COMBINED SOLAR AND PELLET HEATING SYSTEMS

STUDY OF ENERGY USE AND CO-EMISSIONS

Frank Fiedler

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COMBINED SOLAR AND PELLET HEATING SYSTEMS
STUDY OF ENERGY USE AND CO-EMISSIONS

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Abstract

In this study 4 solar and pellet heating systems have been studied with the help of annual dynamic simulations. Two of the systems comprised a pellet stove and two systems were solar combisystems; one with a store integrated pellet burner, the other with a separate pellet boiler.

The aim was to evaluate their thermal performance and their CO-emissions. The systems have been modelled based on lab measurements of the single system components. The used models allow a detailed study of the dynamic behaviour of the systems.

The stove systems have the least primary energy consumption provided the auxiliary electricity is taken into account with a conversion factor of 100%. If the auxiliary electricity is taken into account with a conversion of 40% and/or the systems are placed in the heated area the combisystems need less or a similar amount of primary energy.

Modulating combustion power reduces the number of starts and stops and for most pellet units this reduces the total CO emissions. The obtained annual CO emissions are higher than the values obtained from the standard test methods. It was shown that the average emissions under realistic annual conditions were greater than the limit values of two Eco-labels.

The system performance can be significantly improved by a proper control of the pellet heater and by sizing the pellet heater according to the size of the peak space heating demand.

Based on these findings from the simulations two prototypes of a combined solar and pellet heating system has been designed, built and tested; one for the lab and one that has been installed in a demonstration house. The system is very compact and is suitable for detached houses with no heating room or little space for a heating room.

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ABSTRACT

Due to rising energy prices for fossil fuels and electricity the demand for alternative solutions of heating systems for detached houses is increasing. Combined solar and pellet heating systems are an environmentally friendly alternative offering reliable heating for low energy costs in future.

In this study 4 systems, representing the range of typical solutions of this system type, have been studied with the help of annual dynamic simulations. The aim was to evaluate their thermal performance, their CO-emissions and their suitability for installation in houses with limited space for heating systems. The systems have been modelled in the dynamic simulation program TRNSYS based on lab measurements of the single system components. The used models allow a detailed study of the dynamic behaviour of the systems. This is especially important for the pellet heaters whose thermal performance and CO-emission are strongly dependent on their start and stop characteristics. Two of the systems comprised a pellet stove, which provides the heat for space heating, and a separate solar hot water system. One stove was an air heating stove, the other one was water mantled, which supplies the heat to the building via a radiator system. The other two systems were solar combisystems, one with a store integrated pellet burner, the other with a separate pellet boiler.

The stove systems have the least primary energy consumption provided the auxiliary electricity is taken into account with an conversion factor of 100% and the boilers and store are not placed in the heated area. If the auxiliary electricity is taken into account with a conversion of 40% and/or the systems are placed in the heated area, so that the heat losses can contribute to the space heating, the combisystems need less or a similar amount of primary energy.

The CO-emissions of the systems depend strongly on the characteristics of the specific pellet unit, the control of the pellet unit and the number of starts and stops. The latter is strongly dependent on how the heat from the pellet unit is transferred to the building. Modulating combustion power reduces the number of starts and stops and prolongs the operation time. For most pellet units the reduced number of starts and stops reduces the CO-emissions. The obtained annual CO-emissions represent the dynamic behaviour of the pellet heater under realistic conditions. These values are higher than the values obtained from the standard test methods. It was shown that the average emissions under these realistic annual conditions were greater than the limit values of two Eco-labels.

There is a large potential for system improvements. A proper control of the pellet heater can reduce the CO-emissions but also reduce the primary energy consumption. The heat losses can be dramatically reduced if the pellet heater is dimensioned according to the size of the peak space heating load. An optimisation of the main design parameters of the pellet heater and the heat store can give significant improvements in terms of CO-
emissions and primary energy use. The studied systems are suitable for the Nordic market but only partly suitable for houses without boiler room.

Based on these findings a combined solar and pellet heating system has been designed, built and tested. The system is very compact and is suitable for detached houses with no heating room or little space for a heating room. The flexible system concept allows using different types of boilers and size of the solar system. A prototype of the system with an integrated pellet boiler has been tested and improved during comprehensive lab measurements. It has been shown that it is possible to build a 60x60x200 cm unit including the pellet boiler, the standby store, the hot water and space heating preparation and the module for the solar collector loop. A second prototype with an external water mantled pellet stove has been installed in a detached house in Borlänge and is in operation since July 2006. The results from the monitoring will be used to evaluate the system performance and to obtain information about the system behaviour under real conditions.
SVENSK SAMMANFATTNING

På grund av stigande energipriser för fossila bränslen och el ökar också efterfrågan på alternativa värmesystem för villor. Kombisystem, dvs. värmesystem som kombinerar solvärme och pelletseldning, är ett miljövänligt alternativ som erbjuder pålitlig uppvärmning med låga energikostnader i framtiden.


Kaminsystemen har den lägsta primärenergiförbrukningen under förutsättning att den tillsatta elenergin (tillsattsvärme från elpatronen) räknas med en omvandlingsfaktor (verkningsgrad) på 100 % och att pannorna och ackumulatortanken är placerade utanför det uppvärmda utrymmet (dvs. värmeförlusterna från panna och tank kommer inte huset tillgodos). Om man räknar med primärenergi med en omvandlingsfaktor 40 % för systemets elanvändning så behöver kombisystemen mindre eller lika mycket tillsatt energi. Det samma gäller om pannorna och ackumulatortanken placeras i det uppvärmda utrymmet så att deras värmeförluster kan tillgodoräknas i uppvärmningen.


Det finns stort potential för förbättringar av systemen. Riktig styrning av eldningsutrustning kan minska CO-utsläppen och minskar samtidigt primärenergi-

Med utgångspunkt från resultat från tidigare forskning och resultaten från denna studie har ett system som kombinerar pellet- och solvärme konstruerats, byggs och testats. Systemet är kompakt och avsett för villor utan eller med begränsat utrymme för pannrum. Det flexibla systemkonceptet ger möjlighet för användning av olika typer av pelletseldningsutrustning och storleken på solvärmesystemet. En prototyp av ett system med en integrerad pelletpanna har testats och utvecklats under omfattande laboratoriemätningar. Man har visat att det är möjligt att bygga en 60x60x200 cm enhet inklusive pelletpanna, beredskapstank, tappvarmvattenproduktion och pumpkoppel för solfångarkretsen. En andra prototyp med en extern vattenmantlad pelletkamin har installerats i en villa i Borlänge och är i drift sedan juli 2006. Mätningresultat ska användas till att beräkna systemprestanda och att få information om systemets beteende i verkligheten.
ACKNOWLEDGEMENTS

This thesis is a result of the work carried out at the Solar Energy Research Center SERC in Borlänge within the Nordic research project REBUS during the years 2003-2006. The project has been supported by the Nordic Energy Research and the Dalarna University College.

First of all I want to thank Chris Bales, my supervisor at SERC, for his excellent supervision. His advices were invaluable and always brought me back on track. Thank you for spending so much time for me. Without you this work would have been possible.

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During the project I have been working in close collaboration with Alexander Thür from the Technical University of Denmark in Lyngby. Alexander was for me an inexhaustible source of information and he helped me a lot with his large wealth of experience. Thanks!

I would like to thank all my colleagues for their professional and mental support and the exceptional good working environment at SERC.

I want to thank also my family for the understanding and support for my work in Sweden.

Big thanks also to Yiqi, my soul mate, keeping me going by providing good mood and delicious food during the tough time of thesis writing.

Frank Fiedler
Borlänge, November 2006
LIST OF APPENDED PAPERS

Publications included in this thesis

This thesis is based on the following papers and reports, referred to in the text with Roman numerals.

**Journal papers**


**Contributions from Frank Fiedler**: Main author.


**Contributions from Frank Fiedler**: Main author, System simulations and calculations, System modelling in collaboration with Tomas Persson and Svante Nordlander.

III. Fiedler F, Bales C, Persson T and Nordlander S. Comparison of carbon monoxide emissions and electricity consumption of modulating and non-modulating pellet heating systems. *Accepted for publication in International Journal of Energy Research*.

**Contributions from Frank Fiedler**: Main author, System simulations and calculations, Analysis in collaborations with Chris Bales. System modelling in collaboration with Tomas Persson and Svante Nordlander.


**Contributions from Frank Fiedler**: Main author, Modelling, simulations and calculations, Setup and planning of the optimisation software in collaboration with Chris Bales.
Conference papers


Contributions from Frank Fiedler: Main author. System simulations and calculations, System modelling in collaboration with Tomas Persson and Svante Nordlander.


Contributions from Frank Fiedler: Main author. Market data from Chris Bales, Alexander Thür and Simon Furbo.


Contributions from Frank Fiedler: Lab measurements. Parameter identification for one pellet boiler.
Publications not included in this thesis

Conference papers

Reports
TERMINOLOGY

SH  Space heating
DHW  Domestic hot water
IEA  International Energy Agency
SHC  Solar Heating and Cooling
NTC  Temperature sensor with negative temperature coefficient.
Solar combisystem  A solar heating system that is designed to supply heat for space heating and domestic hot water.
Solar hot water system  A solar heating system that is designed to supply heat for domestic hot water.
Combistore  A heat store with connections for domestic hot water and space heating.
Auxiliary heat source  Supplement heat source of heat, other than solar.
CO  Carbon monoxide
OGC  Organic gaseous carbon
NOx  Nitrogen Oxides
ICS  Integral Collector Storage – Type of solar collector where the heat is stored in the volume of the absorber.
Nomenclature:

- $C_{pg}$: Specific heat flue gas [kJ kg$^{-1}$ K$^{-1}$]
- $\overline{c}_{wat}$: Average specific heat of water [kJ kg$^{-1}$ K$^{-1}$]
- $\overline{c}_{steel}$: Average specific heat of steel [kJ kg$^{-1}$ K$^{-1}$]
- $D_{CO0}$: CO-emission factor, constant part [g MJ$^{-1}$]
- $D_{CO1}$: CO-emission factor, power dependent part [g MJ$^{-1}$]
- $m_1$: Thermal mass of mass 1 [kJ K$^{-1}$]
- $m_2$: Thermal mass of mass 2 [kJ K$^{-1}$]
- $\dot{m}_a$: Combustion air mass flow [kg s$^{-1}$]
- $\dot{m}_g$: Flue gas mass flow [kg s$^{-1}$]
- $\dot{m}_f$: Fuel mass flow [kg s$^{-1}$]
- $m_{CO}$: Mass of emitted CO [kg]
- $m_{CO,\text{cum}}$: Cumulative amount of emitted CO [kg]
- $m_{wat}$: Mass of the water contained in the water mantle of the boiler [kg]
- $m_{wst}$: Mass of the water contained in the store [kg]
- $m_{steel}$: Mass of the steel of the boiler [kg]
- $\dot{m}_{CO,op}$: Mass flow of CO gas during operation of the pellet heater [kg s$^{-1}$]
- $m_{CO,\text{sta}}$: Mass of emitted CO during start [kg]
- $m_{CO,\text{stp}}$: Mass of emitted CO during stop [kg]
- $N_{\text{cum}}$: Cumulative number of starts
- $Q_{\text{aux,tot}}$: Total auxiliary energy supplied to the system [kWh]
- $Q_{\text{cum}}$: Fuel combustion energy [MJ]
- $Q_{\text{sol}}$: Solar energy supplied to the system [kWh]
- $Q_{\text{liq}}$: Heat transferred to the liquid [kWh]
- $Q_{\text{amb}}$: Heat transferred to the ambient [kWh]
- $Q_{\text{int}}$: Heat transferred to the internal mass of the boiler [kWh]
- $Q_{\text{flue}}$: Heat transferred to the flue gas [kWh]
- $P_{CAW}$: Average power, energy weighted [MJ]
- $P_{\text{comb}}$: Actual combustion power [MJ]
- $P_{\text{max}}$: Maximal combustion power [MJ]
- $P_{\text{el}}$: Electrical power [kW]
PN  Nominal power [kW]
SF  Solar fraction [%]
ts  Time step [s]
Ta  Ambient room air temperature [°C]
Tg0 Temperature of combustion gas before meeting mass 1 [°C]
Tg1 Temperature of combustion gas before meeting mass 2 [°C]
Tg2  Flue gas temperature [°C]
Tm1  Temperature of mass 1 (connected to ambient air) [°C]
Tm2  Temperature of mass 2 (liquid heat exchanger) [°C]
Tinhb  Flue gas temperature at the inlet of the air to liquid heat exchanger of the store [°C]
Toh xb  Flue gas temperature at the outlet of the air to liquid heat exchanger of the store [°C]
Toutd Outdoor Temperature [°C]
Tso Average temperature at start of measurement [°C]
Ts  Average temperature at the end of measurement [°C]
Tstart Middle temperature at start of the boiler [°C]
Tstop Middle temperature at stop of the boiler [°C]
UAgm1 Actual UA-value between gas and mass 1 [kJ hr⁻¹ K⁻¹]
UAgm2 Actual UA-value between gas and mass 2 [kJ hr⁻¹ K⁻¹]
UAnilq Actual UA-value between mass 2 and liquid [kJ hr⁻¹ K⁻¹]
UAnm Actual UA-value between mass 1 and mass 2 [kJ hr⁻¹ K⁻¹]
UAma Actual UA-value between mass 1 and ambient air [kJ hr⁻¹ K⁻¹]
UAst Heat loss coefficient to the ambient [W K⁻¹]
Vg,dry,20°C Volume flow rate of dry flue gas at 20°C [m³ s⁻¹]
εw Relative errors in transferred energy
ρCO,20°C Density of carbon monoxide at 20°C [kg m⁻³]
ωCO Volume fraction of CO on dry gas [m³ m⁻³]
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## 3 SYSTEM MODELLING, SIMULATION AND VALIDATION

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XV
Part I

Thesis
1 INTRODUCTION

Rising energy prices for fossil fuels and electricity and the global climate effects from CO\textsubscript{2} emissions and other greenhouse gases force more and more government authorities and end users to explore renewable energy alternatives. In Sweden one third of the total energy supply is used in the building sector of which 87% is used in residential buildings (Persson 2002a). In detached houses on average 80% of the energy is used for space heating and hot water (STEM 2001). Biomass in form of wood pellets and solar thermal energy can reduce the dependency from fossil fuels and electricity drastically. In this thesis system solutions for detached houses consisting of combined pellet and solar heating systems are studied and optimised. In addition, a new system concept suitable especially for the Nordic countries has been developed and tested.

1.1 Background

Until the end of the 19\textsuperscript{th} century wood was the predominant fuel for heating houses in Sweden. After a period of coal, oil became more popular from the 1940’s when oil was imported for industry and the transport sector (Lönnroth \textit{et al.} 1979). During the 1970’s and 1980’s oil crises, increasing taxes for fossil fuels and low prices for electricity have promoted the transition to electrical heating in detached houses. Multifamily houses have been increasingly connected to district heating (STEM 2002). The result of this development is that about 30\% of the 1.6 million Swedish detached houses are heated with purely electricity (SCB 2005).

In district heating plants oil was often replaced with wood and wood residues. This was also the starting point for the first wood pellet production in Sweden in 1980. The use of wood pellets for domestic heating started when the first pellet stoves came on the market. Later pellet boilers and pellet burners, that can replace oil burner in domestic boilers were introduced (Mahapatra \textit{et al.} 2004). In total about 80000 small scale pellet heating systems were installed by the end of 2005.

The dramatically increased prices for oil and electricity over the last few years (Figure 1.1) encourage many house owners with electric heating or and oil heating systems to convert their heating systems. Most popular are air and ground coupled heat pumps. Despite their environmental benefits and low fuel costs, the number of installed pellet heating systems is significantly lower than for heat pump systems. 65000 heat pumps were installed in 2004 (STEM 2006) but only 11500 pellet heating systems (SBBA 2006). Reasons for the lower diffusion are most of all deficiencies in the heaters, difficulties with the implementation in the houses, missing information and dissatisfaction among early adopters (Mahapatra \textit{et al.} 2004).
The first solar heating systems were installed in the mid-1970’s after the first oil crises and when a radical environmental movement was growing. At this time also a discussion about nuclear power was ongoing that made nuclear sceptics to be interested in solar energy (Henning 2000). Self builder groups started to design and install the first solar collector systems. At the same time first solar heating plants for district heating were designed and installed. Several large systems were installed in the following years and Sweden was leading in this technology. The initial government support for solar energy and solar energy research was stepwise reduced and even intermitted in the later years. This caused together with low energy prices a reduction in sales of solar heating (Henning 2000, SEAS 2006). Today, the number of installed solar heating systems for small houses is increasing rapidly with on average 25% per year (see also Figure 2.3).

Solar heating systems for detached houses are usually combined with an auxiliary heating system. A stand alone solar heating system is in most cases economically not feasible due to the low availability or solar radiation at high latitudes in the winter months. The combination of solar and pellet heating systems has several advantages such as:

- almost 100% renewable energy,
- low prices and local availability of the wood pellet fuel,
- improved efficiency and lower emission of the pellet boiler/stove especially during the summer months.

Several manufacturers in Austria, Germany and Sweden offer this kind of combined systems. In 2005 400-1000 combined solar and pellet heating systems have been sold in Sweden according to estimations.

1.2 REBUS project

The REBUS project has been started in the beginning of 2003 as a four year long research project on education, research, development and demonstration of competitive solar combisystems (Bales and Furbo 2004, Furbo et al. 2006). Research groups in
Norway, Denmark, Sweden and Latvia are working together with partners from industry on innovative solutions for solar heating in the Nordic countries. REBUS is funded by the Nordic Energy Research and the participants. The research work in the project is mainly performed within four PhD studies and one postdoc study.

The two Ph.D. studies at Technical University of Denmark (DTU) focusing on the development and improvement of solar heating/natural gas systems and components for the heat storage. At the University of Oslo a postdoc study is carried out on façade and roof integrated solar collectors and solar heating/natural gas systems with high solar fractions. At Dalarna University College/SERC the Ph.D. study is concentrating on the development of combined solar and pellet heating systems. The Ph.D study at Riga Technical University is also carried out on solar/pellet heating systems but with the focus on a low cost concept suitable for the local market.

1.3 Aims

The main aim of the REBUS project, of which this study was a part, was to develop and demonstrate competitive solar combinations for the Nordic market. The aim of this study was to provide the scientific basis for this development, with focus on the combination of solar and pellet heating. As a starting point the study should give an overview about the state of the art of solar and pellet heating systems. Existing combinations of combined solar and pellet heating systems shall be investigated with the aim to answer the following questions:

- How do the different systems perform in terms of thermal performance and carbon monoxide emissions?
- What is the potential for performance improvements?
- Are these systems suitable for the Nordic market?

A system should be designed, tested and installed that is competitive and that is adapted to the conditions on the Nordic market.

1.4 Scope

In this work combined solar and pellet heating systems for detached houses have been studied. This means the focus is on small scale systems. The systems studied provide both heat for domestic hot water and for space heating. The solar heating loop is water based. The systems are studied for Swedish conditions. The systems are studied with the same boundary conditions to allow a comparison between them. The effect of houses different to the reference building has not been studied.

The emphasis in the simulation studies is on the system performance rather than on the performance of single components of the system. The interaction of the boiler/stove, the collector and the store is of strong interest. Energy consumption and emission, in particular carbon monoxide emissions, are key aspects of the system evaluation.

1.5 Thesis outline

This thesis is an aggregated thesis where the main part (Part II) consists of a number of previously published research papers. In Part I of the thesis the background of the topic is
given and the appended publications from Part II are brought into the context of the whole thesis and research work within the project. Additional information on model validation and results on the system development of a new solar heating system are provided. Part I is organized as follows:

Chapter 1: Gives an introduction and background to the area of research and its framework, and also formulates the aims of the study.

Chapter 2: Provides information about the regulations and other boundary conditions for the type of studied systems. In addition a review of the technical development of solar and pellet heating systems is provided.

Chapter 3: The simulation environment and the modelling process of the systems is presented and discussed.

Chapter 4: The simulation results are presented and an optimisation method for the design of solar and pellet heating system is proposed.

Chapter 5: Gives an overview on the system development within the project.

Chapter 6: The results of the research work are discussed.

Chapter 7: The main conclusions of the study are given

Chapter 8: In this chapter recommendations for future work are given.

1.6 Method

An analysis of the state of the art of pellet and solar heating systems for detached houses was the starting point for this study. This included studies of the market, existing systems and system components as well as the pellet heating technology for small systems, which were compared for the main markets in Sweden, Austria and Germany. Relevant regulations from these countries were identified and compared. The results from research institutes and research projects on solar combisystems were also analysed. The second step was to study and identify relevant boundary conditions for solar combisystems for the Swedish market. Based on the survey on market and the previous research results it was decided to focus the study and the development on combined solar and pellet heating systems for detached houses. Previous studies were used to identify relevant existing combined solar and pellet heating systems: two systems with pellet stoves and separate solar water heating and two solar combisystems. These were then modelled in the simulation environment TRNSYS, which was chosen after a study of various tools and analysis of what had previously been used in similar studies. The necessary parameter values for the modelling were obtained from measurements on components in the lab or from previous research work. Some of these measurements were performed by the author, whereas others were made by colleagues at the same institute. The pellet boiler model was validated based on data for several stoves/boilers.

System simulations were performed and the results were analysed in terms of thermal performance and carbon monoxide emissions. Based on the simulation results the systems were evaluated regarding their suitability for the intended environment and the potential for their performance improvement. A method for system optimisation was developed using a multi-criteria approach for the fuel use and CO-emissions. This optimisation method was applied to one typical system, a solar combisystem with an external pellet boiler, but can easily be applied to other combined heating systems. The method was used
to find the optimal system design parameters for both low auxiliary heat consumption and low carbon monoxide emissions.

At the same time a system concept for a solar combisystem was developed. The concept was developed in close collaboration with Alexander Thür, another Ph.D-student in the project at DTU, and industrial partners for the Danish and the Swedish market. The Danish system variant was developed for the use of gas boilers as auxiliary heater, whereas the Swedish variant was developed for the use of pellet boilers or water mantled pellet stoves as auxiliary heater. The concept was based on results from former research, simulation results within the study, boundary conditions from the market and requirements from the industrial partners, resulting in a compact but flexible design with boiler integrated into a technical unit. From the market survey of pellet boilers and stoves, only one pellet combustion unit was identified that could fit into the technical unit, that from a water mantled pellet stove. Prototypes of the system, with gas boiler in Denmark and with a pellet boiler in Sweden, were designed, built and tested. For the Swedish variant it was found necessary to develop the integration of the pellet combustion unit into the technical unit, due to the fact that the combustion unit was used for another application than it was designed for. Measurements were made on pellet feed rates, thermal performance and emissions of the boiler. The results were analysed and then used to adapt the pellet feed motor and controller settings to achieve results comparable to the stove unit. All control features of the system were tested systematically by the author. The next step was to demonstrate the developed system under real condition in a demonstration house. Based on the results from the testing of the first prototype and on the specific conditions in the chosen demonstration house a second prototype was built and installed. The system and the houses are equipped with monitoring equipment allowing analysing the performance of the system.
2 STATE OF THE ART

2.1 Boundary conditions for domestic solar heating systems in Sweden

More than half of the Swedish population (56%) lives in detached houses (SCB 2006). Almost 1.6 million detached houses are in use. The yearly consumption for heating per house is on average about 20 MWh. Newer houses use about 12-13 MWh for heating including hot water (Persson 2002a). Almost a third of the detached houses use only electricity for heating. The increasing prices for fossil fuels have resulted in a doubling of installed heat pumps and a significant increase of bio fuels and district heating comparing data from 2000 and 2004 (SCB 2001, 2005).

![Energy usage in detached houses in Sweden 2004 (SCB 2005).](image)

Figure 2.1 Energy usage in detached houses in Sweden 2004 (SCB 2005).

Figure 2.1 shows that almost a third of the houses use combinations of different heat sources, where often electricity is one of the heat sources. The high electricity consumption for heating is problematic for the electricity production especially due to the high peak load during the winter. A subsidy program of the Swedish government promotes the conversion of electric and oil heating systems (Regeringskansliet 2005).

A third of the Swedish detached houses were built between 1941 and 1970 and another third between 1971 and 1990. Very few houses have been built later on. The houses built between 1941 and 1970 were mostly equipped with a boiler and a water based heat
distribution system. The boiler was placed in a cellar. The houses built between 1971 and 1990 are to a large extent heated with electricity, directly with resistance heaters or with an electrical boiler and a water based heat distribution system. These houses normally have no cellar or separate boiler room and no chimney (Nygren 2003). These houses represent a large potential for the conversion to heating systems based on renewable energy sources.

One of the most often used arguments against solar heating in Sweden is the climate. In fact, the solar irradiation is less compared to Southern Europe and also to Middle Europe. The temperatures are lower the higher the latitude. However, the amount of yearly irradiation on a south oriented, 45° titled surface for Stockholm is only 2% less compared with Stuttgart in the south of Germany. Furthermore, modern solar collectors produce heat even with ambient temperatures below 0°C. However, it can be seen in Figure 2.2 that very little solar radiation is available during the winter months whereas more than sufficient is available in the summer. A seasonal storage of the surplus energy for use in the winter would allow heating a house with an average heat load to 100% with solar energy. The great space demand for the store and the high costs for the store limit the feasibility of such a solution. Thus, an additional heating source for the winter and part of spring and autumn is necessary.

![Figure 2.2 Monthly irradiation for three different locations in Europe on a south oriented 45° tilted surface and space heating and hot water load for well insulated Swedish house with a hot water load of 3100 kWh.](image)

The use of solar heating systems for detached houses started in the 1970’s as a result of the oil crises and emerging environmental movement in connection with the discussion about the development of nuclear power in Sweden. Systems have been initially designed and installed by self builder groups. The self building groups are still active and are organized in the “Svenska Solgruppern” association. The group manufactures the LESOL collector that in 2004 still had a market share of 20% (STEM 2005a). In the 1980’s and 1990’s the market for domestic solar heating systems was exposed to large fluctuations.
mainly to the inconsistent subsidy policy of the government. In recent years the trend is clearly positive with an average increase of 25% (Figure 2.3). Most collectors are installed in small systems, with the majority (about 85%) in combisystems (Kjellson 2006), but the number of solar hot water systems is increasing. Systems with more than 15 m² are mainly systems for multifamily houses or systems connected to district heating. However, the solar heating market grows from a very low level. In 2004 Austria had 0.3 m² collector area per capita whereas in Sweden it was only 0.03 m² per capita (Weiss et al. 2006). The number of new installations is also on average 10 times lower than in Austria (ESTIF 2006).

Figure 2.3 Yearly installed glazed collector area depending on the system size between 1998 and 2005 in Sweden (STEM 2005a, Pettersson 2006).

The poorly developed market for solar heating can not only be attributed to unsteady subsidies and low energy prices. The higher investment cost compared to a conventional heating are a barrier for solar heating systems. Houses without chimney and water based heat distribution system need a high investment which discourages house owners to convert the heating system. For this type of houses very compact solutions are necessary, and these do not exist on the Swedish market. The general willingness to invest in a heating system that costs more but has environmental and long term economical benefits is rather low compared to Austria and Germany. The subsidy of maximal 7500 SEK encourages but is not leading to a break through. There are no building regulations that make the installation of solar collectors obligatory as it is the case in Spain and Portugal. There is little interest from the side of the building companies to collaborate with the solar industry and solar research institutions. Insufficient marketing and lobby work as well as a lack of public information about solar heating are other reasons for the slow development. The Solar Energy Research Center (SERC), the Solar Energy Association of Sweden (SEAS) and other actors have intensified their efforts by publishing information material (FORMAS 2005, Lorenz and Henning 2005, SEAS 2005), information campaigns (SEAS 2006) and improvement of the actual solar systems. More information is necessary especially for installers and plumbers that have close contact with customers.
2.2 State of the art of solar combisystems

2.2.1 Introduction

According to the White Paper "Energy for the future, renewable sources of energy" of the European Commission the market share of renewable energy sources should increase from 6% in 2003 to 12% by the year 2010 (EC 1997). The energy consumption in the building sector represents around 40% of all end energy consumption in the EU, where 75% of the energy is required for hot water and space heating. In 2000 only around 0.11% of the total requirement for hot water and space heating was covered by solar thermal systems. According to the White Paper, this share should be increased to 1.18% by 2010. This corresponds to an installed collector area of 100 million m². Based on the data from 1995 a 20% annual growth rate would give the forecast shown in Figure 2.4. The actual statistics reveals that the growth was much smaller. In 2004 only 15 million m² have been installed compared with the required 24 million m². This is due to variations among the EU countries with high growth rates in Austria and Germany but stagnating market in many other countries.

Solar heating systems for detached houses can be divided in three groups; hot water systems, combisystems and pool heating systems. In domestic hot water systems the solar heat is only used to prepare hot water. In combisystems a part of the space heating demand is also covered by solar heat. Solar pool heating systems are used to heat swimming pools. In this chapter the focus is on solar combisystems.

In 2004 approximately 20 000¹ solar heating systems (hot water systems and solar combisystems) are installed in Sweden. 70-80 % of the collectors are installed in solar combisystems with 10-15 m² per system. For comparison, in Austria with almost the same 

¹ This number is based on the installed collector area and the approximate share of solar combisystems and solar hot water systems
population as Sweden 210 000 DHW and 28 300 solar combisystems are installed with on average 6 and 12 m² respectively (Fink and Blümel 2002).

2.2.2 Research on solar combisystems

Solar combisystems are relatively new types of heating systems. The first combisystems were based on systems with wood boilers coupled to a buffer store where solar collectors could be connected easily. Today a variety of system designs with gas, oil, wood, pellet and electricity as auxiliary heat source exist. Between 1998 and 2002 experts from research institutes and solar industry worked together in Task 26 “Solar Combisystems” of the IEA Solar Heating and Cooling Program. In total 21 design variants from 8 European countries have been analysed and compared. Eight of these systems have then been, based on system simulations, optimised and improved. The results from Task 26 have led to a variety of technical reports and design tools that are available for the public (IEA 2002). Furthermore, a design book for solar combisystems has been published (Weiss 2003).

A European research project on solar combisystem has been carried out in the framework of ALTENER. Seven countries have been participated in the planning, construction and documenting of about 200 combisystems. Some of the systems have been monitored in detail and from some others the energy data have been recorded.

Currently the project NEGST (New Generation of Solar Thermal Systems) is ongoing. The project forms a network of institutes and industry monitoring the innovation activities in the field of solar thermal systems. The research carried out within REBUS and the IEA Task 32 (Advanced storage concepts for solar thermal systems in low energy buildings) are linked to NEGST.

Most research on combisystems has been done at institutes participating in Task 26 and the EU ALTENER project. In the following a more detailed overview on their research activities related to solar combisystems is given.

The Energy research group at University of Oslo (UiO) is working in collaboration with industrial partners on concepts for solar combisystems with low temperature heating. The emphasis of the research work at UiO is on collector materials (especially polymers), building integration and drain-back technology.

At the Technical University of Denmark DTU research on solar heating system and on solar combisystems in particular has been done over many years. The focus here has been on heat transfer and stratification in heat stores. Advanced CFD and PIV simulations and measurement are used to optimise the store construction. Other research topics are solar collectors, large systems as well as tests and simulation of solar hot water and solar combisystems.

The Institute for Thermodynamics and Thermal Engineering (ITW) at the University of Stuttgart has been working in the field of “thermal solar energy” since the beginning of the 1970s. Part of ITW is the Centre for Thermal Solar Systems (TZS), the largest accredited test center in Germany for the testing of solar thermal systems and their components. ITW has been working for long time on the development, testing and simulation of solar combisystems.

The Arbeitsgemeinschaft Erneuerbare Energie (AEE INTEC) in Austria is one of the pioneers in the area of solar thermal research. The collected experience on the design and planning of solar hot water and solar combisystems was published in the hand book
“Heizen mit der Sonne” (AEE 1997). One special area of research at AEE is the use of tiled stoves with water mantle with solar combisystems (Schrottner 2002). AEE INTEC works in collaboration with the Fraunhofer-Institute for Solar Energy Systems (ISE) in Freiburg on sorption stores for the seasonal storage of solar heat. AEE INTEC studied the stagnation behaviour of solar combisystems in detail and has been part of monitoring projects for many solar heating systems.

At the Institute of Thermal Engineering (IWT) at Graz University of Technology larger combisystems for multifamily houses have been studied and optimised (Heimrath 2004). In a study together with AEE INTEC several heating systems with air and water heating distribution for low energy and passive multi-family houses have been investigated (Streicher et al. 2004). Other related research topics at IWT are stagnation problems of solar combisystems (Streicher 2001), solar combistores and phase change materials in heat stores (Heinz and Streicher 2005). A simulation program for solar hot water and solar combisystems has been developed (Streicher et al. 2000). Recently, IWT is working on advanced stores for increased solar fractions, improved boiler performance and lower emissions. The results of this work have not been published yet.

SP the Swedish National Testing and Research Institute is testing components of combisystems such as solar collectors, stores and boilers. SP was also involved in the development of testing methods for solar combisystems.

The Swiss solar testing institute SPF has tested compact solar combisystems with oil or gas boilers as auxiliary source. The tests have been performed on the complete prefabricated systems including the auxiliary heaters, allowing evaluating the interaction of the system components. The systems have been tested by the Concise Cycle Test Method – CCT (Vogelsanger 2003) and simulations using a simplified simulation model of the system.

There are many companies active on the development of solar combisystem, e.g Solvis (Krause and Kuhl 2001), Wagner, Paradigma, Clipsol and many others.

2.2.3 Main results from European research projects

Task 26

For the variety of studied system concepts classifications have been worked out distinguishing the system in terms of storage and auxiliary heat management. The performance of the system concepts are very much depending on the boundary conditions such as climate, heat load, type of collector, type of heat distribution system, type of auxiliary heater and many others. An evaluation method has been developed that takes the boundary conditions to a large extent into account. Using this tool together with an economical evaluation it has been shown that even a rather costly solar combisystem with high fractional saving can be more economic then a less expensive system with small fractional savings. Optimizing the systems by system simulations resulted in the following main suggestions for improvements:

- the store insulation on top should be around 15 cm,
- the store volume that is heated by the auxiliary heater should be as small as possible but still big enough to cover the heat load,
- the temperature of this volume should be as low as possible but still allowing the system to meet the demand.
However, the biggest single influence on the system performance is the choice of the right boiler (Streicher and Heimrath 2003a).

The monitoring and analysis of solar combisystems in Austria during the ALTENER project showed that typically there are still problems with the installation of the systems and the interaction with the conventional heating systems. The first can be attributed to a lack of knowledge among installers but also to the insufficient prefabrication of the systems. The latter is due to lack of a coherent total system design (Riva 2003). In addition, a report has been prepared compiling the most failures and problems that can be caused by an inappropriate installation of a solar combisystems (Ellehauge et al. 2000). Within the ALTENER project a PC-tool for performance estimation of combisystems has been developed. The PC-programme can estimate the performance of a number of different combisystem designs, under different climates and different loads. The collected results of the project can be found at: http://www.elle-kilde.dk/alter-combi/.

The Energy research group at UiO and the company SolarNor have developed a solar combisystem for low temperature heating system (Figure 2.5). The system concept is based on a rectangular unpressurized tank with an integrated DHW tank. The collector loop work with the drain-back principle which makes it possible to omit the use of glycol. The collector absorber has been developed together the company General Electric Plastics and consist of an extruded polymer absorber. The absorber can in principle be produced in any length which gives advantages for the building integration of the collector. The system concept is optimised for floor or wall heating and has the potential to reach high solar fractions. The system is marketed by SolarNor and is mainly installed in new single family and multifamily houses in Norway.

![Figure 2.5 System concept of a solar combisystem developed at UiO.](image)

SPF has tested compact solar combisystems using gas or oil boiler as auxiliary heater. Compact was defined as systems that consist maximally of two units (heat store and boiler). The used heat stores with volumes of 700-950 litre were in the lower range for
solar combisystems. The tests revealed, similar to the results of Task 26, that most deficiencies appeared in the conventional part of the system - the boiler, the control of boiler and the heating system. It was shown that several systems had heat losses due to natural convection of the water at the connections. Problems were reported with the complicated installation of some of the systems and inadequate documentation, especially for the settings of the system controller. Some systems had serious malfunctions and needed to be revised by the manufacturer. The manufacturers of these systems abstained from publishing the testing results on SPF’s webpage. One of the main conclusions from the study was that a central system controller is required to ensure a proper and efficient function of the solar combisystem (Niederhäusern 2003, Vogelsanger and Haller 2005).

AEE INTEC has investigated very detailed stagnation problems of solar combisystems. Comprehensive measurements have been performed on a large variety of hydraulic designs of solar collectors and hydraulic connections of solar collectors. From the results a detailed design guideline for the design of the solar collector loop has been derived (Hausner and Fink 2003, Hausner et al. 2003).

DTU is working intensively on heat stores for solar heating systems. One of the major interests is how stratification in the stores can be achieved and maintained. Different designs for store inlets have been simulated and optimised (Shah and Furbo 2003). Stratification units have been tested (Shah et al. 2005) and new units have been developed (Andersen and Furbo 2006a).

2.3 State of the art of pellet heating systems

The information in this section is based on Paper I. A summary of the present pellet heating technology is given and latest regulations about emissions from pellet heaters are presented.

2.3.1 Pellet heating technology

For the combustion of pellets two types of units can be found on the Swedish market:

- **Central heating boilers** (Figure 2.6) are used to provide heat for single- or multi-family houses. The heat is transferred by an exhaust gas to water heat exchanger to the heat distribution system. The maximal heating power of these devices is in the range of 10 to 40 kW, where some are automatically modulating the power from 30 to 100% according to the heat demand.

- **Stoves** (Figure 2.7), which are used to heat single rooms, compact apartments or even a whole single-family house. The heat from the stove is transferred to the building by heat convection and radiation. Some stoves have additional water jackets and can be connected to a water based radiator system. The heating power is maximal around 10 kW and can be regulated manually or automatically by the room temperature.

**Boilers**

Central pellet heating boilers are basically designed like conventional oil boilers. The fuel is transported from the store to the burner placed in the combustion chamber, where the fuel will be lighted and combusted. The flue gas is conducted in several passages through the heat exchanger and transfers its energy to the water on the other side of the
heat exchanger. A circulation pump transports the heated water to the heat distribution system. To improve the heat transfer and supply sufficient combustion air a fan is installed. The size of the combustion chamber and the heat exchanger need to be adapted to the maximum power of the burner to ensure consistent combustion and a sufficient heat transfer over the whole power range. The whole boiler is insulated and covered with a sheet-metal to prevent damage and reduce heat losses to the boiler location.

In Sweden two types of central heating boilers were identified:

- Two unit boilers are the most common boilers in Sweden. This type of boiler is a combination of a pellet burner and a standard boiler (without burner) often produced by different manufacturers. The standard boiler can be combined with different types of burners. A common case it that an old oil burner will be replaced with a pellet burner. This replacement is very easy to accomplish since the connection flange between boiler and burner is the same for oil and pellet burners. This simplicity is one reason for the high number of installed pellet heating systems in Sweden.

- Integrated boilers are less common on the Swedish market. Most systems of this type are imported, but a few are also manufactured in Sweden. In integrated boilers, as the name already says, the burner is part of the boiler and can not be separated. The design of integrated pellet boilers is based on split log wood boilers. Some of these type of boilers have also an embedded pellet storage.

Unlike Sweden, integrated pellet boilers are the dominating type of pellet boiler in Austria and Germany. Nevertheless some similar products, in terms of basic construction can be found as can be seen in Figure 2.6. Although the basic construction principles are similar, big differences are found in the ‘optical’ design. The Swedish products are designed rather simply suitable for separate boiler rooms or cellars. Austrian and German manufacturers make more efforts on an advanced appearance of their products (Figure 2.6).

![Figure 2.6 Left: Swedish pellet boiler (Effecta 2004), Middle, Right: Austrian pellet boiler (ÖkoFEN 2006).](image)

In terms of comfort the Austria boilers are very user friendly and provide almost the same comfort as gas or oil boilers. In contrast to Swedish boilers the passages and burner are often cleaned automatically by helical screws serving meanwhile as turbulators to improve the heat transfer to the heat distribution fluid. The ash from the combustion
A chamber is also removed without the help of the user and some manufacturers provides an inbuilt ash compressor that reduces the ash removal times from the boiler to a minimum.

Austrian boilers are mostly equipped with an aspirator for the air supply and a lambda sensor for optimal combustion and a modulation of the heating power. These systems reach high boiler efficiencies up to 94%. One manufacturer is even offering a pellet boiler with flue gas condensation. Most Swedish boilers work with fixed combustion power or have a stepwise power control or provide predefined settings for winter and summer operation. In two-unit boilers, the burner is not optimised for the operation in a standard boiler leading to efficiencies lower than 85% and higher emissions compared to Austrian boilers.

The more advanced technology and design of Austrian/German pellets heating systems is of course reflected in a higher price. A complete boiler in a range of 10 to 20 kW costs between 7000 and 10000 Euro including tax, where often the transport system between the pellet store and the boiler is included in the price. For a similar Swedish system, the customer has to pay between 4000 and 6000 Euro including tax. A transport system is usually not included, but changes the price difference not significantly.

In Sweden, Germany, and Austria, the number of pellet boilers is increasing rapidly. In Sweden, the low price for pellets and presumably also the comparable cheap boilers are the driving forces. In Germany and Austria also the governmental incentives, the high comfort, and the good image of environmental friendly technologies encourage the market for pellet heating.

**Stoves**

There are two main types of pellet stoves available, standalone pellet stoves and chimney integrated stoves. The only difference between those two types is that the latter is especially dimensioned to be placed in an open fireplace. The most common stove is the standalone stove.

Standalone stoves usually have an integrated pellet storage, which allows storage of a limited amount of pellets, usually enough for one or two days. A few stoves are on the market which can be coupled with external pellet stores.
Pellet stoves using the same basic principles as pellet boilers. The pellets are combusted in an integrated burner, which is similar to the ones used in pellet boilers. Most pellets stoves use a fall channel from the integrated or external storage to feed the pellets to the burner pot. Through openings in the bottom of the pot the primary air and the hot air for the automatic lighting is supplied. The secondary air is usually preheated through the mantel of the pot and fed by many small openings of the mantle. The aspirator supplying the combustion air for the stove is placed below the burner. Sometimes an additional fan is used to improve the heat transfer from the stove to the ambient air. To simplify the ash removal the pellets are combusted on a manually or automatically operated moveable grate plate allowing the ashes to fall down in the ash container.

**Types of pellet burners**

Depending on how the pellets are fed into the burner three types of pellet burners can be distinguished (Figure 2.8). These are:

- bottom fed burners,
- horizontally fed burners,
- and top fed burners.

Burners with top feeding principle are very frequently used in both pellet boilers and pellet stoves and have the advantage that the pellet store is always separated from the combustion zone and that way the danger of back burn from the furnace is very small. This prevents also a long after glowing if the burner is turned off. Moreover, it ensures the conveying from the top an accurate dosing of pellets according to the current power demand. Disadvantageous is that the falling pellets have a negative impact on the fire-bed, resulting in an increased release of dust and unburned particles. It also causes an unsteady combustion behaviour.

Bottom fed burners are originally designed for the use of wood chip boiler, but are also suitable for pellets. A screw conveyor transports the pellets through the burner pipe and
pushes them on the combustion disk, where the primary combustion (gasification) takes place. The primary air is supplied by the pellet supply or by openings in the burner head. The supply of the secondary air for the combustion of the released gases is placed on the burner disk or provided by air tubes above the disk. No separate ash removal construction is necessary. The ash is displaced by the after coming pellets and falls over the edge of the disk down to the ash container or ash transport system. The combustion with this burner is very consistent but has, due to the supply principle of the pellets, also a long after burning period. Additional safety measures are necessary to minimize the risk of back burning.

Horizontally fed burners are basically similar to bottom fed burners. The only difference is the form of the combustion bed and that for this type of burner an additional ash removal might be necessary.

![Figure 2.8 Types of pellet burners by their feed principle: a) bottom fed burner b) horizontally fed burner c) top fed burner (Hadders 2002).](image)

### 2.3.2 Emissions

The extensive use of wood as fuel for heating purposes in residential areas can lead to a low air quality and health risks if obsolete boilers are used or the heating units are inappropriately used or poorly maintained. Emission regulations are necessary to protect inhabitants from hazardous exhaust gases and dust and to encourage manufacturers to optimise their products for low emissions. Modern pellet boilers are characterized by lower emissions compared to log wood or wood chip boilers and further improvements are possible.

Most relevant emissions from pellet boilers are carbon monoxide, organic gaseous carbons (OGC), nitrogen oxides and particles. Limit values for emission from combustion of small scale wood boilers and stoves are given by the European Standard EN 303-5, which is applied as a Swedish Standard since 1999. The building regulation from the Swedish National Board of Housing, Building and Planning (Boverket) recommend the application of the values from the EN 303-5 but only require the observance of the limit value for OGC.

In Table 2.1 the official limit values for emissions and efficiencies from the European Standard are compared with the current limit values from eco-labels and other regulations in Sweden and Germany. It can be seen that the German eco-label Blauer Engel has the most stringent limit values. The Nordic eco-label Svan-mark is preparing to tighten their limit values. This will force the manufacturers to intensify their efforts to improve their products in terms of emissions. A number of products, mainly from German and Austrian
manufacturers, have already been certified with the Svan-mark and the Blauer Engel-mark showing that the limit values are not too stringent.

Table 2.1 Limit values for emissions from automatic fed pellet heating units with a nominal combustion power smaller than 50 kW, CO- carbon monoxide, OGC-organic gaseous carbon (RAL 2003a, 2003b, Pettersson 2005, Nordic-Ecolabelling 2006).

<table>
<thead>
<tr>
<th>Regulation</th>
<th>Boiler efficiency</th>
<th>Limit value for emission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NOx</td>
</tr>
<tr>
<td>EN 303-5 (class 3)</td>
<td>67+6 log Pₖ</td>
<td>-</td>
</tr>
<tr>
<td>SP-Swedish testing institute, P-mark</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>Nordic Ecolabelling, Svan-mark</td>
<td>72 + 6 log Pₖ</td>
<td>-</td>
</tr>
<tr>
<td>Nordic Ecolabelling, Svan-mark, proposed 2006</td>
<td>75 + 6 log Pₖ</td>
<td>340</td>
</tr>
<tr>
<td>Pellet stoves</td>
<td>90 at Pₖ, 88 at Pₖₘᵢₙ</td>
<td>150</td>
</tr>
<tr>
<td>Blauer Engel¹</td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>Pellet boiler</td>
<td>90 at Pₖ, 88 at Pₖₘᵢₙ</td>
<td>150</td>
</tr>
</tbody>
</table>

¹ To be measured with 13vol-% O₂

2.3.3 Market

For many years Sweden and Austria have been the dominating markets for small scale pellet heating systems. In both countries this expansion has based on a long tradition of wood based heating systems. The markets have been developed independently from each other so that the applied heating technology shows clear differences. In recent years the German market has also been growing rapidly (Figure 2.9) but per capita Sweden and Austria are still far ahead. 2005 was a key year in the Austrian market, as for the first time more pellet boilers than oil boilers were installed (Fanninger 2006). In Sweden pellets are also frequently used in local and district heating plants, whereas in Austria and Germany the domestic market is predominating.
Figure 2.9  Total number of installed pellet boilers, stoves and burners in Sweden, Austria and Germany (EVA 2006, SBBA 2006, Solar-Promotion 2006).

2.4 Combined solar and pellet heating systems

Solar combisystems are by definition solar heating systems that provide domestic hot water and space heating. Combined pellet and solar heating systems include solar combisystems but also comprise systems where the solar system is only providing hot water and the pellet heating system provides the space heating and eventually also some part of the domestic hot water.

2.4.1 Research

The combination of solar and pellet heating is a relatively new research topic. A first detailed study of a solar combisystem containing a pellet boiler has been presented by (Dalenböck 2000). The pellet boiler in this study was a prototype based on a wood boiler that was converted with a pellet burner. The 270 liter water volume contained heat exchangers for the domestic hot water production was also used as solar store by adding an immersed heat exchanger for the solar loop. The studied system was later marketed by a Swedish company.

A combined system with a store integrated pellet boiler developed by the Swedish company Stocksbroverken AB has been tested by (Larsson 2000). Measurements showed that the total heat losses of such a system are lower than for other systems with a separate pellet boiler.

Within the ALTER project combined solar and wood heating systems have been monitored and analysed. Some of the wood heating systems were pellet boilers. The analysis showed that many boilers, both wood and pellet boilers, were overdimensioned, that some system designs were too complicated and that the system were often poorly insulated. Most shortcomings were found in the conventional part of the heating systems.
Recommendations for system improvement were given (Ellehauge and Saebye 2000, Overgaard et al. 2000).

Most research on combined solar and pellet heating systems has been carried out by the Solar Energy Research Center in Borlänge Sweden. Within the project PESTO (Berg et al. 2001) a number of pellet stoves and boilers have been measured and modelled in detail. A TRNSYS model for pellet stoves and pellet boilers has been developed (Nordlander et al. 2006). Interdisciplinary research together with social anthropologists has been carried out for a better understanding of the customer perspective and the barriers for this new technique (Lorenz and Henning 2005). One of the main aims of the project was to find solutions for the conversion of electrically heated houses to solar and pellet heating. A number of typical house designs with electrical heating have been identified and modelled. Persson has investigated how these electrical heated houses can be converted to wood pellet and solar heating using pellet stoves and solar heating systems (Persson and Nordlander 2003, Persson et al. 2005, Persson 2004, 2006). At SERC a store integrated pellet boiler has been developed (Lorenz and Bales 2003).

In 2003 the Nordic collaboration project REBUS was launched with the aim to develop competitive solar heating systems for residential buildings. The Swedish research group was working on a compact solution of a combined solar and pellet heating system (Paper VI). The Swedish National Testing and Research Institute (SP) has been testing components for combined solar and pellet heating systems such as solar collectors, combitanks and pellet heaters (Kovács and Pettersson 2002, Pettersson et al. 2004). ÄFAB, an independent consulting company which is specialized in the field of small scale bioenergy has investigated performance and emissions from number of pellet boilers connected to combitanks (Löfgren and Arkelöv 2003). Since 2003 a European research project named SOLLET is ongoing where a number of mostly larger systems are monitored (SOLLET 2006). SPF, the solar testing institute in Switzerland, has started testing pellet and solar heating systems, but no reports have been published yet (Vogelsanger 2006).

### 2.4.2 Market

A few companies in Sweden, Austria and Germany have developed combined solar and pellet systems. Many other companies sell both pellet boiler and solar heating systems but not as a tuned system. Two main concepts can be seen on the market:

1. Combisystem or solar hot water system with a separate pellet boiler as the auxiliary source.
2. Combisystem with a store integrated pellet burner.

There are also systems with air heating pellet stoves and water mantled pellet stoves. The water mantled stoves can in principle be used as pellet boiler and can be connected to a solar combistore. Some companies sell pellet stoves as a package together with a solar heating system. One of the few companies that have developed their own solar and pellet heating system is the Swedish company Effecta AB. Systems with a store integrated pellet burner are manufactured and marketed by the Austrian company Solarfocus GmbH and the Swedish company Stocksbroverken AB (Figure 2.10).
The Austrian company Energycabin Produktions und Vertriebs GmbH, in collaboration with manufacturers of solar and pellet heating components, is making a combined system with a variable size between 10 kW and 450 kW and 7-48 m² collector area. The systems are delivered as a standalone solution built in a cabin that comprises a complete heating system including heat store, pellets store and chimney (Figure 2.11).

From Germany it has been reported that in 2005 about 10000 combined solar and pellet heating systems have been sold (König 2006). About 400-1000 systems have been installed in 2005 in Sweden according to estimations. For Austria no exact numbers are available but the majority of the actual installed combisystem use pellet boilers or stoves as auxiliary heater (Thür 2006). In 2005, the fist time more pellet boilers than oil boilers have been installed in Austria (Fanninger 2006).
3 SYSTEM MODELLING, SIMULATION AND VALIDATION

In Chapter 3 the modelling of the system, the validation of models and the program that has been used for the simulations are described. A short overview of simulation tools and motivation for the choice of the simulation program is given. Information about the capability and main features of the software are provided. The most important components models of the system, the collector model, the store model and the pellet boiler model are described. A very detailed description of the pellet boiler model is given in Paper VII. The paper includes only a short section about the validation of the model. For this reason a more detailed validation of the model is presented in the section 3.3.

3.1 The simulation environment TRNSYS

Solar combsystems consist of a great number of components such as pumps, pipes, stores, collectors, boiler and control units for the interaction of these components. The complexity increases if the system is studied in interaction with a building. Measurements would be one way of investigation the performance of such systems but require a lot of time and are limited in the results that can be expected. A more comprehensive view of the performance of the complete system and components for different boundary conditions can be obtained by using simulation tools. A number of simulation tools for solar heating systems are available. Overviews of existing simulations programs have been provided by Quaschning (1999) and Bales et al. (2003). The available simulation programs can be categorized in three groups: rough analysis programs, system-based dynamic programs and component based dynamic programs.

The first group comprises computer programs that are basically created as rough design tools. They are based on simple design rules and equations that are taken from spreadsheets and statistical data. These programs can deliver quick results for a limited number of standard systems. The level of detail varies from programs that give rough sizing information to those that give recommendations for the choice of components and other useful information. These programs can not simulate the dynamic behaviour of the system and deliver the results as monthly or yearly data. Only a few programs of this group can be used for solar combsystems. One of the most known examples of this type of programs is F-chart. It is based on a calculation method with the same name developed by Klein et al. (1977).

The second group, system-based dynamic programs, are more flexible and provide more detailed results. The number of system designs that can be studied is still limited but a wider range of boundary conditions such as climate and load data can be used. The
system components can be specified in more detail and can, for some of the programs, be chosen from a database. The computation time is some what longer than for rough analysis programs due to the shorter time step and greater complexity of the equations. System-based dynamic programs are used for the design of solar heating systems and the comparison of system designs. Most programs can simulate both solar domestic hot water systems and solar combisystems. Examples of these commercially available programs are Polysun, T-Sol and SHWin.

Component-based dynamic programs give the user the possibility to simulate, in principle, any kind of system configuration. Components are available as separate modules that are connected together via inputs and outputs. The user can create own modules if the desired component is not available in the program library. The great flexibility makes this type of programs suitable for experts who want to study systems or system components in detail. The high flexibility and the great level of detail also brings with it disadvantages. Modelling of systems with these kind of programs is time demanding and requires good knowledge of both the program and the physics of the system to be simulated. A careful handling of the large number of parameter values is necessary to prevent errors. Several component-based dynamic programs are available that in principle could be used for the simulation of solar combisystems. For the simulations in this work the program TRNSYS has been used (Klein et al. 2004). The main reasons for the choice of TRNSYS were:

- TRNSYS has been used since almost 30 years for the simulation of solar heating systems.
- A wide range of validated component models are available.
- A great competence for simulations with TRNSYS is available at SERC and non-standard models as Type 210 (pellet boiler) have been developed for TRNSYS.
- Simulations of combisystems within former international research projects have been carried out with TRNSYS.

Thus, TRNSYS was a logical choice. TRNSYS is programmed in Fortran and the source code is available to the users. User components can be written in Fortran or other programming languages. The mathematical model for each component, called Type, is a subroutine of the main program and is solved separately and sequentially. That means they are calculated one after the other (sequently). This is also the main difference to other component-based simulation programs where all equations are solved together at once (simultaneously). TRNSYS distinguishes between parameters, which are constant, and inputs, which can be time dependent. If components form a loop, then the equations of the components are solved by iteration. A convergence tolerance limit value, which can be defined by the user, defines the maximal number of iterations and accuracy of the calculation results. A tight convergence limit gives consistent results but will increase the computational time. In general it is necessary to check simulation results carefully and compare them with measurements and/or separate calculations. A limitation of TRNSYS is that systems can only be simulated with a fixed time step. The maximal time step of a simulation is defined by the smallest time step of external input data supplied to the system model. In TRNSYS two solvers can be chosen by the user. Part of the TRNSYS package is the multizone building simulation program TRNBuild (Transsolar 2004).
Building models created with TRNBuild can easily be integrated in TNRSYS and allow users to study the interaction between the building and the thermal/electrical system.

3.2 Modelling of systems and system components with TRNSYS

3.2.1 System model and main boundary conditions

The solar heating systems in chapter 4 have been modelled with the simulation program TRNSYS. Boundary conditions such as the DHW load and climate data are imported to the system through data readers. Within IEA Task 26 Solar Combisystems a variety of systems were modelled and a number of components and boundary conditions were developed (Weiss 2003). Consistent boundary conditions are necessary to compare different designs of solar combisystems. The Task 26 system simulation model that was used for modelling the Swedish system forms the base for the system simulation model in this study.

The DHW load has been modelled with a load profile developed by Jordan and Vajen assuming a daily hot water demand of 200 l (Jordan and Vajen 2002). This corresponds to the hot water demand of a household with 4 persons. The building model that is used in the simulations is one of the building models that was developed by Streicher and Heimrath (2003b) for IEA Task 26. This one zone model represents a well insulated single-family house with a yearly heat demand of about 12200 kWh per year for the climate of Stockholm. The use of a one zone model for the building assumes that the heat in the building is distributed freely, which is a simplification.

3.2.2 Modelling of components

Most of the components used in the system are modelled with Types that are taken from the standard library of TRNSYS (pipes, pumps, controllers etc). These Types have been widely used for many years and are well validated. The main components of a solar combisystem are the components that deliver the heat to the system and that store the energy;

- the solar collector,
- the auxiliary heater,
- and the combistore.

These three components are also most important when investigating the performance of a solar combisystem. The auxiliary heater, here the pellet boiler, the storage tank and the solar collector have been modelled with user programmed non-standard types.

For the combistore the multiport store model Type 140 has been used (Drück and Hahne 1996). This is a very detailed model, with which heat transfer to the store can be modelled via four internal heat exchangers, a mantle heat exchanger, an internal tank and through 10 double ports. The model also allows modelling of stratified inlets and an integrated electrical heater. Heat loss coefficients can be defined for different parts of the store. The model consists of up to 200 fixed nodes each with the same volume. Type 140 has been used by many research groups, e.g. in Task 26. It has been validated for several differently configured stores (Bales 2004).

The solar collectors have been modelled with Type 132 (Perers and Bales 2003). Type 132 uses the “Quasi Dynamic Collector Model” that is also used for testing of solar
collectors, which is based on the well validated “Hottel-Whillier-Bliss” equation for flat plate solar collectors (Hottel and Woertz 1942). The model is suitable for the most common collector types, except ICS collectors where the solar collector and the storage are combined in a single unit. The model has been used in Task 26 and other research projects and has been validated earlier for several collectors (Perers 1993, Perers 1997). For this work the same collector parameters as in Task 26 have been used, representing a modern glazed flat plate solar collector.

At present two TRNSYS models are available for pellet boilers, Type 170 (Fiedler and Knirsch 1996) and Type 210 (Nordlander 2003, Nordlander et al. 2006). Type 210 can be used for pellet boilers and pellet stoves. Another model is under development, Type 269 (Haller 2006), that will be able to use a range of standard fuels but also any user defined fuel by the weight fraction of the chemical elements and the heating value. Only Type 210 can so far simulate the start and stop sequence of pellet boilers and stoves in detail, including the CO-emissions and was thus used for the simulations in this work. Boilers/stoves operating in heating systems for detached houses usually have many starts and stops due to the varying demand. Thus the start and stop behaviour of the boiler/stove has a great effect on the total performance of the system and it is necessary to take that into account when simulating such systems. Type 210 also calculates the leakage losses during non-operation and the electricity consumption. This gives a comprehensive view of the energetic performance of the boiler/stove. Figure 3.1 shows the schematic structure for the heat and mass transfer of Type 210.

![Figure 3.1 Schematic structure of type 210 (Nordlander 2003)](image)

The model separates the pellet heater into two main thermal masses (Figure 3.1). The thermal mass \( m_1 \) represents the part of the stove that transfers the heat to the ambient and \( m_2 \) representing the water jacket of the stove/boiler. Fuel and combustion air entering the stoves/boilers, combust and form a combustion gas that transfers heat first to \( m_1 \) and then...
to $m_2$ before leaving the stove. Heat transfer coefficients define the heat transfer between the hot air mass flow, the thermal masses, the ambient air and the fluid in the water jacket.

Type 210 does not include a chemical combustion model. The temperature of the hot gas is calculated by the mass balance of air and fuel, the heating value of the fuel and the air properties (Eq. 3.1 and Eq. 3.2). The combustion efficiency is assumed to be 100%. This is a simplification, but measurements have shown the combustion efficiency of modern wood and pellet boilers is between 99% and 100% (Olsson 2006).

$$\dot{m}_g = \dot{m}_f + \dot{m}_a$$ \hspace{1cm} \text{Eq. 3.1}

$$T_{g0} = T_0 + \frac{P_{amb} + P_L}{\dot{m}_g \cdot C_{pg}}$$ \hspace{1cm} \text{Eq. 3.2}

The CO-emissions calculated by the model are based on measured data from each pellet heater. The model calculates the CO-emissions as the sum of a power dependent part during normal operation and a lumped constant amount per start and stop. The total cumulated emissions for the whole simulation are calculated with Eq. 3.3:

$$m_{CO,\text{cum}} = N_{\text{start}} \cdot (m_{CO,\text{sta}} + m_{CO,\text{tmp}}) + Q_{\text{tmp}} \cdot (D_{CO2} + D_{CD}) \cdot \frac{P_{\text{CW}}}{P_{\text{max}}}$$ \hspace{1cm} \text{Eq. 3.3}

### 3.2.3 Parameter identification

Realistic results from system simulations can only be obtained if the component models can correctly simulate the real behaviour of the component. This implies a good mathematical model and correct parameter values for the specific component. The parameter values need to be identified from measurement data. This is essentially important for the three components with the main impact on the system performance; the solar collector, the heat store and the pellet boiler. At SERC extensive measurements have been performed to test several heat stores (Persson 2001, Bales 2004), pellet heaters (Berg et al. 2001, Persson 2004, Persson et al. 2006a) and hot water units (Lorenz et al. 1997, Bales and Persson 2002, Persson 2002b). The parameter values for the corresponding TRNSYS models have been identified from these measurement data. For heat stores and hot water units the identification programs DF (Spirkl 1999) and FITTRN (Huber 1998) were used. A guide line for the identification process for TRNSYS models has been developed (Bales 2001).

Three different stores have been used in the simulations, one solar hot water store and two solar combistores. The geometric parameter values for the store dimensions of the solar hot water store have been calculated based on data from a Swedish manufacturer. The coefficients for the heat transfer to the ambient have been calculated based on data from Persson (2004). The obtained data were consistent with measurement results from the Swiss test institute SPF for several well insulated hot water stores. The parameter values for the internal heat exchanger have been taken from measurements on a suitable heat exchanger from another store. The parameter values for the solar combistore that has been used in system 3 were determined from detailed measurements at SERC and can be found in Persson (2003). The parameter values for the second combistore used in system 4 have been identified and validated for the store SERC3 in the doctoral thesis of Bales (2004).
For the system simulations a typical flat-plate collector with optically selective coated absorbers was used. The parameter values are the same as those that have been used in Task 26 and can be found in (Weiss 2003).

The parameter identification and validation for Type 210 has been primarily based on lab measurements. The setup for the measurements can be seen in Figure 3.2. The parameter identification process comprises of several steps. The heat transfer coefficients of the model described in the previous section have the greatest impact on the thermal performance. As the heat transfer of the boiler is power depended, the heat transfer coefficients in the model are divided in constant and power dependent parameters. For the parameter identification steady state measurements for different combustion powers, which cover the operation range of the boiler, have been performed. Data from these measurements were then used to identify the UA-values by the help of a Visual Basic program containing the mathematical model of the Type 210. This program is integrated in Excel and uses the inbuilt solver to find the optimal parameter values. Other parameters, such as those defining the behaviour of the pellet heater for start/stop phases, were identified directly from the measurement data. The parameters for the thermal masses $m_1$ and $m_2$ were calculated based on the physical size of the boiler. This is followed by a fine adjustment by comparing measured and simulated start and stop sequences. A detailed description of the parameter identification process can be found in Persson et al. (2006a).

In Figure 3.2 the setup of the test stand at SERC for measurements on pellet boilers can be seen, with a boiler on the test stand. The tested pellet boiler is hydraulically connected to a standby store, which can be used as a cooling or heating load for the boiler. Flow rate and inlet/outlet temperatures are measured to calculate the heat removed or supplied from the water mantle of the boiler. The flue gas flow rate is determined by pressure difference measurements with a Prandtl tube in the chimney. The inlet/outlet temperatures of the combustion air are measured in order to calculate the flue gas losses. A gas analyser measures the gas components in the flue gas; carbon monoxide, carbon dioxide, NOx and oxygen. The weight of the pellets including pellet store, from where the pellet fuel is transported to the boiler via a flexible feeding screw, is measured by a weight cell mounted on the ceiling of the lab. The room temperature is measured at different heights for heat loss calculation of the boiler. One temperature sensor is also placed in the water mantle of the boiler at the same position as the sensor for the internal boiler controller.
3.3 Validation

The component models used for the simulation studies of the four combined solar and pellet heating systems in Chapter 4 have been validated earlier except the pellet boiler/stove model Type 210. The standard component models from the TRNSYS library have been used for many years and are validated against real components. The following main non-standard components have been used in the simulations:

- the collector model Type 132,
- the store model Type 140,
- and the boiler model Type 210.

The collector model in Type 132 is a physical model that is also used for testing of solar collectors and is referred as the “Quasi Dynamic Test Method” (Perers 1993). The method is used by testing institutes and researchers for collector tests and, implemented in Type 132, for simulations of solar collectors. The same is valid for the store model Type 140. A validation has been done by Bales (2004) for three heat stores with different designs. For Type 210 some data from earlier measurement have been compared with data from simulations of a pellet stove (Paper VII), which showed a good agreement. However, no proper validation had been done yet for a pellet boiler. Consequently, a validation of Type 210 has been carried out. The validation has been carried out with the pellet boiler described in section 5.2. For the validation simulated and measured data are compared for the same boundary conditions. The measured data used for the validation are different to those used for the parameter identification. For the validation measured and simulated heat transfer rates and the CO-emissions have been compared.
Heat transfer rates

The data used for the validation are from a 9 hrs measurement sequence including start and stop phase. The measurement setup can be seen in Figure 3.2. During the main combustion phase the combustion power has been varied in three steps, 7 kW, 9 kW and 12 kW (see also Figure 3.3). Temperatures and mass flows of the in- and outlets of the boiler have been measured. The mass flow rate of the pellet fuel has been calculated from the change in weight of the pellet store. The weight measurement data contains noise that is mainly caused by the pellet feeding screw transporting the pellets from the pellet store to the boiler. It was necessary to use a noise filter to obtain an usable pellet mass flow rate. The weight of the pellet has been measured with an sampling rate of 10s and averaged for one minute values before filtering. The data have been filtered with the Autosignal (version 3.1) with a denoising filter using the Savitzky-Golay filter option. The Savitzky-Golay is an effective time domain smoothing method based on least square polynomial fitting across a moving window within the data (Seasolve 2003). The following filter parameters have been applied:

- width of moving window: 2
- polynomial model order: 2
- number of passes: 11

During the measurement sequence the boiler was connected to a heat store that in turn was connected to a load. The load values have been varied simulating different load situations as they can be found in real operation. The dashed line in Figure 3.3 shows the load varying between constant values representing the heating load and short or longer peak draw-offs representing the tapping of domestic hot water.

![Figure 3.3 Measurement sequence of the pellet boiler used for the system simulation. The data show the combustion power, the heat rate to the liquid and the load](image)

The resulting energies are compared with the energies obtained from the simulation model. For the simulation the model uses the following measured input data of the boiler:
• the combustion air inlet temperature and fuel mass flow rate,
• the water inlet temperature and mass flow rate,
• the indoor and outside ambient temperature,
• and the mass flow rate of the pellet fuel.

In Figure 3.4 the measured and simulated heat rates to the liquid and the flue gas are presented together with the measured combustion power that is an input to the model. The peaks in the heat rate to the liquid are caused by the load draw-offs. The temperature drop in the water mantle of the boiler is also influencing the combustion power. A lower temperature in the water mantle decreases also the flame temperature which is the controlled parameter of the boiler. The boiler tries to keep the flame temperature constant by adapting the pellet and combustion air flow.

![Figure 3.4 Combustion power, measured and calculated heat transfer rates to liquid and flue gas for the validation sequence.](image)

In Figure 3.5 the relative errors comparing measured and simulated values for the fuel energy power are presented. The relative errors are given separately for the total sequence and the sequence without start and stop phase.
Figure 3.5 Relative errors for the REBUS boiler validation sequence.

The relative errors in transferred energy $\varepsilon_W$ were calculated using Equ. 3.4 where subscript $s$ stands for simulated and subscript $m$ stands for measured.

$$\varepsilon_W = \frac{Q_s - Q_m}{Q_m} \cdot 100\%$$  

Equ. 3.4

The relative error for the total heat transferred to the liquid is less than 1%. The relative errors for the total heat transferred to the ambient and flue gas are significantly higher, 12.9% and -15.1% respectively. This is a big relative deviation but corresponds to only 1% and -1.6% respectively of the total energy flow for this sequence. In addition, it has to be considered that the uncertainty of the measured flue gas flow is relatively high. Furthermore, the energy transferred to the ambient was not measured but calculated with Equ. 3.5.

$$Q_{amb} = Q_{comb} - Q_{liqu} - Q_{flue} - Q_{int}$$  

Equ. 3.5

Where $Q_{int}$ is the internal energy that is stored in the thermal mass of the boiler (Figure 3.6). $Q_{amb}$ is calculated based on the theoretical values of the steel and water mass of the boiler and their heat capacity.
Figure 3.6 Heat flow from the pellet boiler to the standby store and the load. The solid arrows represent measured quantities and the dashed arrows represent calculated quantities.

\[
Q_{\text{int}} = (C_{p,\text{wat}} \cdot m_{\text{wat}} + C_{p,\text{steel}} \cdot m_{\text{steel}}) \cdot (T_{\text{stop}} - T_{\text{start}})
\]  
Equ. 3.6

Where start and stop temperatures are the average boiler temperatures at start and stop of the measurement sequence. Thus, the calculation of \( Q_{\text{amb}} \) as the remaining term in Equ. 3.5 includes the greatest uncertainty of all terms.

**CO-emissions**

For the validation of the CO-emissions the same measurement sequence has been used as for the validation of the heat transfer rates. The CO content of the flue gas was measured with a flue gas analyzer. The amount of emitted CO per time step was calculated with Equ. 3.7.

\[
m_{\text{CO}} = \omega_{\text{CO}} \cdot \dot{V}_{\text{g,dry,20}^\circ\text{C}} \cdot \rho_{\text{CO,20}^\circ\text{C}} \cdot t_s
\]  
Equ. 3.7

\( \omega_{\text{CO}} \) is the volume fraction of CO in the dry flue gas and \( \dot{V}_{\text{g,dry,20}^\circ\text{C}} \) is the volume flow rate of the dry flue gas at 20°C.

The measured and simulated CO-emissions are presented in Figure 3.7. It can be seen that the measured start and stop emissions are significantly higher than the emissions that have been simulated. The parameters identified and used for the simulations are 4.4 g CO (~600 ppm at 11 vol% O2) for the start and 1.4 g CO (~300 ppm at 21 vol% O2) for the stop phase and represent average values identified from a measurement of another sequence with several start and stops. This measurement sequence can be seen in Figure 3.8. During this sequence the boiler was operated with modulating power. The combustion power as well as the start and stop temperatures were controlled by the boiler outlet temperature. This means that the boiler is reducing the combustion power when the boiler outlet temperature is getting close to the default stop temperature. The result is that the boiler finally stops with the smallest combustion power and with little pellets left on the grid. This is how the boiler operation is controlled in the so called boiler mode. During the validation sequence the boiler was controlled with fixed combustion power and was
stopped at maximal combustion power so that much more pellets were left on the grid. This explains the difference in stop emissions. Generally the emissions for start and stop vary a lot and variations of ±100% have been seen. From additional measurements under normal operating conditions it has been seen that the identified parameters for the start and stop emissions agree well with reality.

The comparison in Figure 3.7 shows that during operation the simulated CO-emissions are significantly higher than the measured CO-emissions. The difference between simulated and measured emissions during operation is 32% and for the total sequence 4%. Generally, it is difficult to model the CO-emissions very accurately. The CO-emissions are not only dependent on the actual combustion power and the amount of combustion air but can also be influenced by the fuel properties, the temperature in the combustion chamber and the fouling of the combustion chamber and the heat exchanger. Soot and ash deposits can increase the CO-emissions dramatically (Berg et al. 2001). However, for the purpose of the study the accuracy of the CO modelling is sufficient. An extension of the model taking into account the maintenance of the burner and boiler might increase the accuracy of the model.

Figure 3.7 Measured and simulated cumulated carbon monoxide emissions for the validation sequence including start and stop.
Figure 3.8 Carbon monoxide and flue gas mass flow for a measurement sequence of the REBUS boiler with modulating combustion.
As the market review of IEA Task 26 revealed, there are a large number of system designs for solar combisystems (Suter et al. 2000). The focus in this study is on combined solar and pellet heating for Nordic conditions. For this combination many system designs are possible. Beside the work of Persson (2004, 2006), who was studying the options for the conversion of electrical heated houses with pellet stoves and solar heating systems, no detailed studies have been done on this type of combination.

Solar combisystems are by definition solar heating systems that provide domestic hot water and space heating. Combined pellet and solar heating systems include solar combisystems but also comprise systems where the solar system provides hot water and the pellet heating system provides the space heating and eventually also some part of the domestic hot water.

The simulation studies in chapter 4 investigate the detailed performance of different types of combined systems. The aim was to get information on which system designs are most efficient, how much CO is emitted for given boundary conditions and where the largest potential for optimisation is. Four system designs have been chosen for the simulation study. The choice of the four system designs represents very different systems but typical solutions from the wide range of system designs on the market (Figure 4.1).

In the second part of the chapter an optimisation method for combined solar and pellet heating systems is presented.

4.1 System description and boundaries

4.1.1 Studied systems

Four systems have been simulated representing the variety of system concepts of combined solar and pellet heating systems on the market (Figure 4.1). Two systems with pellet stoves, one air cooled (system 1) and one with a water mantle in addition to being air cooled (system 2). System 3 has a store integrated pellet burner and system 4 has a separate pellet boiler and store. Systems 1 and 2 have separated space heating (pellet stoves) and solar hot water systems with electric auxiliary heating. Systems 3 and 4 are solar combisystems with pellet auxiliary heaters. The four system designs that have been simulated in this study are all available on the Swedish market, with pellet heaters that are sold there. The main parameters for the systems are given in Table 4.1 and the variation of efficiency and CO-emissions with the combustion power for the boilers/stoves is shown in Figure 4.2 and Figure 4.3 respectively. These show the wide range of combustion power (6-20 kW) and CO-emission characteristics.
System 1 is the simplest system using separate units to provide domestic hot water and space heating. A pellet stove transfers the heat to the building by convection and radiation. This requires a building with open interior design in order to allow a good heat distribution to the building. The power of the stove is automatically and continuously modulated according to the room temperature, but has a limiting minimal power. In the specified power operation range between 2 and 6 kW the stove reaches efficiencies between 83 and 89 % under stationary conditions (Persson 2004, Persson et al. 2006a). The domestic hot water is provided by a solar hot water system comprising a 320 litre store and 5 m² of solar collectors. The solar circuit is coupled to the storage by a heat exchanger immersed in the bottom of the store. The auxiliary heat is provided by an electric heater in the top third of the store.

System 2 is rather similar to system 1 but the pellet stove delivers heat to the building in two ways: directly by convection and radiation as in system 1; and indirectly through an inbuilt heat exchanger (water mantle) to the water based radiator system. Approximately 80% of the heat produced can be transferred to the radiator system when the stove is operated under stationary conditions with the maximum combustion power (Persson 2004, Persson et al. 2006a). The stove is on/off controlled by the room temperature, operating by default with the maximum power.

System 3 is a solar combisystem with a store integrated pellet burner and a water based radiator system. All required heat for hot water and space heating is taken from the combistore, the water for space heating directly and the domestic hot water by two immersed heat exchangers placed in the bottom and the top of the combistore. The heat from the solar heating circuit is transferred by another immersed heat exchanger in the bottom of the store. The store integrated pellet burner delivers heat by a gas to liquid heat exchanger consisting of horizontal pipes in the upper part of the store. The burner is on/off controlled by a sensor placed in the storage tank above the burner. The pellet burner has a maximum power of 25 kW, enough capacity for single family houses with a high space heating demand. The burner can be adjusted for summer operation to half of the maximum combustion power, and this is what was used in this study (12 kW). The solar collector area for systems 3 and 4 is 10 m² which is typical for Swedish solar combisystems.

System 4 is also a combisystem but uses a separate pellet boiler as the main auxiliary heat source. The pellet boiler is coupled to the upper part of the store and has an internal water volume of 140 litres. The on/off-controlled boiler contains integrated heat exchangers for hot water preparation, which is common in Swedish boilers, but this was not used in the system. No connections are available to couple the boiler to a solar circuit. Consequently only the space heating part of the boiler was used and connected to a combistore. The pellet boiler has the option for a standby operation where constantly a very little amount of pellet is burned to keep the burner warm. In this study the boiler has not been operated with the standby mode, but has been turned off completely when no heat was demanded. For the CO-emissions a theoretical value for standby emissions has been calculated.
Figure 4.1 Investigated system designs. Two systems with a pellet stove (system 1 and 2), one with a store integrated pellet burner (system 3) and one with a pellet boiler (system 4).
Table 4.1 Overview main system size parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>System 4</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. (min.) power pellet heater</td>
<td>6 (2.0)</td>
<td>11.6 (2.0)</td>
<td>12¹ (8.1)</td>
<td>20 (7.8)</td>
<td>kW</td>
</tr>
<tr>
<td>Max. power load limited pellet heater</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>kW</td>
</tr>
<tr>
<td>Start temperature pellet heater, for stoves the room temperature for the boilers the store temperature</td>
<td>19</td>
<td>19</td>
<td>65</td>
<td>60</td>
<td>°C</td>
</tr>
<tr>
<td>dT for heater start and stop</td>
<td>1.2</td>
<td>2</td>
<td>20</td>
<td>15</td>
<td>K</td>
</tr>
<tr>
<td>CO emission during start phase</td>
<td>0.5</td>
<td>2</td>
<td>1.2</td>
<td>1</td>
<td>g/start</td>
</tr>
<tr>
<td>CO emission during stop phase</td>
<td>1.35</td>
<td>1.2</td>
<td>6.4</td>
<td>6²</td>
<td>g/stop</td>
</tr>
<tr>
<td>Max. radiator heating power</td>
<td>-</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>kW</td>
</tr>
<tr>
<td>Design temperature radiators</td>
<td>-</td>
<td>65/55</td>
<td>40/35</td>
<td>40/35</td>
<td>°C</td>
</tr>
<tr>
<td>Collector area</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>m³</td>
</tr>
<tr>
<td>DHW/combi store size</td>
<td>0.320</td>
<td>0.320</td>
<td>0.631</td>
<td>0.729</td>
<td>m³</td>
</tr>
<tr>
<td>Auxiliary volume pellet heater</td>
<td>-</td>
<td>-</td>
<td>0.265</td>
<td>0.286</td>
<td>m³</td>
</tr>
<tr>
<td>Store height</td>
<td>1.54</td>
<td>1.54</td>
<td>1.43</td>
<td>1.58</td>
<td>m</td>
</tr>
<tr>
<td>Electr. power ignition pellet heater</td>
<td>880</td>
<td>260</td>
<td>654</td>
<td>407</td>
<td>W</td>
</tr>
<tr>
<td>Electr. power pellet heater, constant</td>
<td>2</td>
<td>2</td>
<td>9</td>
<td>5</td>
<td>W</td>
</tr>
<tr>
<td>Electr. power pellet heater, power dep.</td>
<td>23</td>
<td>23</td>
<td>116</td>
<td>116</td>
<td>W</td>
</tr>
</tbody>
</table>

¹ The burner has two main settings: 12 kW for “summer” and 25 kW for “winter”.
² the boiler emits additional 3g CO per hour if kept in standby operation
Figure 4.2 Thermal efficiency versus combustion power of the four pellet heating units and the stove in system 2 with the settings used in the simulations in (Persson 2004) and (Persson et al. 2005).

Figure 4.3 CO-emissions per MJ pellets versus combustion power of the four pellet heating units and the stove in system 2 with the settings used in the simulations in (Persson 2004) and (Persson et al. 2005).
4.1.2 Boundary conditions

The systems have been modelled in TRNSYS as described in section 3.2.1 and 3.2.2. The systems have been simulated for the same boundary conditions that have been used for the simulations of the Swedish combisystem in IEA task 26.

The main boundary conditions are:

- Stockholm weather data (METEONORM 1999) based on long term monthly average values,
- yearly space heating load of about 12200 kWh,
- yearly domestic hot water demand of about 3100 kWh supplied by a tapping profile developed by Jordan and Vajen (2002),
- solar collector and store size were not varied but chosen as typical for a good system performance,
- heat losses from combisystems and from DHW stores are not used as heat gains in the house (except in simulation variant V3 in Paper II),
- boilers and stoves are only used during space heating season. During the rest of the year an electrical heater was used as a backup in the store.

The building model for the simulation has also been taken from Task 26. The SFH 60 model is a one zone model of a single family houses with a specific space heating demand of 60 kWh/m² for Zurich climate. This house model corresponds to a well insulated house. The systems have been simulated for a one year period with a simulation time step of 3 min. The simulations have been performed for several parameter variations which are described in the results section.

4.2 Results

The main findings from the system simulations in Paper II and Paper III are presented. The absolute values shown in section 4.2.1 and 4.2.2 differ slightly from the values presented in the papers. This is due to a wrong parameter setting for the calculation of the solar radiation. This resulted in solar gains that are between 20-30% too low and a space heating demand that is (due to lower passive gains of the building model) 5-10% higher than when using the correct settings. In the following sections the results with the correct parameter settings are presented. The conclusions for the simulation results of the comparison of the systems for different simulation variants have not been effected by this error.

4.2.1 Thermal performance and heat losses

In this section the main simulation results for the study of thermal performance and heat losses of the previous described systems are presented. A detailed presentation of the results and a discussion of the results can be found in Paper II. The systems have been simulated for three variants:

V1 – All pellet heaters are controlled on/off,
V2 – All pellet heaters are modulating,
V3 – The (complete) heating system is place in the heated area of the building.
Some main assumptions need to be considered when evaluating the results of the system simulation:

- The one zone model implies that the heat is freely distributed in the building.
- For the evaluation of the system the auxiliary energies have been calculated based on the heating value of the pellet fuel and used electricity, where the electricity has been calculated with a conversion efficiency of 100%.
- In V3 heat losses contribute to the space heating only if the room temperature is below 24 °C.

The left graph in Figure 4.4 shows the total energy consumption of the systems for the three simulations variants divided into subsections of the particular usage. The right graph shows the total consumption subdivided in the particular heat sources that have supplied the energy. The main findings from the simulations are:

- Stove systems have the lowest energy consumption of all systems if store and boiler heat losses do not contribute to the heating load.
- If the complete systems are placed in the heated area, the combisystems consume as much as or less auxiliary energy than the stove systems.
- Operating the boiler with modulating power is not always improving the thermal performance.
- The performance of each system is very dependent on the characteristics of the pellet heater and the quality of the store insulation.

![Figure 4.4 Total energy consumption (left) and total energy input by source (right) of the four systems for three simulation variants.](image)

**4.2.2 CO-emissions and electricity consumption**

In this section the main simulation results for the study of CO-emissions and electricity consumption of the previous described systems are presented. A detailed presentation of the results and a discussion of the results can be found in Paper III. The systems have been simulated for three variants:
V1 – All pellet heaters are controlled on/off.
V2 – All pellet heaters are modulating.
V3 – The maximal combustion power of the pellet heater has been reduced to 6 kW and control is on/off.

Some main assumptions need to be considered when evaluating the results of the system simulation:

- The one zone model implies that the heat is freely distributed in the building.
- For the evaluation of the system the auxiliary energies have been calculated based on the heating value of the pellet fuel and used electricity, where the electricity has been calculated with a conversion efficiency of 100%.
- Boilers/stoves in V3 are generic, the maximal combustion power has been reduced, but the boiler characteristics from Figure 4.2 and Figure 4.3 have not been changed, just scaled in relation to the new maximum combustion power. The UA-values of the pellet units are kept the same.

The main results are presented in Figure 4.5 and Figure 4.6 and can be summarized as:

- Modulation power reduces the CO emission for 2 of 4 systems.
- The boiler in system 4 has higher emissions due to high start/stop emissions and emissions from standby operation.
- The electricity consumption of the pellet heater is slightly lower if operated modulating.
- Reducing the maximal power of the pellet heaters decreases the CO emission and the total energy consumptions of the systems.

Figure 4.5 Annual CO-emission of four pellet heating units integrated in combined solar and pellet heating systems.
4.3 System optimisation

The results from the previous sections showed that the performance of the systems can be relatively easily improved by the way the stove or boiler is controlled. The main performance figures studied were the auxiliary energy demand and the carbon monoxide emissions. It could also be seen that a design parameter as the boiler size has a large impact on the system performance. However, the boiler operation and the boiler size are only two of several design parameters that influence the system behaviour. In order to improve the system performance those parameters with the largest impact should be optimised. The parameters are not independent from each other, which complicates the optimisation. A manual optimisation can be rather time demanding and the obtained parameter values might not give the best system performance. A better way is to use computer tools that can simplify the search for the optimal design parameter. An optimisation method based on TRNSYS and the optimisation tool GenOpt has been described in Paper IV. In the following section a summary of the paper is presented.

4.3.1 Method

Summarized the method consists of the following steps:

- Lab measurements to identify the parameter for the system components.
- Choice of system on which to apply the optimisation method.
- Modelling of the system in a simulation program.
- Definition of the objective function – discussion.
- Definition of the main boundary conditions.
- Sensitivity analysis: which parameters have the largest impact on the objective?
• Definition of the constraints of the parameters.
• Definition of optimisation method and choice of optimisation tool.
• Application of the optimisation tool.

4.3.2 System description, boundary conditions and modelling

A solar combisystem similar to system type 4 in the previous section was chosen for testing the optimisation method. Except for the store size the system is very similar to the system that has been developed during the REBUS project (see chapter 5). The system consists of a 730 liter store, a 12 kW pellet boiler, a solar collector system with an area of 10 m², a hot water preparation unit and the control unit for the space heating (see Figure 4.7). The upper part of the combistore, the standby volume, is heated by the pellet boiler if not enough solar heat is available. An electrical heater provides a backup for the summer when the boiler is turned off. The solar collector loop, which is normally filled with a water-glycol mixture, is separated from the solar store charging loop by an external plate heat exchanger. The store is charged from the solar system by a stratifying unit that delivers the solar heat to the height in the store with the same temperature as the solar heated water. The hot water unit and the space heating loop are connected to the top of the store. There is a mixing valve to provide the desired tap water and space heating temperature. The return flow from the hot water and space heating loop enters the combistore via a second stratifying unit, ensuring low temperatures for the solar collector.

The auxiliary heater is a pellet boiler that has been developed and tested within the REBUS project. The thermal performance of the boiler can be seen in Figure 5.6. The CO-emissions per MJ fuel are low for maximal power but increase significantly with lower combustion powers. Start and stop emissions are relatively low compared with the other pellet boilers. The boundary conditions such as climate data and DHW load are the same as for the system models described earlier in this chapter. The heating demand has

![Figure 4.7 Schematic hydraulic plan of the system. The grey shading shows the system borders for the optimisation study.](image-url)
been modelled with a load file instead of a building model to save computational time. However, the load file was created for the same house model and climatic and gives essentially the same yearly space heating load.

The modelling of the systems has been done with the same component models as described in section 3.2.2. The parameter values for the collector are the same as in the simulations studies in section 4.2 and 4.3. The store parameter values are the same as used for the store in system 4. The parameter values for the pellet boiler have been identified from lab measurements on the REBUS boiler (Persson et al. 2006a).

4.3.3 Sensitivity analysis

In this section the impact of several system parameters on the performance of the system are shown and discussed. These were chosen based on previous experience and on work in the literature. The impact of these parameters on the objective targets, the annual primary energy use and the CO-emissions, are illustrated in Figure 4.8: auxiliary heated standby volume (a); the hysteresis for the boiler control of this standby volume, dT (b); the minimum boiler power, P_{bmin} (c) and the set temperature for the standby volume, T_{boil} (d). The primary energy use consists of the pellet fuel energy (lower heating value) and the electricity used for heating, based on a conversion factor of 3.0. The parasitic energy use has not been considered.

The lower limit for the size of the standby volume is determined by the DHW load that has to be covered. The upper limit of the boiler power is limited by the size of the actual used boiler. The range for the set temperature of the boiler corresponds to the specifications of the boiler. The boiler was controlled in modulation mode, the lower limit of the modulation range being the value that was varied (Figure 4.8c). A general constraint for all parameter is that the complete space heating and hot water load has to be covered.

The default values for the parameters were: standby volume 140 litres, dT of 15 K, P_{bmin} of 3.4 kW, and T_{boil} of 70°C. All studied parameters influence the number of starts and stops of the boiler which in turn influence the boiler efficiency and the CO-emissions. The total CO-emissions are not a linear function of the number start/stop of the boiler. This can be seen in Figure 4c.

From Figure 4.8 it can be seen that the greatest impact on the primary energy use is the set temperature of the standby volume and for the CO emission it is the modulation band width. The modulation band width influences the number of starts and stops of the boiler and the average combustion power, which in turn influence the CO-emissions.
4.3.4 Objective function and optimisation tool

The objective function is the output function of the system simulation that is going to be optimised. In this study this is a two-dimensional quantity consisting of primary energy use and CO-emissions. The sensitivity analysis has shown that each of the studied parameters has a relatively high impact on the auxiliary energy consumption and/or the CO-emissions. Consequently all parameters have been included in the optimisation process. To get a single objective function ($\phi$) based on these two values, weighting factors have been used, as defined in:

$$
\phi = Z_{aux} \cdot (Q_{base} + 3 \cdot Q_{ass} + Z_{co} \cdot m_{aux})
$$

Equ. 4.1
Where \( Z_{\text{aux}} = 1 - Z_{\text{CO}} \) \hspace{1cm} \text{Eq. 4.2}

and the energy quantities have units of MWh and emissions units of kg.

The complexity of the system and number of independent parameters do not allow an analytical optimization. Instead a numerical optimization is necessary. In this study the program GenOpt (Wetter 2002) was used as GenOpt has already been applied in other simulation studies for parameter optimisation with TRNSYS (Wetter 2001, Bales 2003, Salazar et al. 2003). Several algorithms to solve different optimisation problems can be chosen from the GenOpt library. For this study the Hooke-Jeeves algorithm has been applied (Hooke and Jeeves 1961), an algorithm that has been used in previous studies (Wetter 2001, Bales 2003).

The constraints of the parameters and the step sizes were defined as input data for GenOpt. The chosen range and step size during the optimisation were similar to those used in the sensitivity analysis; however, the algorithm was set to reduce the step size by 50% near a minimum.

4.3.5 Results

The results for the studied system can be seen in Figure 4.9. The optimisation has been performed for five values of weighting factors for primary energy use and CO-emissions. It shows that the primary energy demand can be reduced to 17.7 MWh and the CO emission to 13.7 kg if the system is optimised for both targets with a weighting factor of 0.5. These values are quite close to the individual optima for primary energy use and CO-emissions of 17.3 MWh and 12.7 kg CO respectively, achieved for weighting factors of 1.0 and 0.0 respectively. The same results are achieved for weighting factors of 0.25, 0.5 and 0.75, suggesting that the optimum is fairly flat and that the step sizes for the parameters are relatively large.

![Figure 4.9 Results of the optimisation, depending on weighting factor \( Z_{\text{aux}} \) and \( Z_{\text{CO}} \).](image)

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Chapter 5 deals with the work that has been done within the REBUS project to develop a new solar combisystem for detached houses. The boundary conditions in terms of the requirements from the market, the building and the project partners are described. The system concept is explained with its main features. The chapter focuses on the integration of the pellet boiler into the system design. An overview is given about the testing of the first prototype of this new combined solar and pellet heating system.

5.1 The system concept

The principle system concept and the status of the development of this new solar heating system is described in Paper VI. The following section includes the main content of the article together with an introduction bringing the concept in context with the previous simulation study.

5.1.1 Boundary conditions and system requirements

In chapter 2.1 the country boundary conditions for the development of a new solar combisystem have been described. It could be seen that the largest potential for the implementation of solar combisystems is for existing detached houses that are built in the 1970’s and 1980’s. These houses are built without cellars and heating rooms, forcing the heating system to be placed in the living area, which implies one of the major requirements for the system — a compact design. Further conditions can be summarized as:

- relatively low space heating demand,
- auxiliary heater should be flexible to choose,
- radiator or floor heating system,
- low investment and operation costs,
- high reliability and easy maintenance,
- flexible size of the solar heating part of the system.

Similar conditions for existing houses are found in Denmark. As in Sweden, the focus of the Danish REBUS research group working at the Technical University of Denmark (DTU) was to find solutions for existing houses. Consequently it was decided to develop a joint concept for both countries.

The system concept was developed in close collaboration with industrial partners who were responsible for the manufacturing and later marketing of the systems. The industrial partners contributed with their experience and market knowledge to the development process. As they have to manufacture and market the system they also set constraints in
terms of costs and production feasibility. The concept also had to fit into their product range. Thus the resulting design represents a compromise between optimal performance and constraints imposed by the industry partners. The development steps for the REBUS system are presented in Figure 5.1.

Figure 5.1 Development steps for the REBUS system.

According to the described boundary conditions, especially to achieve the required compactness of the system, it was decided to build the system into cabinets of 60x60x200cm. The system has been built into two cabinets; one cabinet contains the solar tank; and the second cabinet contains all other hydraulic components including the auxiliary heater (Figure 5.2). These are referred to in the following as the “solar store unit” and the “technical unit” in the rest of the thesis. The 60x60 concept has the following advantages:

- 60x60cm is a standard size for kitchen and laundry devices such as refrigerator and washing machines, which is beneficial for the integration of the system in houses without heating room.
- The cabinets give the system an attractive appearance.
- The production facilities for these cabinets are available at the industrial partner.
- Existing cabinet frames can be relatively easily modified to suit the system concept.
- Water tanks, insulation technique and tank connections can be used from the existing production range.

The main disadvantage is that the compact size limits the storage capacity for the solar heat – a typical example for a compromise between economy and system performance. However, the hydraulic concept that will be presented in the following allows larger stores or several stores if the space conditions allow it.

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5.1.2 The hydraulic concept

A number of hydraulic concepts have been discussed with the main industrial partner. The chosen concept uses a simple buffer tank with pipe in- and outlets inserted from the bottom of the tank that is placed in one cabinet. All components necessary for the operation of the system, the auxiliary heater, the hot water and space heating preparation are included in the second cabinet, the technical unit. This has the advantage that the whole space in solar store unit can be used for the solar tank. Another even greater advantage is that the technical unit can be installed independently from the solar store unit. That makes it possible for the manufacturer to sell this part of the system separately as a complete heating system and thereby increasing the market potential of the technical unit. House owners can benefit from this flexibility by adding the solar part of the system at a later time when e.g. more investment capital is available.

The system concept has been developed for the use of different auxiliary heaters. For the Swedish market the most promising solution is the combination of solar with a pellet boiler or stove. A system with a gas boiler is more suitable for the Danish market where, unlike in Sweden, a well extended natural gas distribution system exists. Consequently, two variants of the system concept have been developed, a Swedish variant with a pellet boiler and a Danish variant with a gas boiler.
Most hydraulic components have been put together as modules. One module is the hot water and space heating preparation module. A second module comprises the components for the solar circuits. A modular design is an advantage in the manufacturing process.

![Hydraulic Scheme](image)

**5.1.3 The solar store unit**

The solar store unit contains a simple buffer store with no internal heat exchangers. All inlets and outlets are realized with 18 mm PEX (cross-linked Polyethylene) pipes. The pipes are closed at the end and have holes on the sides near the end ensuring horizontal charging and discharging and preventing mixing of the store. This is a rather simple and low cost solution to achieve and maintain stratification in the tank. To reduce the heat transfer to the cold part in the bottom a second PEX pipe is placed over the inlet and outlet pipes going to the top or middle of the tank. Measurements and simulations have been performed with this configuration and have shown that the system performance is slightly better than with external tank connections (Thür 2005). The hydraulic concept allows the use of other stratifying devices as well as external connections of the tank. This makes it possible to use other tanks that are already installed and shows again the flexibility of the concept.

The external connections, if all in the bottom of the store, simplify the integration in a 60x60 or 70x70 cabinet and allow insulation with very few thermal bridges. The store is totally foamed with Polyurethane and is put on the bottom frame without any metallic connection. Since no fresh water is stored, in principal no corrosion protection is necessary.
5.1.4 Hot water preparation and space heating

The preparation of the domestic hot water in a solar combisystem can be realized with three different concepts: with a tank in tank system; with one or two heat exchangers (one in the bottom and one in the top) immersed in the solar store or with an hot water preparation unit based on an external plate heat exchanger. For the REBUS concept it was decided to use a hot water unit for the hot water preparation. The reasons for that decision are:

- The simplest tanks without any heat exchanger, which might disturb the stratification in the tank, can be used.
- There is no additional legionella\(^1\) prevention necessary.
- A proper designed hot water unit will give low return temperatures to the tank and increase the solar gains.

The latter has been studied very detailed at SERC for several hot water units (Lorenz et al. 1997, Bales and Persson 2002, Persson 2002b). Hot water units have also been studied at AEE and SPF (AEE 1997). The studies at SPF have not been published due to an agreement with the involved manufacturers of the tested hot water units.

A hot water unit creates better stratification than the other two solutions and additionally can better utilize the whole water volume what is essential for small stores. The disadvantages of a hot water unit are that normally an additional pump is necessary and additional heat losses from the pipes and the heat exchanger (Andersen and Furbo 2006b). In addition, there is a greater control effort, which will, together with the higher price of a plate heat exchanger compared to immersed spiral tube heat exchangers, increase the costs. However, in the REBUS system only one pump is used for space heating and hot water preparations and the greater flexibility and higher energy savings justify a higher price.

The domestic hot water preparation is controlled by regulating mass flow and temperature on the source side of the heat exchanger by the speed controlled circulation pump (P4) and a quick acting electronic mixing valve (V4) (see also Figure 5.3). The hot water preparation concept allows the user to choose the tap water set temperature, but the maximal temperature is limited to 55°C to prevent scalds and lime stone deposition in the plate heat exchanger. The Swedish building regulation require that the system must be able to supply at least 50°C at the water taps but not more than 60°C to prevent scalds (Boverket 2006).

The space heating loop uses the same pump and mixing valve to deliver the required mass flow and temperature to the heating system. Radiator and floor heating distribution systems can be connected. A fast switching valve (V5) changes the operation from space heating to DHW preparation or vice versa, based on a signal from a flow sensor in the DHW circuit.

Depending on the return temperature from the DHW preparation/space heating system and the temperature in the tank the return flow is directed to different heights of the store or directly to the inlet of the boiler to keep the bottom of the tank as cold as possible.

\(^1\) Legionella are bacteria that can grow in warm water, ideally with a temperature between 35-46°C. Inhaling or aspirating legionella can cause pneumonia. (Lin Y E 2006)
5.1.5 Auxiliary heater – gas and pellet variant

The wish to use the system concept for gas and pellet boilers requires two system variants. This is mainly due to the different dynamic behaviour of these types of boilers. A gas boiler usually has a small thermal mass and needs only a few seconds to start up whereas a pellet boiler needs 10-20 min until it can deliver heat at the required temperature. The maximal peak hot water demand for a single family house is about 30 kW (filling a bath tub). Both system variants must be able to supply such a heat load at any time. A gas boiler can, provided that the boiler has a peak power of about 30 kW, deliver the hot water demand directly. Gas boilers with smaller maximal power than the domestic hot water peak load and pellet boilers can not deliver the hot water demand directly. A pellet boiler with the size of the hot water peak load would not be suitable for the REBUS system due to the space requirement and the bad performance for the operation with an average load much smaller than the maximal power (Paper II and III).

The solution for the system with a pellets boiler is to use a standby water volume that is constantly kept above the hot water set temperature. This standby volume works as a buffer to cover the hot water peak power. The standby volume can be realized either by a second tank that is placed in the technical unit and keep the technical unit independent from the solar store unit or by using the upper part of the solar store in the solar store unit. For the Swedish system the first solution was implemented. The size of the standby store of 80 litre was a result of the available space in the technical unit, which is enough to supply the heat for one bath tub.

The Danish system uses a 30 kW gas boiler and does not require the standby volume. The chosen condensing gas boilers is very efficient but also rather expensive. The alternative would be the use of a simpler non-condensing gas boiler with a lower power in which case a standby volume would be necessary. The standby volume as an additional tank as it was realized in the Swedish system variant can be seen in Figure 5.8.

The pellet boiler can (and normally should, see Paper II and III) be operated with modulating operating power to keep the number of starts and stops low. The pellet boiler used in the Swedish system modulates the combustion power controlled by the inbuilt controller based on the boiler water temperature.

5.1.6 The controller

A system controller has been developed for:

- the control of the hot water preparation and hot water circulation,
- the space heating,
- the solar circuit
- and to some extent the pellet boiler.

The combustion control of each boiler is complex and can not easily be integrated. Integrating the control routines for the different system circuits and components allows optimizing the interaction of the system components and improving the total system performance.
5.2 The integration of the pellet boiler

As described in the previous chapter compactness and smart appearance are important for the chosen market segment where the units are to be installed in the living space. Typical pellet boilers are due to their size, shape and their connections not suitable for such rooms. A separate boiler would beside the two 60x60 units also further increase the space demand. The space heating peak demand of typical Swedish single family houses is typically below 10 kW (Persson 2004). This allows the use of a small boiler with a relatively low combustion power.

5.2.1 The selection of the boiler

Pellet boilers are available in several variants and sizes (see chapter 2.3). Typical sizes of boilers in Sweden are 10, 15, 25 and 40 kW. Today many of these boilers can modulate the power or at least can regulate the power in steps and have some automatic cleaning and ash removal devices (Bioenergi 2006). The integration of the boiler in the technical unit the outer dimensions needed to be less than 60x60cm. During the design phase in 2004 no suitable pellet boiler was available on the Swedish market. The boilers were too large in size and combustion power. An alternative was found in terms of a water mantled stove from an Austrian manufacturer. The original stove has a size of 60x60x114cm and contains a 38 kg pellet store and the pellet feeding unit between store and combustion unit. According to the manufacturers data 85% or the useful heat goes to the water mantle, the rest to the ambient, which is a good value considering that the stove has no insulation. The stove is rated for a combustion power range between 3 and 12 kW with 10 intermediate modulation steps. This stove was chosen for the Swedish REBUS system due to its compactness, power range and good heat transfer to the water.

The combustion control objective of the stove is the flame temperature. The flame temperature is kept constant for each power step within a certain range. This is achieved by controlling air flow and pellet mass flow. The stove has automatic grate cleaning but the air to liquid heat exchanger and the combustion chamber need to be cleaned manually. The combustion power can be set manually or is controlled by the water outlet temperature depending on whether the stove is operated in the “stove mode” or “boiler mode”. The stove has a controller input that can be used to start the stove externally. Usually this contact is connected to a room thermostat to prevent overheating in the room where the stove is placed. The stove was tested by the Austrian testing institute for agricultural technique showing above average performance and low CO-emissions (BfL 2003). A cross section of the original stove can be seen in Figure 5.4.
5.2.2 Modification and testing of the boiler

Due to the restricted space available it was not possible to integrate the complete stove in the cabinet. Instead, only the core combustion unit has been used for the system. This inner part measures 45cm (width), 30cm (depth) and 88cm (height). This allows integrating the stove in the cabinet and leaves space for piping and insulation. However, a number of modifications were necessary to make the unit suitable for the system concept such as:

- replacing the front window by an insulated front door,
- reconstruction of the pellet feeding system,
- adjustment of the combustion parameter,
- and insulation of the hot parts.

The front window (a door with a window) had to be replaced with an insulated steel door since the unit should be used as a boiler not as a stove. That means that as little heat as possible should be transferred to the ambient. With the same goal, additional insulation has been mounted around the water mantle. With these modifications the stove can not considered to be anymore a stove rather a boiler and is referred here after as boiler.

In the original stove the pellets are transported from the integrated pellet store via a straight feeding screw into a cell lock from where they fall into the combustion chamber. The pellet store and the feeding screw were removed and the cell lock was turned 90°
allowing the mounting of a flexible screw from the side. The length of the screw can be adapted to the distance between technical unit and pellets store.

Changing the heat losses in the front part by the replacement the front window with an insulated door influences the temperature in the combustion chamber. The original front door also had small openings letting air flowing over the inner part of the window to keep it free from soot and ashes. This air was originally contributing to the combustion. In addition, the new feeding screw has a different feeding rate characteristic (Figure 5.5) that is changing the amount of fed pellets for each combustion step and by that the combustion in general. The technical unit was mounted in the test stand at SERC (see Figure 3.2) and tested with the applied modifications. The final tests of the improved pellet boiler were carried out with the insulated boiler but without the outer cabinet sheet plate walls. This results in larger heat transfer to the ambient than in real use, but the objective was first of all to adjust the internal controller parameter to give good combustion.

The modifications worsen the combustion as can be seen from the CO-emissions in columns 4 and 5 of Table 5.1. The CO-emissions are much higher than then for the original stove (column 2 and 3). From the CO₂ values it can be seen that too little combustion air is supplied. This is mainly due to the missing air supplement from the window cleaning. These results showed that the combustion parameters need to be adjusted.

Figure 5.5 Combustion power with the original and modified pellet feeding unit.
Table 5.1 Comparison of measurement results of the original and modified stove/boiler

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original stove</th>
<th>Modified boiler</th>
<th>Improved boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>minimal power</td>
<td>nominal power</td>
<td>low power</td>
</tr>
<tr>
<td>Supplied amount of fuel</td>
<td>0.8 kg/hr</td>
<td>2.5 kg/hr</td>
<td>1.3 kg/hr</td>
</tr>
<tr>
<td>Flue gas temperature</td>
<td>74 °C</td>
<td>138 °C</td>
<td>113 °C</td>
</tr>
<tr>
<td>Fuel capacity</td>
<td>3.6 kW</td>
<td>12.1 kW</td>
<td>6.4 kW</td>
</tr>
<tr>
<td>Heat flow liquid</td>
<td>69%</td>
<td>76%</td>
<td>69%</td>
</tr>
<tr>
<td>Heat flow flue gas</td>
<td>6%</td>
<td>9%</td>
<td>14%</td>
</tr>
<tr>
<td>Heat flow ambient</td>
<td>25%</td>
<td>15%</td>
<td>17%</td>
</tr>
<tr>
<td>Concentr. of CO₂</td>
<td>5.6%</td>
<td>9.8%</td>
<td>4.4%</td>
</tr>
<tr>
<td>Concentr. of CO</td>
<td>180 ppm</td>
<td>146 ppm</td>
<td>525 ppm</td>
</tr>
</tbody>
</table>

The adjustments of the combustion parameters have been done in collaboration with the manufacturer, who gave suggestions for the adjustment and delivered the equipment to program the controller software. The adjustments have been done based on the CO and CO₂ values in the flue gas for three different combustion powers. The new pellet feeding mechanism was adjusted to give roughly the same characteristics as the original feeding system before the internal controller settings were optimised. The set value for the flame temperature has been decreased by 3% and the combustion air was increased up to 7% depending on the combustion power. The results of the combustion parameter adjustments can be seen in Table 5.1 and in Figure 5.6 and Figure 5.7.
Figure 5.6 Heat transfer rates to the liquid and ambient, original stove, after the modifications and after combustion optimisation.
5.2.3 Integration of all components in the cabinet

The limited space in the technical unit made it necessary to use a non-standard tank for the standby store. A standard cylindrical tank 80 ltr would have taken the whole space in the upper part of the cabinet of the technical unit and no space would have remained for the DHW/SH preparation module. Therefore a rectangular 80 ltr store dimensioned to fit into the cabinet was used and later insulated with 5 cm mineral wool. The space behind the pellet boiler was used to install boiler pump, boiler mixing valve and pipe connections between the upper and lower part of the cabinet. In the lower part of the cabinet the hydraulic unit for the solar charging loop was installed. The arrangement of the modules and components can be seen in Figure 5.8.
5.3 Testing of the first prototype system

After finishing the main design phase of the system development and the integration of the pellet boiler the next step was to test the complete prototype. This included the testing of the hydraulic design and the functioning of the electronic controller. Some tests had already been done for the pellet boiler, mainly for the pellet supply and the combustion control, as described in the previous section. The integrative concept of the REBUS system concept includes also the controller. There is one system controller managing the components and their interaction. Only the boiler has a separate controller. A completely new control software was developed by the Danish REBUS partner DTU and the industrial partner. The controller software contains five main control subroutines:

1. Space heating controller,
2. Domestic hot water control,
3. Tank controller,
4. Solar controller,
5. Boiler controller.

For testing the controller software and the behaviour of the components and their interaction the system was connected to three external hydraulic loops, simulating the solar collector array, the domestic hot water demand and the space heating load. For each
test the controlled components and the aim are specified (Table 5.2). One test is here described more in detail, the testing of the DHW unit, as this is the test that required the most further development of the control algorithm.
Table 5.2 Tests performed on the prototype of the REBUS system to verify the controller functions.

<table>
<thead>
<tr>
<th>Control part</th>
<th>Test</th>
<th>Components</th>
<th>Aim</th>
</tr>
</thead>
</table>
| Solar         | Charging of the solar store and standby by solar  | V1, V7, P1, P2 | • Stratified charging of the solar store  
• start and stop solar pumps  
• Antifreeze protection of the heat exchanger in case of temperatures below 0 °C in the collector pipes.  
• Stop if tank temperature is too high and restart after this stop. |
| Boiler        | Charging of the standby store by the boiler       | P3, Boiler start/stop input | If Standby set temperature is too low boiler will be started and charges the store until the set temperature is reached. |
| Boiler        | Full discharge                                    | P3         | When the boiler has stopped the boiler pump will continue running until the boiler outlet temperature is nearly equal to the boiler inlet temperature. |
| DHW           | Hot water tapping with different set temperatures and flow rates | DI1, V4, P4 | If flow sensor DI indicates DHW, V4 and P4 are controlled to prepare the hot water with the desired temperature. |
| Space heating | Space heating start, stop and temperature control | V4, P4, V5 | Start and stop of space heating depending on outside and room temperature. Regulation of the forward temperature depending on the outside temperature. |
| DHW/space heating | Test V5                                         | V5         | Change the operation of V4 and P4 from SH to DHW and back depending on whether there is hot water tapping or not. |
| Store         | Return flow management                            | V3         | Depending on the return temperature of the SH or DHW loop and the tank the return is going to the different levels of the store or the boiler. |
| General       | DHW reservation                                   | V5, V4, P4 | If the temperature in the standby store is lower than the temperature necessary for DHW preparation then SH is suppressed. |
5.3.1 Development of control for DHW preparation

One of the most critical tasks in the system concept is the hot water preparation. As described earlier has the preparation of hot water by an external heat exchanger several advantages compared with hot water preparation with heat exchanger immersed in the heat store. Figure 5.9 shows the hydraulic scheme of the REBUS DHW unit. The DHW unit must fulfill the following requirements:

1. Provide hot water with a constant tapping temperature for a wide range of flows (200-800 ltr/hr),
2. Prevent limestone depositions on the plates of the heat exchanger,
3. Ensure low return temperatures from the heat exchanger to the heat store,
4. Hot water must be available soon after the tapping starts,
5. The tapping temperature must be adjustable by the end user (40-55°C).

The flow sensor DI1 indicates the hot water demand as soon as a water tap is opened. Pump P4 will start to pump water from the heat store through the source side of the heat exchanger. The electronically controlled mixing valve V4 is mixing the water from the heat source to the set temperature of T10. The set temperature for T10 is the desired tapping temperature T12 plus a dT for the heat exchanger. The desired tapping temperature can be chosen from the controller interface. The set value is limited to 60°C to prevent lime stone depositions in the heat exchanger.

To ensure a low return temperature (T11) it is necessary to adapt the flow rate on the source side to the flow rate of the tapping on the demand side of the heat exchanger. This means effectively to regulate the heat rate transferred by the heat exchanger. This was implemented by controlling the speed of pump P4. The flow rate is controlled depending on the tapping temperature T12. If the tapping temperature is sinking below the set
temperature the flow rate on the source side will be increased and if the tapping
temperature exceeds the set temperature the flow rate will be decreased. The dynamic
characteristic of the speed control of P4 has also to reflect quick changes of the tapping
flow rate. Here both V4 and P4 must operate consistently to fulfil this task.

The first tests showed that the speed controlled pump that was originally used was not
suitable for a constant hot water temperature. The internal controller of the pump did not
allow regulating the flow for very small flow rates. As an alternative a conventional
circulation pump that was continuously speed controlled with an external phase modulator
controller, and at a later stage with a frequency converter controller, was used and gave
good results. Another hardware problem was the slow reaction time of the temperature
sensors T10 and T12. The standard NTC sensors are encapsulated in a $\varnothing 6\text{mm} \times 30\text{mm}
metallic cylinder and are connected to the pipe with a clip profile sheet (Figure 5.10 left).
The relatively high thermal mass gives a slow temperature response. A solution was found
for T12 by installing the sensor in a very thin sensor pipe which was placed directly in the
outlet of the heat exchanger. For T10 (and later also for T12) another standard sensor
construction was found with very little thermal mass that was easy to install on the outside
of the pipe (Figure 5.10 right).

After selecting the proper hardware, tests were made used to identify the type of
controller that is necessary to obtain a stable hot water temperature for different flow rates,
set temperatures and operation conditions in the system. The tests have shown that the
best performance can be achieved if both P4 and V4 are controlled by PID. Several tests
were then performed to identify a parameter set giving good results for a wide range of
operation conditions. Figure 5.11 shows a sequence with different flow rates (F4) and set
temperatures for T12. It can be seen that the most critical conditions for the control are
flow rates below 0.3 m$^3$/hr. There is also an overshoot at the start of the hot water
preparation. The amplitude of the overshoot depends on the position of the mixing valve
when the tapping starts and the temperature in the heat store. The controller software was
optimised to avoid situations where the mixing valve is fully open during the start.
However, it can be seen from T12.1 in Figure 5.11, overshoots and small oscillations are
well compensated by the pipe between heat exchanger and water tap. T12.1 has been
measured in a distance of about 4m from the heat exchanger.
5.4 Demonstration system

While the first prototype system was tested in the lab, the design of the second prototype was started. The second prototype system has been installed as a demonstration system during 2006 and is being monitored under real conditions.

It was decided to use the original water mantled stove instead of the integrated boiler. This was due to two reasons:

1. The integrated boiler has shown to work well but the industry partner have not yet been able to make it into a product suitable for demonstration.
2. The variant with a separate stove is an attractive alternative for house where a chimney in the living room exists.

The demonstration system should operate in the houses not only during a monitoring period, but also as the property of the house owner, it should operate as long as a conventional heating system. The boiler has been tested intensively in the lab and was working reliably with the new feeding mechanism. However, the installation of this boiler in a real house requires more product development from the manufacturer side. The boiler controller needs to be updated with the modified parameter settings and a warranty must be provided for the customer before the boiler can be installed. Furthermore, it is necessary to adapt and test the feeding mechanism with a commercial pellet store.

The search for a suitable demonstration house and discussions with the Swedish industrial partner disclosed that the missing chimney in the room where the system could be installed is often a hinder for the installation of the REBUS system. In many houses, especially older houses, there is often a chimney in the living room, connected to a fireplace. A separate stove is a good alternative in such cases and shows the flexibility of the REBUS system concept.
As the boiler for this version does not need to be integrated in the technical unit additional space was available. This space was used for a standard 80 litre tank for the standby store instead of the custom product of the rectangular store in the first prototype. The technical unit has a lower height of only 1.67 cm. This was necessary due to the reduced height of the room where the system has been installed.

Another area of practical development has been solar module (Figure 5.12) that has to fit into the bottom of the technical unit. This has been designed and built together with the Swedish industrial partner. Due to its compact and well thought out design, it can also be used in other systems.

![Figure 5.12. The solar module developed at SERC together with the industrial partner Solentek.](image)

Furthermore, the store capacity has been increased from about 300 liter for the first prototype to 360 liter for the demonstration system. The increase in volume has been achieved by a 5 cm larger tank diameter. Due to the limited space left for insulation, 2.5 cm at the thinnest part, 2 cm vacuum insulation panels were used around the parts with the thinnest insulation. Finite element calculations at the Danish research partner showed that with the vacuum insulation the UA-value for the sides of the new tank is the same as for the old one even though the new one has a larger surface. The vacuum insulation has a lambda value of 0.005 W/mK. In comparison the normally used Polyurethane foam has a lambda value of 0.021 W/mK. Vacuum insulation panels are a very interesting insulation option for advanced stores (Schultz 2004).

<table>
<thead>
<tr>
<th>UA-values stores</th>
<th>Solar store (300/360 liter lab/demohouse)</th>
<th>Standby store (80 liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lab</td>
<td>2.0 W/K</td>
<td>2.6 W/K</td>
</tr>
<tr>
<td>demohouse</td>
<td>1.8 W/K</td>
<td>0.9 W/K</td>
</tr>
</tbody>
</table>

Table 5.3 UA-values of the stores in the lab system and the demonstration system
The comparison of the UA-values of the heat store in Table 5.3 shows that the larger store (360 liter) has even a lower UA-value than the standard store (300 liter). The UA-values have been calculated from measurements in the lab and in the demo house. At the start of the measurements the stores are heated up and mixed. The temperatures in the store and the ambient temperature are measured for a certain time period until the store temperature has been significantly decreased. The UA-value calculation is based on this temperature difference and the thermal mass of the store and is calculated as follows:

\[
UA_s = \frac{m_{\text{wat}} \cdot C_{\text{wat}}}{C_{\text{lat}} \cdot \ln \left( \frac{T_{so} - T_s}{T_s - T_a} \right)}
\]

Where \(T_{so}\) is the average temperature of the store at the start of the measurement, \(T_s\) the average temperature at the end of the measurements and \(T_a\) is the average temperature during the measurement. The thermal mass \((m_{\text{wat}} \cdot C_{\text{wat}})\) is estimated from the water volume of the store that in turn has been calculated from the geometry of the store. The thermal mass of the insulation and the steel of the tank has not been included in the calculation.

The standby store in the lab is a rectangular tank that is insulated with 4 cm mineral wool. The standby store in the demonstration system is a standard cylindrical tank with 4 cm Polystyrene insulation and additional Polyurethane foam insulation in the spacing between the tank and the cabinet.

In the chosen demonstration house the chimney has been used for a wood stove in the kitchen and an open fireplace and a tiled stove in the living room. The technical unit and the solar store unit find place in a small room that was earlier used as a second bathroom. The water mantled stove is installed in the living room connected via copper pipes to the technical unit. 10 m² collectors have been installed on the roof supplying the system with solar heat.

The system was installed in a detached house in Borlänge in July 2006 (Figure 5.13). The system is equipped with monitoring equipment that will record the system performance for at least one year. The first data from the summer months show that the system works as expected. Some minor adjustments were necessary due to changes in the placement of the hydraulic components in the technical unit.
Figure 5.13  Demonstration site during installation of solar collectors (left), and installed solar tank and technical unit (right).
6 DISCUSSION

In this chapter the results from the simulation papers and the previous chapters are discussed.

6.1 Thermal performance

6.1.1 Useful heat from heat losses

In most system studies the heat losses are considered as waste heat due to the fact that the heating system is often placed in a boiler room that is not part of the heated area of the building. The type of building that has been identified as most relevant for this study requires the installation of the heating system in the heated area. The simulation results show that a large fraction of the heat losses can be used for space heating (Figure 6.1). For the stove systems, system 1 and system 2, the heat losses considered are the heat losses from the hot water stores. The heat losses of the solar combisystem, system 3 and system 4, consist of the store heat losses and the heat losses from the burner/boiler. Note that the pellet heaters were turned off during the summer months. That the heat losses can contribute to the space heating presumes that the systems are installed in the heated area and that the heat can be freely transferred to the building. In the simulation this is assumed but requires in reality a building with an open design. With this assumption and considering only heat losses that occur when the room temperature is below 24 °C, between 68% and 91% of the heat losses can be used for space heating (Figure 6.1). In general the potential savings are lower for the stove system since only the heat losses of the DHW store can contribute. The heat from the stoves is already part of the space heating.

These results represent the extreme case of perfect heat transfer within the building. In most cases buildings consist of several rooms, in one of which the heating system is installed. To what extent the heat losses can contribute depends on how good the heat transfer between the rooms is, and especially on whether the doors are closed or not. This has been shown by Persson (2004) who has studied the heat transfer from pellet stoves placed in one room using a detailed multi-zone building model and a model for heat transfer between rooms dependent on whether doors are open or not.

The placement of the system in the heated area might cause an overheating problem. A critical location could be e.g. the kitchen where heat from cooking, electrical appliances and people can cover partly or completely the heat load. Persson has studied systems where water mantled pellet stoves provide heat for space heating and for some cases also domestic hot water for several multi-zone house models. The stoves were placed in the living room or in the hall. His simulations showed that these stoves must have a high heat rate to the liquid (>80%) to prevent serious over heating problems. Even for stoves with
high heat rates to the liquid (as used in system 2) situations occurred where the room temperature exceeded 23°C. In his study the stoves were then turned off and individual electrical radiator panels in the other rooms provided the required space heating during these periods. If the heat stores are also placed in the living area, even bigger overheating problems can occur. This should be studied in more detail by simulations and measurements under real conditions. Recently, a water mantled stove with a heat rate of 95% to the liquid at nominal power has been launched (Wodtke 2006). Such products together with improved insulation of the heat stores and pipes could be a solution for the overheating problem.

![Graph](image)

Figure 6.1 Effective store, boiler and burner losses of the four systems depending on their placement. Grey columns for placement outside the heated area and black column for placement inside the heated area, where heat losses are heat gains only if the temperature in the building is below 24 °C.

6.1.2 Impact of electrical heating

The presented studies show that the stove systems have, if heat losses do not contribute to the space heating, the best thermal performance. However, this is based on two important assumptions: the heat can be freely distributed within the building, and that the electricity used is taken into account with a conversion efficiency of 100%, whereas the calculated boiler/stove efficiency is used for pellet energy. Systems 1 and 2 use more electricity than systems 3 and 4, due to the fact that the auxiliary heat supply for domestic hot water is electricity, and only approximately half the hot water load is covered by solar. The pellet stove in system 2 is water mantled and can in principle be connected to the hot water store to replace the heat produced by the electrical heater.

In Table 6.1 the total auxiliary consumption (pellet + electricity) of the four systems is shown for three scenarios for on/off control and modulating control. In the first scenario it is assumed that the electricity used for heating was produced with a conversion efficiency
of 90% which can be considered the case for Norway with a high share of hydro power. For the second scenario the auxiliary electricity has been calculated with a conversion efficiency of 40% which is comparable with the average European mix. In the last scenario the electricity used by system 2 has been replaced by heat from pellet assuming an efficiency of 80%.

The results in Table 6.1 show that the stove systems perform worse than the solar combisystems if electricity is taken into account with the European conversion factor. The combisystems perform better as long as they do not need much electricity as backup for summer operation. System 2 has lowest energy consumption for the third scenario where the water mantled stove is coupled to the top of the domestic hot water store and replaces the electrical heating. Persson (2004) has simulated this system among a large variety of other stove systems for a number of houses. The comparison shows also in his study that this system performs better than others.

The combisystems could also perform better if a boiler/burner with load optimised combustion power would be used and the tank in system 3 is better insulated. The hot water stores in systems 1 and 2 are stores with good insulation standard, whereas the heat losses from the store in system 3 are relatively large.

Table 6.1 Total primary energy use [kWh] assuming store and boiler heat losses do not contribute to space heating. The fields with grey background indicate the best values for the specific scenario and case (modulating or on/off).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>System 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ηConvEl=90%</td>
<td>16907 16782</td>
<td>16972 18425</td>
<td>18361 18828</td>
<td>18523 17280</td>
</tr>
<tr>
<td>ηConvEl=40%</td>
<td>20003 19898</td>
<td>20087 21507</td>
<td>19088 19500</td>
<td>18976 17680</td>
</tr>
<tr>
<td>ηConvEl=40% and system 2 with all pellet</td>
<td>20003 19898</td>
<td>17283 17833</td>
<td>19088 19500</td>
<td>18976 17680</td>
</tr>
</tbody>
</table>

6.1.3 Seasonal operation of the boiler

Figure 6.2 Auxiliary energy demand during the summer months for the four systems. For seasonal operation the pellet units are turned off during the summer months. An electrical heater functions as a backup when not enough solar heat is available. Figure 6.2 shows the auxiliary energy usage, with electrical conversion factor of 100%, of the four systems during the summer months June, July and August. It can be seen that the combisystems consume significantly less auxiliary energy if the burner/boiler is turned off during the summer months and instead the electrical backup heater provides the DHW demand (Figure 6.2). This confirms the results by other simulation studies (Bales 2003, Persson et al. 2006b). This is due to the poor efficiency of the pellet heaters for small loads, 64% for the burner in system 3 and 52% for the boiler in system 4. Similar results have been obtained from measurements on gas and oil boilers during summer operation (Thür et al. 2004). The pellet burner in system 3 has almost no thermal mass and very little surface for heat losses and has therefore a better efficiency, but causes higher heat losses of the store due to the fact that the upper part of the store in system 3 is poorer
insulated than the store in system 4. This is the reason for the high electrical auxiliary demand when the burner is turned off. With an electricity conversion factor of 0.4 (for the European electricity mix) the primary energy savings would still be 19% for system 3 and 73% for system 4. This is not only due to pellet fuel saving but also due to higher solar gains when the auxiliary is provided with an electrical heater with somewhat lower set temperatures than for the pellet heater. For the summer months the solar gain will then increase by 12% for system 3 and 8% for system 4 respectively. There are no changes for the summer operation of the stove systems. The stoves provide only heat for the space heating.

![Graph showing auxiliary energy demand](image)

Figure 6.2 Auxiliary energy demand during the summer months for the four systems. For seasonal operation the pellet units are turned off during the summer months. An electrical heater functions as a backup when not enough solar heat is available.

### 6.1.4 Other factors

Operating the pellet heaters with modulating power can improve the thermal performance (Figure 4.4) but this depends, as for the CO-emissions, on the characteristic of the burner, mainly the air factor for the different combustion powers. An automatic combustion air control, based on measuring the flame temperature or the composition of the flue gas, and an automatic cleaning systems for the heat exchanger and the burner would ensure optimal combustion conditions.

The heat losses from the burner in system 3 and the boiler in system 4 differ significantly. The losses to the ambient and the flue gas losses are much smaller for the burner in system 3 which is due to the smaller surface and the large air to liquid heat exchanger (Figure 4.4 –left). However, the store losses of system 3 are much higher, some of which can be attributed to the connections of the burner and the exhaust pipe at the top of the store which cause thermal bridges. Generally, a one unit system as system 3 has the potential to be more energy efficient than a system with a separate boiler, due to the reduced heat losses from the connecting pipes and reduced total surface area. Improved
tank insulation would reveal this for system 3 more clearly. Such a system also saves space and installation cost. One of the most efficient solar combisystem tested within Task 26 was such a system with an integrated gas burner (Weiss 2003). Larsson (2000) has also studied the boiler/store from system 3 and his results agree with those here.

Both systems 3 and 4 have significant leakage losses when the burner/boiler is turned off. The leakage air flow is caused by the temperature difference between the water volumes of the store (system 3) or the boiler (system 4) and the outdoor temperature. The leakage losses account for 250 kWh for system 3 and 540 kWh for system 4. A leakage prevention mechanism should be installed in these systems.

Sizing the boiler according the space heating peak load gives better thermal performance. This can be seen from Figure 4.6 (right). This can be attributed to the longer operation time of the pellet boilers with lower losses from start and stop. However, the pellet heaters for this simulation variant are generic and the results need to be validated for real stove and boilers. From the latest market review it has been seen that some manufacturers have responded to the new demand for small boilers. Three boilers with a maximal combustion power below 12 kW can now be found on the Swedish market (Bioenergi 2006).

6.2 Emissions

6.2.1 Control strategy

Modulating combustion power can reduce CO-emissions compared to on/off operation. However, the CO-emissions reduction is dependent on the relation between start/stop emissions and emissions during operation for different combustion powers. It also depends on how many starts and stops can be saved, which in turn depends on the load that is to be supplied. Figure 6.3 shows that no improvement for the two stove systems with modulating power (V2) can be seen compared to on/off control (V1). On the contrary the stove in system 2 even emits more than three times the amount of CO when operated with modulating power. This is contradictory to the simulation results from studies by Persson (2004) and Persson et al. (2005) for the same stove. The main reason can be found in Figure 4.3 showing the specific CO-emissions for the same stove with the parameter values used by Persson (stove system 2 with optimised air factors) and the parameter values used for this study (stove system 2). The high emissions for low combustion power illustrated in Figure 4.3 are caused by the great combustion air surplus cooling down the temperature in the combustion zone of the stove. The parameters for the combustion air factor used for these simulations were obtained from measurements of the stove with the default air factor settings, whereas Persson adjusted the settings in-situ to get improved thermal performance (see Figure 4.3). This suggests that it is to be recommended that the air settings be adjusted by the installer at the installation site. The extremely low CO-emissions for system 2 for on/off control can easily be understood by the low emissions at full power (12 kW) and the relatively small number of starts/stops and their related emissions.

The results in this study for system 1 also differ compared to the results from Persson. The modulating operation reduces the CO-emissions significantly in Persson’s study, whereas in this study almost no difference can be seen. Persson used a multi-zone house model and electrical heaters as backup ensuring a good thermal comfort. This results in shorter operation times of the stoves and a higher number of starts and stops (~4600 for
system 1 and ~1800 for system 2). Operating the stoves with modulating combustion power reduces the number of starts and stops drastically (~700 for system 1 and ~400 for system 2). For the one-zone house model used in this study there are fewer starts and stops and thus a relatively small contribution to the annual CO-emissions. Thus a further reduction in the number of start/stops causes a small change in the total emissions which is balanced by the higher emissions during operation with low power.

Operating the pellet burner/boiler units in system 3 and 4 with modulating combustion power decreases the CO-emissions by 9% and 13% respectively. Both burner and boiler have relatively constant and comparatively low emissions for different combustion power (Figure 4.3) so that the lower number of starts and stops are not balanced by higher emissions during operation with lower combustion power. Even more starts and stops could be saved if the pellet heaters would be sized according to the peak load of the space heating. This is important, as the contribution of the start/stops for the combisystems is nearly half of the total emissions during the year due to the large value for individual start/stops.

Keeping the boiler in system 4 in standby (by constantly combusting a little amount of pellet) increases the CO-emissions dramatically. The assumption here is that the start emissions are the same as if the boiler would not kept in standby. This has not been investigated in detail and the standby operation has not been included in the system simulations. Instead, the standby emissions in Figure 6.3 have been determined by separate calculations based on measurement of the boiler during standby operation.

![Figure 6.3 CO-emissions for start/stop, normal operation and standby of the pellet heaters in the four systems. The three variants are the same as described in section 4.2.2.](image)

Modulation of the combustion power can also reduce the stop emissions as has been described in section 3.3. The stop emissions for the studied boiler were significant lower when the boiler stopped at the lowest combustion power compared to when the boiler stopped with highest combustion power. This can be attributed to the lower amount of
pellet smouldering on the grid during the stop phase. The burner in this study was working with the top fed principle. It should be investigated if the CO-emission could be reduced in this way even for bottom fed burners and horizontal fed burners. For the simulations in chapter 4 this effect has not been taken into account.

6.2.2 Comparison with emission regulations

The example of system 2 shows how important correct combustion air settings are for a good thermal performance and low CO-emissions. Ash, slag and soot deposits in the air to liquid heat exchanger and the burner can also affect thermal performance and CO-emissions. Measurements on system 3 during the PESTO project have shown how quick CO-emission can increase if burner and heat exchanger are not regularly cleaned and the ash box is not emptied (Berg et al. 2001). The CO-emissions exceeded the Swedish CO limit values of 2000 mg/m³ relatively shortly after the burner/heat exchanger were cleaned. Figure 6.4 figure shows the measurements results of the daily average CO-emissions of the burner. The manufacturer recommends a weekly cleaning of the burner and heat exchanger in the tank. When the lines are interrupted the system has been stopped for cleaning and maintenance. On the 12th of December new turbulators have been installed with a larger air resistance. From the 19th of December the CO-emissions increase drastically within short time. This can be explained by the new turbulators which cause more and quicker deposits of ashes and soot in the heat exchanger and the high heat load during these days with higher ash and soot release. On the 4th of January the burner and heat exchanger were, unlike the earlier cleaning cycles, cleaned very carefully and the ash container was emptied. It can be seen that the CO-emissions are after that cleaning relatively constant and it can be concluded that unburnt pellet particle smouldering in the ash container have contributed to the earlier increase of CO-emissions. Modern stoves and boilers with automatic combustion air control and automatic cleaning of heat exchanger and burner and ash removal system can probably better ensure proper functioning of such system with low emissions and high efficiency. Such boiler have also the advantage that they require much less maintenance by the user. This can be a big advantage for customers who were used to heating systems that require no or very little maintenance by the user. Such customers probably prefer when changing heating system to have again a system with little maintenance requirements.
As Table 2.1 in section 2.3.2 shows there is a trend towards more stringent limit values for emissions and boiler/stove efficiency. The building regulations of the Swedish National Board of Housing Building and Planning do not specify limit values (Boverket 2006) but recommend the testing of biomass boilers according the European Standard EN 303-5. The EN 303-5 requires tests at nominal and minimal effect of the boiler. The limit value for CO is 3000 mg/m$^3$ and most pellet heaters have no problem to fulfill these requirements. A benchmark for Swedish pellet burner and boiler is the P-mark certificate from the National Testing and Research Institute (SP). The requirements for CO-emissions are stricter for CO (2000 mg/m$^3$) and OGC (75 mg/m$^3$) and need to be fulfilled at nominal power (load) and at partial load of 20%, 40% and 60% of the maximal load. The future benchmarks are set by Eco-labels such as the Svan-mark of the Nordic Ecolabeling and the Blauer Engel-mark in Germany. The limit values for these labels are given for nominal combustion power and low combustion power. For the Swan-mark the boilers and stoves are tested similar to SP with nominal and three partial loads. The specified limit values for the emissions must be met for the nominal combustion power and an average of the three tests with lower combustion power. The German Eco-label Blauer Engel specifies separate limit values for nominal and the lowest possible combustion power.

Start and stop emissions are not included in these tests, or only partly if the lowest applied load is lower than the lowest combustion power. However, as Figure 6.3 shows, they can stand for a large fraction of the total annual emission. Thus, the start and stop emissions on a yearly basis should be included in future regulations and labels.

In Figure 6.5 the CO-limit values for the two Eco-labels are shown together with the CO-emissions from the four studied systems, all in mg per MJ pellet fuel. The rather high limit value of the Standard EN 303-5 of 1314 mg/MJ is not indicated in this Figure. It can be expected that also the limit values from the Standard will more stringent in future. In Figure 6.5 it can be seen that only system 2, if on/off controlled, would fulfil the recently proposed limit values for the Svan-mark if the start and stop emissions and realistic conditions are taken into account. None of the stoves and boilers would fulfil the
requirements for the Blauer Engel-mark. The dashed area shows the emissions of the stoves and boilers at nominal combustion power measured at SERC. These are higher than the required level for the most stringent eco-label and the average annual emissions are even much greater except for the stove in system 1 that has very little start and stop emissions. This shows the limitation of the limits, set for simple constant loads, as used in the current norms and eco-labels, and suggests that they should be revised to include an estimation of total annual emissions based on the operation of the boiler and the average load.

Note that for system 4 only the emissions for start/stop and normal operation are included but not the emissions for standby. These emissions have been excluded because no measurement data for the pellet consumption during standby were available.

Figure 6.5 Average annual CO-emissions of the four systems in mg per MJ pellet fuel in comparison with limit values of the Eco-labels Svan-mark and Blauer Engel-mark according Nordic-Ecolabelling (2006).

A number of pellet boilers have obtained the Svan-mark and Blauer Engel-mark (Blauer Engel 2006, Miljömärkningen 2006), which shows that the requirements are not too stringent. In some countries governments and local authorities encourage the installation of pellet boilers and stoves with subsidies which are tied to Ecolabel products and/or low emissions (Pettersson 2005). This gives manufacturers with Ecolabel certified products an advantage on the market compared to other competitors.

Combining solar and pellet heating systems can reduce significant CO-emissions compared to operating only a pellet heating system. This combination prevents the summer operation of the pellet heater with low efficiency and high emissions. In addition, the pellet heater can, if coupled to the solar combistore, heat a larger water volume resulting in longer operation hours and less start/stop emissions. Simulations have shown that the CO-emissions for a solar combisystem are 45% lower compared to a pellet
heating system using the same boiler (Persson et al. 2006b). Thus, the emissions for systems with large sized pellet boilers and without solar heating will be even greater than those shown in Figure 6.5 and consequently even further away from the eco-label limits.

### 6.2.3 Other emissions

It has been shown that emissions can be significantly reduced and boiler efficiency increased if the pellet boiler uses a modern automatic combustion air control (Eskilsson et al. 2004). This study shows that operation strategy, proper sizing and use of solar heating can reduce CO-emissions. Carbon monoxide is an important part of the total emissions and is a good indicator of the combustion efficiency. However, there are also other emissions from pellet boilers and stoves. Studies have shown that the level CO is not the only indicator for emissions (Olsson 2006). A good combustion efficiency decreases CO and other emissions but can increase emissions of other OGC as Figure 6.6 shows.

![Figure 6.6 Proportion of antioxidant methoxyphenols and carcinogenic benzene for applied biomass combustion at increasing combustion efficiency (Kjällstrand 2002).](image)

The boiler model should be developed to include other emissions than CO so that annual values can be obtained for realistic applications. Olsson and Kjällstrand (2006) recommend to include methane, benzene and representative polycyclic aromatic hydrocarbons in future limitation values for pellet boilers.

### 6.3 Electricity consumption

The electricity consumption of the boilers/stoves is lower when operated in modulating mode (Figure 4.6-left). This is mainly due to the lower number of starts/electrical ignitions. The boilers in this study use more electricity than the stoves. This is due to the greater maximum combustion power, which requires stronger electrical devices and longer feeding units as the pellets need to be transported from external stores. No improvement can be seen for the boilers/stoves with load limited maximal combustion power, in fact electrical use is larger due to the longer running times. However, for V3
with reduced combustion power, the electrical use was assumed to be the same as for the full power versions. For the stoves, this is probably relatively accurate, but for the boilers a lower electrical use for pellet feed and fans is to be expected if the combustion power is reduced so significantly.

6.4 Optimisation

The application of the optimisation method for one system showed that it is possible to obtain design parameter sets for low auxiliary consumption and low CO-emissions at the same time. As expected, optimizing for either only CO-emissions or only primary energy use gives better values for the respective target compared to optimizing both targets simultaneously. However, the differences are not large: 17.3 MWh contra 17.7 MWh for primary energy use; and 12.7 kg CO contra 13.7 kg for CO-emissions. The CO-emissions are lowest when the boiler is operated on/off. This is a bit surprising but can be explained by the relatively low start/stop emissions of this boiler and the low specific emissions at nominal power. That means the higher start/stop emissions which are caused by the on/off control are balanced by the lower emissions during operation. This is only valid if a boiler heats a relatively large standby volume with a large dT so that the number of start and stops are not very much higher compared to when the boiler modulates the combustion power.

The method can in principal be used for all kinds of combined systems provided that the input data for the TRNSYS components are available or can be obtained from measurements. Some data could be taken from the certification tests from testing institutes. The boilers and stoves are usually tested with constant operation conditions for the maximal power and for different loads smaller than the maximal load. The latter might not be tested in steady state which might make it necessary to perform additional steady state measurements. If the thermal performance and the CO emission are not linear at least two more test points with lower combustion power are required. Additional measurements are necessary to obtain parameters for the modelling of the start and stop phase of the boiler. These are necessary for any estimation or calculation of annual emissions.

Different weighting factors to combine primary energy use and CO-emissions to a single value have been studied. For the given boundary conditions of load, solar collector and store size a weighting factor of 0.5 based on energy units of MWh and emissions units of kg was shown to give a good compromise for the two values. Weighting factors of 0.25 and 0.75 gave the same results due to the relatively large step size and presumably a relatively flat optimum.

The results could be further refined by decreasing the step size in the setup of the optimisation tool. Eventually a parameter set with even better results could be found. However the improvements would probably not be significant. The optimisation runs are rather time demanding since the system is modelled in detail with a time step of 1.5 min. This is certainly a disadvantage of the method but can be compensated with increased calculation power. The optimisation has been carried out only with the Hooke-Jeeves algorithm from one starting point which the sensitivity analysis had shown to give reasonable results. Further work could concentrate on multi-starts using the same algorithm, or other algorithms could give better optima, as suggested by other studies (Wetter 2001, Krause et al. 2002). However, the main focus of the study was whether it
was possible to get low (near minimum) values for both the emissions and primary energy use with the same parameter set, and this has been shown to be possible.

The results are based on the boiler characteristic and the control strategy of the boiler and the interaction between boiler and store. For boilers with different characteristics or control strategies, different optimisation results might be obtained. Thus, the achieved parameter combination is only valid for this specific configuration. Nevertheless, the way the boiler is connected to the store is very common and the characteristics of the boiler are similar to other pellet boiler of this size. Consequently, it can be expected that with the same parameter configuration also good result would be achieved for boilers with similar characteristics.

6.5 Rebus concept and system development

The development of the REBUS system concept and the scientific work for this thesis has been carried out in parallel. Not all results from the system simulations were known when the system concept was developed. Constraints from the industrial partner had to be considered. It has been shown that it is possible to build the technical unit extremely compact in a 60x60x200cm cabinet, including the pellet boiler, the standby store, the hot water and space heating preparation and the solar loop module for the solar collector loop. The actual built system is suitable for houses with no heating room but, due to the restricted size for the two units, can not give high solar fraction. However, the flexible concept makes it possible to have a large solar fraction by using a larger store and going away from the 60x60 constraints or with several stores. Alternatively, the heat could be stored in the building itself, concrete floor heating or PCM walls, but this has not been studied yet.

A prototype of a pellet boiler based on a commercial water mantled stove with very low CO-emissions has been designed and adapted to the system concept. The modifications on the stove required a readjustment of the combustion control. Figure 5.7 shows that the adjustment gave similar or lower CO-emissions for the prototype boiler. The boiler has lower emission compared to the pellet heaters used in the system simulations (Figure 6.7). Insulation and optimised combustion air settings improved the heat transfer rate to the liquid by 6-9% and by that the boiler efficiency with the same percentage (Figure 5.6)
Figure 6.7 CO-emissions of the four pellet heaters used in the simulation in comparison with the REBUS boiler.

The system is still rather complex with many hydraulic components. The complexity reflects the high effort to achieve the highest thermal performance. A simplification study should be done investigating which components can be saved with the smallest performance losses. Due the time limitation this has not been done yet.

There is a serious constraint for the combination of solar and pellet heating systems such as the REBUS system. Most houses that have been built in the 1970’s and 1080’s have not chimney. It has been turned out the houses owners tend do avoid an additional investment for the chimney and install instead a heat pump system. This has become more obvious during the search for a suitable demonstration house and has been confirmed by the Swedish industry partner who already markets combined solar and pellet heating systems.

The monitoring of the demonstration system will give the possibility to evaluate the system concept under real conditions. The fractional solar savings for such a small system are of great interest. Furthermore, answers to possible overheating problem will be given. Temperature sensors have been installed in the living room where the stove is installed and in the separate room where the system is installed.
Rising energy prices for fossil fuels and electricity encourage house owners to look for alternative solutions of heating systems. Combined solar and pellet heating system are an environmental friendly alternative offering reliable heating for low energy costs in future.

In this study typical solutions of this system type have bee studied by the help of dynamic simulations with the aim to evaluate their performance and their suitability for the installation in houses with limited space for heating systems. The results have been used as a basis for the development of new system concept of a solar combisystem for the Nordic market.

For the simulation study four typical system solutions of combined solar and pellet heating systems have been selected, modelled and simulated for one year. Two of the systems comprised a pellet stove, which provides the heat for space heating, and a solar heating system for the domestic hot water production. One stove was an air heating stove, the other one was water mantled stove, which supplies the heat to the building via a radiator system. The other two systems were solar combisystems, one with a store integrated pellet burner, the other one with a separate pellet boiler.

The stove systems have a lower energy consumption as the solar combisystems provided the auxiliary electricity is taken into account with an conversion factor of 100%. This is mainly due to the higher stove efficiency and the lower heat losses of the domestic hot water stores systems. If the auxiliary electricity is taken into account with a conversion of 40% and/or the systems are placed in the heated area, so that the heat losses can contribute to the space heating, the combisystems need less or a similar amount of auxiliary energy.

A seasonal operation of the pellet heaters by using an electrical heater for the auxiliary heat demand in the summer months is benefic. Even with an electricity conversion factor of 0.4 between 19% (system 3) and 73% (system 4) of the primary energy can be saved. This is due to the low efficiency of the pellet heater in the summer and due to higher solar gains with lower set temperatures for the standby volume.

The CO-emissions of the systems depend strongly on the characteristics of the specific pellet unit, the control of the pellet unit and the number of starts and stops. The latter is strongly dependent on the way how the heat from the pellet unit is transferred to the building. Modulating combustion power reduces the number of starts and stops and prolongs the operation time. For the most pellet units the lower number of starts and stops reduces the CO-emissions, except for those having much higher CO-emissions at low combustion power than at nominal combustion power (system 2). In general, the operation strategy of the pellet heater should be decided by the characteristics of the boiler and the operating conditions in the system.
The obtained annual CO-emissions represent the dynamic behaviour of the pellet heater. This gives emission values for the operation of the pellet units under realistic conditions. These values are higher than the values obtained from the standard test methods. From the comparison of the annual emissions with the limit values from Eco-labels can be seen that most pellet heaters would not fulfil the requirements. Future test methods should determine the annual CO-emissions for realistic operating condition. More efforts are necessary from the manufacturers of these systems to reduce the CO-emissions; by a improved combustion and system control.

There is a large potential for system improvements. As mentioned a proper control of the pellet heater can reduce the CO-emissions but also reduces the auxiliary consumption. The heat losses can be dramatically reduced if the pellet heater is dimensioned according to the size of the peak space heating load. An optimisation of the main design parameter of the pellet heater and the heat store can give significant improvements in terms of CO-emissions and primary energy use.

Automatic combustion control, automatic heat exchanger, burner cleaning and ash removal would ensure constant combustion conditions with high efficiency and low emissions and would probably improve the comfort and acceptance of the customers.

The electrical consumption of the pellet heaters could be reduced. The two pellet heaters of the combisystems consume (without pumps) up to 2% of the auxiliary energy. The stoves consume less then a quarter of the pellet heaters of the combisystems, even they use similar technique for lighting and feeding.

The studied systems are suitable for the Nordic market but only partly suitable for houses without boiler room. The stove system 1 with an air pellet stove is a good solution for houses where no water based heat distribution system is available. With this system comfortable temperatures in the whole building can only achieved it the building has a open plan structure or an air based heat distribution systems.

System 2 with the water mantled stove requires a water based distribution system. The stove needs to have a great heat rate to the water (>80%) and should if possible be placed in room with good heat exchange to other rooms of the building to prevent local overheating. The solar domestic hot water system in system 1 and 2 can be build in a 60x60cm cabinet which simplifies the integration in the building. The SDHW system allows to turn off the stoves in the summer increasing their efficiency and reducing emissions. The disadvantage of a separate stove and SDHW system is that a big part of the DHW demand and store losses during the heating season must be covered with electricity. Alternatively the water mantled stove could be coupled to the DHW store and replace the electricity.

The solar combisystems would technically fulfil the requirements but are physically not suitable for the use in the detached houses without heating room. In order to be integrated in e.g the laundry room or the kitchen the store but also the boiler need to be more compact preferably in not larger than 60x60x200cm. The systems have also rather high heat losses which can cause overheating problems if they are installed in a relatively small room without heat transfer to the rest of the building. A suitable system must also fit from its appearance to such a room. This means it should not look like a boiler or store rather than a refrigerator or washing machine. Furthermore, are owners of houses that have previously been heated with electricity often not willing to spend time with maintenance of the heating system. The studied systems are for these reasons not or only under certain conditions suitable for houses without heating room.
For any of the systems a chimney is required which is in houses built in the 1970’s and 1980’s often not available. Owners of such houses tend to avoid additional investment and prefer to install other system solution, e.g. heat pumps. Alternative solutions with reduced requirements on chimney should be investigated and solutions where the heating system is a unit separated from the building.

Within the REBUS project a completely new compact solar combisystem has been developed that can be used in houses with very little space for the heating system. The system concept allows the use of different auxiliary heaters. The Swedish system variant has been designed for the use with small pellet boilers or water mantled pellet stoves. The system is built in two 60x60 units, where in one of the units the solar store is integrated and in the other unit all hydraulic components. It has been shown that it is possible to build this unit including the pellet boiler, the standby store, the hot water and space heating preparation and the module for the solar collector loop. The 60x60 approach limits the solar store size and by that the solar fraction, but the flexibility of the system concept allows the extension of the system or the installation of a larger stores. A prototype has been tested and further developed in the lab. A second prototype has been installed in a house in Borlänge and will be monitored for one year. The system uses a water mantled pellet stove that is placed in the living area. The results from the monitoring will be used to evaluate the system performance and to obtain information about the system behaviour under real conditions.


8 Future Work

The work of this thesis deals with a wide field between theoretical investigations and the development of a new system concept of a combined solar and pellet heating system. It was not possible to study all interesting aspects and new questions occurred during the work. More work should also be carried out on the tools and the method that have been used in this study. The aspects that should be object of further studies are the following:

- The simulation model for the pellet heater Type 210 should be improved by calculating other emissions and particles. The modelling of the thermal mass of the water mantle with a single node model is unsatisfying. A multi node model would improve the modelling of the dynamic behaviour of the pellet heaters.

- It should be investigated how more accurate measurements of the pellet fuel weight or the pellet mass flow can be realized. Improved measurements would allow a better analysis of the dynamic behaviour of the pellet heaters.

- The present method for the parameter identification of Type 210 is time demanding and requires accurate measurements. An improved method should be developed with a better accordance to measurement data.

- It should be studied more in detail how the heat losses from the system, if placed in the living area, affect the temperature in the room where the system is installed depending on the room size and the insulation value of the system.

- The prototypes of the Swedish REBUS systems have been modelled in TRNSYS, but no system simulations have been done yet. Simulations should be performed to compare the two system designs, the one with the integrated boiler and the one with the water mantled stove, with each other and with the other systems simulated in this study. The simulation results should be compared with measurement in the lab and the measurements from the demonstration system. The simulations should also be used to study the overheating problem in more detail and to optimise the system design parameters.

- The variant with the integrated pellet boiler should be further developed in collaboration with a manufacturer of pellet boilers. The combustion control should preferably be automatically controlled based on flue gas sensors.

- The potential of flue gas condensation should be investigated and, if possible, simpler and less expensive chimneys could be used for the condensed flue gas.
• New materials with higher heat capacity to increase the store capacity should be investigated, while keeping the system as compact as possible. This could increase the solar fraction and a larger standby volume could improve the performance of the pellet stove/boiler by reducing the start and stops.

• A cost benefit analysis of simplifications of the REBUS system design should be performed.

• Improved solutions for the integration of the heating system and the pellet storage and transport system should be developed in collaboration with house manufacturers and other industry partners.

• Another focus for the research and development for competitive solar heating systems should be on systems for new houses. Here is a large potential for the development of systems that can reach high solar fraction.


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**Paper I:** Fiedler F. The state of the art of small-scale pellet-based heating systems and relevant regulations in Sweden, Austria and Germany. *Renewable and Sustainable Energy Reviews*. 2004; vol. 8, no. 3, pp. 201-221.


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**Paper III:** Fiedler F, Bales C, Persson T and Nordlander S. Comparison of carbon monoxide emissions and electricity consumption of modulating and non-modulating pellet heating systems. Accepted for publication in *International Journal of Energy Research*. 
Part II

Included papers