present and future silicon PV systems (Alsema et al, 2006).

One issue that has raised concerns is the use of cadmium in a few types of PV panels. Cadmium in its metallic form is a toxic substance that has the tendency to accumulate in food chains. Current PV technologies lead to cadmium emissions of 0.3 – 0.9 µg/kWh over the whole life-cycle (from coal it is 3.1 µg/kWh and from natural gas it is 0.2 µg /kWh). Most of these emissions arise through the use of coal power for the manufacturing of the modules (Alsema et al, 2006).

6.2.3 Hydrogen production

Although hydrogen is generally considered to be a clean fuel, it is important to recognize that its production may have negative impacts on the environment. The system of producing hydrogen studied here consists of wind turbines, transmission lines, electrolysers, compression and storage units.

According to a report prepared by the National Renewable Energy Laboratory, NREL (Spath, Mann, 2004), wind turbine production and operation is responsible for 78% of the net greenhouse gas emissions. Electrolysis production and operation is responsible for 4.4% of the net greenhouse gas emissions, and hydrogen compression and storage is responsible for 17.6% of the net greenhouse gas emissions during the production of hydrogen. In terms of other air emissions (like particulates or sulfur oxides) the majority come from the process steps in manufacturing the wind turbines as well.

What is more, there are almost no emissions as a result of plant operation; therefore the longer the operation, the higher the environmental performance can be expected from this kind of systems.

6.2.4 Proton exchange membrane fuel cells

Environmental impacts (greenhouse gas emissions, wastes production, etc.) associated with the production of proton exchange membrane fuel cells are mainly caused by the platinum group metals (PGM) for the catalyst, gas diffusion electrode (GDE), the materials and the energy for the flow field plates.

The most important materials assembled are (Pehnt, 2001):

- Platinum group metals (PGM)
  Mining of PGM results in significant environmental impacts, particularly because of SO_2 emissions along the production chain.
- Graphite
  Two production paths of graphite can be distinguished: natural graphite and manufactured graphite (produced typically from coke and coal tar). Both processes consume significant amounts of energy.
- Membrane
  The membrane from an ecological point of view is not very relevant because of the low energy consumption and the closed-loop production process.

Figure 6.2 shows the results for an automotive fuel cell stack. The "Bottleneck" components responsible for most impacts are the gas diffusion electrode and the flow field plate. The GDE is responsible for 74% of the total acidification and more than half of the global warming gas emissions. The flow field plate is the second most harmful component because of high electricity input for resin impregnation of the plate (17% of the electricity consumption and 13% of the global warming potential)

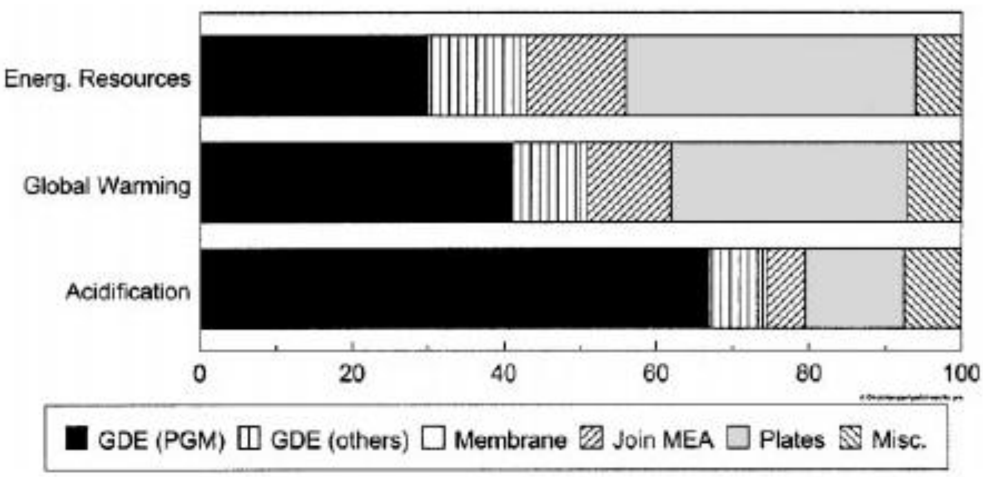


Figure 6.3 Contribution of the stack components (mobile stack, small recycling and renewable share) to selected environmental impacts (Pehnt, 2001).

The stationary stack results in impacts multiplied by a factor of 2 to 5. This is mainly due to the higher PGM loading, the higher input of graphite and the lower power density at lower current densities. Environmental impacts of stationary fuel cell stacks are higher than those of mobile stacks, but on the other hand they are evened out by the higher lifetime expectancy and the higher potential to recycle part of the stack. The situation changes when PGM is recycled. Assuming PGM recycling of 90%, production of the total system contributes to less than 8% of life-cycle emissions. Therefore, in stationary systems, the impacts of stack production are of much less relative importance than in mobile systems.

There are few issues that can be improved for the further development of fuel cells. Reduction of impacts by the use of Platinum Group Metals has the highest importance. An efficient recycling process is necessary for economic and ecological reasons. Recycling the catalyst can reduce the environmental impacts for PGM production by a factor of 20 (primary energy demand) to 100 (SO_2 emissions), assuming recycling of 75% for mobile stacks and 90% for the stationary stacks.

For the long-term improvements, the elimination of some components and their integration into the stack (like air compressors) is proposed. Recycling of components (like flow plates) is also very important.

6.2.5 Solid oxide fuel cells

Manufacturing of solid oxide fuel cells sometimes involves a number of rare materials and compounds the mining of which may be a great burden for the environment. On the other hand the operation of a SOFC leads to minimal direct emissions due to relatively low (compared to combustion engines or turbines) operating temperatures (for thermal NO_x emissions) and gas cleanup requirements (the required SO_2 removal) (Pehnt, 2000).

Figure 6.3 presents Global Warming Potential in CO_2 equivalent for one kilowatt hour of electricity from different power sources.

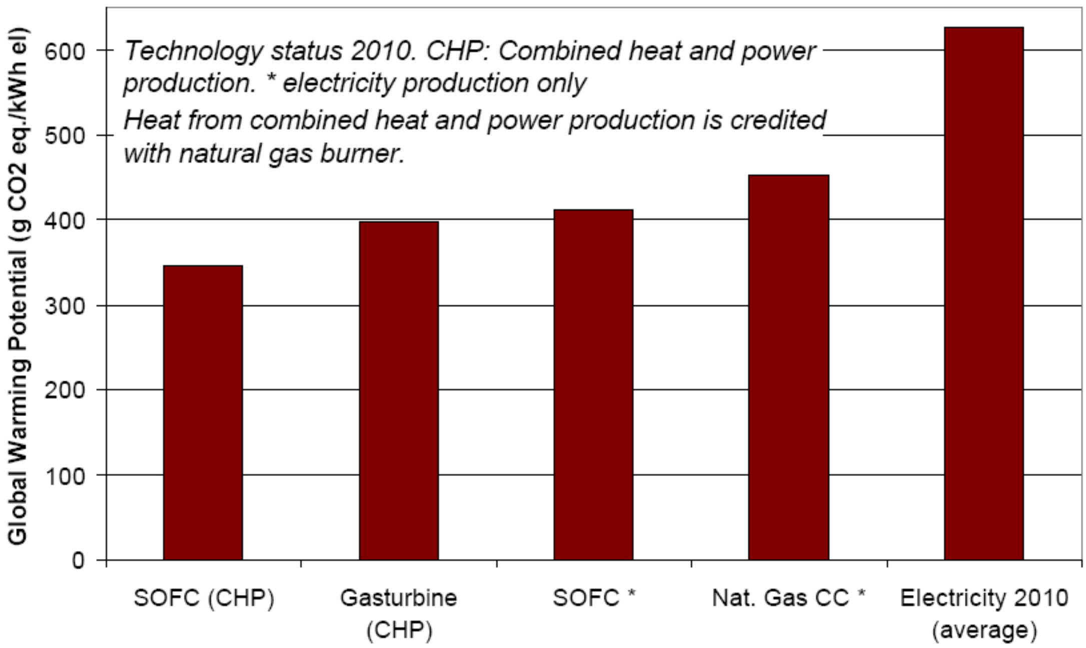


Figure 6.4 Global warming potential for different power sources (Pehnt, 2000).

In terms of global warming potential, an SOFC in cogeneration is 12% more efficient than a gas turbine and 47% more efficient than the future projected German electricity mix. However, there is a strong competition in new gas turbines and combined cycles (CC) power plants.

Due to stainless steel used in the manufacturing of solid oxide fuel cells the potential impact of greenhouse gas emissions may be quite high.

The use of biofuels in fuel cells combines the low direct emissions with extremely low resource consumption and greenhouse gas emissions. Figure 6.4 presents environmental impacts (in 10^{-3} person equivalents per kWh_{el}) from SOFC using synthesis gas from wood gasification, a gas turbine using the same gas (in 2010) and the German electricity mix. Data were normalized to person equivalents by dividing the impacts by the average daily per capita impact in Germany.

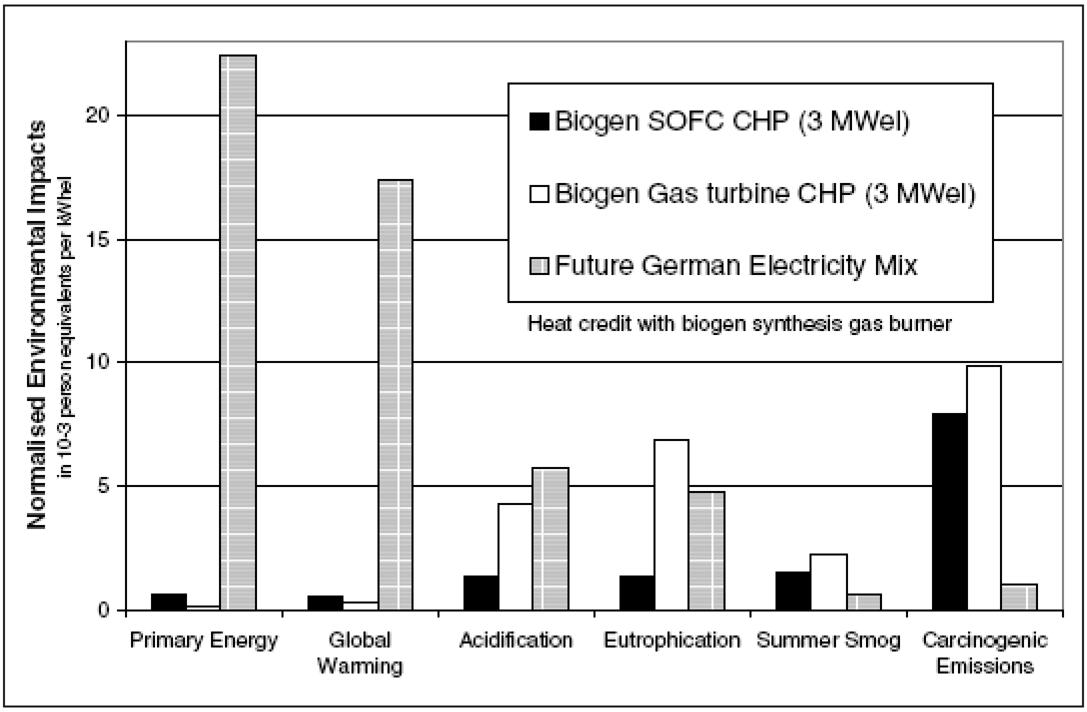


Figure 6.5 Normalised environmental impacts of different electricity generating systems converting synthesis gas from gasified wood (Pehnt, 2003).

The primary energy demand and the greenhouse gas emissions can be drastically reduced by both the SOFC and the gas turbine. The advantages of the fuel cell when coupled with biogenous fuels are, on the one hand, the more efficient use of biomass and, on the other hand, avoiding an increased emission level, which is typical for many other biomass based energy converting systems (Pehnt, 2003).

7 CONLUSIONS

The alternatives for providing electricity and heating energy to settlements presented in the thesis may become reality in the near future. Increasing the share of renewables as well as progressing building insulation standards will force engineers to look for new solutions in the field of heat distribution.

In the discussed options, the biggest problem was energy storage for the periods of limited energy delivery from the renewable sources. Because the idea was to keep the households completely separated from the national grid or any other kind of energy providing utilities, the amount of energy that has to be accumulated is very high, immediately leading to large storage units. The best example is the battery system, which has to take around four cubic meters of space and weighs eight and a half tons. The easiest solution for this problem is to decrease the time periods of shortage in the primary renewable energy supply. This can be done by connecting the settlement to grids operating in a larger area. More varied energy sources (particularly more wind turbines in different locations) cause higher security of energy supply. In the future, international, long distance connections of grids with renewable electricity should work the same way as present grids with fossil-fuel based electricity, which should considerably increase the security of green energy supply and allow smaller storage units.

In terms of energy efficiency and environmental impacts, the alternative with biogas reformed in solid oxide fuel cells seems to have the least environmental footprint. Good performance of the fuel cell (especially in terms of electricity generation) along with biogas from renewable sources causes a minimal burden to the environment. In the case of local emissions and related impact categories, fuel cell power plants in all stationary applications allow considerable reductions compared to separate electricity and heat production, as well as compared to competing CHP systems. Fuel cells promise energy converters for portable, mobile, stationary applications. Depending on the fuel cell technology, the application area, the input fuel etc., mainly environmental advantages can be expected. In the operation of the proton exchange membrane fuel cell, the bottleneck process is the production of hydrogen. Hopefully, in the future, efficiency improvements are expected for electrolysers, PEFCs and SOFCs as well. Less demand for platinum in PEFCs, advancing technology in SOFCs and higher hydrogen production rates in electrolysers will improve efficiencies of energy systems.

The next important issue is the promotion of cogeneration. Combined operation of power plants (whether standard heat engine or fuel cell) always brings advantages in energy efficiency and fuel utilization. Especially in a proton exchange membrane fuel cell, capturing the excess heat significantly increases the total efficiency, therefore the use of PEFC in residential applications should always be considered for combined operation.

Considering the most likely alternative to be applied, two options seem to be closest to deployment. As in the described project in Krefeld, it would be necessary only to switch from natural gas to biogas as input fuel. If further development would bring significant fuel cell cost decreases, then it would be possible to put a fuel cell in every house and avoid heat distribution losses. The second best solution is renewable electricity supply and storage of surplus energy in a hybrid system of batteries, hydrogen and proton exchange membrane fuel cells. The latest report on a hydrogen mini-grid system in Yorkshire, UK (mentioned in section 3.2.2) reveals technical details of the project (Environmental Energy Technology Center, 2009). The installed wind turbine is a Vestas V29, the same as proposed in the alternative described in section 4.3.4 and the remaining arrangement of the system is very similar to the options described in the thesis. The authors of the project claim that the energy store will be the largest store of green hydrogen anywhere in Europe (200 kg at 350 bars).

In terms of life cycle assessment, only a comprehensive study would give clear answers about greenhouse gas emissions and resources consumed. The idea of the thesis was to perform an LCA of alternatives, however lack of data and time made it impossible to perform this task. Another interesting subject would be an economical study of the energy chains. Undoubtedly, the presented solutions, which use emerging technologies, are still too expensive. Nevertheless, carrying out sensitivity analyses and assuming cost learning curves through mass production may give interesting results.

In summary, the thesis showed that energy distribution by electricity and gases will be more efficient than heat distribution and with the use of distributed generation it is possible to completely avoid losses during heat delivery. Households can be supplied with 100 percent renewable energy, and although there are some technical issues (especially in terms of energy storage), the possibilities exist and it should be expected that soon the inhabitants of residential areas will be the first proud users of fully renewable energy supply.

8 SUMMARY

The thesis presents a general overview of concepts that can replace traditional district heating and power generation. The first three chapters present an up-to-date overview of concepts of district heating, efficiency standards of buildings and statistics of renewable energy resources in Germany and the European Union.

The thesis can be a start-up review for following research, especially in the field of life cycle assessment. Performing LCA of the proposed alternatives along with an economical study would give the full and comprehensive picture of future energy systems. I personally hope that in the next year at RES, the Fuel Cell Systems and Hydrogen specialization will have a student who will undertake this interesting task.

For myself, by the considerable literature analysis about wind energy systems I am very satisfied with the information I obtained in this field. I believe that what I have learned during preparation of the thesis will certainly be useful in my future work.

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