Development of a Dynamic Modelling Technique for Sizing Wood Chip Boilers

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Abstract

Scandinavian countries in particular have low winter temperatures and rural areas with low building densities. It is quite common in these situations to build small and medium size district heating networks to provide buildings with heat. These networks incorporate typically one boiler house that takes care of the heat generation. This boiler house is equipped with one or more suitable boilers that may be oil or gas fired or they may consume some solid fuel which is often wood based, mainly wood chips or pellets. This kind of district heating (DH) system is owned by the municipality, energy service company/co-operative or both. In many cases the municipality owns the network but the heat supplier owns the boiler house and other equipment that relate to the heat production.

The purpose of this study was to develop three models that allow more accurate dimensioning of wood chip boilers.

- The first model developed was a steady state one. It relied on average temperature data and the supposition that the need for heat in buildings is almost linearly dependent on the outside temperature.
- The second model was divided in to two sub-models; a dynamic model for an annual heat consumption calculation in a single building and a dynamic model that enables the connection of the consumptions of several buildings of a district heating system to be studied on an annual basis.
- The third model was a short term simulation model that makes it possible to study interactions in the district heating system including the boiler plant, the distribution network and the consumer sub-stations.

According to the study, the steady state model gives satisfactory results, notably if the domestic hot water consumption is estimated to be somewhat more than it evidently is. The steady state model gave smaller percentages of annual heat production for the wood chip boiler if its capacity was less than approximately half of the peak, compared with

the dynamic model. As the capacity of the wood chip boiler was more than approximately half of the peak, the steady state model gave bigger percentages for the wood chip boiler than the dynamic model. The turning point seemed to relate to the minimum sustainable output of the wood chip boiler so that as the minimum output came down the turning point went up.

The study gives some general outlines about the dynamics of the system. One of the most useful is the understanding that a peak in the network immediately causes a certain load in the boiler plant, and another load takes place when the cooled water returns from the consumer to the boiler plant. If the consumer is located close to the boiler plant and the peak lasts for a while, these two loads may overlap. By proper sizing of crucial pipelines, the designer may impede the overlapping and size the boiler somewhat smaller.

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Contents

1. Introduction

1.1 Background

In Northern Europe, particularly in Scandinavian countries where winter temperature tends to fall rather low and rural areas with low building densities exist, it is quite common to build small and medium size district heating networks to provide buildings with heat. Those networks incorporate typically one boiler house that takes care of the heat generation. This boiler house is equipped with one or more suitable boilers that may be oil or gas fired or they may consume some solid fuel which is often wood based, mainly wood chips or pellets. These kinds of district heating (DH) systems are owned by the municipality, energy service company/co-operative or both. In many cases the municipality owns the network but the heat supplier owns the boiler house and other equipment that relate to the heat production.

Wood fuels have been in use throughout the history of mankind. Since man learned to utilise fire for heating, illumination and cooking, the main fuel has been wood if it has been available. Using branches and logs as fuel continued till the industrial revolution when coal, natural gas and oil gradually replaced wood as a main source of energy. Wood based fuels are, however, rising again because it can be seen that fossil fuel reserves do not last forever and burning fossil fuels releases huge amounts of carbon oxides into the atmosphere where they probably cause a temperature rise and climate change. There is a mutual understanding that carbon dioxide among other gases causes what is called the green house effect: High frequency solar radiation passes it easily in its way to the globe. The reflecting radiation with a longer wavelength does not pass the gases in the atmosphere that easily but part of them reflect back to the earth causing a temperature rise.

When it comes to heat generation, it does not – in the short term – matter very much whether one burns coal or wood. Both include carbon that is released to the atmosphere in the form of carbon dioxide. The amount of carbon dioxide released is pretty much the same per produced heat unit because carbon is the main combustible element both in wood and coal. The difference can be seen in the longer term: Whereas burning coal releases carbon that has been away from the atmosphere for millions of years, burning wood releases carbon that has been extracted from the atmosphere during past decades. And the same amount of carbon will be extracted again provided that new trees are allowed to grow and felling does not exceed annual growth. That is why wood fuels can be called renewable fuels. Using them does not actually increase the carbon dioxide content in the atmosphere.

Logs are suitable for open fires and manually fed boilers and are still widely used in places where there is no need to use the fireplace or boiler when nobody is present. District heating boilers are, however, supposed to be capable of working on their own; therefore a certain level of automation is required. Feeding logs in a combustion chamber is difficult to arrange automatically. As the particle size becomes smaller and more homogenous it is easier to build up an automatically operating fuel feeding system for a boiler. The smallest boilers tend to use wood pellets as fuel. Medium size and larger boilers are typically run on wood chips.

Pellets are made of wood powder or dust by pressing the raw material in a special machine to a high pressure for a short period of time. That makes the lignin work as a glue and the result is a very homogenous fuel both in size and in heat value. Pellets have a cylindrical shape with a diameter of less than 10 mm and length around 20 mm. The bulk density is approximately 600 kg/m^3 and the lower heat value around 4.7 kWh/kg. Moisture content is extremely low; typically less than 10 per cent (weight basis).

Wood chips can be made of whole trees including branches and needles, logging residues or round wood. Also slab wood and other (sawmill) industrial by-products can be used. Chips are produced in a chipper that may be driven by a tractor or a lorry or may be a stand alone unit. The size and shape of wood chips is not as uniform as is the case with pellets: Wood chips have approximately the size and shape of a medium size or large coin. The hydraulic diameter is around 20 – 40 mm and the thickness is something like 5 mm. The bulk density is approximately 200 kg/m^3 and the lower heat value, depending on the moisture content, is between 1.7 and 4.1 kWh/kg. Moisture content varies between 20 and 60 per cent (weight basis). It is difficult to make the chips drier than 20 % without artificial drying. On the other hand, chips containing more than 60 % water are practically impossible to burn in any incinerator without an additional energy feed. In general, smaller units require more uniform and dryer fuel than the larger ones which are capable of handling bigger particles and more variations in the moisture content.

Heat entrepreneurship is widely adopted at least in Finland and Austria. The idea is that local people create a co-operation or a company to take care of heat production. In most cases these people own some woodlands and are capable of providing the boiler plant with wood fuel. Very often they use small diameter wood from thinning, logging residues from clear felling and other material that is difficult to sell to the saw or paper industry. They also operate the plant. At least some of them become familiar with the boiler plant and take care of boilers and other equipment. They bring wood chips to the storage, monitor the plant regularly, carry out the de-ash operations and even sweep soot from boilers when necessary. In case of malfunction they get alarms to their cell phones, so they do not have to stay in boiler houses if everything seems to be working fine. Some heat entrepreneurs own the boiler plants they run, some operate units that are owned by someone else. Heat entrepreneurs are paid by the heat they generate and supply in the heating network, so it is their own problem if they use low quality fuel which causes alarms and restless nights. In many cases the entrepreneur is liable for supplying heat whatever the situation. If they have trouble with the wood chip boiler, they have to produce the heat with a back up boiler which typically uses light oil as fuel. As light fuel oil is a lot more expensive than wood chips, it makes financial sense to the entrepreneur to try to produce heat from wood chips as much as possible and limit the usage of oil to the minimum.

Wood chip heating systems have become much more reliable than they were some thirty years ago. They are, though, many times more complicated than similar oil or gas fired heating systems. This is mainly due to the nature or the fuel; however uniform wood chips are they are still solid fuel and cannot be fed through pipes and controlled by valves. The fuel storage and the whole feeding system are large, rather expensive and include many parts that can get jammed or broken. It is always possible that foreign particles e.g. stones or icy clumps are delivered to the fuel storage with wood chips. They may cause a lot of harm in the fuel feeding system. The boiler is also rather complex compared to an oil or gas fired boiler. Solid fuels take much more time to incinerate than liquid or gaseous fuels. That makes the boiler bigger and thus more expensive.

There are basically two reasons for installing back up boilers. One is that due to the complexity of the system it is probable that sooner or later some problems occur with the wood chip system. It is also possible that broken parts cannot be mended or replaced just like that, which can lead to a rather long system down time, and it is something that cannot be tolerated. The other reason for installing back up boilers is that as wood chip boilers are rather expensive, they are usually sized not for the peak load but somewhat lower. The peak is then covered with oil or gas. The back up boiler may also be used during low load periods, typically in summer.

The district heating system incorporates the boiler house, piping network and the heat consumers i.e. buildings that draw heat from the system. Heat is generated at the boiler house, delivered to the consumers in the form of hot water through the supply pipeline which is insulated and situated below the ground. In the building there is a sub-station which separates the district heating system water from the building's heating system. The sub-station includes typically two or three heat exchangers: One for the heating system (radiators or floor slab), the other for domestic hot water preparation and possibly a third one for pre-heating the ventilation supply air if such a system exists in the building. In the heat exchangers, heat transfers from the supply water to the secondary side which leads to a certain temperature drop in the primary side. The cooled water then travels back to the boiler house through the return pipeline which is situated beside the supply pipe. Pumps in the boiler house keep the circulation on. The primary supply and return temperatures plus the flow rate are measured at the sub-station. The amount of transferred heat can then be calculated. It is in the heat supplier's interest that the temperature drop in the primary flow is as big as possible at the sub-station, because a high temperature drop means low flow rates which, in turn, mean low pumping costs.

1.2 Objective and method

The objective of this study was to compare two sizing methods for a wood chip boiler plant. The first one, some variations of which have been in use for a long time, was based on average prevailing temperature data and the other one takes into account most of the variables that have an impact on the demand for heat in buildings. Finding out the reliability of the sizing method for wood chip boilers and district heating systems that is based on average prevailing temperature data was the essential objective. The method of the study was to introduce the sizing methods and then carry out a case study with them. Three calculation applications in Microsoft Excel have been developed as part of the study and they are introduced.

What makes both this study and one of above applications special is that the operation of the boiler plant including all the main components, district heating network and heat consumer sub-stations are connected. In most studies and computer applications, it is possible to observe only one or two aforementioned factors. As a matter of fact, no equivalent studies nor computer applications have been found. Of course, such studies or applications can exist, though.

1.3 Review of the thesis

The structure of the work is as follows: The first Chapter brings out some fundamentals that relate to using wood as fuel and small district heating systems. A literature review, covering some studies and computer applications that relate to the subject matter of this study, follows in the second Chapter. Then, in Chapter 3, the development of a steady state model to determine the size of a wood chip boiler is introduced. A case study, in which the above model is used, follows directly. Chapter 4 presents the development of three dynamic models: The first one is for calculating the annual division of the need for heat in a single building. The second one connects the above annual data of several buildings and adds the district heating network so that the result is knowledge of the demand for heat of the whole district heating system through the year. The third model is for simulating short-term fluctuations in a district heating system which is comprised of the boiler plant, the distribution network and the heat consumer equipment. Chapter 5 introduces an application of the two first aforementioned models. The same case that was studied with the steady state model will be studied again with the dynamic models. In Chapter 6, some short-term calculations with the third dynamic model are carried out. They relate to the same case study as calculations in the previous chapter. Discussion of results achieved with the application follows in Chapter 7. Finally, conclusions and further research needs are given in Chapter 8.

2. Literature review

2.1 Introduction

Literature on district heating (DH) systems focuses on rather large installations. The studies incorporate statistical mathematics for predicting the behaviour of the consumers, so that the heat production unit would be able to anticipate the changes in the need for heat even before the changes take place. Another area of interest is the heat loss from the pipe work. Several studies have been carried out concerning the impact of insulation thickness, pipe installation methods or DH water temperature on the heat loss. Of course, several studies have also been carried out on heat production units. The emphasis, though, is in the generation of heat, not in the interaction between the heat production unit and the consumers. The available software is mainly suitable for modelling or simulating the behaviour of the heat consumer. These programs take into account many sophisticated things such as the thermal mass of the building or available heat gains. Some programs focus on the DH network.

2.2 Research on district heating systems

Regarding small and medium size district heating systems Dahm [1] investigates the interaction between the DH network and the consumers. Both the network and the buildings were modelled, buildings especially in detail. The tool is TRNSYS and the simulation period is one year. Measurements from two small DH systems were carried out to compare and validate the results. The task of the study was to describe the thermal performance of small district heating systems as a whole. To achieve this, the DH system was divided into three parts: The load, the house sub-stations and the heat distribution system. Hourly weather data, recorded by Swedish meteorologists, were used. The heat capacity of the buildings was taken into consideration. To achieve that, among other things, a typical reference building was introduced. As for the sub-stations, those equipped with heat storages were modelled in a different way from those including just heat exchangers and control valves. As domestic hot water (DHW) consumption takes place in rather short periods, the simulation time step for it was only 2 minutes whereas for heating and ventilation it was 15 minutes.

Different variations of district heat distribution systems were modelled: Two pipes and four pipes modules (where DHW and heating water flow in separate pipes) and different supply and return design temperatures. The idea was to find the most cost effective design temperatures and pipe module concepts.

When it comes to the simulation program, the utilised weather data included the outside temperature and solar radiation. User habits included domestic hot water usage and room temperature. Thermal capacitance effects included both the heat capacity of the building and the distribution pipes. Transport effects included heat transport effects, particularly the speed of the heat carrier in the distribution pipeline.

The reference building was defined to fit average requirements of new Swedish houses. It made it possible to compare different system alternatives of a small district heating network regarding heat distribution, house sub-stations and house heating systems. Infiltration, ventilation, window types and shading, internal heat gains (including occupants, lights and other electric power consumption) and radiator heating models were included in the model. On the other hand, heat generation was excluded from the model.

The selected tool, TRNSYS, made it possible to model buildings, heat exchangers, heat stores, control valves, pumps and space heating systems rather effortlessly. The emphasis of the study was not on the modelling of the above components but on the validation and the results achieved. The consumption of domestic hot water causes difficulties in this model, because even though the typical times when DHW is consumed are known, it is not known exactly in which building the consumption takes place, as it is probable that not every consumer uses hot water simultaneously. This makes some inaccuracy in modelling the distribution network. As heat generation was left out from the model, it is presumably suitable for systems where there is plenty of hot water available, for example some sub-systems of larger district heating networks.

Aronsson [2] carried out a study on energy consumption of a large amount of buildings. The measuring project took place in the city of Gothenburg, Sweden and it lasted for 18 months. Flow rates and temperatures, for example, were measured. Interesting data on domestic hot water consumption in residential buildings were gained. In the study, it turned out that it is rather difficult and laborious to find out the correct initial data: For example, building floor areas can be gained from the local building authorities but they are quite often contradictory to data achieved from other sources. What is more, the actual heated area is normally somewhat bigger than what is said in the records. This is due to the fact that some parts of the building cannot be included in the living area even though they need to be kept warm. Renovations tend also to increase the heated area, but the documents are not always revised. The study did not include any modelling but it contains valuable data on the variation of the heat consumption in buildings.

Larsen *et al.* [3] studied how the dynamic properties of a DH network change if the network is simplified drastically. The simplification was needed to reduce simulation time, as it was known that simulating a complete network is very complex due to the large amount of variables. The method includes the calculation of the flow and temperature distribution in the network and taking into account the pressure drop and heat losses. The first step is to calculate the primary flow at each consumer sub-station. This was done by using the logarithmic mean temperature; the heat exchangers were not modelled, though. The calculation procedure incorporates basically three steps: Calculating the flow and return temperature at each sub-station, calculating the flow in the network which is based on the flow at sub-stations and, finally, calculating the temperatures at different points of the network which are based on the flow rates, initial temperatures and heat losses. Then the same procedure starts again. Not only the heat capacity of the water flowing in the network was included but also the heat capacity of the steel pipe is taken into consideration when calculating the flow temperatures. The heat loss from a pipe is calculated considering the flow temperature to be constant through its travel from the inlet to the outlet. It was thought that as the temperature drop is small in an insulated pipe, the deviation caused from this simplification is negligible.

The method was validated by applying it on a real case study, in which a network with over a thousand pipes was reduced to less than ten pipes. The results showed that such relatively simple networks are able to maintain most of the dynamic characteristics of the original networks. Reduction is done by bunching up customers which are geometrically close to one another. The drawback of the model is – as neither the heat consumers nor heat exchangers were modelled that it assumes the return water temperature from all the heat exchangers to be equal.

Benoysson *et al.* [4] have an economical approach to the operation of the boiler plant. In a DH network the time lags are big which affects in many ways the optimisation of the system. The idea was to trace the temperatures and temperature related physical properties of water at different points (nodes) in the network so that the operational (mainly pumping) costs could be maintained at the minimum. The heat capacity of both the water and the steel pipe were included in the model.

The heat loss was calculated between nodes based on the inlet temperature, flow velocity, ambient temperature and the total U-value of the insulation and the surroundings. The pipe size, flow velocity and the distance between the nodes give the time a certain water mass spends in its way between two adjacent nodes.

The model assumes that secondary side temperatures of the heat exchanger at a customer sub-station as well as heat load at a given moment are known. The primary side return water temperature can thus be calculated rather effortlessly.

The iterative calculation procedure checks at each calculation step whether the base load boiler is capable of generating enough heat to meet the needs of the consumers. If necessary, the back-up boiler is taken into operation. The boiler plant itself was not modelled in detail, though it is possible to determine it to be a combined heat and power (CHP) plant. In this case, optimisation of power production is included. The study did not try to predict the heat demand but it assumed that the time dependent demand is known and it tried to find solutions for optimising the supply water temperature at different situations so that the total costs would be at the minimum.

The model can be useful for the operator of a medium size or large boiler plant. The dynamics of the network was modelled properly but as neither the boiler plant nor the consumer were included in the same detail, the simulation of the whole system from the heat production to its consumption cannot be done with this model.

Larsen *et al.* [5] compared two aggregated models for simulation and operational optimisation of district heating networks. The first one was developed in Denmark and the other one in Germany. The models are defined for a steady state situation but, according to the study, they can be used for dynamic simulation with good accuracy. Both models incorporate simplifying the network by means of changing a tree structure to a line and removing short branches. The Danish method assumes that all primary side return flows have the same temperature as they leave the heat exchangers and after that they start to cool slowly due to the heat loss to the ground, whereas the German one assumes that the return temperatures are constant. The heat loss coefficients are adjusted so that the heat balance is kept. The same difference is in the supply pipes: In the German model, the temperature of the flow is constant but the Danish one takes the cooling into account. When it comes to pressure drops in the pipe work, the German model is more specific incorporating the pipe surface roughness and fittings such as tees and elbows, for example. The German model is capable of removing loops from the network by transforming them into serial pipes or splitting them to two serial pipes and a branch. The Danish method does not have the corresponding ability. The heat consumer's heating installations are handled in a more specific way in the Danish model: It calculates the primary return temperature as a function of heat load, primary supply temperature, secondary side temperatures and the heat transfer area of the heat exchanger; The German model uses a prescribed return temperature which is a function of heat load (outside temperature) and supply temperature, which also depends on

outside temperature. That is to say that neither of the models are capable of handling domestic hot water peaks, as such.
Both models were tested with a DH network close to Copenhagen in Denmark. The total length of the DH pipe work was approximately 8.3 km. There were some 8000 dwellings, five schools and a city centre with many shops and institutions connected to the DH network via 23 sub-stations. The building density compared with the length of the pipe work was very high. That is why the annual heat loss was only some 3 per cent. The measurements included at each sub-station primary and secondary supply and return temperatures, pressures in the supply and return lines and cumulating heat consumption readings. The interval for reading above data was 5 minutes and the total measurement period lasted 5 days in December 2000. The heat supply from the boiler plant was measured at the same time. The standard deviation of the error between the real and calculated heat production at the plant and the real and calculated return water temperature at the plant were used as evaluation criteria for the models. It turned out that both models work well provided that the network was not over-simplified. According to the study, the Danish model allows the number of pipes to be reduced from 44 to 3 without significantly increasing the errors in the case study. With the German method, the minimum number of pipes was around 10.

These two methods focus on the dynamics of the network and possibilities to make a network with several nodes plainer without losing the accuracy of the simulation. The Danish model includes rather sophisticated consumer calculations, which leads to fairly accurate return water temperatures from the heat exchangers provided that the heat loads and the design values of the heat exchangers are known. The German model, on the other hand, focuses more on the flow dynamics in the pipe work and uses constant values at consumer sub-stations. The generation of heat was not included in these two models.

Dotzauer [6] created a simple model for prediction of loads in district heating systems. Stochastic models that incorporate detailed modelling of the network and utilisation of accurate weather forecasts often face problems due to insufficient measured data (temperature, flow and pressure) in the network and lack of suitable weather forecasts. The simple model was based on the assumption that the demand for heat can be described sufficiently well as a function of the outside temperature and the behaviour of the heat consumers. As only the total heat consumption of a building is typically known, it is important to divide it somehow to the outside temperature dependent and non-dependent parts. The study pointed out that not even the outside temperature dependent part of the heat consumption depends linearly on the outside temperature. For example, in summer when space heating is not required, fluctuations in outside temperature do not affect the need for heat. The same goes for the coldest periods in the winter when heating equipment work with their full output all the time, cooling of the outside temperature does not change the situation.

The study presented a method for calculating the demand for heat of all the buildings as a whole in different outside temperatures. Parameters are selected so that the outcome is sufficiently close to the measured data. They can also be used in taking into account the influence of the wind, for example. The behaviour of occupants (in particular the utilisation of domestic hot water) was assumed to follow yearly, weekly and daily patterns. The yearly pattern can be found in historical files. If the number of consumers has changed significantly from previous years, it was advised to use data from a few previous weeks and extrapolate it to cover the whole year. The weekly and daily patterns are modelled by using relevant parameters. In many cases it may be so that weekdays have one consumption profile and weekends another or all the days of the week have the same profile, if distinction between different days cannot be found.

The model was validated with two separate district heating systems in Stockholm, Sweden. In contrast to a real situation, weather forecasts were not used but measured outside temperatures were fed in. In these two case studies, the relative error between the real heat consumption and the calculated one was in the region of 6 to 8 per cent in the winter and 13 to 15 per cent in the summer (when the behaviour of the heat consumers plays bigger part than in the winter). The model is far more simple than many other, more sophisticated ones that are used for the same purpose. Yet, it gives satisfactory results for predicting heat demand in the network provided that accurate weather forecasts are available and the behaviour of the heat consumers follows a regular pattern that can be identified.

Heller [7] studied heat load modelling for large DH systems and introduced a 'basic model': A general load model where it is assumed that loads are a composition of additive elements that are based on physical theory. The necessary parameters and the significance of the load components can be found by analysing data that has been measured at an existing DH system. According to Heller, for a typical DH system four components can be found that together make the total heat load: Space heating for buildings, domestic hot water preparation, distribution heat load and additional work-day loads. The last one means loads that are dependent on the day of the week. Some simple models were presented briefly in the study, the degree-day method was one of them. Of simulation methods, a steady state model where temperatures and flow rates are kept constant was compared briefly with dynamic simulation which can handle changing surroundings to a given system by computing the characteristics for the system in very short intervals, time steps. Within a time step the simulation may be similar to the steady state computation. According to the writer, there are two basic paradigms for building dynamic models: stochastic and deterministic. The former good for handling arbitrary load patterns, such as the simultaneousness of consumer based heat consumption like taking shower. The latter have the ability to explain things in a more physical manner. In the study, Heller focused on a deterministic model where the load is found for rather short periods, for example minutes or hours, and the system boundaries are constant during the simulation period. The model was built by using TRNSYS as a simulation tool. It made it possible to model several sub-systems separately. In the work, three representative time series for heat loads were applied to avoid modelling the dynamic behaviour of the buildings. This is a vastly used method since typical heat loads are a lot easier to handle than the thermal dynamics of a building. Three different types of buildings were modelled. They represent typical buildings connected to a Danish district heating network.

As for the domestic hot water usage, a stochastic model developed in a previous study was adopted: Four categories of loads were included: 1) Small draw-off, like washing hands, 2) Medium draw-off, like dish washing, 3) Baths and 4) Showers. Each category is represented by a Gaussian-distribution curve describing the interrelation between the flow rate and the number of draw-offs. What is more, the following factors are considered: Yearly, weekly, daily and weekday influences are taken into account by means of probability coefficients. The probability of the demand during the year is described by a sinusoidal function with an amplitude of 10 per cent. The probability in relation to the weekday was described for each category. For the daily distribution, profiles are defined for each category, defining together a profile with two peaks in the mornings and evenings with a constant demand during the rest of the day and no demand at all in the night. The holiday distribution was defined by dates. For defined holidays the probability distribution for the hot water consumption was reshaped for the given day. The stochastic approach leads to significantly lower domestic hot water peaks because the model does not suspect the consumption to take place simultaneously in all the buildings.

The model includes not only the heat distribution losses in the district heating network but also heat losses that take place in the building's pipe work. When it comes to the latter, the author says that domestic hot water circulation (to make hot water available very fast from any faucet) causes, according to literature, a huge heat loss compared with the heat loss from the actual hot water flow but, as the results differ a lot from source to source, circulation heat loss in buildings was left out from the model.

Dynamic simulation of heat losses from the DH network was carried out by simplifying the structure of the network before the actual calculation. The author pointed out that most of the reported network simplifying concepts are either poorly documented or not easy to apply. However, it was considered necessary to simplify the structure of the network to avoid very extensive calculations.

The model was tried with a case of a network connecting 1320 buildings. They were mainly old, single-family buildings. The total length of the district heating network was some 4000 metres. Annual heat loss was, according to measurements, approximately 23 per cent. The domestic hot water consumption doubled in the summer due to tourism. It was noticed that without adjustment, the model gave too high a load in the winter and too low in the summer. After finding and correcting the appropriate parameters, the model gave results that correlated well with measurements. The study brought out that models incorporating several parameters need to be validated with a real case, which in turn demands extensive measurements. If such data for validation are not available and the parameters cannot be estimated reliably, the author preferred the degree-day method.

Lundgren *et al.* [8] studied experimentally the operation of a 500 kW wood chip boiler during fluctuations in the need for heat. The boiler was a grate type one, but the construction of the combustion chamber was more sophisticated than what can be found in a typical grate type boiler. There was also a heat storage water tank with a volume of about 35 m^3. This size of heat storage can seldom be found in a 500 kW boiler plant. The initial idea for installing such a tank was to gain the following five benefits: 1) The heat storage can be used to cover temporary heat load peaks instead of taking a back-up boiler into operation. 2) It can be used to counter-balance the thermal output of the wood chip boiler and this way improve the combustion efficiency by limiting the starts and stops close to the minimum. 3) Smoother operation decreases the emissions of harmful pollutants. 4) The heat store can be used as a heat reserve during short maintenance periods such as sooting or de-ashing or during breakdowns. 5) In case of a failure of the district heating pumps, the storage tank is able to take the heat generated by the boiler for so long that the boiler output has come down to a level that would not cause the boiler water to overheat. The fuel feed rate of the boiler is controlled by adjusting the time between the piston strokes. The piston causes the grate to travel and thereby the fuel on the grate moves towards the lower end of the grate and more fuel enter at the upper end, simultaneously. The time between the piston stokes depends on the space heating demand, moisture content of the fuel and running time of the fuel feeding screw. Also the boiler water temperature controls the fuel feeding rate so that the boiler water does not overheat. The primary and secondary air plus flue gas rates are calculated according to the piston stroke rate. New operational values are calculated every hour based on changes in the heat consumption.

Experimental simulations were carried out with the boiler. Heat load fluctuations in three different seasons: winter, summer and spring/fall were simulated assuming that heat demand depends linearly on the outside temperature so that the heat demand is at its minimum at +17 °C and at its maximum when the outside temperature is -30 °C. Heat load peaks caused by domestic hot water consumption were set manually to take place in the morning, at lunch-time, at dinner-time and in the evening. The heat load peaks were intended to last for about one to two hours and to be in the range of 150 to 200 kW. The experiments were carried out with the boiler alone and with the heat storage tank. The results brought out that the boiler alone was capable of increasing its output by some 10 kW/min but the combination of the boiler and the storage tank could make an increase of some 40 kW/min at the beginning of the peak. The final conclusion of the study was that for a small district heating system, a large heat storage tank helps to keep the boiler in operation during the summer when heat demand fluctuates most and it also helps to keep the boiler operating smoothly which, according to measurements carried out, prevents emission peaks. The aim should be to operate the boiler at as constant a thermal output as possible.

Böhm *et al.* [9] monitored the energy consumption in a district heated apartment building in Copenhagen, Denmark. Their specific interest was in the thermodynamic performance of the building. The living area of the building was 2090 m^2 and it consisted of 35 apartments. There were two heat exchangers separating the building from the district heating network; one for space heating and the other one for domestic hot water (DHW) preparation. The latter system also incorporated a 1 m^3 hot water tank in the secondary (building) side, which made it possible to use rather a low design capacity for the DHW heat exchanger (23 kW). The design temperature for the secondary supply flow to the radiators was 70 °C and the return 50 °C respectively. The supply temperature was controlled by outside temperature so that the flow temperature was 70 °C if the outside temperature fell below -12 °C. As the outside temperature went up, the supply water temperature came down linearly so that at +12 °C it was 50 °C. Above that point the slope changed so that at 17 °C outside temperature the supply water temperature was 30 °C. At 18 °C the circulation pump stopped.

The basic concept was to use existing measuring equipment as far as possible. There was already a data collection system installed by the housing company in order to monitor the performance of the building. The data for the study was collected from five sources: 1) Consumption data obtained from manual reading of cold water and district heating meters, 2) Temperature data from existing Pt 100 sensors installed in the domestic hot water system, 3) Data on the space heating system that was collected in a data logger (there were thermocouple sensors measuring temperatures installed on the surfaces of some pipes, a flow meter that measured the flow in the radiator circuit and pressure transmitters that measured the pressure difference over the radiator system circulation pump), 4) Pulse signal data on the instantaneous consumption of heat measured by the district heat energy meter and 5) Power consumption data on the circulation pump obtained from the frequency converter.

The results showed that the monthly heat demand as a function of degree-days was rather linear. This is to say that the heat consumption seemed to depend strongly on the outside temperature. The consumption of domestic hot water seemed to fluctuate by a surprising extent: The monthly consumption varied from 55 to 100 m^3 during the measuring period of 4.5 years. No clear yearly or monthly pattern in the consumption profile could be found. The temperature difference between the primary side district heating supply and return waters over the heat exchangers varied between 25 °C in the summer and 50 °C in the winter. The study brought out that different sources give rather divergent values for domestic hot water consumption and heat losses due to hot water circulation in the building. However, at least in Scandinavia, outside temperature dominates the heat consumption of a building so that possible deviations in the domestic hot water consumption do not spoil the calculations. In the case study, it also came out that heat exchangers operated rather far from their design values: The space heating heat exchanger was dimensioned for 180 kW but it actually gave only 60 kW at the design outside temperature. The design secondary flow rate was 7.7 m^3/h but the measured value was 1.7 m^3/h. The temperature difference was designed to be 20 °C but it was measured to be 36 °C. When it comes to the domestic hot water heat exchanger, the design value was 23 kW but it was measured to give 40 kW. There was also a measuring period of a week during which the division of heat consumption was studied. It was in January 2002 and the outside temperature varied between -8 and + 5 °C. The heat demand for space heating responded clearly to the outside temperature; the graphs were almost mirror images of each other. The heat load due to the domestic hot water consumption, on the other hand, did not reflect the outside temperature but there was a clear consumption profile that repeated each day, even though not all the days had a similar profile. It seemed that there were two or three peaks but the consumption was rather steady during the day whereas during the night it went to zero.

Sjödin *et al.* [10] studied the calculation of marginal cost of a district heating utility by demonstrating three models for calculating it. One was a manual spreadsheet method, the other one involved an optimising linear-programming framework and the third method was a least-cost dispatch simulation model. District heat is a monopoly product; there is only one local supplier for it, if any. That is why the pricing should be explicable so that the price of heat is not artificially kept high, for example to be able to sell electric power at a cheap price. Many heat selling companies produce heat and power in CHP plants. The competition in the electricity market is rather hard as it can be delivered far from the generation point, contrary to district heat which is a local product. One socially acceptable pricing policy is that prices should equal short range marginal costs of DH generation. This kind of pricing does not, however, guarantee full cost coverage for the producer. Another widely adopted pricing policy is that the price of district heat is set just below the price customers would pay for alternative heating, for example heating with oil or electricity.

When district heat is produced with heat only boilers (there is no electric power production), the calculation of marginal costs is rather simple. As combined heat and power (CHP) comes in, the calculation becomes more complex: If the CHP production is to be viable, the market value of produced electricity and heat need to exceed the total generation costs of the CHP plant.

A case study was carried out and the three models were tested with it. It turned out that calculated marginal costs with them were similar.

Poredos *et al.* [11] suggests that not only the quantity but also the quality of district heat should be considered when pricing thermal energy, for example district heat. According to the authors, energy loss depends mainly on supply and return water temperatures (heat loss to the ambient ground) and on the friction losses related to the flow in the pipe. It was recommended in the study that consumers who cause bigger energy loss, for example due to requiring higher supply water temperatures or flow rates because of inadequate cooling in the heat exchanger, should pay higher unit prices for delivered heat than those who do not cause additional energy loss. Several equations and graphs were presented to show how energy loss in a district heating network depends on for example supply and return water temperatures. A method for calculating the price of heat for consumers using supply water at different temperatures was introduced.

Arvastson [12] has a mathematical approach to predict the behaviour of the customers connected to the network so that action can be taken beforehand based on outside temperature changes. Palsson [13] uses the same kind of approach as Arvatson, in addition to incorporating a heat storage tank and combined heat and power production. Sejling [14] shows another rather similar method for predicting heat load based on outside temperature changes. Lehtoranta *et al.* [15] put a little more emphasis on daily, weekly and yearly rhythm that can be found in the need for heat.

2.3 Computer applications

There are also computer software available for simulating the interactions in the DH network or the thermal behaviour of buildings. Some of them are presented briefly in the following section. It needs, though, to be remembered that these programs are more like tools which cannot be used in simulating a whole district heating system just like that. What they can offer are more or less easy to use equations for modelling physical phenomena related to heating. If one needs to simulate a district heating system, he has to build the application from pieces the programs offer.

There are several computer programs available that are useful in many heating, ventilation and air-conditioning (HVAC) related problems. TRNSYS is probably the best known of them. It has been used for more than 25 years. It was developed in the University of Wisconsin in the USA, the code has been written in Fortran. Its modular system approach makes it one of the most flexible tools available. TRNSYS (TRaNsient SYstem Simulation Program) includes a graphical interface, a simulation engine, and a library of components that range from various building models to standard HVAC equipment to renewable energy and emerging technologies. It also includes a method for creating new components that do not exist in the standard package. It can be used in HVAC analysis and sizing, multi-zone airflow analyses, electric power simulation, solar design, building thermal performance and analysis of control schemes for example. TRNSYS is designed to simulate the transient performance of thermal energy systems. It relies on a modular approach to solve large systems of equations described by Fortran subroutines. Each Fortran subroutine contains a model for a system component. Each component has inputs and outputs. By creating an input file, the user directs TRNSYS to connect the various subroutines to form a system. The TRNSYS engine calls the system components based on the input file and iterates at each time step until the system of equations is solved.

Another American Fortran based program is HVACSIM+. Contrary to TRNSYS, which is a commercial product, it can be obtained free of charge to non-profit making organisations. It is a simulation model of a building HVAC system and HVAC controls, the building envelope and the heating or cooling plant. The main program of HVACSIM+ employs a hierarchical, modular approach and advanced equation solving techniques to perform dynamic simulations of building, HVAC or control systems. The modular approach is based on the methodology used in the TRNSYS program. The problem with HVACSIM+ may be that it requires a lot of user computer literacy. Calculation time when solving simultaneous equations tends to be rather long, too.

IDA (the company, Equa Simulation Technology Group, does not specify what the letters stand for) is a program developed in Sweden. As a matter of fact, there are several IDA programs that relate to HVAC simulation. IDA Simulation Environment (IDA SE) is a general purpose modelling and simulation tool for modular systems where components are described with equations. Each component contains somewhere between a single and a few hundred differential and/or algebraic equations. Ready-made components are interconnected by the user in arbitrary combinations. IDA SE suits solving non-linear algebraic problems without requiring initial guesses from the user. It is based on a general purpose differential-algebraic equations solver which relies on precompiled models of physical components. Component models are packaged as Windows dynamic link libraries and their interconnection into systems is described in a system description file. IDA Indoor Climate and Energy is a whole-building simulator allowing simultaneous performance assessments of all fundamental issues to building design: Form, fabric, glazing, HVAC systems, controls, light, indoor air quality, comfort, energy consumption etc. It is a tool for simulation of thermal comfort, indoor air quality and energy consumption in buildings. The mathematical models in IDA ICE (Indoor Climate and Energy) are described in terms of equations in a formal language, NMF (Neutral Model Format).

An UK company IES Ltd is selling programs called ApacheSim and ApacheHVAC. With Apache one can simulate most HVAC processes. It uses a flexible component based approach which makes it possible to assemble systems on the screen as designed. Apache makes it possible to assess many aspects of thermal performance, from annual energy consumption and carbon emissions to individual surface temperatures. ApacheSim and Apache HVAC are thermal analysis products and they simulate aspects of thermal performance like solar shading and penetration, HVAC systems and control. Several modules are available: Geometrical modelling; building data input and visualisation; management of data relating to materials; occupancy, plant operation and climate; shading analysis; heat gain calculations; heat loss calculations; dynamic thermal simulation; natural ventilation and indoor air quality analysis; HVAC system simulation.

EnergyPlus is a program that one can get without any charge. It is a building energy simulation program that was developed, in the USA, for modelling building heating, cooling, lighting, ventilating, and other energy flows. EnergyPlus uses a simple ASCII input file. It reads input and writes output as text files. Hourly weather data from stations across the world is continuously collected and stored into a local database. The data is available through a web interface. Most stations have information for dry bulb temperature, wet bulb temperature, wind speed/direction, atmospheric pressure, visibility, cloud conditions, and precipitation type. As the program comes from the USA it is natural that the emphasis on weather data is on their continent. There are, though, quite a lot information from many places in Europe, too.

GRADES Heating and Heat NEXUS are simulation tools for a district heating (or district cooling) system. They were developed for design and simulation of rather large DH systems. They include control of pumps and valves and an automatic PID control module. The interface is very user-friendly: Once the network has been modelled (which is easy if there is a suitable map available), the user will be able to see many details such as temperature, flow rate or pressure in the networks just by clicking the mouse button at the right point of the network. One can also change the value of the ambient ground, for example, to see how it affects the heat loss; or change the size of a pipe between given nodes to see how it affects the division of flow in the system. The programs are network design tools and do not include heat production equipment or details of the consumers' installations. They were created by a company called Process Vision Oy, Finland.

Flowra 32 (formerly Kaver) is another design and simulation tool for district heating networks. The interface is graphic with this application, too, and the features are close to those of GRADES or NEXUS. The program was developed by Finnish companies Electrowatt-Ekono Oy and Komartek Oy, the latter of which nowadays develops it alone.

2.4 Summary

Even though most of the studies referred in Chapter 2.2 are rather extensive, practically all of those that relate to modelling include some simplifications. In particular, modelling of the district heating network seems to require so much computational capacity that several researchers have studied whether it could be simplified so that it would still maintain its dynamic behaviour. Studies [3], [5] and [7] suggest that the network can be simplified substantially and the model still gives satisfactory results. This finding has been utilised in this thesis.

Dynamic modelling of the heat consumption of several buildings has been carried out by using suitable time steps instead of continuous modelling [1], [5]. It became clear that due to so many variables that change relatively slowly it is not meaningful to use very short time steps. This only retards the calculation but it does not make it significantly more accurate.

Consumption of domestic hot water is the difficult part when modelling the need for heat of a building. Outside temperature dominates the need for space heating, but domestic hot water consumption depends on the people who occupy the building. Aronsson's [2] research on the heat consumption of several buildings in Sweden gives valuable data concerning this subject.

3. Development of a steady state model to determine the size of a wood chip boiler

3.1 Introduction

In a feasibility study on purchasing a wood chip boiler to provide heat for a group of buildings, one should be able to find out the best fitting size for the boiler. When wood chip boilers are concerned, two things have to be born in mind; they are a lot more expensive than similar oil-fired boilers and they cannot be used if the heat demand is very low. These two facts lead to the conclusion that the optimal capacity for a wood chip boiler does not equal the maximum heat demand but is somewhat less. The objective is to specify a boiler capacity that would be able to produce a good deal of heat with a reasonable purchase price.

In a typical case there are several existing buildings that are heated separately using light oil as fuel. The annual oil consumption is known or at least it is rather easy to find out. Some buildings may be included in the study even though they do not exist yet. These buildings have been designed, however, more or less accurately and their heat consumption can be predicted or calculated quite effortlessly.

Every year has its own distinctive weather conditions. Many things have an influence on the heat consumption of a building, the most significant one being the outside temperature. In Finland, the Meteorological Institute has recorded prevailing outside temperatures through many years in several different localities. It has also published the average temperature durations in some places. These files tell how many hours per year, on average, any outside temperature occurs. Figure 3.1 shows the average temperature durations in Oulu between 1961 and 1980.

As can be seen in figure 3.1, the most common outside temperature is around 2 °C in Oulu, which is located in the northern part of Finland. It can also be seen that the coldest periods do not last long and neither do the very warmest ones.

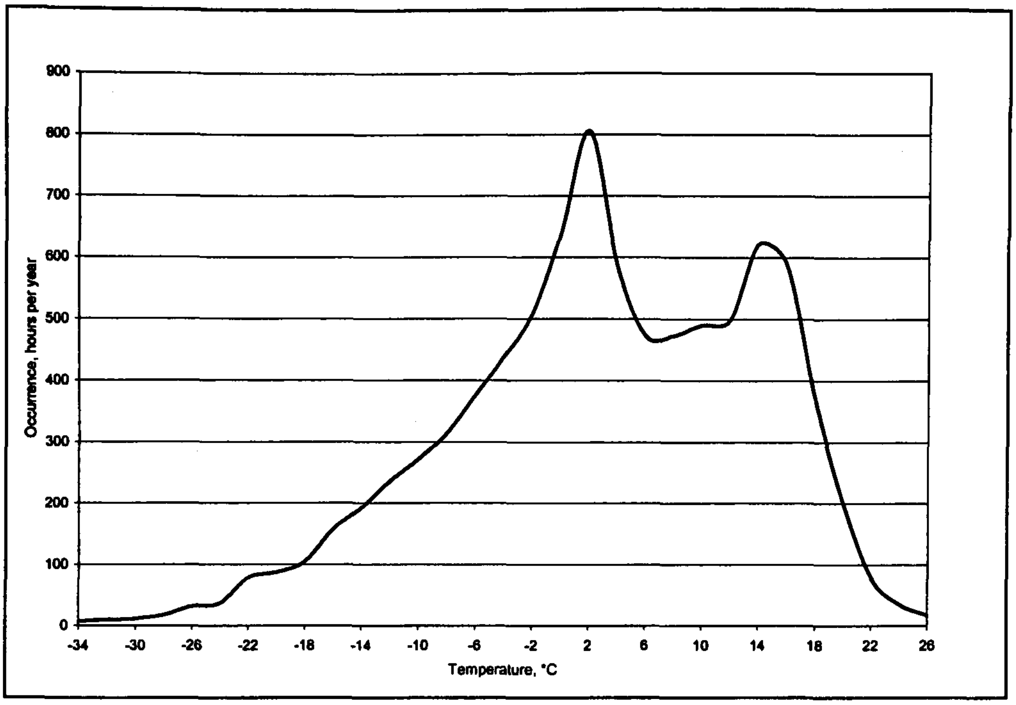

Figure 3.1. Average temperature durations in Oulu.

As well as temperature durations, the average monthly division of heat demand is known. It was also based on temperature measurements in many places through several years. The product of time and temperature difference between the target (inside) temperature and the prevailing outside temperature is called the degree-day number and it tells how the heat demand is divided on a monthly basis assuming that solely prevailing outside temperatures determine the need for heat of buildings. In Finland the target temperature is normally 17 °C.

Figure 3.2 shows the average division of heat demand in Oulu. According to it, the summer-time heat demand is almost non-existent.

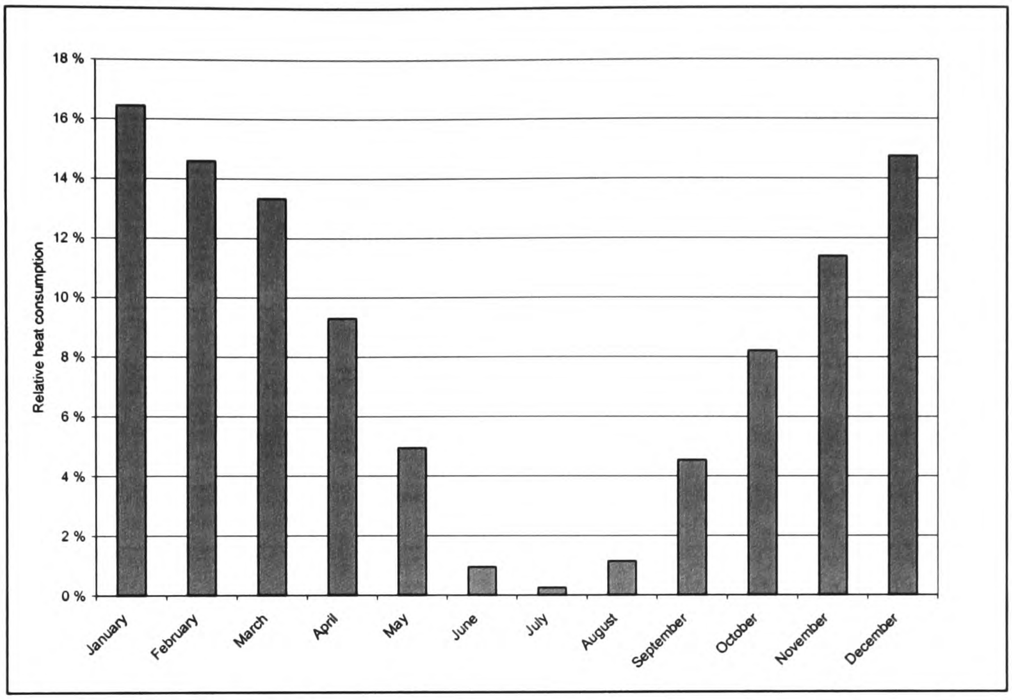

Figure 3.2. The monthly division of heat demand in Oulu.

The consumption of domestic hot water (DHW) changes the pattern of heat demand somewhat. It is known that the consumption of DHW remains approximately constant through the year, so despite warm prevailing temperatures heat is needed and consumed in the summer, too. The amount of heat needed for DHW preparation is seldom known exactly and it typically has to be estimated. In Finland it is generally between one fourth and one third of the total annual heat consumption when residential buildings are concerned.

If separate heating systems are replaced with a district heating (DH) system, new pipelines will have to be installed. These pipelines cause heat loss that has not occurred before. So the heat production of the new boiler plant will most likely exceed the previous total produced by the separate oil-fired boilers. Heat loss from the district heating network to the ground depends mainly on the temperature difference between the interior and exterior of the pipe and the insulation cover on top of the pipe.

The supply temperature will be adjusted according to the prevailing outside temperature. In Finland it is typically around 115 °C at its highest (when the outside temperature is at its coldest). The lowest value for supply water temperature is around 70 °C and it occurs in summer when heat is needed solely for domestic hot water preparation. The temperature of the return water depends on how much heat is consumed, the sizing of heat exchangers, the supply water temperature and the bypass flow. The temperature of the ground changes along with the outside temperature. As can be noticed, the pattern is rather complex and the annual heat loss to the ground cannot be calculated readily. That is why pipe manufacturers' brochures are typically used when heat loss has to be estimated. These brochures tell the heat loss depending on pipe size, insulation thickness and average supply, return and ground temperatures.

As was mentioned before, the total oil consumption is typically known. Since the heat value of light oil is known and the efficiency of transforming chemical energy into hot water can be estimated, the actual heat consumption of the building can be calculated. Typically it is 80 to 90 % of the heat value of the oil it consumes. Part of it is consumed for domestic hot water preparation. The rest is used for the actual heating of the building. This part is supposed to be proportional to the outside temperature just as is the heat loss to the ground.

3.1.1 Design conditions

Authorities have set design temperatures for different parts of Finland to be used in sizing heating equipment for buildings. They define the conditions which the heating system should be able to cope with. If the outside temperature goes below the design temperature, the inside temperature is allowed to decline somewhat.

Hence one can find inputs of the heating system corresponding with different outside temperatures, assuming that the maximum heat input occurs at the design temperature and below it and that the heat input goes down linearly as the outside temperature rises till it has reached a level where no heating is needed any more. That level is normally around 15 °C because some heat will be liberated in the interior from solar radiation, electricity usage and people. Thus, suitable temperature duration data and the annual heat consumption are needed. Figure 3.3 illustrates the relative heat input in different outside temperatures. The design temperature is -32 °C and heating is supposed to end at 16 °C.

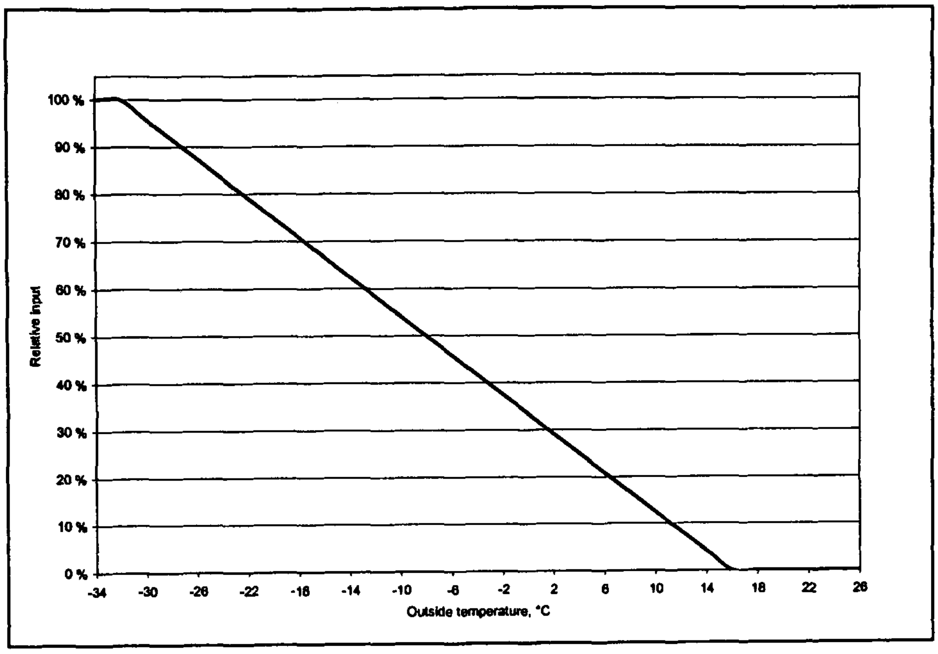

Figure 3.3. The relative heat input against outside temperature.

As figure 3.3 brings out, the consumption of heat remains constant (100 %) below the design temperature and above the 'heating ends' –point (0 %).

Multiplying temperature durations (figure 3.1) by relative heat input (figure 3.3) and dividing by total hours gives us the annual heat consumption against different outside temperatures. Figure 3.4 illustrates this:

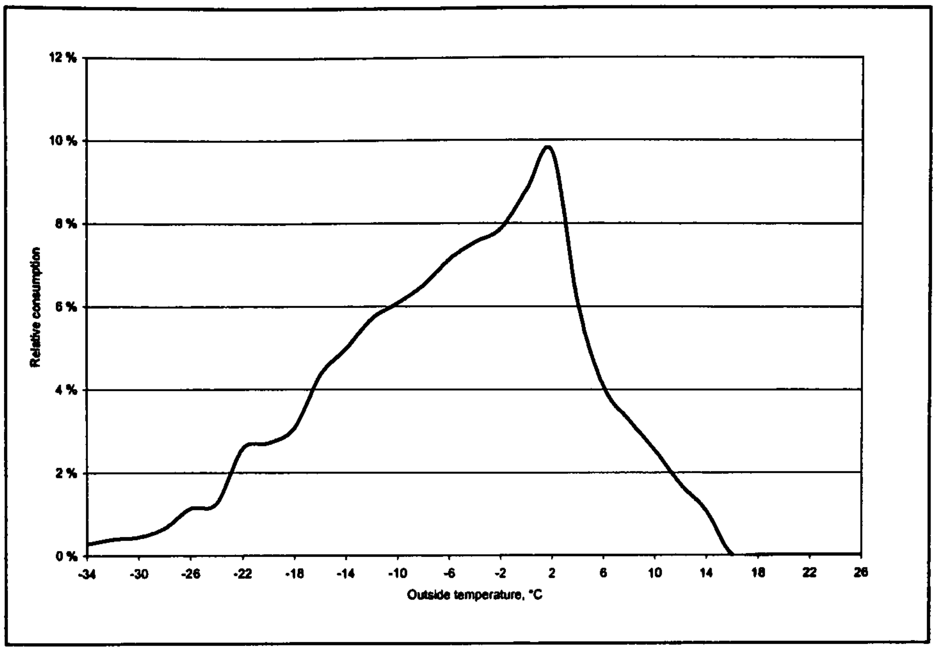

Figure 3.4. The annual heat consumption against outside temperature.

It can be seen in figure 3.4 that most of the annual heat consumption occurs in rather moderate temperatures; cold periods do not last long and are therefore of less importance than somewhat warmer periods. If the peak demand is known, as usually is the case, one can substitute the kilowatts for the percentages in figure 3.3 and thus multiplying them with hours will result in kilowatt-hours in figure 3.4. In general, the value of the peak demand has to lead to the desired annual consumption; so it is not necessarily the same as the sum of present boiler capacities.

The consumption of domestic hot water occurs momentarily but in this sort of calculation procedure one cannot deal with it the way it actually takes place. Therefore it has to be assumed that DHW is consumed all the time at a constant rate because it is not known how the consumption is divided in different outside temperatures. It is quite easy to calculate what constant input would lead to the energy consumption that is supposed to be the share of DHW. This constant input is then multiplied by temperature durations and added to the annual heat consumption. Figure 3.5 shows the effect of DHW consideration in the heat consumption against different outside temperatures. The share of DHW is 25 % of the total heat consumption. The broken line is identical with figure 3.4 and the full line includes the use of DHW.

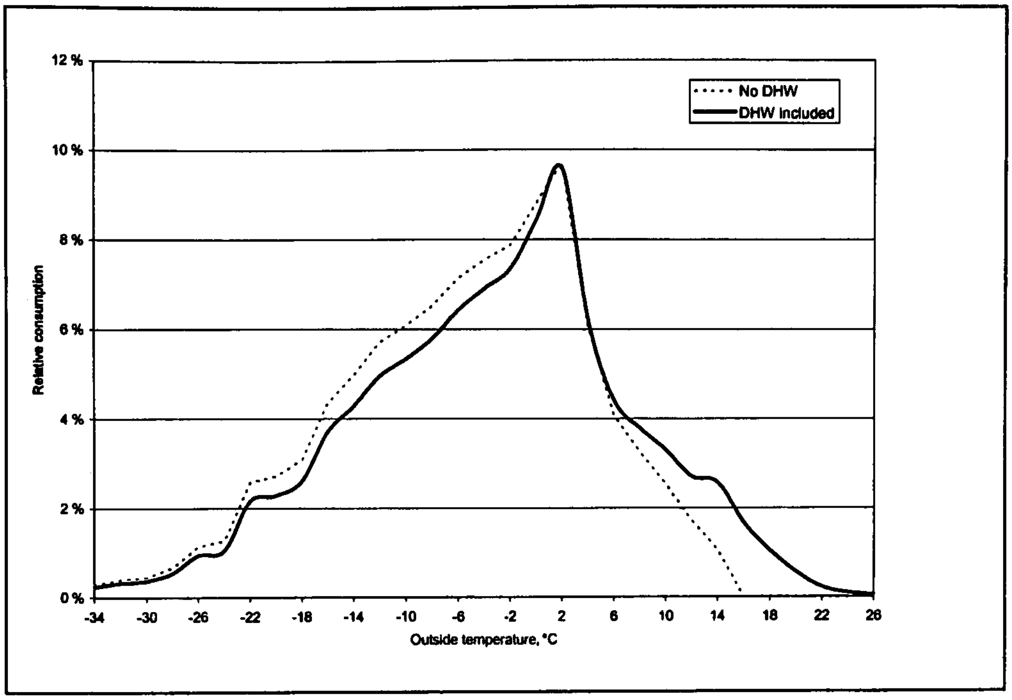

Figure 3.5. The annual heat consumption against outside temperature. The use of domestic hot water included (full line).

As figure 3.5 brings out, the pattern becomes a bit more even when DHW is included. Otherwise the shape is distinctively the same. One may similarly add the constant input for DHW to the input in different outside temperatures (figure 3.3) and thus find out its significance. Figure 3.6 shows this. The share of DHW is 25 % of the total heat consumption which leads to a constant input of approximately 8 % of the maximum input. The broken line is identical with figure 3.3 and the full line includes the use of DHW.

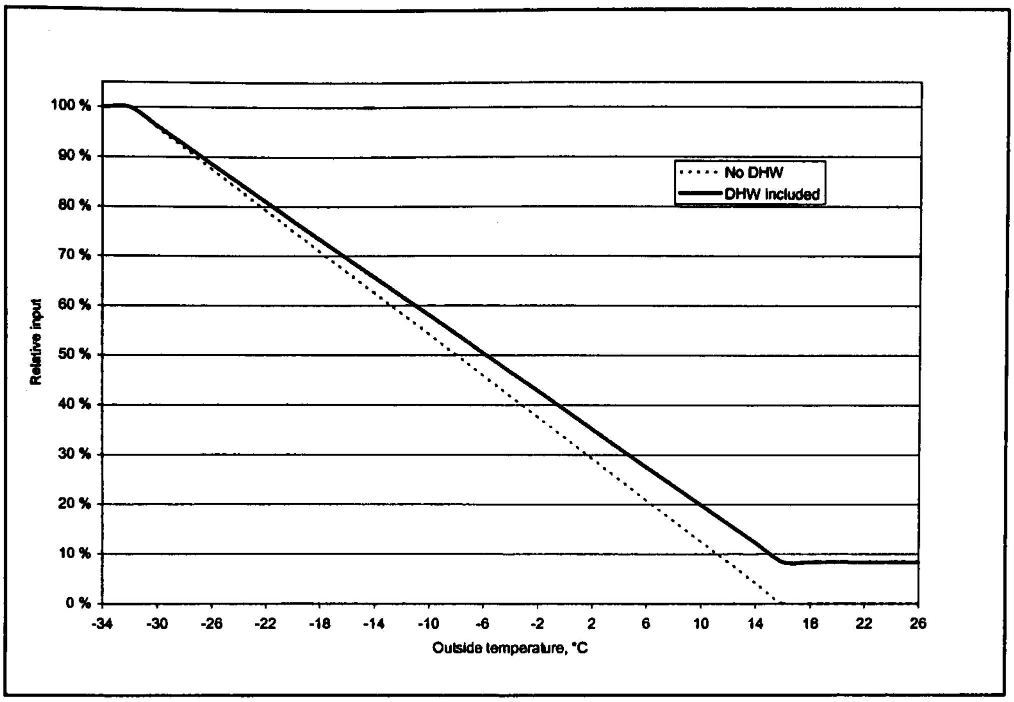

Figure 3.6. The relative heat input against outside temperature. The use of domestic hot water included (full line).

3.1.2 Boiler sizing

Now that the division of input is known, one may test what kind of boiler would give the best result if the biggest possible share of the heat production is the aim. One may then presume that the minimum sustainable output is a constant percentage of the maximum output. For example, if the maximum output is 1000 kW and the minimum 200 kW, it is between these two values that the wood chip boiler is able to operate. When the outside temperature is so high that the heat demand including DHW preparation and heat loss is below 200 kW, heat must be produced with some other equipment than the wood chip boiler. As the input rises above 1000 kW, the exceeding part must be produced with, for example oil. By using figure 3.6, one is able to specify outside temperatures that correspond with the above limits. Then, by using figure 3.5, one can determine which part of the annual heat consumption can be covered with the wood chip boiler. This is illustrated in figure 3.7: The broken line shows heat demand (input) and the full line shows how the wood chip boiler is able to operate if its capacity is 60 % of the maximum demand and its output is not allowed to decline below 20 % of its capacity, that is 12 % of the maximum demand.

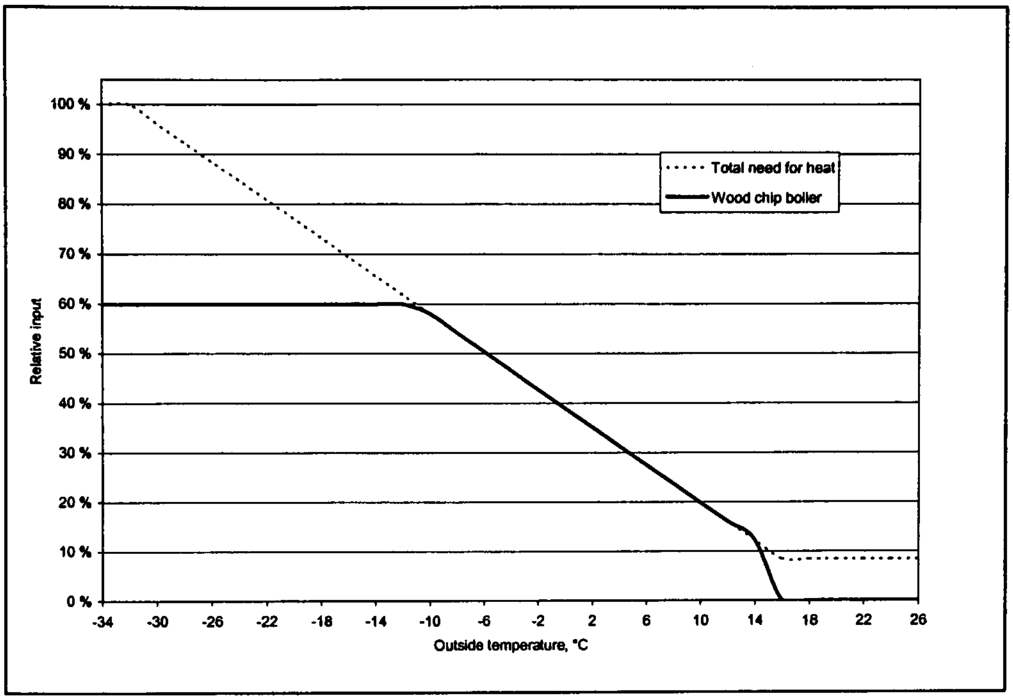

Figure 3.7. Heat demand (broken line) and wood chip boiler's output (full line) against outside temperature.

Figure 3.8 shows what kind of annual heat consumption share would the aforementioned wood chip boiler be able to produce. It can be seen that between -12 °C and 12 °C it could produce all the heat demanded. As the temperature declines below -12 °C, its share becomes smaller. This is, though, of minor importance because there are so few hours when the temperature is below this point. Distinctively more important is the slumbering output of the wood chip boiler: If the boiler could remain in operation in the summer, it would be able to produce practically all the heat needed. Even now its share is approximately 90 %. In general, a wood chip boiler should be sized in Finnish climate conditions to 40 - 60 per cent of the peak load. With it, one can typically get a share of about 80 to 90 per cent of the annual heat consumption.

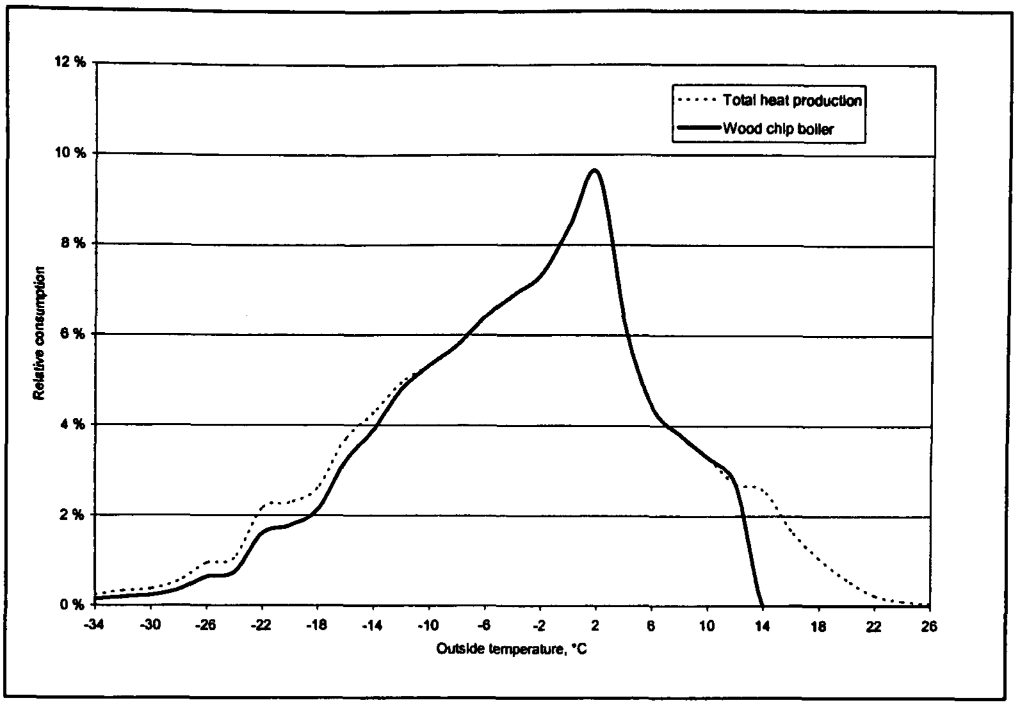

Figure 3.8. Wood chip boiler's share of the annual heat production (full line).

To find out the annual wood chip consumption and the diurnal consumption in the coldest periods, when the wood chip boiler operates at its maximum output, one needs to have an idea of the quality of the fuel. The most important thing to consider is the moisture content. If it, as well as the bulk density of the wood chips are known, both the diurnal and annual consumptions are easy to calculate because the heat value of wood (kWh/kg or MJ/kg) depends practically solely on its moisture content. It is important to have an idea of the annual consumption so that one may consider how much work and time it takes to produce the fuel for the boiler plant. The maximum diurnal consumption is needed when sizing the fuel storage.

The efficiency of the boiler has a certain impact on its fuel consumption. Typically it is not known exactly at this stage but it can be estimated. The annual efficiency of a wood chip boiler is around 80 % if the boiler is in a good condition, as it is supposed to be.

It is obvious that the wood chip boiler would be out of use for some time due to maintenance and reparation. Again, it is difficult to say how often it would break down, but it is obvious, anyway, that failures would take place more often than with an oil-fired boiler since wood chip boiler units are quite a lot more complicated. One might suspect that the wood chip boiler would be out of operation e.g. 1 - 2 % of the heating period.

With all the above information, one is able to calculate annual wood chip and oil consumptions with different boiler capacities leading to annual costs and savings. As the purchase price can be estimated, it is quite simple to solve whether the savings are sufficient to pay the investment back in the required period. The running of the boiler plant and the supplying of the fuel can be arranged in many different ways. Nevertheless, the question is: How much cheaper would it be to produce the heat, or at least a good deal of it, with wood chips compared with present heating systems. Another important question is: What would the total cost of purchasing a wood chip heating system be. As answers to these two main questions are found, the feasibility study is virtually completed.

The above described model represents the type that is quite often used when feasibility studies for small and medium size wood chip boiler plants are carried out. As a matter of fact, in many cases the studies are done with even more simplified models. The main idea in this sort of model is that one relies on average weather data (that is prevailing outside temperatures) and assumes that the heat demand is linearly proportional to the outside temperature.

The main weakness of this model is that it does not take into account the fact that domestic hot water usage takes place momentarily, certainly not at a constant rate. Another weak point is that as different outside temperatures are dealt with based on degree-days, the model has no clue in what kind of continuous periods these temperatures occur. For example, if it is known that a temperature of 12 degrees occurs one hundred hours per year, and we know that it corresponds with a relative output of 15 % of the wood chip boiler's maximum output, the model tells us that as the heat demand is less than 20 % of the boiler's maximum output, the boiler will be out of operation during the whole period of 100 hours. In reality, it is probable that many periods, when temperature rises so high that the boiler's output is below the minimum slumbering output, are so short that the boiler can cope with them pretty easily provided that the outside temperature goes down quite soon or domestic hot water usage increases so that more heat load will exist. This kind of situation could take place in spring and autumn, when daytime temperatures may rise rather high but then fall again in the evening.

The same phenomenon could take place in a reverse order: If low outside temperatures prevail in short periods in the middle of warm periods, it is probable that the wood chip boiler will not be taken into operation but the heat will be generated with the back-up boiler. The model would suspect that as the temperature is low, the wood chip boiler is in operation.

There is still one more limitation in the model: It does not take into account the accumulative effect of the pipe work. It is obvious that large heating networks that contain a lot of water, are to an extent capable of levelling off peak loads and shorter periods of low heat consumption as well. The heat loss from the pipe work helps as well to keep the wood chip boiler in operation during low load periods. In the model, it is assumed that heat losses are proportional to outside temperature the same way as heat consumption. That is of course not true, because heat losses exist even in the summer when no heat is needed for actual heating of the buildings. It is, though, obvious that as heat losses to ground are something like 10 to 15 % of the total heat production and they definitely are somehow related to outside temperature, the error might not be significant.

3.2. An application of the steady state model

One of the main objectives of this study is to estimate how reliable is the above described model for sizing wood chip boilers and carrying out feasibility studies on small and medium size district heating systems. There is a case that has been studied with this method at the beginning of this millennium. This case will be presented in order to show how the model works. Later on, another model will be presented and the same case will be studied. This model has some restrictions due to which it is not strictly comparable with the steady-state model. That is why some initial data have been changed to make the models comparable. For example, in the original study prevailing temperature data was from Tampere, now it is from Helsinki. The boilers were somewhat oversized in the original study, now the idea is to find the optimal size. There were also two different district heating network sizes under investigation, whereas one is quite enough for this purpose. These changes have been made to make both studies in line with each other so that possible differences in results can be seen.

3.2.1. The subject

Karvia is a market town –size municipality in the south-western part of Finland with approximately 5000 inhabitants. Buildings in the market town are mainly residential, schools and shops. This is not the first feasibility study for the municipality, another one has been carried out a couple of years earlier [16]. The numbering of the buildings is the same that was used in the previous study. As some dwellings have now been left out, the numbering is not entirely continuous.

Investigating the viability of purchasing a district heating network and a boiler plant was the purpose of this study. Furthermore, the aim was to estimate the costs of implementing the project and to determine the marginal price of produced heat.

From the outset it was clear that if a district heating system is purchased, the only possible investor will be the municipality of Karvia. Moreover, it was clear that if the boiler plant was purchased, it would be a co-operative that supplies the primary fuel and runs the boiler plant. The municipality pays to the co-operative for produced heat and delivers it further to consumers. Should buildings not be owned by the municipality, their owners would have to pay a proper price for the delivered heat. It is obvious that light fuel oil will be used as a secondary fuel if the wood chip boiler plant is purchased. In this case, it would be so that the owner of the boiler plant would supply the oil needed and the co-operative would only get paid for the heat produced from wood chips.

The boiler plant would be situated in the southern part of the district heating (DH) network close to Karvian Konepaja, which is a machinery works and a substantial consumer of heat. From there the network would extend to the terraced houses near the street Aukustinkatu. The majority of the substantial heat consumers along the DH network would join the network. The total length of the network would be approximately 4700 metres. The map can be seen in the Appendix as figure I where the position number of the boiler plant is 0.

Table 3.1 gives basic information on the buildings that would presumably join the DH network. The buildings have been numbered the same way as in the previous study. Therefore some numbers have been skipped, as it has become evident that those buildings would not join the network, even though they were considered as potential heat consumers in the previous study. Information about light fuel oil consumption is based on the owners' announcements. Authorities of Karvia were able to give some detailed information on the oil consumption of the buildings owned by the municipality. They could also tell the sizes of all the buildings in square metres and cubic metres. Furthermore, they knew the existing heating systems of the buildings. The correctness of announced oil consumption figures could then be assessed by dividing the annual heat consumption by the space of the building. The quotient should be approximately the same within the same sort of buildings.

Consumers from 1 to 13 are owned by the municipality. Their annual heat consumption is about 3020 MWh that is 51 % of the total consumption. It became clear that only consumer number 16, Karvian Konepaja, is somewhat complex when it comes to its heat consumption. The machinery works consists of two buildings, the smaller of which is a paint shop heated by blower heaters that use oil. It appeared that the paint shop might consume considerable amounts of heat in summer, too. The larger building is a more traditional machinery works where many kinds of metal works are being done. The building is heated by radiant heaters that use liquefied petroleum gas as fuel. The temperature remains rather low in winter. According to the owner, the annual oil consumption is around 100 000 litres. The consumption of liquefied gas remained obscure. It seemed probable that the larger building would not be connected to the DH network, but if the price was suitable, the connection would not be out of the question.

Table 3.1. Heat consumers of the network.

Nr	Building or group of buildings	Total space m^3	Oil consumption litres/year	Calculated heat consumption MWh/year	Approximate peak load kW
1	Upper Sec.Sch + 2 terraced houses	12440	89162	758	350
2	Gymnasium + fire station	10691	35489	302	267
3	Library	2250	9665	82	56
4	Old people's home	6600	74876	636	350
5	Rest home	1090	incl.in nr 4	incl.in nr 4	incl.in nr 4
6	Iltarusko-terraced houses	2970	18719	159	incl.in nr 4
7	Day centre living quarters	2640	12134	120	100
8	Day centre	1250	10438	89	50
9	Old clinic	3010	21740	185	72
10	New clinic	3220	not known	225 1)	113
11	Lower Secondary School	3040	13908	118	76
12	New city hall	9680	3254	276	170
13	Old city hall	1560	8050	68	34
16	Karvian Konepaja works	47220	100000	850	400
17	Terraced houses Leppipelto	4800	37719	321	115
18	Terraced houses Karvian Kaari	5332	46000	391	128
19	Terraced houses Yläsatakuntatie	10410	74623	634	229
20	Terraced houses Karvian Haapa	3210	21921	186	71
33	Terraced houses Kyläkarviantie 14	2040	12000	102	30
34	Bank building Osuuspankki	2070	26000	221	75
34	Cafeteria Hellun Herkku	1710	incl.in nr 34	incl.in nr 34	incl. in nr 34
40	Church office building	1690	8900	76	60
44	Office building Pankkitalo	1800	not known	80 1)	45
45	Cafeteria + apartment Nassukka	1000	not known	40 1)	25
Total		**141723**	**653859**	**5920**	**2816**

1) Heat consumption estimated

The consumption of heat is based on the oil consumption data of the buildings. It has been supposed that the efficiency of the existing heating system has been 85 %. Some owners were able to give accurate data on oil consumption of the buildings through many years. Some data were less accurate. All the received consumption figures were checked by comparing them with consumption of similar buildings.

The peak loads of the buildings were estimated according to the sizes and use of the buildings. Again, peak loads can be defined rather accurately as building sizes and purposes of use are known; wall constructions and ventilation rates are virtually the same in buildings of same type and age.

The wood chip boiler plant would be placed in the southern part of the network. It is obvious that from the technical point of view better places for the boiler plant could be found: If the plant is in one end of the network, the main pipeline will have to be of a large diameter because virtually all the produced heat is transferred through it. Large diameters mean expensive pipe work and possibly increased heat loss to the ground.

Wood chip boiler plants are not, however, as reliable as the ones that use oil. It is therefore possible that in unfortunate circumstances the boiler plant causes trouble to its surroundings. Ash or soot may escape with the flue gas and conveyors may cause noise. Repetitive fuel supply may also disturb the neighbourhood. Authorities of Karvia decided that if the boiler plant is purchased, it will not be situated in the vicinity of schools or residential buildings.

3.2.2. Heat output and consumption

The DH network has not been dimensioned exactly. Nevertheless, approximate pipe sizes have been estimated to determine the heat loss to the ground. It has been supposed there would be separate pre-insulated supply and return lines. The pipe material would be steel and the insulation polyurethane. The annual heat loss has been read in a pipe manufacturer's (Powerpipe Ltd) brochure according to pipe dimensions. There were three insulation classes available the first of which gives the thinnest insulation cover on the pipe and the third the thickest. Flow temperatures are close to average supply and return temperatures in a typical Finnish DH system (supply 85 °C and return 55 °C). The ground temperature is the average outside temperature in southern Finland (5 °C). Pipe dimensions have been selected according to peak loads. It is, however, obvious that not all customers would consume heat at the maximum rate simultaneously. Therefore it is probable that estimated pipe dimensions tend to be rather large. However, there are buildings along the network that possibly join later on. Selecting large pipe diameters makes it possible to increase the amount of customers. Table 3.2 shows the flow pipe sizes and diameters of insulated pipes with class 1 and class 2 pipes. The insulation material is polyurethane and there is approximately 5 mm thick plastic cover on it.

Table 3.2. Pipe dimension and insulation cover thicknesses with second and third class insulation.

Pipe dimension	Flow pipe outer dimension, mm	Plastic cover outer dimension, mm (class 2)	Plastic cover outer dimension, mm (class 3)
DN 125	139.7	250	280
DN 100	114.3	225	250
DN 80	88.9	180	200
DN 65	76.1	160	180
DN 50	60.3	140	160
DN 40	48.3	125	140
DN 32	42.4	125	140
DN 25	33.7	110	125

Table 3.3 shows approximate pipe dimensions, lengths and expected heat loss to the ground with the second and third class insulation. The lengths include both supply and return lines.

3.2.3 Accuracy

With the exception of Karvian Konepaja works, all the buildings that belong to the survey are rather steady when their heat consumption is concerned. The oil consumption of the vast majority of them has been recorded through many years. It is unlikely that there would occur any major changes in the future and, even if there should, they probably would not all lead to the same direction but they would presumably offset one another.

Table 3.3. Estimated pipe dimensions, lengths and annual heat loss to the ground.

Pipe dimension	Length, metres	Heat loss (class 2), MWh	Heat loss (class 3), MWh
DN 125	1295	477	363
DN 100	395	114	100
DN 80	640	177	155
DN 65	645	171	148
DN 50	685	160	140
DN 40	355	65	67
DN 32	455	83	76
DN 25	245	41	37
Total	**4715**	**1288**	**1086**

Karvian Konepaja is a lot more complicated consumer of heat than the others. The paint shop needs heat occasionally if the paint takes too much time to dry. It is therefore difficult to estimate the amount of heat needed through the year. The larger building, the workshop, could also be connected to the DH system. It is, however, a tall building and radiant heaters are probably most suitable for it, particularly when the huge doors have to be opened and the air changes rapidly.

It is possible that there will be another workshop close to the existing one within the next few years. Connecting it to the DH system would seem reasonable because it could be designed so that district heat could be used and no existing heating system would have to be disassembled. For instance, floor slab heating might be applied.

As table 3.1 shows, only the oil consumption of the paint shop has been taken into account and it is not necessarily an accurate figure either: The company has by no means recorded its oil supplies meticulously.

3.2.4 The distribution of energy consumption

A great deal of the energy that customers consume is needed for compensating for heat losses caused by ventilation and heat transfer through the envelope. The rest is used for domestic hot water preparation. It is generally assumed that heat losses depend on the difference between the outside and inside temperature almost linearly. The inside temperature remains constant during the heating season. It is therefore the outside temperature that determines the heat loss to the exterior.

There are facts that do not support the above argumentation. Firstly, prevailing wind conditions do affect heat losses both through the envelope and by infiltration. Secondly, heat loss to the ground, especially from a cellar, is practically independent from variations in the outside temperature. Naturally, in the long run, changes in the outside temperature alter the ground temperature and thus the due heat loss, too. In addition, ventilation rates may be changed according to the outside temperature.

The heat loss of a building to the ground is rather scant, though, compared to other heat losses. In this case there are not so many buildings with such a sophisticated air-conditioning system that would make varying the ventilation rate according to prevailing outside temperature possible. Furthermore, outside temperatures are systematically recorded and their durations in different localities are known. Wind conditions, on the other hand, are extremely difficult to include in the calculations; so the only practical way is to rely on data on prevailing outside temperatures. Pipe work is assembled rather close to the ground surface, so heat losses from the network can be expected to follow the same pattern as heat losses from buildings.

In this study it has been assumed that 80 % of the total heat consumption is used for heating purposes. Domestic hot water preparation takes the rest. Accurate figures are not available, the above division is purely estimated.

The expected peak load has been calculated by means of average outside temperature durations in Helsinki in a test year (1979). This is because the same weather data is used in further calculations. Normally, average temperature data would be used. In figure 3.9, one can see as a comparison the differences in temperature durations between the test year (full line) and the average in years 1961 to 1980 (broken line). It can be seen that the temperature durations in the test year are not quite as stable as they are in average in the period of twenty years, but the shape is distinctively the same.

It has been expected that when the outside temperature falls to -26 °C, the need for heat is at its highest. If the temperature still falls, the need for heat will remain the same; the inside temperature may fall, though. Furthermore, it has been expected that when the outside temperature elevates above 15 °C, the buildings do not need any more heating. As the temperature varies between above values the need for heat varies correspondingly between maximum and nil.

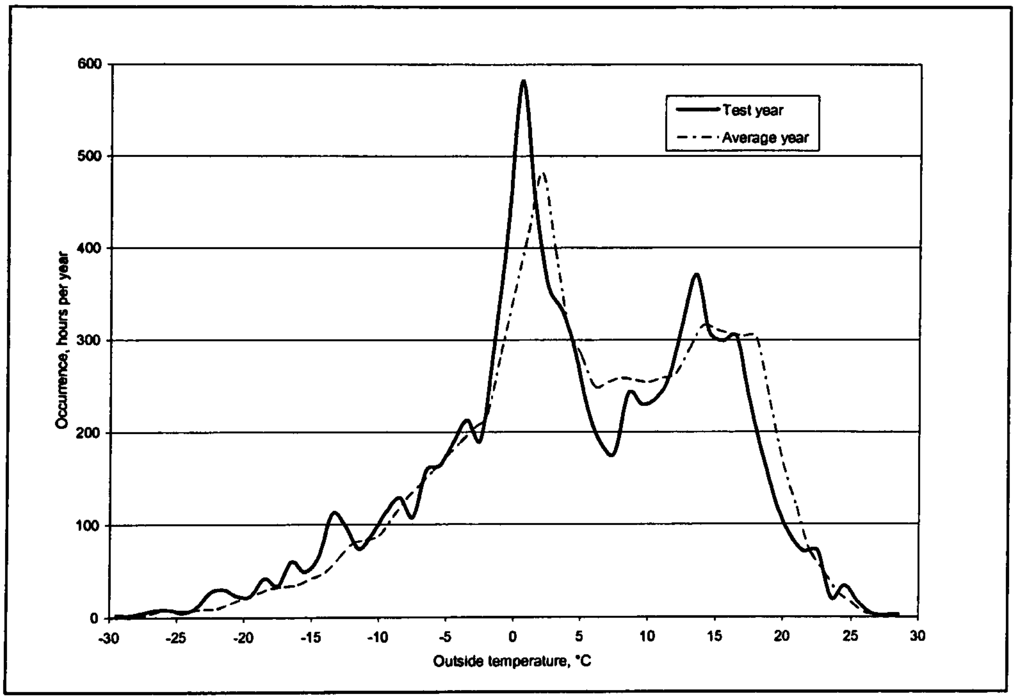

Figure 3.9. Outside temperature durations in Helsinki in the test year (full line) and average outside temperature durations in Helsinki 1961-1980 (broken line).

Domestic hot water preparation consumes heat occasionally. In this model, it is difficult to include it in the calculation the way it occurs. The problem is dealt with assuming the consumption to be constant all through the year. As table 3.1 shows, the annual heat consumption is approximately 5900 MWh. The heat loss to the ground is, depending on the insulation thickness, between 1100 and 1300 MWh (table 3.3) that is 15 – 18 % of the total heat production (7000 – 7200 MWh). Hereafter it is supposed that the third class insulation would be selected and all the calculations have been carried out accordingly.

With a heat production of 7006 MWh, the domestic hot water preparation would be 1184 MWh as it is supposed to be 20 % of the consumed heat. That would say the constant DHW preparation rate would be 1 184 000 kWh/8760 h = 135 kW. As it is believed that when it comes to the actual heat consumption and heat losses (7006 – 1184 = 5822 MWh) the consumption would be 100 % at the design temperature (-26 °C) and the lowest outside temperature when no heat would be required for heating and ventilation systems (plus heat losses) is 15 °C and the need for heat goes linearly between these two points as described in figure 3.3 it can be found out what maximum output would lead to above annual consumption. After some iterations it can be seen that if the peak load is 2406 kW, the annual consumption will be 5822 MWh. This can be seen in the Appendix, table I. Heating includes heat losses.

So, the peak load for heating, ventilation and heat losses is about 2400 kW. Naturally, if domestic hot water consumption should occur simultaneously with a low outside temperature, the actual peak load would be larger since in this calculation it has been expected that domestic hot water is used at a constant rate. Such peaks do not, however, last long and the large volume of hot water in the boiler and the pipe work is supposed to be able to offset them. The thermal mass of buildings makes them also of less importance.

3.2.5. The boiler plant

The wood chip boiler would be able to use peat and some other solid fuels as well, although the primary fuel would presumably be wood chips. In grate boilers solid fuel is incinerated on a grate in a combustion chamber. Conveyors bring fuel from a nearby store to the boiler plant the rate varying according to the output of the boiler.

In spite of the fact that every potential consumer in this survey already has an existing heating system, it is recommended an oil-fired boiler to be included in the new boiler plant, too. Should the wood chip boiler get out of order, a back up heat source would be needed. Producing heat in the network from several points causes difficulties in adjusting temperatures. Some customers would, moreover, substitute heat exchangers for their existing heat sources so that they could not be used in any circumstances.

Sizing

In this particular case, the heat demand of most of the consumers adapts more or less linearly to variations in the outside temperature. Practically only Karvian Konepaja, namely the paint shop, may act unpredictably as a customer of heat. The typical sizing policy can therefore be applied in this study. Another question is to what extent would the demand of heat change in the future. There are several buildings along the DH network route that would conceivably join if the network was constructed even though they do not belong to this survey.

With a peak load of 2.4 MW, the normal sizing policy would offer wood chip boiler capacities between 1 and 1.5 MW. That size of a boiler would correspond with 40 to 60 per cent of the peak load. At this point it is thought that the minimum sustainable output of the wood chip boiler is 20 % of its nominal output. Figure 3.10 shows what kind of share of total heat production would be expected with wood chip boiler sizes between 700 and 2000 kW. The calculation has been carried out with 50 kW steps. The bumpy shape of the curve is mainly due to the minimum slumbering output being a constant percentage of the nominal output. As the need for heat has been calculated with 1° steps, it so happens that at certain outside temperatures the slumbering output is just a little bit too high. Thus, the model expects that as the slumbering output is higher than the input, the wood chip boiler cannot be in use. As temperature goes down 1°, the demand for heat increases enough to make the model decide that the wood chip boiler could now be in use. That leads to an abrupt increase in the wood chip boiler's annual share. To avoid it, one should know the temperature durations at smaller steps, e.g. 0.1° and calculate with small differences in the capacity of the boiler. On the other hand, it is not necessary to get a smooth shaped curve, because one can quite easily see the general shape of the curve in figure 3.10.

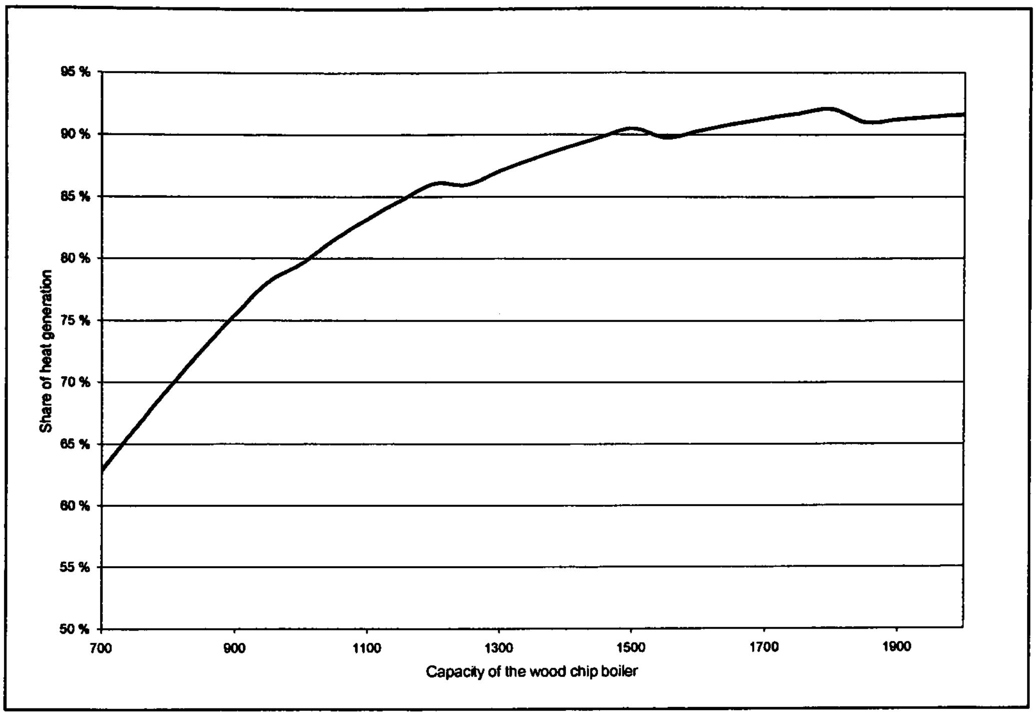

Figure 3.10. Wood chip boiler's share of annual heat production against boiler capacity.

It can be seen that above 1500 kW the increase in the heat generation share is more or less non-existent. To make a decision would require that one should be aware of the prices of wood chip boilers of different sizes. What is more, one should also know what sizes are available. The pricing of boiler plants is by no means easy to comprehend. There are some items that do not seem to be dependent on the boiler size, whereas some items are extremely sensitive to the size. The technology tends to change at certain size, e.g. simple auger feeders are typical for small boilers but bigger ones usually incorporate more robust feeding systems. These kind of changes lead to abrupt changes in the prices, too. Table 3.4 shows the estimated prices of some boiler plant sizes that are available. The prices are purely estimated, the idea is just to show how this sort of information can be used for finding the optimal size of the boiler.

Table 3.4. Price estimates of boiler plants with different wood chip boiler sizes.

Boiler sizes	Price estimation, €
0.7 MW wood chip + 2.5 MW light fuel oil	380 000
0.9 MW wood chip + 2.5 MW light fuel oil	400 000
1.2 MW wood chip + 2.5 MW light fuel oil	460 000
1.5 MW wood chip + 2.5 MW light fuel oil	500 000

By comparing data in table 3.4 with figure 3.10, one can see that changing from 0.7 MW to 0.9 MW would increase the heat generation share by about 20 % (from 63 % to 75 %). The price, though would only increase by 5 %. Further, changing from 0.9 MW to 1.2 MW would increase the heat generation share by about 14 % (from 75 % to 86 %). The price would go up by some 15 %. From 1.2 MW to 1.5 MW would increase the share by about 5 % (from 86 to 90) and the price respectively by some 9 %. It seems evident that the most suitable size for a wood chip boiler in this case would be either 0.9 MW or 1.2 MW. The method is an approximate one and it is not possible to see exactly which of the above sizes would be better. Both seem to be equal.

In this case, it could be reasonable to choose the bigger boiler size (1.2 MW) because some buildings beyond this survey might join the network later on. The machinery works could also build a new building that would draw heat from the system.

In this study, the utilisation degree is supposed to be 100 %, which means that the wood chip boiler is expected to be out of order or under maintenance only in summer. Normally, the utilisation degree is around 98 - 99 % in the calculations, but as mentioned earlier, the results will be compared with results from another method, and it is convenient to make this calculation as simple as possible to make the comparison easier.

Table 3.5 shows how the heat generation would be divided between wood chip and oil fired boilers in different outside temperatures. The lowest sustainable (slumbering) output is supposed to be 20 % of the maximum (actually nominal) output that is 0.2 * 1200 = 240 kW.

Table 3.5. Wood chip boiler output in different outside temperatures.

Outside temperature °C	Duration hours p.a.	Total output kW	Wood chip boiler output kW	Wood chip boiler heat production MWh
28,5	3	135	0	0
27,5	2	135	0	0
26,5	4	135	0	0
25,5	16	135	0	0
24,5	34	135	0	0
23,5	20	135	0	0
22,5	71	135	0	0
21,5	71	135	0	0
20,5	89	135	0	0
19,5	122	135	0	0
18,5	174	135	0	0
17,5	234	135	0	0
16,5	304	135	0	0
15,5	299	135	0	0
14,5	308	192	0	0
13,5	371	250	250	93
12,5	317	307	307	97
11,5	259	364	364	94
10,5	236	422	422	99
9,5	230	479	479	110
8,5	242	536	536	130
7,5	177	593	593	105
6,5	187	651	651	122
5,5	224	708	708	159
4,5	289	765	765	221
3,5	333	822	822	274
2,5	358	880	880	315
1,5	450	937	937	422
0,5	582	994	994	579
-0,5	423	1052	1052	445
-1,5	295	1109	1109	327
-2,5	192	1166	1166	224
-3,5	213	1223	1200	256
-4,5	189	1281	1200	227
-5,5	164	1338	1200	197
-6,5	159	1395	1200	191
-7,5	108	1452	1200	130
-8,5	129	1510	1200	155
-9,5	113	1567	1200	136
-10,5	90	1624	1200	108
-11,5	74	1682	1200	89
-12,5	98	1739	1200	118
-13,5	112	1796	1200	134
-14,5	65	1853	1200	78
-15,5	49	1911	1200	59
-16,5	60	1968	1200	72
-17,5	34	2025	1200	41
-18,5	42	2082	1200	50
-19,5	23	2140	1200	28
-20,5	23	2197	1200	28
-21,5	30	2254	1200	36
-22,5	27	2312	1200	32
-23,5	11	2369	1200	13
-24,5	5	2426	1200	6
-25,5	8	2483	1200	10
-26,5	8	2541	1200	10
-27,5	5	2541	1200	6
-28,5	2	2541	1200	2
-29,5	3	2541	1200	4
				6028

The wood chips are supposed to contain moisture 40 % (wet basis). The annual efficiency of the wood chip boiler is expected to be 80 %, just like the one of the back-up boiler. According to above figures the wood chip boiler with an output of 1.2 MW would be able to produce 6028 MWh that is 86 % of the total (7006 MWh) production. Figure 3.11 shows the expected division of total heat production through the year. The division is based on average monthly degree-day data.

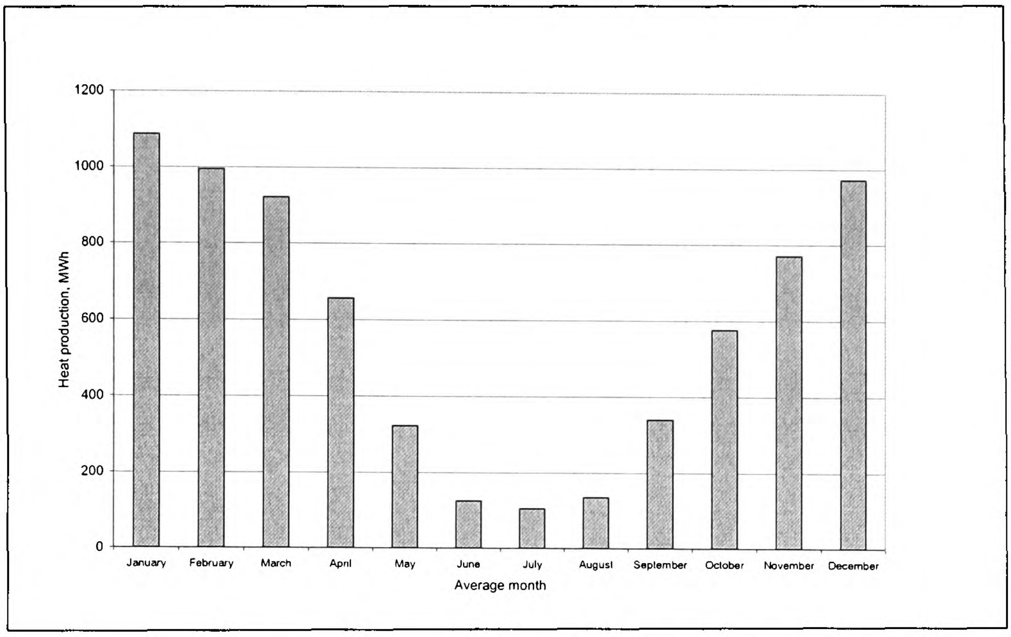

Figure 3.11. Monthly division of heat production.

Figure 3.12 shows the division of heat production at different outside temperatures. The picture clarifies, why there were abrupt steps in figure 3.10: Each column represent a certain temperature and the corresponding heat generation. When it comes to higher temperatures, the columns have only one colour. It means that heat is generated either by the wood chip boiler or the oil-fired boiler. As one of these columns changes colour, it means that a considerable amount of heat is generated with the other boiler and the division of heat generation changes rather rapidly. If, for example, the minimum sustainable output of the boiler were 21 % instead of 20 %, the column at 13.5 °C would change from wood chips to oil, which would alter the wood chip boiler's share from over

86 % to less than 85 %. The situation would remain constant with slumbering outputs up to 25 %, only above 25 % would the would chip boiler's share decline again.

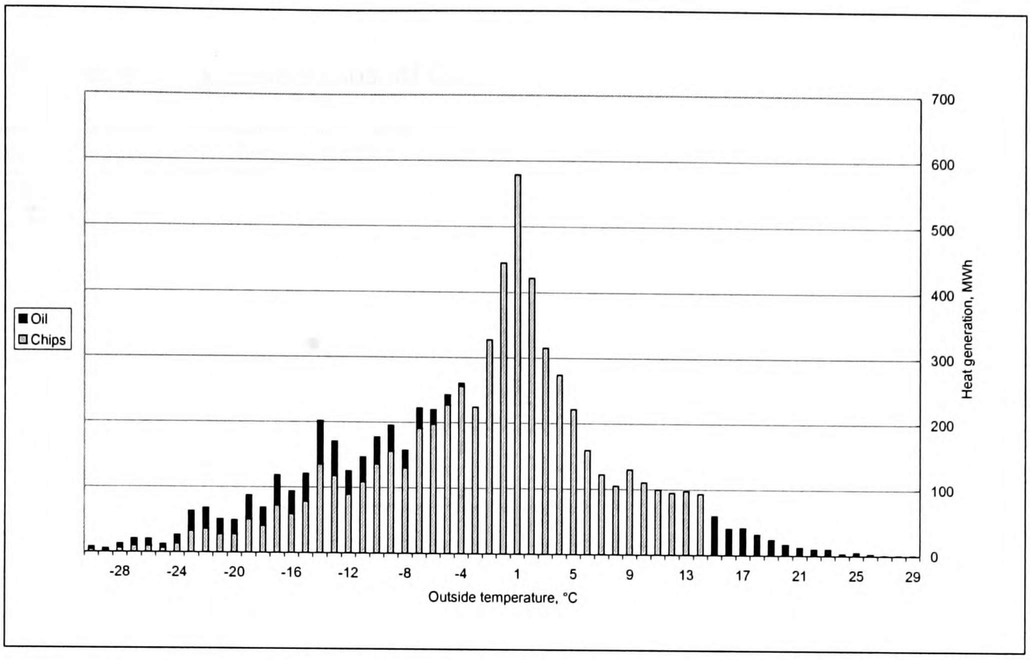

Figure 3.12. Division of heat production in different outside temperatures.

As 6028 MWh is the expected amount of heat produced from wood chips annually, the average efficiency of the boiler is taken as 80 % and the average moisture content is expected to be 40 % (weight basis), the annual wood chip consumption is approximately 10500 m^3 and the diurnal consumption something like 50 m^3 when the boiler is operating at its nominal output. Oil consumption is roughly 120 m^3 per year. The lower heat value of wood containing 40 % water is close to 2.86 kWh/kg and the density of wood chips with the same moisture content is around 250 kg/m^3 depending on particle size and wood species.

3.2.6. Feasibility study

The cost of the boiler plant has been estimated earlier. There are plenty of data available on costs of district heating pipe work installations. Unfortunately, the costs vary a lot from case to case. In this study, the unit prices, €/metre, are basically the same that were used in the previous study [16]. As those prices are from year 1998, they have been corrected upwards by 15 %. Table 3.6 shows the prices and the total cost of the district heating network.

Table 3.6. Estimated cost of the district heating network, VAT excluded.

Pipe dimension	Length, metres	Price, €/m	Subtotal, €
DN 125	1295	212	274862
DN 100	395	193	76216
DN 80	640	174	111141
DN 65	645	154	99564
DN 50	685	145	99130
DN 40	355	135	47949
DN 32	455	135	61456
DN 25	245	135	33091
Total	**4715**	**1288**	**803408**

Estimated costs of the whole system are shown in table 3.7. Foundation work includes the water and electricity supplies. District heating pipe work includes the purchasing and assembling of the pre-insulated pipe modules and the excavation work. Heat measuring equipment is supposed to be installed in connection with every customer at a cost of 2000 euros each. District heating sub-stations which include heat exchangers, pumps, valves expansion tanks etc. are taken into account in buildings that are owned by the municipality. Their cost is expected to be 7000 euros each.

Table 3.7. Estimated cost of the district heating network, VAT excluded.

Item	Cost, €
Boiler plant: 1.2 MW wood chips + 2.5 MW oil	460000
Store for wood chips, 200 m^3	included above
Foundation work	30000
District heating pipework	803000
Heat measuring equipment	46000
District heating sub-stations	91000
Total	**1430000**

The boiler plant and the district heating network would be purchased by the municipality. The same goes for DH sub-stations in buildings that are owned by the municipality. So this is what the municipality would have to pay for. After purchasing the heating system, the municipality would hand the boiler plant over a local energy service co-operative (or company), which would supply wood chips and operate the plant. The municipality would pay to the co-operative for all the wood-based heat the co-operative delivers to the district heating network. Once delivered in the network, the heat would belong to the municipality. From the network the heat would be delivered to consumers. As for the buildings that are not owned by the municipality, the price for heat would be significantly higher than the price the municipality pays to the co-operative. It would still be somewhat cheaper for the owners of the buildings than heating with oil. Selling heat to customers would bring money to the municipality. The part of the heat that would be delivered to buildings owned by the municipality would be sold with the same price that the municipality pays to the co-operative. This would mean that the owner of the buildings (the municipality) would save a lot of money by getting the heat much cheaper than before. The marginal price is the maximum price the municipality would be able to pay to the co-operative for wood-based heat delivered to the network so that the municipality would break even over the repayment period (in this case 20 years).

The procedure was to determine the marginal prices for produced and sold heat. Prices are compared to present costs resulting from heating with oil. The idea is that the municipality would be able to pay off the loan by instalments with the profit it makes by the savings in heating expenses and the selling of heat to other customers.

It has been supposed that maintenance or any other costs would not change substantially from their present level. Neither would the use of electricity change significantly.

Table 3.8 shows the results of the calculation. The concepts are explained below.

- *Total investment cost* includes all the foreseeable expenses related to purchasing the district heating system the municipality would have to pay for.

- *Financial support* is the assumed subsidy the municipality would get from the state. It is typically 15 % of the total cost excluding the district heating network and substations. In this case, though, it is 15 % for the boiler plant, foundation and DH pipework.
- *Repayment period* is the time in which the investment is paid, payback period.
- *Interest rate* is the assumed rate of interest, on average, during the above period.
- *Annual instalment* is the part payment for the investment.
- *Oil price* is the assumed price of light fuel oil on average in the repayment period.
- *Heat production from wood chips* is the assumed amount of heat that would be produced with the wood chip boiler. The municipality pays for this to the co-operative.
- *Heat produced from oil (the back-up boiler)* is the assumed amount of heat that would be produced from oil in the coldest and warmest periods and when the wood chip boiler should be out of order or under maintenance.
- *Heat loss to the ground* is the energy that would be lost. The municipality pays for it to the co-operative but cannot charge it to the customers.
- *Cost of oil (the back-up boiler)* is the annual cost of purchasing oil for the back-up boiler with the estimated oil price. The efficiency of the back-up boilers is supposed to be 80 %. It is somewhat less than such boilers can achieve because of their relatively low degree of use.
- *Price of sold heat* is the price the municipality would charge to those customers of heat that do not belong to the municipality. In this case it is 90 % of the price of heat generated with light fuel oil (85 % efficiency). Typically, it has to make economic sense for the consumers to join the system, so the heat needs to be cheaper when it comes from the network compared with oil or electricity. In its own buildings, the municipality would consume heat with the price it pays for the co-operative.
- *Marginal price of produced heat* is the cost paid to the co-operative that would lead to same expenses as the present heating system with oil, provided that oil

price would be, on average, what has been assumed and heat would be sold as estimated at the specified price.

Table 3.8. Marginal price of produced heat, VAT excluded.

Item	Value	Unit
Total investment cost	1430000	€
Financial support	193950	€
Repayment period	20	years
Interest rate	3.0	%
Annual instalment	83082	€
Oil price	0.40	€/litre
Heat produced from wood chips	6028	MWh
Heat produced from oil (the back-up boiler)	978	MWh
Heat loss to the ground	1086	MWh
Cost of oil (the back-up boiler)	48916	€
Price of sold heat	42.4	€/MWh
Marginal price of produced heat	**22.1**	**€/MWh**

The calculation of table 3.8 is shown in the Appendix, table II.

3.2.7 Sensitivity analysis

As the calculation is based on several estimations, some items have been studied more exactly. The effects of changing some values in the calculation can be seen in the following figures. Only one variable has been changed at a time. The first one is the price of oil: figure 3.13 shows how oil price alters the marginal price for produced heat. The price of sold heat remains 10 % cheaper than that produced from oil, so it changes along with the oil price.

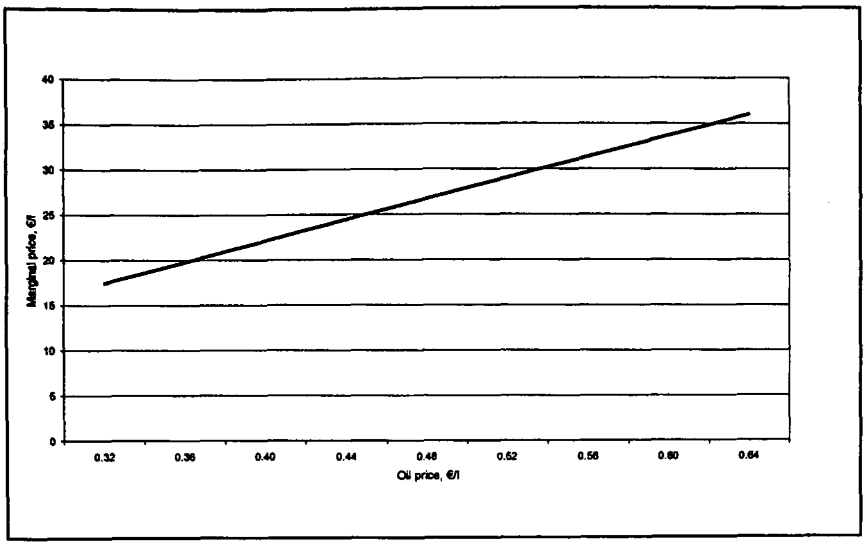

Figure 3.13. Marginal price of produced heat against oil price, VAT excluded.

It can be seen that oil price of 0.36 €/litre would make it possible to pay about 20 €/MWh for produced heat. As the price of oil goes up, the marginal price follows linearly. Figure 3.14 shows the importance of the payback period.

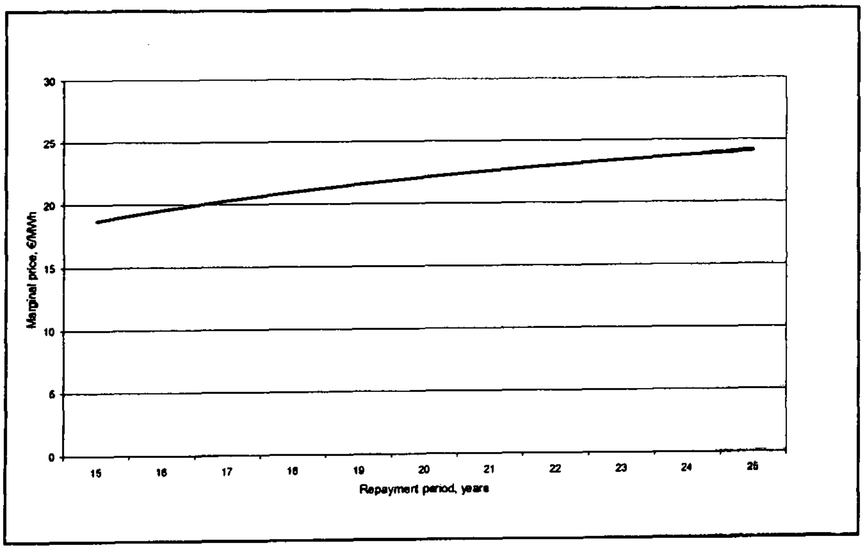

Figure 3.14. Marginal price of produced heat against repayment period, VAT excluded.

As can be seen in figure 3.14 if the period of repayment is between 16 and 17 years with an oil price of 0.34 €/litre, the marginal price for produced heat is 20 € /MWh. Figure 3.15 plots the marginal price against the rate of interest.

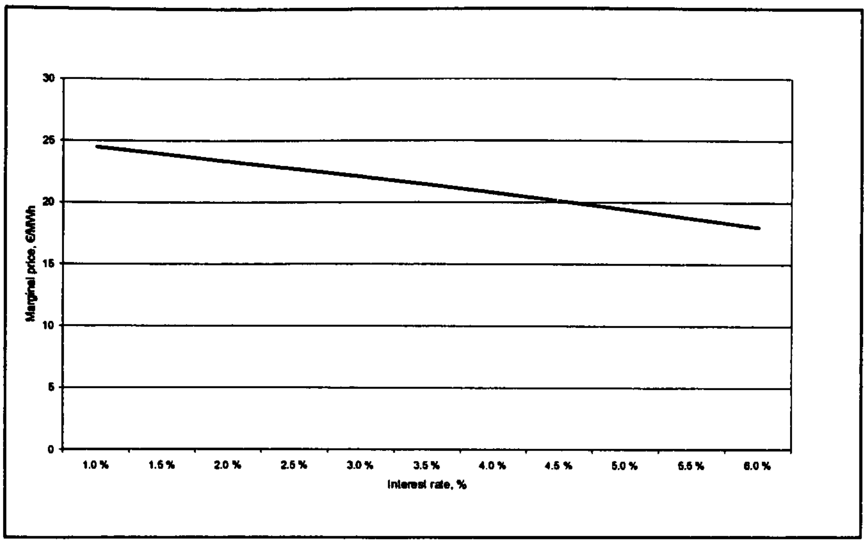

Figure 3.15. Marginal price of produced heat against the rate of interest, VAT excluded.

It can be noticed that an interest rate of 4.5 % would lead to 20 €/MWh with an oil price of 0.34 €/litre. Figure 3.16 brings out the significance of cost estimates. The financial support has been subtracted from the investment, so the capital cost stands for what the municipality would have to pay.

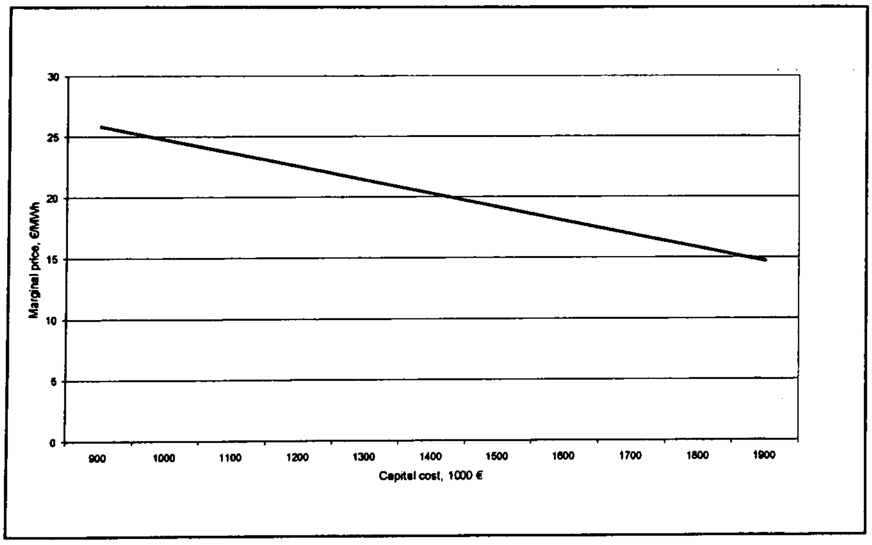

Figure 3.16. Marginal price of produced heat against total cost with a subsidy of 15 % of boiler plant, foundation and DH pipe work, VAT excluded.

3.2.8. Conclusions

At the time the study was carried out, 20 €/MWh seemed to be a reasonable average price for heat produced from wood chips, in Finland. In larger boiler plants with bigger heat production the price may have been a bit lower and in the small ones (output less than 500 kW) it was often somewhat higher. In this study, it seems that the municipality would be able to pay around 22 €/MWh, a pretty good price for a boiler plant of this size. It is, though, to be remembered that in the calculation interest rates were low, oil price rather high and the payback period was lengthy. All these things help to make the project seem viable. Twenty years is a long period, however, and many things can change during that time. Nevertheless, with the knowledge that was available at the moment the study was carried out, it would make economic sense for the municipality to purchase a wood chip boiler plant and a district heating network.

Finally, it should be pointed out that changing heating fuels from fossil sources to renewable ones is not purely a question of deriving profit. According to international agreements Finland, too, needs to cut down the use of fossil fuels and carbon dioxide emissions. This could be a step in that direction. It is obvious that in the future the government will have to change the taxation policy, so that using fossil fuels becomes less attractive compared to renewable ones. Moreover, it is to be remembered that a bio-fuel boiler plant brings a lot of work to the locality: If the wood chips are produced locally, it will certainly employ local people just like running the boiler plant. Not to mention that the considerable amount of money which at the moment is being paid to international oil companies could as well be paid to a local co-operative and local contractors.

4. Development of a dynamic model for the sizing of a wood chip boiler

4.1 Introduction

To be able to evaluate the accuracy of the sizing method that is based on outside temperature durations, the degree-days, another method has been developed. Contrary to the degree-day method that does not involve information on *when* different outside temperatures prevail, this more dynamic method calculates the demand for heat for each building in the network for every hour of the test year. The idea is to simulate the buildings as heat consumers so that one could find the heat consumption profile for each building and, later on, combine separate heat consumption profiles to get information on how the district heating network operates as a whole.

The initial idea was that there would be one spreadsheet application which would be able to calculate the division of heat consumption and combine the results of such calculations of all the buildings that belong to the same district heating network. Later on, it became evident that the capacity of the software would not allow handling so much data simultaneously. That is why the procedure calculates the division of heat consumption for each building separately. This is done with the sub-model introduced in Chapter 4.2. The next model that, introduced in Chapter 4.4, includes the district heating network, the capacity and limits of the wood chip boiler and the annual heat consumption data of all the buildings that comes from the first sub-model. These two models, introduced in Chapters 4.2 and 4.4, are linked by manual cut and paste of data across the spreadsheets. The first model is required to get detailed data on the heat consumption of each building and the other one studies the whole network including consumers and the wood chip boiler as a district heating system on an annual basis. The third model, introduced in Chapter 4.5, is not linked to the two above models. Of course, the same initial data can be used regarding, for example, the DH network, but essentially the approach is different. The model includes detailed information on the boiler plant and the consumer sub-stations and it is suitable for modelling rather short periods, something like a couple of hours. This is how it differs from the two above models that focus on the division of annual heat consumption. The modelling platform for all above models was Microsoft Excel 2002.

To find out the accurate heat consumption profile for any building would require extensive measurements for a long period of time. Therefore, this sort of information is normally not available. In the method that is presented in this work, below the starting point the annual heat consumption was known from experience and the peak load is known, as well. Furthermore, it is generally known that heat losses, on the one hand through the envelope and on the other hand through ventilation, are approximately proportional to the temperature difference between the exterior and the interior. And, thirdly, it is generally known that there are several heat gains in a building that cause heat liberation in the interior which, to a certain extent, reduce the need for heat from the actual heating systems.

The calculation procedure is based on the above mentioned facts. The weak point for the method is that detailed information on the structure and usage of the building is difficult to find. The more one uses general estimations instead of detailed facts the more inaccurate the method becomes.

4.2. Input data for the single building model

Below are listed data that the user needs either to find out or to estimate. Some items are considered constants, whereas some are supposed to vary. The actual calculation procedure is introduced later on.

4.2.1. Constant values

- Heat input for the heating system at the design temperature. (The peak load for radiators, floor heating or any other system to heat the building)
- Heat input for the ventilation system at the design temperature with full ventilation rate. (The peak load for pre-heating the supply air with full flow rate)
- Heat input for the ventilation system at the design temperature with reduced ventilation rate. (The peak load for pre-heating the supply air with reduced flow rate,

typically when the outside temperature is very low or when the occupants are not present)

- The design outside temperature
- The supply air / exhaust air ratio
- The effectiveness of the heat recovery heat exchanger when the ventilation system operates at full flow rate
- Flow arrangement of above heat exchanger; cross flow or counter flow
- Inside temperature during the heating season
- Secondary side inlet and outlet temperatures of the domestic hot water heat exchanger
- Orientations of the facades of the building
- Window area for each I separately
- Shading angle of direct radiation for each I separately
- Radiation transmissivity coefficient of windows for each I separately
- Visibility coefficient between windows and the vault of sky for each I separately
- Reflectivity of ground
- Visibility coefficient between windows and ground for each I separately
- Latitude and longitude of the locality
- Proportion of heat liberated inside the building from domestic hot water consumption

4.2.2. Hourly varying values

- Operation hours of the ventilation system with full flow rate
- Operation hours of the ventilation system with reduced flow rate
- Consumption of domestic hot water
- Starting times and durations of three separate periods of domestic hot water consumption and their proportions of the total diurnal domestic hot water consumption
- Power dissipated by electric lighting and the sleeping and waking hours of the occupants

- Power dissipated by any other device and the proportion of energy that is liberated inside the building
- Hours of attendance of the occupants
- Hourly output of any other heat gain

4.3. Calculation procedure of the single building model

The application has been intended to be used for a single building or a group of buildings that are located close to one another. It is not capable of calculating the annual heat consumption of the building or the group of buildings, the consumer of heat. On the contrary, it is supposed that the annual heat consumption is known. The function of the application is to determine the division of the known heat consumption so that one is able to see how much heat the consumer draws from the district heating network at any given hour. The total calculated consumption of heat needs to be equal to the actual heat consumption. Prevailing outside temperatures and incident radiation (direct, scattered and reflected) emitted by the sun in year 1979, which is the Finnish test year, are taken advantage of by the application. The measurements have been carried out by The Finnish Meteorological Institute at three localities. The application calculates all the weekdays (Monday – Friday) with the same way and weekends (Saturday – Sunday) with another way. For instance, schools and office buildings are typically not used in weekends. In residential buildings it may happen that occupants spend more time inside in weekends than in weekdays. Saturday and Sunday are, however, considered to be equal days.

4.3.1. Need for heat

Figure 4.1 illustrates the heat equilibrium in a building. All the heat that enters the building has to leave it approximately at the same time, if the inside temperature is to be constant. Heat is carried in through radiators, supply air and heat gains which may be either external or internal. Heat leaves the building because of conductive transmission and convective filtration through the envelope of the building and convectively with the exhaust air and hot water that gets in the drain. Part of the heat of the exhaust air is transferred to supply air if there is heat recovery in the ventilation system. Domestic hot water supply is concerned here as a heat gain. Heat is taken from the primary heating source for radiators, supply air heater (ventilation) and domestic hot water preparation. In the application, natural ventilation has been ignored: It has been considered negligible compared with forced ventilation system.

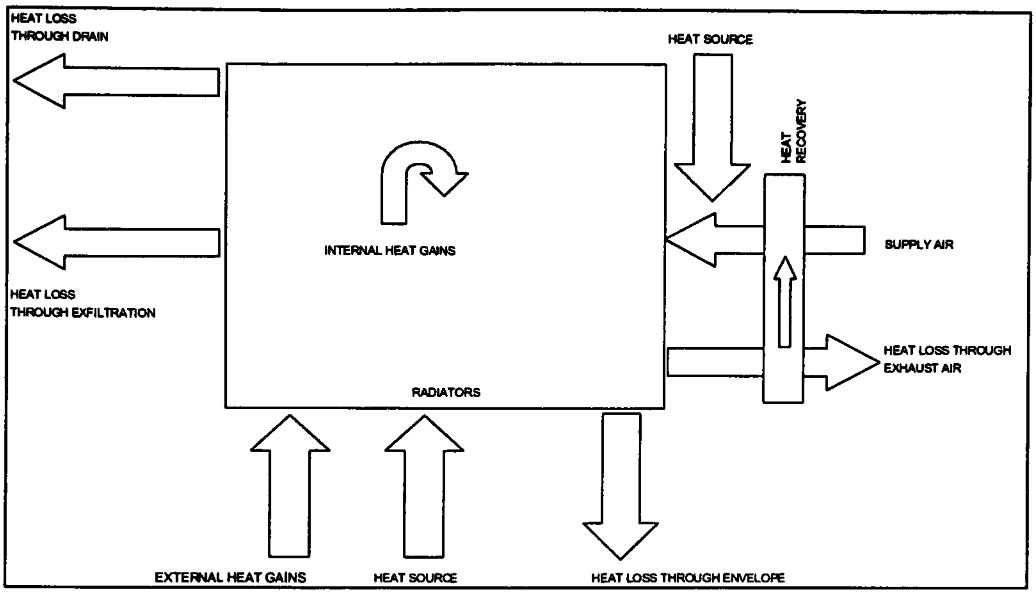

Figure 4.1. Heat equilibrium in a building.

The need for heat and the heat gains are calculated on an hourly basis through the year, which leads to 8760 results. The need for heat is considered to be proportional to the temperature difference between the outside and inside temperatures so that the design heat input occurs at the design temperature and the need for heat ceases to exist as the outside temperature reaches the inside temperature. The need for heat is calculated as follows:

$$q = \frac{T_i - T_d - (T_o - T_d)}{\frac{T_i - T_d}{q_d}} \qquad [4.1]$$

where

q is the need for heat, kW

T_i is the inside temperature, °C

T_d is the design (outside) temperature, °C

T_o is the prevailing outside temperature, °C

q_d is the design heat input, kW

The need for heat for the supply air pre-heating is calculated the same way. The flow rate of the ventilation may not have more than two different values, one of which is the full rate and the other one a reduced rate. The latter may as well be zero. Again, the need for heat is based on the difference between the outside and inside temperatures compared to the design heat input at the relevant flow rate.

The domestic hot water (DHW) consumption occurs rather momentarily and irregularly. As the calculation is carried out on an hourly basis, very short periods of DHW consumption cannot be dealt with. On the other hand, one is generally not able to say how the consumption varies in different buildings, without extensive measurements. In the application, there are a maximum of three separate periods, each of which last one hour, for the DHW consumption. One fills in how the total diurnal DHW consumption is divided into the aforementioned three parts. The input required for preparing domestic hot water is calculated for each of above periods as a mean input for a period of one hour:

$$q = n \cdot V \cdot \rho \cdot c_p \cdot (T_h - T_c) \qquad [4.2]$$

where

q is the average heat transfer rate for DHW preparation, kW

n is the share of diurnal DHW usage for a given hour, %

V is the diurnal DHW usage, dm^3

ρ is the density of the DHW, $\frac{kg}{dm^3}$

c_p is the specific heat of the DHW, $\frac{kJ}{kg \cdot °C}$

T_h is the temperature of the DHW, °C

T_c is the temperature of the cold water, °C

4.3.2. Heat gains

4.3.2.1 Heat recovery

The major part of the heat a building needs comes from the heating system, but not all of it. There are several heat sources in addition to radiators and supply air which mainly account for heating. They are referred as to heat gains and they are useful as far as they do not exceed the need for heat.

Heat recovery from exhaust air to supply air is the most significant heat gain on an annual basis provided that a heat exchanger exists. To what extent does the temperature of the supply air rise due to heat recovery depends on the effectiveness of the heat exchanger. As the effectiveness at full flow rate ventilation is set in the input data, values for other ventilation rates can be calculated, according to [17] as follows, in a cross flow case:

$$\varepsilon = 1 - \exp\left[\left(\frac{1}{C_r}\right)(NTU)^{0.22}\left\{\exp\left[-C_r(NTU)^{0.78}\right]-1\right\}\right] \qquad [4.3]$$

And in a counter flow case, according to [18] respectively:

$$\varepsilon = 1 - \frac{1 - C_r}{\exp\left[NTU(1 + C_r)\right] - C_r} \qquad [4.4]$$

where

ε is the effectiveness of the heat exchanger.

C_r is the ratio of heat capacity rates in the primary and secondary sides so that whichever is greater is the denominator. The value varies thus between 0 and 1.

NTU is the number of transfer units. It is calculated as follows:

$$NTU = \frac{U \cdot A}{C_{\min}} \qquad [4.5]$$

where

$U \cdot A$ is the U-value of the heat exchanger, kW/m^2°C, times the heat transfer area, m^2.

$C_{\min}$ is the smaller of the heat capacity rates of the heat exchanger, $\frac{kJ}{°C \cdot s}$

It is assumed at this point that the overall heat transfer coefficient remains constant and no phase change occurs in the heat exchanger. The density and specific heat of air are also supposed to remain constant. These simplifications have been resorted to in order to keep the calculations at a reasonable level. As most of the input data (including the effectiveness of the heat recovery system) is based on assumptions and average values, it is not reasonable to calculate some items precisely. Accurate calculation would require knowledge of the structure of the heat exchanger so that velocities and Reynolds numbers could be determined. Furthermore, Prandtl number and Nusselt number would have to be calculated, which would require knowledge of viscosity, density and thermal conductivity of air at different temperatures. All these calculations repeated 8760 times would take quite a lot of computing capacity compared to the advantage gained. As heat recovery along with changing ventilation flow rates is more an exception than a standard, its importance in this connection is relatively small. Essential is that the effectiveness goes up as the flow rates come down.

4.3.2.2 Solar radiation

There are some terms related to solar radiation that need to be discussed before the equations are expressed.

Altitude of the sun is the angle a direct ray from the sun makes with the horizontal at a particular place on the surface of the earth. For a given date and time, the altitude of the sun is different at different places on the globe.

Azimuth of the sun is the angle the horizontal component of a direct ray from the sun makes with the true north-south axis.

Declination is the angular displacement of the sun from the plane of the equator of the earth. It varies through the year between 23.5 ° and -23.5 °.

Figure 4.2 clarifies concepts altitude and azimuth.

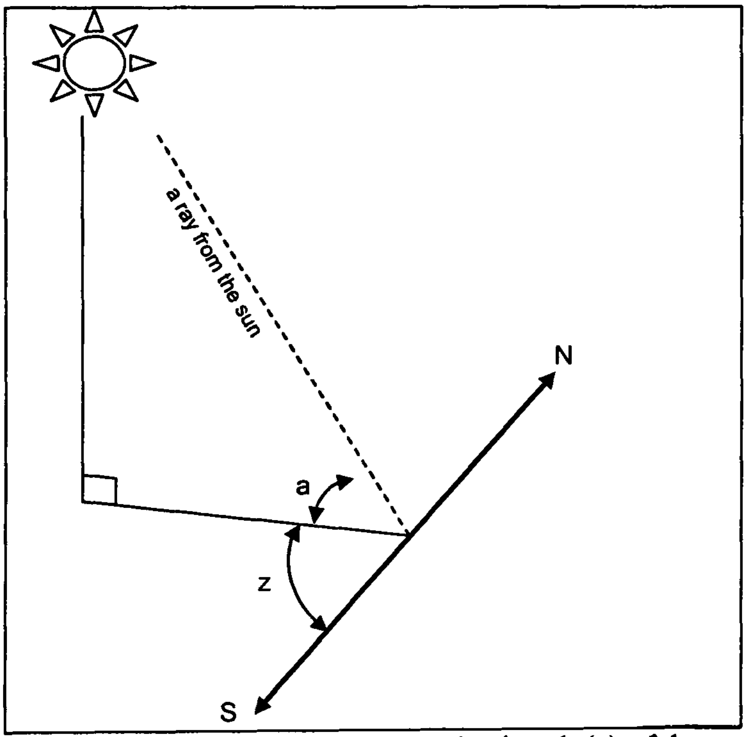

Figure 4.2. Altitude (a) of the sun and azimuth (z) of the sun.

The declination is calculated, according to [18] as follows:

$$d = 23°27' \cdot \sin\left(360 \cdot \frac{284+n}{365}\right) \qquad [4.6]$$

where

d is the declination of the sun

n is the day number, starting from 1 on January 1st.

The altitude is calculated as follows:

$$\sin a = \sin L \cdot \sin d + \cos L \cdot \cos d \cdot \cos \tau \qquad [4.7]$$

where

a is the altitude of the sun

L is the latitude of the location

d is the declination of the sun

τ is the hour angle, which is 0 when the sun is in the south and every subsequent hour increases its value by 15 degrees; preceding hours decrease its value from zero respectively

When calculating the hour angle *sun time* must be used instead of official time. It is calculated, according to [18] as follows:

$$t_{sun} = t_{off} + 4 \cdot \left(Lo_{time} - Lo_{loc}\right) \div 60 + E \div 60 \qquad [4.8]$$

where

t_{sun} is the sun time (hours, minutes)

t_{off} is the official time in the time zone (hours, minutes)

Lo_{time} is the longitude of the time zone

Lo_{loc} is the longitude of the locality

E is the time difference, in minutes, which is calculated as follows:

$$E = 9.87 \cdot \sin 2B - 7.53 \cdot \cos B - 1.5 \cdot \sin B \qquad [4.9]$$

where

$$B = 360 \cdot (n - 81) \div 364 \qquad \text{(in degrees)} \qquad [4.10]$$

where

n is the day number, starting from 1 on January 1st

In the application, direct radiation through windows is calculated according to the altitude of the sun. Orientations of the facades, window areas, shading angles and radiation transmissivity coefficients determine the amount of direct radiation. Recession of the windows has not been taken into account. The radiation transmissivity coefficient is considered a constant, even though the angle between the surface and incident rays does actually affect it. The effect of Venetian blinds and curtains has been ignored. Shading angles are considered constant for each I, even though they tend to change along with the position of the sun. It may also occur that shading is different in winter when trees are without leaves. These facts have been ignored, however, for the sake of simplicity. Figure 4.3 points out that the intensity of incident direct radiation (I_v) can be calculated geometrically if the altitude (a) and the deviation from the normal to the window (a) plus the incident total radiation (I) are known.

The component of direct radiation normal to a vertical window is:

$$I_v = I \cos a \cos n \qquad [4.11]$$

where

I_v is the component of direct radiation normal to the window, W/m^2

a and n are angles that can be seen in figure 4.3, °.

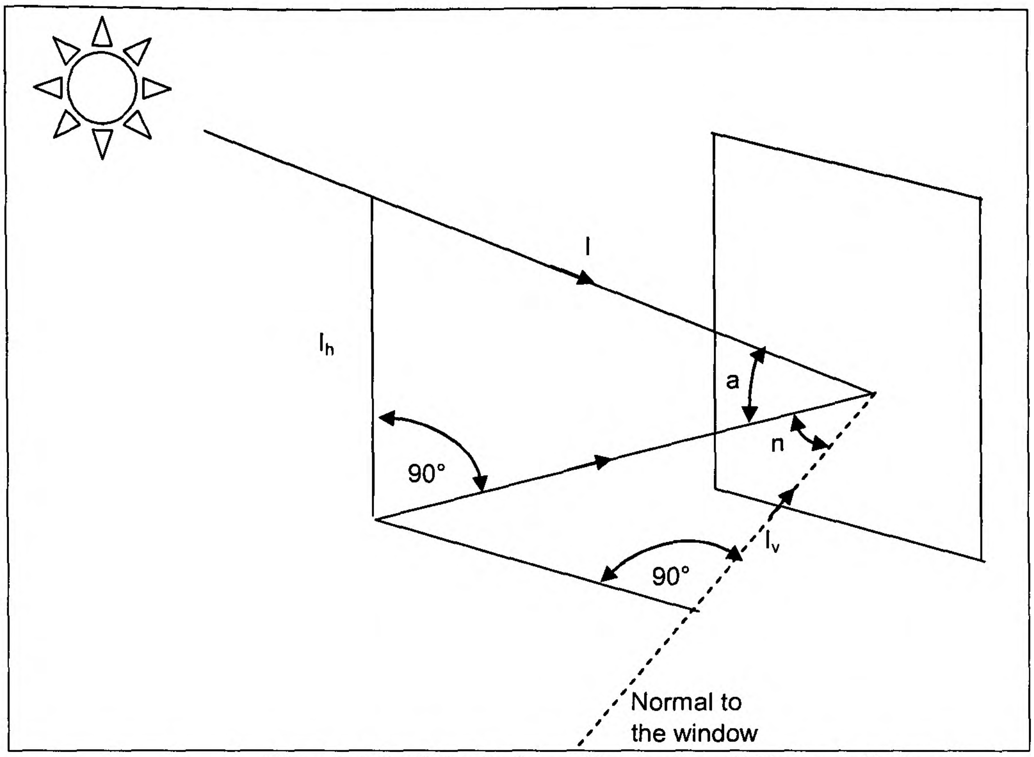

Figure 4.3. Calculation of intensity of direct radiation.

Figure 4.4 clarifies the concept shading angle.

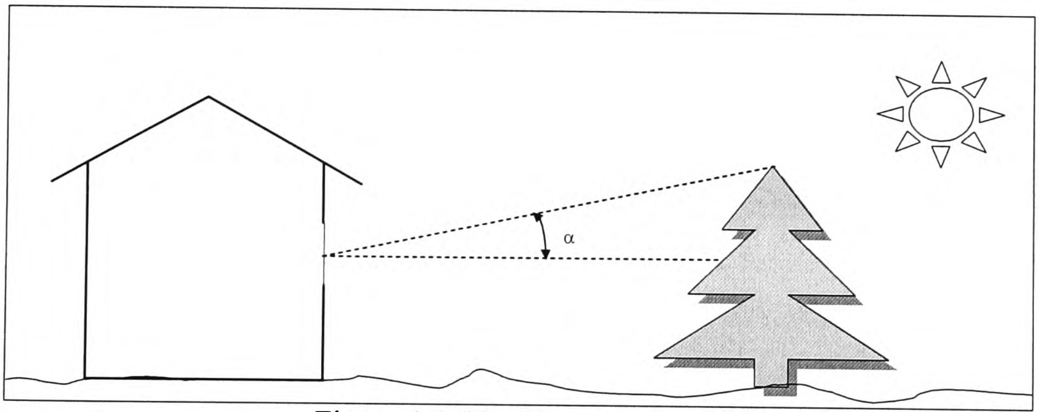

Figure 4.4. Shading angle for direct radiation.

Scattered radiation through windows is calculated practically the same way as direct radiation. The main differences are that visibility coefficients have been substituted for shading angles and the position of the sun has been ignored. It has been assumed that the intensity of the radiation from the vault of the sky is equally divided. This is not strictly true as the radiation tends to be more intense in that part of the sky which is close to the sun, but again it would lead to very complex mathematics if one tried to solve the exact amount of radiation passing through a particular window. And despite sophisticated mathematics, the result might be completely false if, for example, the occupant should adjust the slats of Venetian blinds in a different angle from what one had expected. Figure 4.5 clarifies the concept of the visibility coefficient. It is a percentage telling how well the vertical window can see the sky, 100 per cent means that there is nothing between the sky and the window, that is the angle is 90 °. In that case the intensity of scattered radiation incident to the window would be 50 % of what comes to a horizontal plane, since a vertical plane can only see 50 % of the vault of the sky.

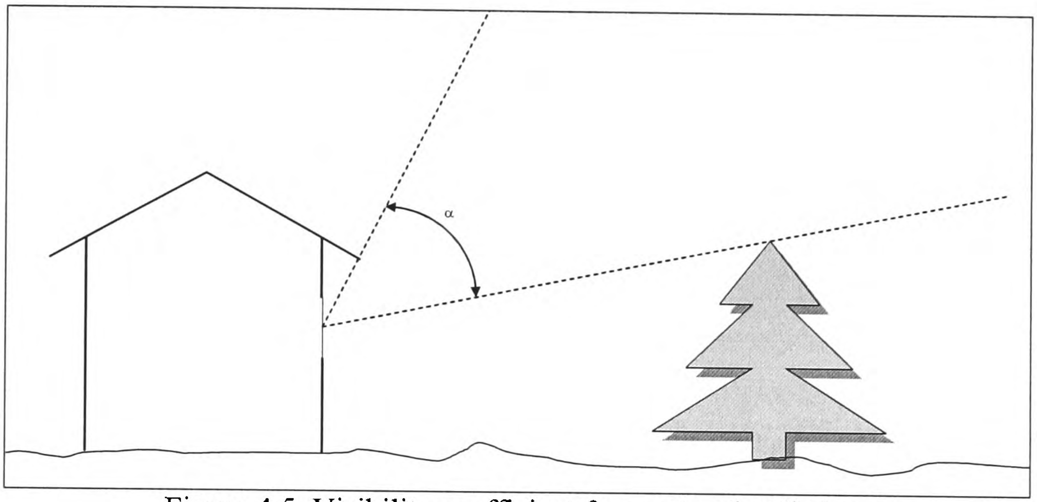

Figure 4.5. Visibility coefficient for scattered radiation.

Reflecting radiation through windows is calculated practically the same way as scattered radiation. The main difference is that the radiation comes from the ground, not from the sky. There is a visibility coefficient between windows and the ground which determines how well the window can see the ground, that is reflecting solar radiation. It is rather difficult to determine geometrically the visibility coefficient, because it is not only the ground that reflects solar radiation; trees and buildings reflect it too. Moreover, it is evident that areas close to the window are more significant than distant areas, when it comes to solar radiation reflecting from ground to a particular window. That is why, in reality, the visibility coefficient needs to be estimated rather than calculated. Only if there seems to be nothing restricting the reflecting radiation from accessing the window, the case is simple: The visibility coefficient is obviously 100 %. In the application, the coefficient is constant for all the windows in the same I. Moreover, there is a reflectivity coefficient describing the nature of the ground. It is a constant, though it actually changes along with the season. For example, snow reflects radiation in a different way compared to grass. The reflecting radiation is of minor importance, however, and it would be more or less impossible to determine how the reflectivity coefficient changes in different places along the year as there are so many things that affect it.

4.3.2.3 Other factors

Illumination causes heat liberation in the interior. In the application, all the power that is consumed for illumination is supposed to be dissipated as heat and liberated inside the building. The lighting of the exterior needs therefore to be extracted from the total lighting power before feeding it in the application, which assumes that the illumination is on, with full power, if the sun is below the horizon and the occupants are present but not sleeping. As they leave the building, go to sleep or the sun rises, the lights go off.

Power dissipated by electric appliances, for example cookers or washing machines cause heat liberation in the interior. The heat gain depends on the power of the device and the proportion of energy that is liberated inside the building. If the device is located inside the building and it is not connected to the exterior, the major part, if not all of the energy it consumes, dissipates finally to heat. On the other hand, for example washing machines tend to store some part of the energy into hot water which they discharge in the drain.

How much heat occupants' metabolism causes depends on their activity. In the application the amount is 60 watts per individual. That is a rather low value, but it is based on Finnish authorities' instructions. Only the sensible heat is taken into account.

As domestic hot water is consumed, some part of the heat is transferred to the interior. Which part stays in the interior and which leaves the building with the sewage depends on the purpose of use. It is obviously very difficult to define the proportion as it is a changing one. That is why it has been ignored in the calculations even though the user is able to feed a value in the application to represent the portion of heat that stays in the building. Should there be any other heat gain than described above in the building, the user may feed in times and wattages of its occurrence.

4.3.3. Heat input

The main question is how much heat does the building draw from the district heating system. The input is calculated on an hourly basis as the sum of demand for domestic hot water preparation and demand for heating and ventilation minus heat gains. So, the heat gains reduce the need for heat for heating and ventilation but they cannot be used in domestic hot water preparation. It is quite clear that heat gains reduce the need for heat of the radiator system, provided that the thermostatically operated radiator valves operate as they should. To what extent are the heat gains of use when it comes to the heat consumption of the ventilation system, depends on the automatic controller of the system. In the application, it has been assumed that the automatic control system tries to keep the inside temperature at its desired value. In the heating period this will be taken care of either with the heating system or with the ventilation system. Accordingly, if heat gains exceed the need for heat from the radiator system, the automatic control system reduces the temperature of the supply air so that the inside temperature remains constant.

Depending on the size of the building, changes in the outside temperature do not affect the need for heat simultaneously as they take place. It means that the curve illustrating the need for heat is somewhat smoother than the one showing variations in the outside temperature. The time lag is typically not known. In the application, one may calculate the need for heat as an average of several hours. The total annual consumption remains the same but the changes occur more smoothly.

The heat the building draws from the district heating system at a given hour consists of the average heat demand described above and the heat needed for domestic hot water preparation. These two values of every hour of the year are transferred to the application which adds up the heat demands of separate buildings.

4.4. Calculating the heat demand of a small district heating system

The function of the application is to add up the separate heat demands of the buildings that are connected to a district heating network. It also calculates the heat loss from the pipe work to the ground so that one is able to see what output is required from the boiler plant at any given hour. In this application, too, the output is calculated on an hourly basis. Not more than 20 buildings or group of buildings can be dealt with the application. The final objective is to find out which portion of the heat production could be carried out by the wood chip boiler and how much heat would be produced by the (oil-fired) back-up boiler.

Below are listed data that the user needs either to find out or to estimate. The actual calculation procedure is introduced later on.

4.4.1. Input data

- Not more than 8 different pipe sizes in the district heating (DH) network
- Total length of each pipe size
- Thickness of the insulation of different pipe sizes
- Thermal conductivity of above insulation
- Thickness of the plastic jacket on the insulation of different pipe sizes
- Thermal conductivity of the plastic jacket
- The vertical distance between the centre line of the pipe and the ground
- Thermal conductivity of the ground layer ambient the pipe
- The highest outside temperature the buildings require heating
- The supply district heating water temperature at above outside temperature (i.e. the minimum temperature for DH supply water)
- The design outside temperature of the locality
- The supply water temperature at above outside temperature (i.e. the maximum temperature for DH supply water)
- The maximum output of the wood chip boiler

- The lowest sustainable output of the wood chip boiler
- Period of year when the wood chip boiler is not in operation
- The impact of the heat loss on the supply water temperature (the final supply water temperature is less than the initial one, the mean value is used in heat loss calculations)
- The return water temperature

4.4.2. Calculation procedure

The temperature of the supply water is supposed to vary linearly according to the outside temperature. When the outside temperature is at the design temperature (set by the user) or below it, the supply water temperature reaches its highest value (set by the user). As the outside temperature is elevated, the supply water temperature comes down linearly until the outside temperature at which the building ceases to need heat (set by the user) has been reached. From that point on the temperature of the supply water remains constant. It needs to be high enough for domestic hot water preparation.

The heat loss from the pipe work to the ground reduces the temperature of the supply water, just as it does to the return water as well. Because the heat loss depends on the temperature of the fluid and the temperature in turn depends on the heat loss, it is not possible to find an algebraic solution for the temperature of the fluid. In fact, temperatures are not the same in different parts of the network. In the application, the problem is dealt with by assuming that the average supply water temperature is a couple of degrees lower than it is at the boiler plant. The user may fill in a coefficient for the calculation of the aforementioned temperature difference. The heat loss is not constant and neither is the reduction in temperature due to it. When the heat consumption is high and the flow rates, too, the temperature of the fluid does not undergo a reduction to such an extent as it does when the fluid is hardly flowing at all.

The temperature of the return water is even more problematic. In order to be able to determine it, the heat exchangers and the whole district heating network should be modelled. And the calculation on an hourly basis would not give correct results as the consumption of domestic hot water occurs rather occasionally and, on the other hand, the pipe work acts as an accumulator: The average temperature in the return pipe is not necessarily the same as the average temperature of the return flows from the heat exchangers at any given moment. However, the annual heat loss from the network to the ground is typically 10 to 20 % of the total heat output. Some two thirds of it occur from the supply pipe which is at a distinctively higher temperature than the return pipe. So, the heat loss from the return pipe is around 5 % of the total output. Even if its average temperature was estimated somewhat incorrectly, the deviation would be rather small, though.

The temperature of the ground follows the outside temperature. It is obvious, though that there is some kind of thermal inertia and rapid changes in the air temperature do not affect simultaneously the ground temperature. For example, snow cover reduces the heat transmission from the ground to air. On the other hand, windy weather may accelerate the cooling of the ground. Therefore, it is difficult to say exactly what the time lag is in different situations. In the application, the ground temperature is an average of the outside temperature of 24 preceding hours.

Thermal resistance of the pipe consists of insulation thickness on the pipe, its thermal conductivity and the thickness of the plastic jacket on the pipe and its thermal conductivity. The resistance of the steel pipe is considered negligible. The thermal resistance of the insulation and plastic jacket is calculated, according to [18] as follows:

$$R_E = \frac{1}{2 \cdot \pi \cdot k_i} \cdot \ln\left(\frac{D_p + 2 \cdot l_i}{D_p}\right) + \frac{1}{2 \cdot \pi \cdot k_j} \cdot \ln\left(\frac{D_i + 2 \cdot l_j}{D_i}\right) \qquad [4.12]$$

where

R_E is the thermal resistance of the insulated pipe, $\frac{m \cdot °C}{W}$

k_i is the thermal conductivity of the insulation material, $\frac{W}{m \cdot °C}$

D_p is the outside diameter of the pipe (without insulation), m

l_i is the thickness of the insulation cover on the pipe, m

k_j is the thermal conductivity of the plastic jacket, $\frac{W}{m \cdot °C}$

D_i is the outside diameter of the insulation (without jacket), m

l_j is the thickness of the plastic jacket on the insulation, m

The thermal resistance of the ground is calculated, according to [18] as follows:

$$R_M = \frac{1}{2 \cdot \pi \cdot k_g} \cdot \ln\left(\frac{2 \cdot l_g}{D_i} + \sqrt{\left(\left(\frac{2 \cdot l_g}{D_i}\right)^2 - 1\right)}\right) \qquad [4.13]$$

where

R_M is the thermal resistance of the ground, $\frac{m \cdot °C}{W}$

k_g is the thermal conductivity of the ground, $\frac{W}{m \cdot °C}$

D_i is the outside diameter of the pipe (with insulation), m

l_g is the vertical distance between the centre-line of the pipe and ground surface, m

The U'-value including both the resistance of jacketed insulation and the resistance of ground is calculated as follows:

$$U' = \frac{1}{R_E + R_M} \qquad [4.14]$$

where

U' is the overall heat transfer coefficient per metre of pipe, $\frac{W}{m \cdot °C}$

R_E is the thermal resistance of the insulation and jacket per metre of pipe, $\frac{m \cdot °C}{W}$

R_M is the thermal resistance of the ground per metre of pipe, $\frac{m \cdot °C}{W}$

As the maximum output and the lowest sustainable output of the wood chip boiler have been defined and the application calculates the hourly inputs to the network, it can be seen how many hours per year the heat demand is beyond the operational range of the wood chip boiler. This is not, however, the result of the calculation. A wood chip boiler is very difficult to use if the heat demand lasts only a couple of hours at a time. In the application, if the heat demand remains for 4 hours below the lowest sustainable output level or the average output during more than 4 hours is not more than 75 % of the said level, the heat production of the wood chip boiler ends. There will have to be a period of 24 hours during which the average output is not less than the minimum sustainable output plus 25 % and the lowest momentary output during the same period is not less than the minimum sustainable output minus 25 % before the wood chip boiler is taken back into operation. The justification of the above figures is discussed in Chapter 5.7.2. It is also possible to determine a period when the wood chip boiler stays completely out of operation. By using the graphs illustrating the monthly heat demand the user is able to see if there is a period when using the wood chip boiler would be too laborious. In general, it is more or less impossible to set strict rules for defining in what kind of conditions the wood chip boiler could be used. Eventually, it depends very strongly on the operator of the plant and the fuel that is available. It is known from experience that extremely dry wood fuel is not suitable when the output is low; back-fires tend to cause trouble. As for the operator, if one is prepared to go to the boiler plant several times a day, it is possible to keep the wood chip boiler running almost year round. Many operators find that too troublesome compared with the gain, and they switch the wood chip boiler off as the demand for heat declines to a certain level.

4.5. The model of the operation of the boiler plant and the district heating network

As the previous application can be used in determining the division of annual heat consumption on hourly basis, it is not able to deal with momentary variations in the system. Yet it is known from experience that the most difficult situations occur when the need for heat varies rapidly. What kind of problems can be expected and how could they be taken into account are crucial questions. For example, it is known that the district heating network acts as an accumulator but what is the significance of that. Should it be taken into consideration when sizing the boilers or some other equipment in the heating system? What kind of fluctuations in the temperatures or the rates of the flows can be expected and how should they be dealt with?

The application for modelling the short-term operation of the district heating network and the boiler plant is able to simulate virtually all the things of any importance in the system. Therefore it can be used in surveying changes in any part of the heating network, given that certain simplifications may reduce its usability. It is possible to determine the boilers to be connected in parallel, when all the flow goes through the wood chip boiler if its capacity is sufficient for the heat demand. Only when its capacity is not big enough the two-way valve before the back-up boiler starts to open letting part of the flow pass the wood chip boiler. The other alternative is that the boilers are connected in series. It means that all the water flows firstly through the wood chip boiler and then through the back-up boiler. If the temperature after the wood chip boiler is below the desired value, the back-up boiler elevates it. Otherwise it just lets the water flow through.

4.5.1. The confines of the model

The calculation procedure is rather complex and it takes quite a lot of computational capacity. There are 240 time steps during which each of the variables are calculated. The equations for calculating the temperature of the district heating water are placed on a spreadsheet on a stepped way so that each time step starts one column right from the previous one. As there are limited number of columns, the number of time steps has had to be limited respectively. So the period of simulation is rather short: Depending on the time step it is something like a couple of hours. As it takes some time to get the system in to a state of balance, when only minor changes occur, the effective simulation time is less than the total calculation time. It is possible though, to simulate a period of several hours if no major changes in the heat consumption occur in that period.

The geometry of the district heating (DH) network in the application is fairly simple, so one obviously needs to simplify the actual network somewhat before feeding in details of it: There are not more than four nodes, and not more than three consumers can be connected to each of them. In addition to this, a branch pipeline can be connected to three of the above nodes and three consumers can be connected to the other ends of the branch pipelines. That makes a maximum of 21 consumers in a maximum of seven different nodes altogether. Just as it was possible in the previous application, it is also possible here to make bunches of separate buildings that are located close to one another, so that the actual amount of buildings may exceed 21. Figure 4.6 shows the geometry of the network and the parallel connection of the boilers and figure 4.7 with series connection respectively. S_1 to S_4 are nodes in the supply line and R_1 to R_4 in the return line respectively. Heat exchangers and by-pass lines can be seen between nodes S_4 to R_4 as there are three sub-stations each of which containing three heat exchangers. Similar installations exist between other six node pairs even though they are not visible in figures 4.6 and 4.7.

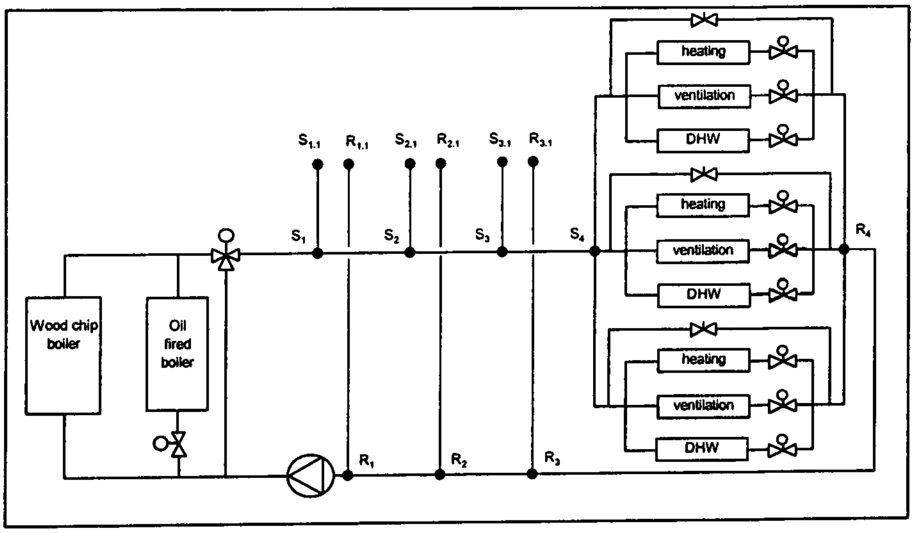

Figure 4.6. Diagram of the boiler plant and district heating network, boilers connected in parallel. Complete consumer system shown between nodes S4 and R4 only.

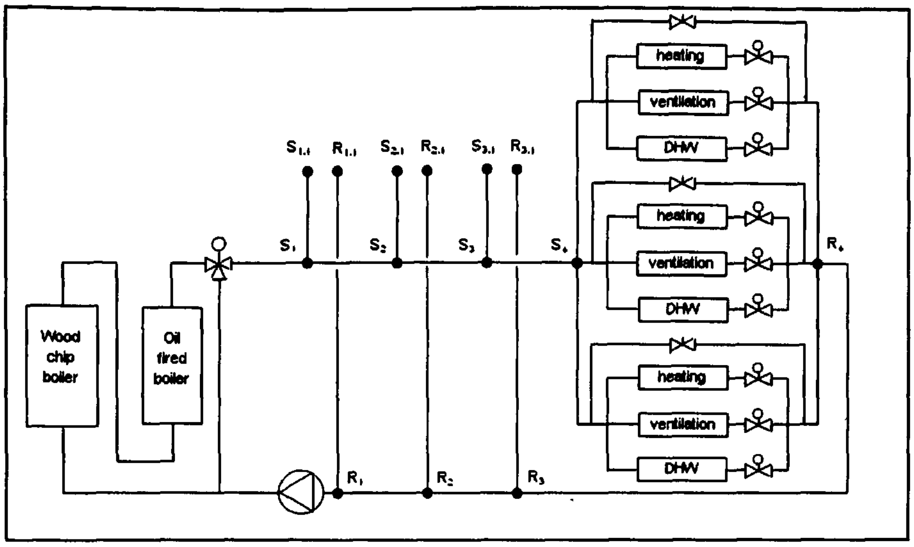

Figure 4.7. Diagram of the boiler plant and district heating network, boilers connected in series. Complete consumer system shown between nodes S4 and R4 only.

4.5.2. The district heating system

Heat is generated in the boiler plant and delivered to customers via the network. All the customers (i.e. buildings) are equipped with sub-stations which incorporate heat exchangers and other necessary equipment for heat transfer from the district heating supply water to radiators, ventilation supply air heaters and domestic hot water. The flow rate in the primary (district heating) side of the heat exchanger is regulated by a control valve so that the out flowing temperature in the secondary side is at desired temperature. Figure 4.8 shows the basic connection of two heat exchangers, one of which is for the radiator system and the other one for domestic hot water preparation. This is a simple connection as there are only two heat exchangers which are connected in parallel. There could as well be a third one for the ventilation system (supply air heating) and the domestic hot water heat exchanger could be connected partly in series with some other heat exchanger so that cold water would be pre-heated before entering the actual domestic hot water heat exchanger. In the application, though, all heat exchangers in any sub-station are connected in parallel.

Figure 4.9 shows more in detail a sub-station with two heat exchangers: One for the radiator system and the other one for domestic hot water. There is also a circulation system in the secondary side of the domestic hot water heat exchanger. Its purpose is to keep the domestic hot water pipes filled with hot water all the time so that one gets instantly hot water from the faucet without having to wait until the cooled water has been drained and hot water arrives at the faucet.

Figure 4.10 gives an idea of the control system for heating or ventilation. In both cases the secondary side out flowing temperature is controlled by a control valve in the out flowing (return) primary flow. The set point for the secondary side temperature is calculated based on outside temperature. The colder the weather the hotter the water that is needed.

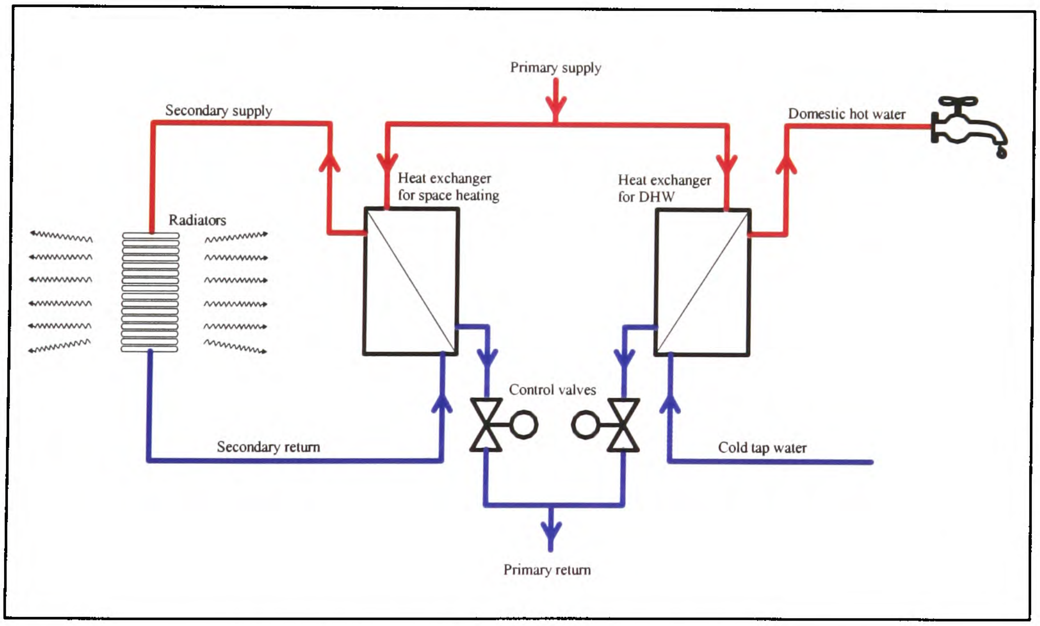

Figure 4.8. A simple heat exchanger connection.

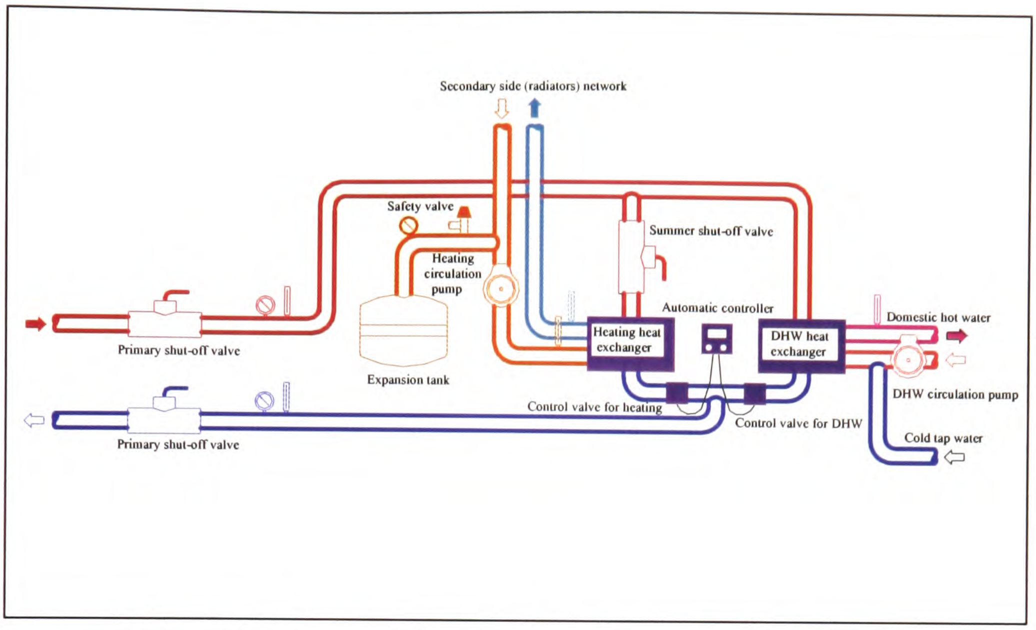

Figure 4.9. A consumer sub-station with two heat exchangers.

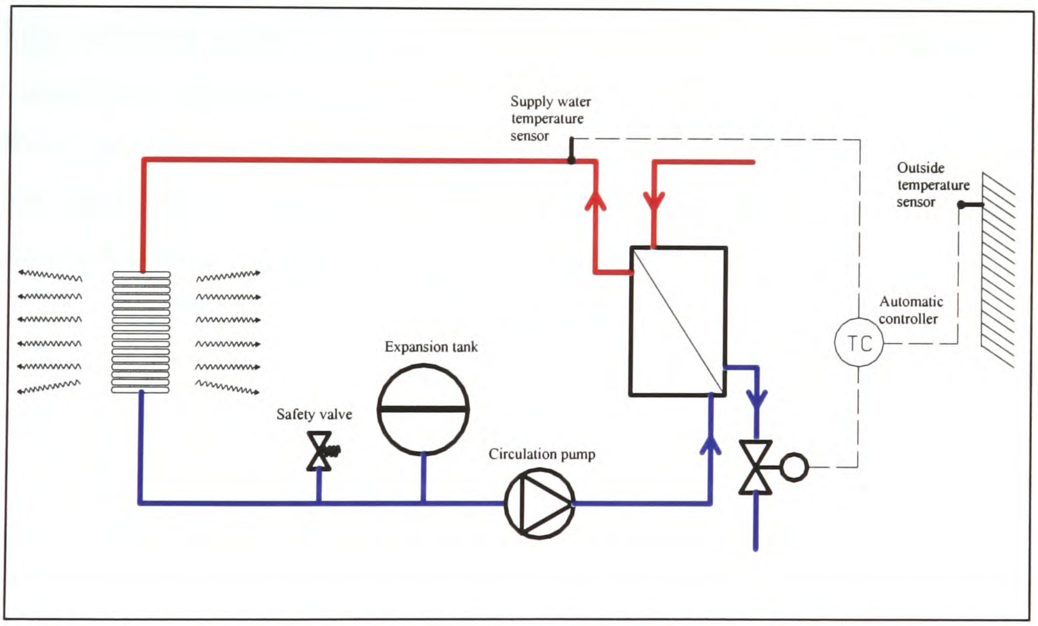

Figure 4.10. Supply water temperature control.

4.5.3 The operation of the model

The application needs basic information on the consumers of heat: Sizing of heat exchangers, design heat inputs, the location of the building in the network etc. Some information on the DH network is required: Pipe sizes, distances between the nodes, insulation on the pipe work etc. In addition to that one needs to define the outside temperature and the ground temperature plus details on heat consumption in the simulation period of each consumer separately.

All the foregoing facts relate to heat distribution or consumption. In the application, also heat production has been included in the system. There is a wood chip boiler and an oil-fired boiler in the plant. One needs to fill in information on the capacities and volumes of the above boilers and valves and automatic control equipment in the plant. Boilers can be connected either in parallel or series.

The calculation procedure is that each variable is solved based on initial data that has been fed in. As most of the variables depend on other variables (e.g. a given heat output can be produced with an infinite combination of temperature differences and flow rates), algebraic solutions cannot be found. That is why the calculation procedure is iterative: The application uses the trial and error method to find an equilibrium between the variables. An increase in the heat consumption leads to growing flow rates and when the desired input has been reached, the flow rate remains steady until either the heat consumption or the incoming flow temperature changes.

The time step determines the accuracy of the calculation. If every variable is at its desired value, all the adjusting devices remain stationary until the equilibrium ceases to exist. That kind of situation occurs very rarely. Normally there are deviations between the desired values and the actual ones. The application tries to remove the deviation by regulating the relevant device, e.g. by opening or closing a valve, increasing or reducing the output of the boiler etc. All the changes the application does to the regulating devices (except for increasing or decreasing the output of the wood chip boiler) take place at a constant rate. That is why a long time step causes trouble: Even a small deviation may become a huge one if the regulating device operates over a long period without the controller checking the situation. No sooner than at the following calculation step will the application notice that the deviation has increased. It will then try to eliminate it even more effectively which leads to repeated over- and undershoots called cycling. By setting the calculation step short, one can see that regulation devices tend to act smoothly and no cycling exists. The main drawback is that short calculation steps lead to a short simulation period because there are only 240 calculation steps to be used. Another way to reduce cycling is to set the regulating devices rather slow so that they will not be able to change the situation a lot even if the time step is lengthy. That kind of arrangement is useful if there is not much variation in the heat consumption during the simulation period.

In the DH network, flow rates and temperatures are constant during each calculation step. New temperatures are calculated at every calculation step based on heat loss to the ground and mixing flows. Flow rates are calculated according to positions of control valves and the resistance of flow in the network.

4.5.4. Input data

The user feeds in following information on the system.

4.5.4.1 Heat consumers

- Design values (inflow and outflow temperatures, pressure drop, heat transfer rate) for every heat exchanger in the system. *The actual heat transfer rates at the design temperature are supposed to match with heat exchanger design values.*
- Heat input for the supply air pre-heating at the design outside temperature with reduced ventilation rate (if a reduced ventilation flow rate is available)
- Pressure drop (with the design flow) of the pipes connecting the heat exchangers to the nearest node. *Pressure drops with other flow rates are calculated based on that pressure drop is proportional to the square of the flow rate.*
- Potential by-pass flow at sub-stations with a given pressure difference. *By-pass flow depends on the available pressure difference across the by-pass line which, in turn, depends on the flow rate in the network because pressure difference at the boiler plant is kept constant. Thus, when the flow rate in the network is close to zero the pressure difference generated by the pump is almost completely available for the by-*

pass line. When the flow rate increases, pressure drop in the network goes up, too, and the available pressure drop for the by-pass line decreases depending on how far the place is from the boiler plant.

- The time it takes the control valve stem to move from one extreme position to the other one if the automatic controller is not reducing its rate. A separate valve for each heat exchanger. *Motorized valves tend to move rather slowly to avoid growing oscillation, cycling, in the control system. In the application it is even more important not to make the control valves to move too fast, particularly if the time step is lengthy.*
- Periods of heat consumption: Starting and ending moments and consumption rates for not more than two separate domestic hot water consumption periods per consumer; starting moment for heating and starting moment for ventilation with full and reduced flow rate. *It is not recommended to make many changes in the heat consumption rate at one calculation period because the effects tend to get mixed and it is difficult to see what actually results from a given change. It is advisable to let either heating and ventilation or domestic hot water consumption stay constant during the calculation period and make a few changes to the other one.*

4.5.4.2 District heating network

- Distances between the nodes in the network
- Pipe sizes between the nodes. *The application does not size pipes, the user needs to select the pipe diameters beforehand. Naturally, they can be changed if it seems reasonable.*
- Pressure drops between the nodes with design flow rates. *Pressure drops with other flow rates are calculated based on that pressure drop is proportional to the square of the flow rate.*
- Thickness of the insulation of different pipe sizes. *There are several thicknesses available. They also tend to relate to the pipe diameter so that large pipes have thicker insulation than small ones. The user needs a catalogue from a manufacturer to fill in the thicknesses.*

- Thermal conductivity of above insulation. *When it comes to resistance to heat transmittance, only the resistance of the insulation and ambient ground are taken into account. Neither the steel pipe nor the plastic jacket on the insulation are included in the calculations. Their significance has been considered negligible at this point.*
- The vertical distance between the centre line of the pipe and the ground. *This relates to the resistance to heat transmittance from the fluid to air.*
- Thermal conductivity of the ground layer ambient the pipe. *This relates to the resistance to heat transmittance from the fluid to air.*

4.5.4.3 The wood chip boiler

- The maximum output. *It is known that the maximum output of a boiler depends not only on the structure of the boiler but also on the quality of the fuel. Notably moisture content of chips determines the output that can be reached. The user needs to consider what sort of fuel could be available and what output could then be achieved.*
- The minimum (sustainable) output. *When it comes to the output, it is evident that there is a limit for the combustion rate that the boiler can sustain. If the rate goes below that limit the boiler is not able to increase its output again but the flames will die. The calculation procedure does not let the output of the wood chip boiler go below the limit which is set by the user.*
- The volume of the water space of the boiler. *The calculation does not take into account any kind of stratification in the temperature of the boiler water. It is thought that flow in the water space of the boiler is sufficient for complete mixing so that temperature is equal all over the boiler.*
- The biggest possible increase in the output when the boiler operates at its minimum output as the starting point and when the boiler operates close to its maximum output respectively. *It has been assumed at this point that a wood chip boiler is able to increase its output faster if the initial output is relatively high compared to a situation where initial output is low and, thus, the combustion chamber is rather empty and temperature in the chamber pretty low. The calculation presumes that the ability to increase the output (kW/minute) is linearly proportional to the initial*

output. The user has to estimate the slope of the correlation, it may as well be a horizontal line. The same goes for decreasing the output: The calculation presumes that it is more difficult to drop the output if the boiler is operating at full power compared to a situation where the output is initially low. Again, the user has to make the decision about the correlation between the boiler's ability to decrease output and the initial output.

- The biggest possible decrease in the output when the boiler operates close to its minimum output as the starting point and when the boiler operates at its maximum output respectively.
- The desired value for the boiler water temperature. *Boiler water temperature is quite often kept constant in spite of fluctuations in the need for heat. There is a motorised valve that mixes cooled return water with the supply water if the supply water temperature shall be at lover temperature than the boiler water.*
- Three coefficients that determine how effectively the controller tries to eliminate the deviation in the boiler water temperature. *There is always some kind of deviation between the desired and actual value. In general, the bigger the deviation the faster the automatic control system tries to eliminate it. In real installations the control is taken care of by a PID controller. In the application there is a controller that acts like a PI controller, so it reacts faster if the deviation is bigger and it tries to remove the deviation completely. Still, it is not a real PI controller and the coefficients are not transferable to a real installation.*
- Two coefficients that determine how the thermal mass of the boiler is taken into account. *It is extremely difficult, without extensive measurements, to say how long it takes before the output of the boiler really starts to change after the automatic controller wishes it to do so. Moreover, it is evident that the rate of change is not constant even if the controller is trying to make a major change in the output. However, it might be interesting to see what the result would be with different thermal masses. Even though the user does not know the behaviour of the boiler in this respect, he might get an idea of the significance of the thermal mass by experimenting with different coefficients that have an impact on the inertia of the*

boiler in the calculations. It is also possible to leave the inertia out of the calculations completely.

4.5.4.4 The oil-fired boiler

- The output of the burner. *In the application, the output of the oil-fired boiler is not modulating but it is under on/off control.*
- The volume of the water space of the boiler. *The calculation does not take into account any kind of stratification in the temperature of the boiler water. It is thought that flow in the water space of the boiler is sufficient for complete mixing so that temperature is equal all over the boiler.*
- The desired value for the boiler water temperature. *There is an automatic control unit that exercises control over the oil burner. It tries to maintain the boiler water temperature at its desired value.*
- The set point for the boiler water temperature that makes the burner to start. *As the boiler water temperature goes below its desired value, the burner does not start immediately. Only when a given temperature is reached, the boiler starts and remains in that condition until the desired value has been reached.*

4.5.4.5 The regulation of supply water

- The time it takes the three-way-valve stem to move from one extreme position to the other one if the automatic controller is not reducing its rate. *The function of the three-way valve is to mix hot boiler water and cooled return water so that supply water entering the network is at its desired temperature (which depends on outside temperature). In the application, there is no PID- or any other control that would take into account the deviation in the supply water temperature from its desired value and increase the speed of the valve movement if the deviation is large. The valve stem is simply moving at a constant rate as long as the desired value has been reached. The movement is typically rather slow: In real installations it may take 20 to 30 minutes to move the stem from one extreme position to the other one.*
- The shape of the characteristic curve of the three-way valve: either linear or equal-percentage. *In the application both ports of the valve need to have the same type of*

characteristic, so it is not possible to set one port as a linear one and the other as an equal-percentage.

- The pressure drop in the wood chip boiler and its pipe work, with the design flow rate. *Certain pipes and fittings are only for the wood chip boiler, when the boilers are connected parallel. The user needs to find out or estimate the pressure drop in these pipes and fittings with a given flow rate. With other flow rates the pressure drop is calculated based on the fact that pressure drop is proportional to the square of the flow rate.*
- The pressure drop in the pipe work that is common to both boilers, with the design flow rate. *When the boilers are connected in series, all the pipes and fittings serve both boilers. If there is a parallel connection, only some pipes and fittings serve both boilers. The user needs to find out the pressure drop in these pipes and fittings with a given flow rate.*
- The pressure drop in the boiler circuit port of the fully open three-way valve in relation to total pressure drop in the circuit that is regulated by it, with a given flow rate, called the authority of the valve. *The authority is considered important for a control valve: In practice it means that there needs to be rather big a pressure drop over the control valve even if it is fully open. If there is not enough authority in the control valve, the regulation becomes unstable. The drawback with a high authority is that it causes excess pressure and, thus, pumping costs increase. A typical authority of a control valve regulating the temperature of the supply water is around 50 %.*
- The set point for the difference between the desired and actual values of the supply water temperature that starts to open the two-way valve and lets the oil-fired boiler take part in heat production. *This is only for parallel connection; in series connection all the flow goes through both boilers and there is no two-way valve between them. When the back-up boiler has been disconnected from the system with a motorised valve, it is a common practice that the motorised valve is only let to open if the difference between boiler water (or supply water) desired temperature and the actual value becomes rather large, otherwise the back-up boiler tends to disturb the control*

of the wood chip boiler. It is a fact that there is almost always some kind of fluctuation in the wood chip boiler water temperature. Only when the wood chip boiler is clearly not capable of generating enough heat to meet the needs should the back-up boiler start to back it.

- The time it takes the two-way-valve stem to move from one extreme position to the other one if the automatic controller is not reducing its rate. *Only for parallel connection. The stem travels at a constant rate. If the rate is too high, the control becomes unstable. In real installations the time from fully open to fully closed or vice versa is something like 15 to 20 minutes.*
- The shape of the characteristic curve of the two-way valve: either linear or equal percentage. *Only for parallel connection.*
- The authority of the two-way valve. *Only for parallel connection. Just like with the three-way valve, the pressure drop across the fully open control valve needs to be around 50 % of the total pressure drop in the circuit to ensure good controllability.*
- The flow rate through the fully open two-way valve in relation to the total flow rate in the boiler circuit. *Only for parallel connection. When the two-way valve is fully open, part of the boiler circuit flow goes through the back-up boiler, and the rest through the wood chip one. The closer the valve gets, the bigger portion flows through the wood chip boiler. The division of flow in the fully open situation is a design value that depends on the capacities of the boilers. In practice, the desired division is reached by installing manually adjustable control valves near the boilers.*
- The pressure difference between the supply and return lines at the boiler plant that the automatic control system keeps steady by adjusting the rotation speed of the pump. *This is the simple and typical way to carry out control over the district heating pump. There is a frequency converter that keeps the pressure difference between supply and return pipes at its desired value in spite of fluctuations in the total flow rate. More advanced would be to measure the pressure difference for instance at the end of the network or, even better, in the middle of the network. That kind of arrangement would, though, involve data transfer from the measuring point to the boiler plant where the control unit typically exists. That is why the most simple alternative is quite often chosen. It has been chosen for this application, too.*

4.5.4.6 The conditions

- The outside temperature during the simulation period. *As the simulation period is a few hours at the most, the outside temperature is constant through it.*
- The ground temperature. *The same that was said about the outside temperature goes for this one, too.*
- The calculation step. *If the user is trying to find out e.g. what the temperatures in different parts of the network are after a very steady period (night), rather long calculation steps can be used. The step can be something like two minutes which leads to a simulation period of eight hours. If, on the other hand, the user wants to see how the wood chip boiler acts when rapid changes in the heat demand occur, the calculation step needs to be in the region of 10 to 15 seconds which leads to a simulation period of 40 to 60 minutes. The shorter the step the easier it is to keep the calculations in control. Too long a step may cause growing fluctuation that the iterative calculation method cannot handle but all the cells become filled with error messages.*
- The highest outside temperature at which the buildings require heat. *This is for creating the correlation between outside temperature and supply water temperature.*
- The outflowing supply water temperature at above outside temperature. *Even if the buildings do not need heat for space heating or supply air preheating, they need, occasionally, domestic hot water. It is prepared in a heat exchanger that is located somewhere in the building. Cold tap water flows through the secondary side of the exchanger and becomes domestic hot water. In the primary side of the heat exchanger flows district heating water. It needs to be hot enough to heat the cold water in the secondary side to its desired value, which in Finland is 55 °C. So the primary flow supply temperature shall not be less than around 70 °C depending on the sizing of the heat exchanger.*
- The design temperature of the locality. *This is for creating the correlation between outside temperature and supply water temperature, which is at its highest temperature at the design outside temperature. If the weather gets even colder, the supply water temperature remains at its maximum.*

- The out flowing supply water temperature at above design temperature. *This is the highest temperature for the supply water, in Finland typically 100 to 115 °C depending on the sizing of the heat exchangers.*
- Initial temperatures in separate nodes in the network. *As the simulation period is relatively short, it makes sense to calculate beforehand temperatures in different parts of the network by using longer time steps and constant flow rates. These values can then be used as initial values for a simulation period with short time steps.*
- Initial positions of control valves. *The same goes for this: it is advisable to calculate beforehand the initial values for control valves in different sub-stations, so that the system is easy to get in a state of balance quickly when a short simulation period starts.*
- Initial combustion rate of the wood chip boiler. *It is a good idea to try what output corresponds with the need for heat plus the heat loss and use that value as an initial one when the short simulation period starts so that no valuable simulation time is lost for getting the system in an equilibrium.*

4.5.5. Calculation procedure

The initial positions of control valves, the combustion rate of the wood chip boiler and flow temperatures at different points in the system have either been set by the user or are approximated by the application. To get the system in a state of balance (when only minor variations occur) quickly, requires typically several simulation periods so that the user will find the most suitable initial values. It is no use trying to solve several problems at one simulation period. The application is most useful when only a couple of changes in the heat consumption occur in the simulation period. There will then be enough time to get the system adequately in a state of balance before the first change takes place and enough time left to see how the change affects the system and how the deviations level off, if they do at all.

The starting point for the calculation comes from the need for heat by the consumers. As the heat consumption both for radiator and ventilation systems is supposed to be proportional to the outside temperature, the application calculates the heat demand for each consumer based on design temperature, actual outside temperature, design input and starting moments in the simulation period. The application does not include the secondary side of the heating system, that is radiators and coils of the ventilation system. The return temperatures of the secondary side are supposed to be proportional to the outside temperature as will be discussed later.

The application calculates whether the actual consumer's input matches with the required one. If it does, nothing will be changed, but if it does not, the application adjusts the relevant flow rate by altering the position of the stem of the control valve (at the sub-station) so that the required input will be delivered. As heat exchangers are concerned, heat transfer depends on the mass flow, temperature difference between the inflow and outflow of the primary side and the specific heat of the fluid. The inflow temperature of the primary side as well as both temperatures of the secondary side are known but the outflow of the primary side depends on heat transfer rate in the heat exchanger which, in turn, depends on the effectiveness of the heat exchanger. To solve the effectiveness, several intermediate calculations will have to be carried out.

The flow rates through the heat exchangers plus the by-pass flows determine the total flow rates at different points of the network. As the diameters of pipes are known, the velocities can be calculated. In the supply lines, it is only the heat loss to the ground that affects the temperature of the flow once it has departed the boiler plant. In the return line, the main factor is the mixing of flows from separate sub-stations.

4.5.5.1 Properties of water

The specific heat capacity and the density of water are calculated according to the temperature. As neither of the above properties are linearly proportional to the temperature, equations to approximate these values have been established. When it comes to specific heat, there are actually two equations; one for temperatures above 30 °C and one for temperatures below that point. The temperature range for the equations is from 0 °C to 130 °C which is sufficient for heating systems. Figure 4.11 shows how the approximation of specific heat goes with initial values from literature and figure 4.12 shows the same on density respectively.

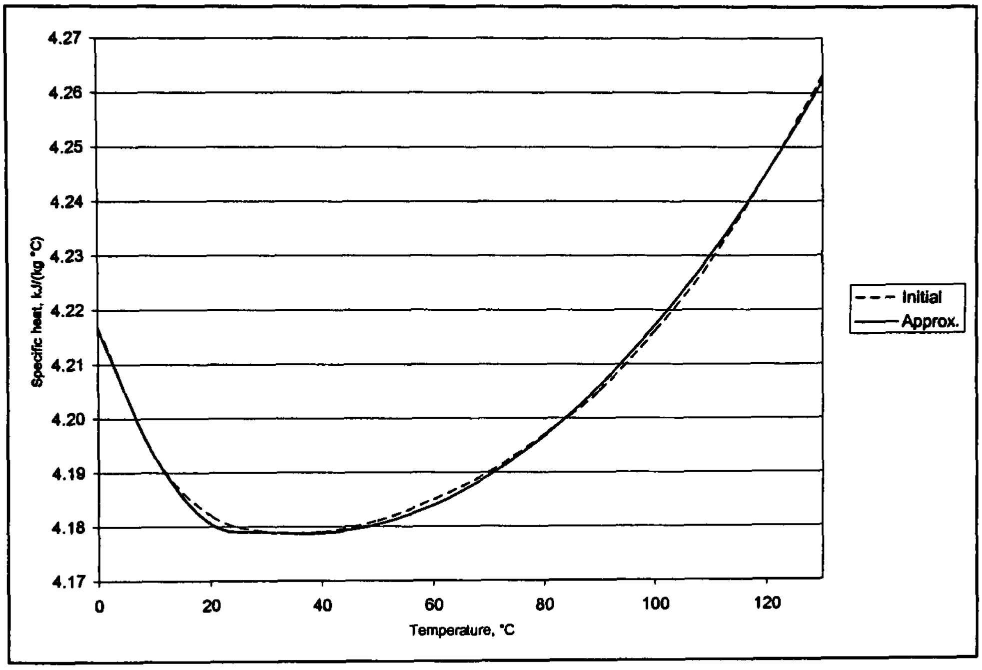

Figure 4.11. The approximation of the specific heat of water.

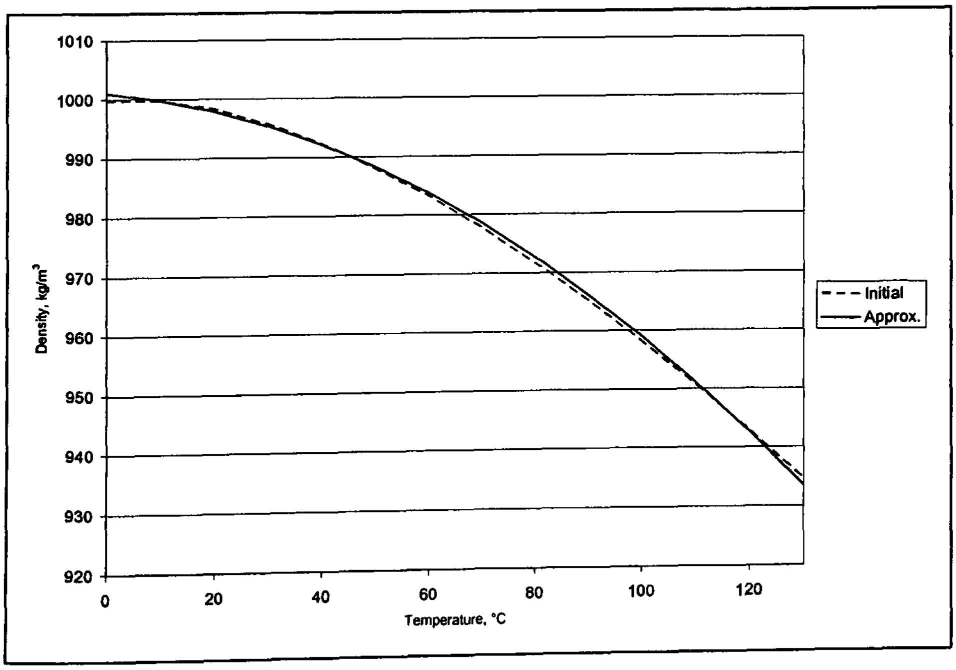

Figure 4.12. The approximation of the density of water.

4.5.5.2 Heating system

Figure 4.13 explains the operation of the heating (radiator) system. It is a block diagram that includes the most significant parts of the calculation procedure and their relations to one another.

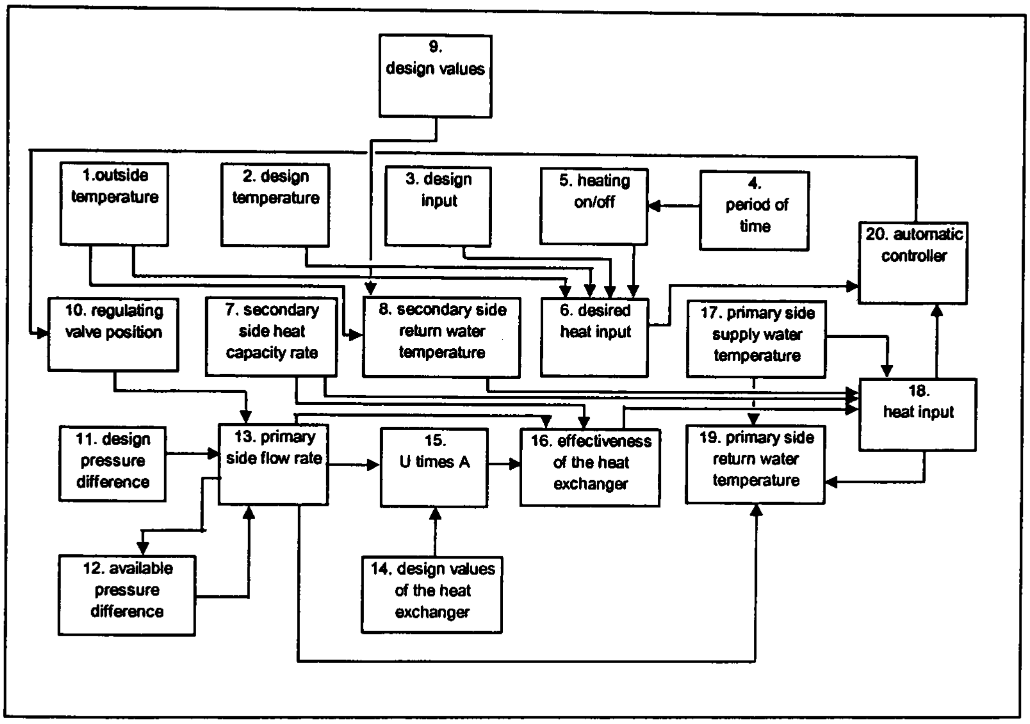

Figure 4.13. Heating system.

1. *Outside temperature* is set by the user. It is the temperature of the ambient air.
2. *Design temperature* is set by the user. It is the outside temperature that results in full heating input.
3. *Design input* is the input (in kilowatts) that is required to keep the building warm when design outside temperature takes place.
4. *Period of time* relates to relevant calculation step. The time step is set by the user and there are 240 calculation steps. The user decides at which calculation step the heating demand starts.

5. *The heating is either on or off* depending on the starting moment described above.
6. *Desired heat input* is based on outside temperature, design temperature, design input and, naturally, whether the heating is on or not. Figure 3.3 in Chapter 3.1.1 shows how the desired heat input varies along with outside temperature.
7. *Secondary side heat capacity rate* is a constant. It is the result when the mass flow rate is multiplied by the specific heat of the flowing liquid. As both the flow rate and the temperature of it are supposed to be unvarying, no changes in it should take place.
8. *Secondary side return water temperature* is a constant. It is the temperature of the flow that returns from the radiator network to the heat exchanger. The secondary side network is supposed to be so large that the return temperature remains constant even if the supply temperature is cycling somewhat. Figure 4.14 shows how the return water temperature varies along with outside temperature. The design temperature is -25 °C and as the outside temperature rises above 15 °C no heat is needed. At that particular temperature the return water temperature is close to room temperature: 20 °C and at the design outside temperature it is 40 °C. In reality, the relation between outside temperature and secondary side return temperature is not quite linear. It means that the line in figure 4.14 should be somewhat curved upwards. Depending on the radiators, a linear relation gives a few degrees too low return water temperature at the middle of the range. But as the heating system in the building is not included in the model, linear approximations are satisfactory. Important is that secondary side temperatures are proportional to outside temperature so that they go down as the outside temperature goes up.

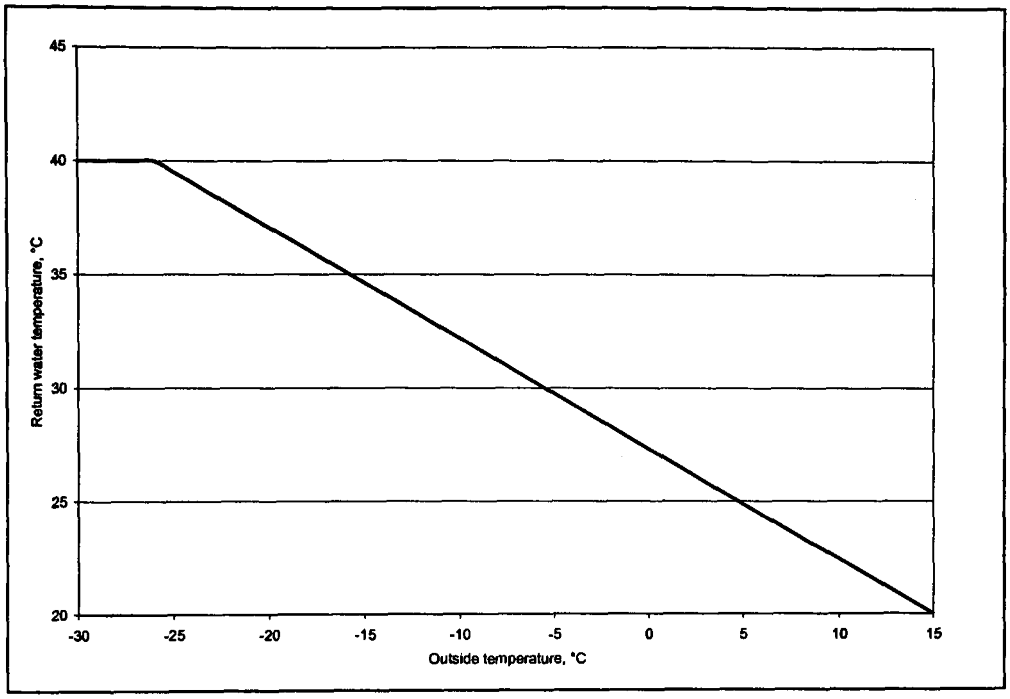

Figure 4.14. Secondary side return water temperature against outside temperature.

9. *Design values* are the temperatures of the secondary side return water at the design outside temperature and the outside temperature where need for heat ceases to exist respectively.
10. *Regulating valve position* tells whether the control valve regulating the primary side flow through the heat exchanger is close, open or something between. It may have values between 0 and 100 %. It is supposed that the flow rate at a given pressure difference is directly proportional to the position of the valve.
11. *Design pressure difference* tells what pressure difference is required so that the flow through the fully open valve is exactly the designed one (at the design temperature).
12. *Available pressure difference* is calculated by taking off all the pressure drops in the district heating network and the sub-station from the pump head at the boiler plant: what is left will be used over the control valve or the by-pass line.

13. *Primary side flow rate* depends on the position of the control valve and the available pressure difference against the design pressure difference. The flow depends on the pressure differences as follows:

$$\dot{m} \text{ is directly proportional to } \sqrt{\frac{\Delta p_a}{\Delta p_d}} \qquad [4.15]$$

where

$\dot{m}$ is the mass flow, $\frac{kg}{s}$

Δp_a is the available pressure difference, kPa
Δp_d is the design pressure difference, kPa. It is set by the user.

The mass flow is also directly proportional to the position of the valve.

It shall be noted that it is actually the volume flow that is proportional to pressure difference and the position of the valve the way described above. The mass flow has been used for the sake of saving computational capacity. The difference is negligible at this point because the real valve would operate in a slightly different manner, anyway.

14. *Design values of the heat exchanger* include all the inflowing and outflowing water temperatures at the design outside temperature and the capacity to transfer heat from the primary side to the secondary side at the design outside temperature with the design water temperatures respectively. Above figures lead to design flow rates at both sides of the heat exchanger.
15. *U times A* is a value that describes the ability of the heat exchanger to transfer heat at given flow temperatures. It depends on one hand on the heat transfer area and on the other hand on the heat transfer coefficients. As an increase in the flow results in increased turbulence, the heat transfer coefficients grow up along with it. The relation is not very simple, however, because the degree of turbulence depends on the shape and size of the cross-sectional area of the flow passage as

well as on the velocity of the flow. In the application, the relation between the primary side flow rate and the U-value of the heat exchanger is as follows [19]:

U-value is directly proportional to $\dot{V}^{0,55}$ [4.16]

where

U-value is the overall heat transfer coefficient, $\frac{kW}{m^2 \cdot {}^\circ C}$

$\dot{V}$ is the volume flow, $\frac{dm^3}{s}$

The design U times A value is calculated as followed:

$$U \cdot A = \frac{q}{T_{lm}} \qquad [4.17]$$

where

q is the (design) heat transfer rate, kW

T_{lm} is the (design) log mean temperature difference, °C. It is calculated as follows:

$$T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \qquad [4.18]$$

where

$$\Delta T_1 = T_{p,i} - T_{s,i} \qquad [4.19]$$

and

$$\Delta T_2 = T_{p,o} - T_{s,o} \qquad [4.20]$$

where

$T_{p,I}$ is the (design) temperature of the primary side supply (in) flow, °C

$T_{s,I}$ is the (design) temperature of the secondary side return (in) flow, °C

$T_{p,o}$ is the (design) temperature of the primary side return (out) flow, °C

$T_{s,o}$ is the (design) temperature of the secondary side supply (out) flow, °C

16. *Effectiveness of the heat exchanger* is the ratio of the actual heat transfer rate for a heat exchanger to the maximum possible heat transfer rate. In the application heat exchangers are supposed to be of the counter flow type and the effectiveness is calculated with equation [4.5].
17. *Primary side supply water temperature* depends on the out flowing temperature at the boiler plant and the heat loss to the ground.
18. *Heat input* is the amount of heat that is transferred from the primary side to the secondary side. It is calculated as follows [17]:

$$q = \varepsilon \cdot C_{\min}\left(T_{p,i} - T_{s,i}\right) \qquad [4.21]$$

where

q is the heat transfer rate, kW

ε is the effectiveness of the heat exchanger.

$C_{\min}$ is the smaller of the heat capacity rates of the heat exchanger, $\frac{kW}{°C}$

$T_{p,I}$ is the temperature of the primary side supply (in) flow, °C

$T_{s,I}$ is the temperature of the secondary side return (in) flow, °C

19. *Primary side return water temperature* is the temperature of the flow from the heat exchanger, °C. It is calculated as follows:

$$T_{p,o} = -\left(\frac{q}{C_p} - T_{p,i}\right) \qquad [4.22\}$$

where

$T_{p,o}$ is the temperature of the primary side return (out) flow, °C

q is the heat transfer rate, kW

C_p is the primary side heat capacity rate of the heat exchanger, $\frac{kW}{°C}$

$T_{p,1}$ is the temperature of the primary side supply (in) flow, °C

20. *Automatic controller* compares the desired heat input to the actual one and regulates the position of the control valve stem if there is need for such an operation.

4.5.5.3 Ventilation system

Figure 4.15 explains the operation of the ventilation system as a heat consumer. It is a block diagram that includes the most significant parts of the calculation procedure and their relations to one another. It is almost identical to the previous one describing the operation of the heating system. As a matter of fact there is only one distinction between them; block number 5 is an on/off controller in the heating system whereas in the ventilation system there may be two different values for the ventilation rate. One of them may, of course, be zero.

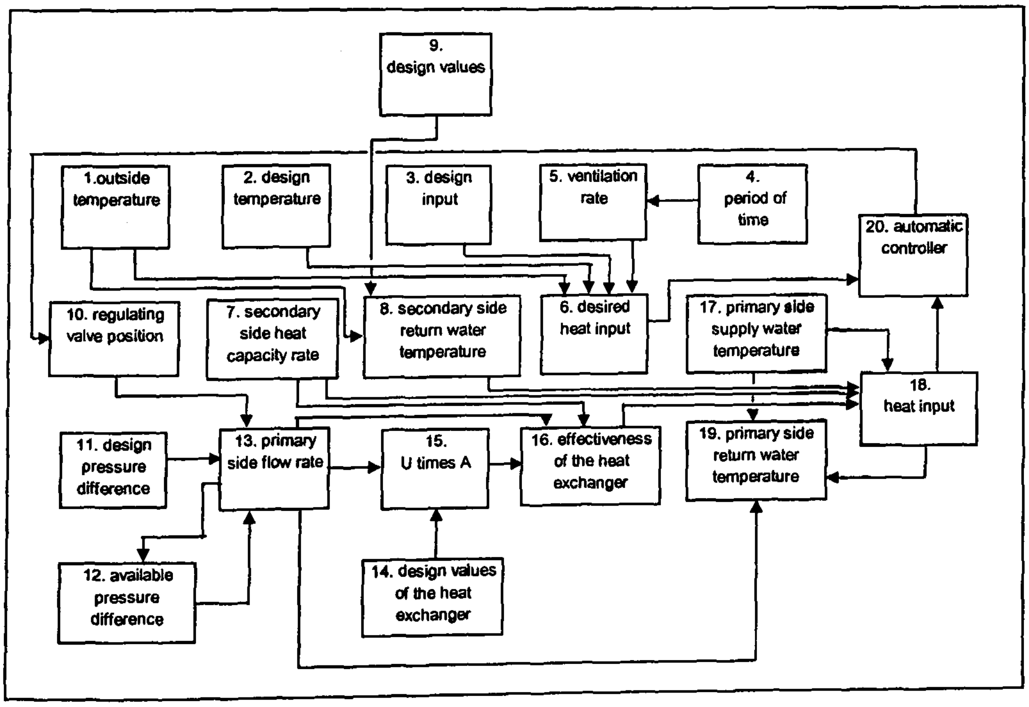

Figure 4.15. Ventilation system.

The design values of the heat exchanger are determined with the full ventilation rate at the design outside temperature. There may be a heat recovery system that reduces the need for heat from the district heating network. It has been assumed in the application, though that the effectiveness of the possible heat recovery heat exchanger is constant and, thus, the heat input is proportional to the outside temperature the way figure 3.3 shows. The design temperature and the relevant temperature limits are the same that are used with the heating system. The design values of the heat exchanger (in- and out flowing temperatures) may, however, differ from corresponding values of the heating system.

4.5.5.4 Domestic hot water system

The main distinction between the domestic hot water system and either the heating or ventilation system is that the outside temperature does not play any part in determining heat consumption when the DHW system is concerned. Furthermore, there is no secondary side flow circuit as is the case with heating and ventilation systems: The cold water is just heated up in the heat exchanger and it becomes domestic hot water, which then never returns to the exchanger (if there is no circulation pump to keep the pipes filled with hot water continuously). Figure 4.16 explains the operation of the DHW system. It is a block diagram that includes the most significant parts of the calculation procedure and their relations to one another.

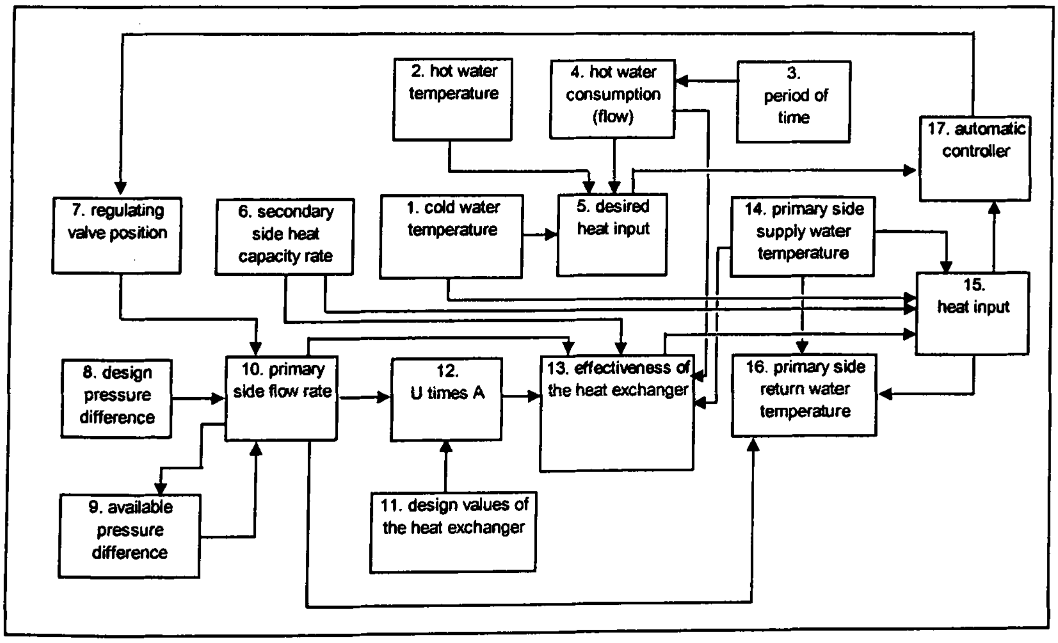

Figure 4.16. Domestic hot water system.

1. *Cold water temperature* is the temperature of the water that flows in the secondary side of the heat exchanger. It is a constant and set by the user.
2. *Hot water temperature* is the temperature of the water that flows out the secondary side of the heat exchanger. It is a constant and set by the user.
3. *Period of time* relates to relevant calculation step. The time step is set by the user and there are 240 calculation steps. The user decides at which calculation step the DHW consumption starts and to what extent.
4. The *flow rate* of DHW depends on the period of time in the calculation.
5. *Desired heat input* is based on the flow rate and the relevant temperatures as follows:

$$q = \dot{V} \cdot \rho \cdot c_p \cdot (T_h - T_c) \qquad [4.23]$$

where

q is the (desired) heat transfer rate, kW

$\dot{V}$ is the DHW volume flow, $\frac{dm^3}{s}$

ρ is the density of the DHW, $\frac{kg}{dm^3}$

c_p is the specific heat of the DHW, $\frac{kJ}{kg \cdot °C}$

T_h is the temperature of the DHW, °C

T_c is the temperature of the cold water, °C

6. *Secondary side heat capacity rate* is a constant. It is calculated as follows:

$$C = \dot{V} \cdot \rho \cdot c_p \qquad [4.24]$$

where

$\dot{V}$ is the DHW volume flow, $\frac{dm^3}{s}$

ρ is the density of the DHW, $\frac{kg}{dm^3}$

c_p is the specific heat of the DHW, $\frac{kJ}{kg \cdot {}^\circ C}$

7. *Regulating valve position* tells whether the control valve regulating the primary side flow through the heat exchanger is close, open or something between. It may have values between 0 and 100 %. It is supposed that the flow rate at a given pressure difference is directly proportional to the position of the control valve stem.
8. *Design pressure difference* tells what pressure difference is required so that the flow through the fully open valve is exactly the designed one (with full DHW consumption).
9. *Available pressure difference* is calculated by taking off all the pressure drops in the district heating network and the sub-station from the pump head at the boiler plant: What is left will be used over the control valve or the by-pass line.
10. *Primary side flow rate* depends on the position of the control valve and the available pressure difference against the design pressure difference.
11. *Design values of the heat exchanger* include all the inflowing and out flowing water temperatures and the capacity to transfer heat from the primary side to the secondary side at the design conditions. Above figures lead to design flow rates at both sides of the heat exchanger.
12. *U times A* is a value that describes the ability of the heat exchanger to transfer heat at given flow temperatures.
13. *Effectiveness of the heat exchanger* is the ratio of the actual heat transfer rate for a heat exchanger to the maximum possible heat transfer rate.
14. *Primary side supply water temperature* depends on the out flowing temperature at the boiler plant and the heat loss to the ground.

15. *Heat input* is the amount of heat that is transferred from the primary side to the secondary side.
16. *Primary side return water temperature* is the temperature of the flow from the heat exchanger, °C.
17. *Automatic controller* compares the desired heat input to the actual one and regulates the position of the control valve stem if there is need for such an operation.

4.5.5.5. District heating network

Figure 4.17 explains the calculation procedure in the district heating network from the boiler plant to the heat exchanger and back. It is a block diagram that includes the most significant parts of the calculation procedure and their relations to one another. In the diagram there is only one consumer with only one heat exchanger. In the actual calculation procedure, there may be up to 21 consumers with up to 63 separate heat exchangers.

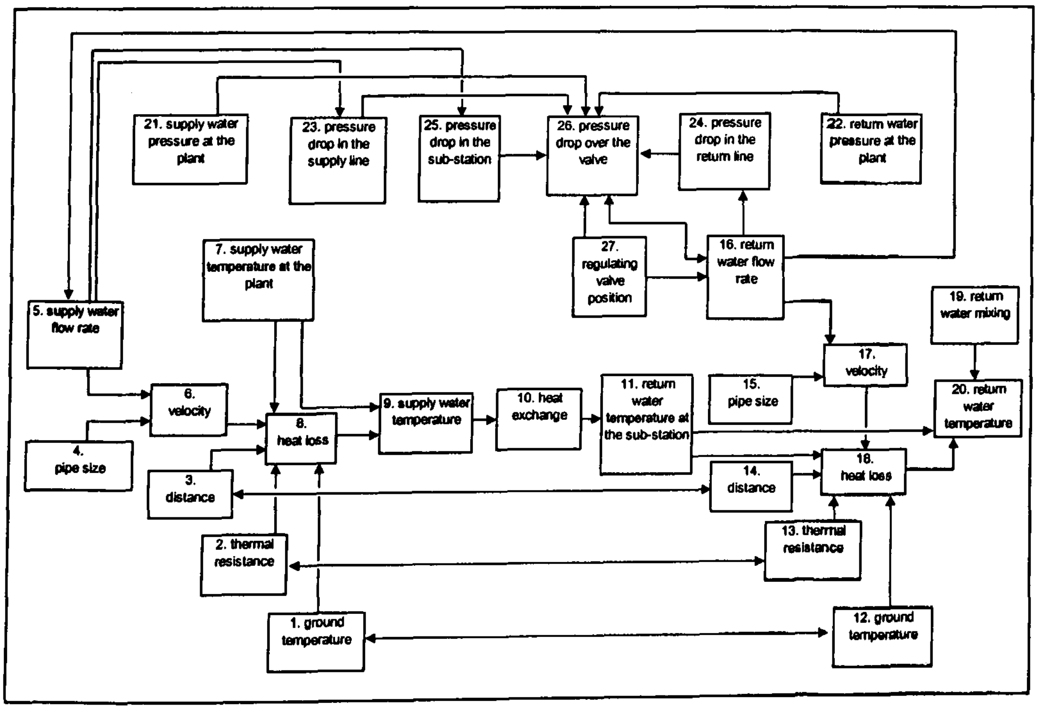

Figure 4.17. District heating system.

1. *Ground temperature* is set by the user. It is the temperature of the earth's surface, °C.
2. *Thermal resistance* is defined by the user. It consists of insulation thickness on the pipe, its thermal conductivity, thickness of ground layer on the pipe and its thermal conductivity. The thermal resistance of the insulation is calculated as follows [18]:

   $$R_E = \frac{1}{2 \cdot \pi \cdot k_i} \cdot \ln\left(\frac{D_p + 2 \cdot l_i}{D_p}\right) \qquad [4.25]$$

   where

   R_E is the thermal resistance of the insulation per metre of pipe, $\frac{m \cdot °C}{W}$

   k_i is the thermal conductivity of the insulation material, $\frac{W}{m \cdot °C}$

   D_p is the outside diameter of the pipe (without insulation), m

   l_i is the thickness of the insulation cover on the pipe, m

   The thermal resistance of the ground is calculated with equation [4.13].

   The U'-value including both the resistance of insulation and the resistance of ground is calculated with equation [4.14].

   Hence, heat loss from a given pipe to ground depends on the temperature difference between fluid and ground and the length of the pipe.

3. *Distance* is the length of pipeline between two adjacent nodes, m. It is set by the user.
4. *Pipe size* is the inner diameter of pipe between two adjacent nodes, m. It is constant between any two adjacent nodes and set by the user.

5. *Supply water flow rate* depends on which part of the network is concerned. At the boiler plant it is the sum of separate flows through all the control valves and heat exchangers situated at consumers' sub-stations.
6. *Velocity* of the flow depends on pipe size and volume flow rate as follows:

$$v = \frac{4 \cdot \dot{V}}{\pi \cdot D^2} \tag{4.26}$$

where

v is the velocity of the flow, m/s

$\dot{V}$ is the volume flow, $\frac{m^3}{s}$

D is the inner diameter of the pipe, m

7. *Supply water temperature at the plant* is the temperature of the out flowing water as it leaves the boiler plant.
8. *Heat loss* is the heat transfer from the supply water to the ground causing temperature drop.
9. *Supply water temperature* after temperature drop is calculated as follows [18]:

$$T_1 = T_0 - \frac{U' l \cdot (T_0 - T_g)}{\rho \cdot c_p \cdot \dot{V}} \tag{4.27}$$

where

T_1 is the final temperature of the flow, °C

T_0 is the primary temperature of the flow, °C

U' is the overall heat transfer coefficient per metre, $\frac{W}{m \cdot °C}$

l is the length of the pipe, m

ρ is the density of the flow, here a constant: 1000 $\frac{kg}{m^3}$

c_p is the specific heat of the flow, here a constant: $4200 \frac{J}{kg \cdot °C}$

$\dot{V}$ is the volume flow, $\frac{m^3}{s}$

As can be seen, the temperature of the flow is considered constant during the calculation step. Due to proper insulation and relatively high velocities this does not cause any significant error. The same goes for specific heat and density.

10. *Heat exchange* is the stage where heat is transferred from the primary side flow to the secondary side flow in a heat exchanger located at the consumer's sub-station.
11. *Return water temperature at the sub-station* is the temperature of the primary flow after leaving the heat exchanger.
12. *Ground temperature* is set by the user. The value is the same as in block 1.
13. *Thermal resistance* is defined by the user. The value is normally the same as in block 2.
14. *Distance* is the length of pipeline between two adjacent nodes. The value is normally the same as in block 3.
15. *Pipe size* is the inner diameter of pipe between two adjacent nodes. value is normally the same as in block 4.
16. *Return water flow rate* depends on which part of the network is concerned. The mass flow rate is the same as in the supply pipe; volume flow is slightly different because of changes in the density.
17. *Velocity* of the flow depends on pipe size and volume flow rate as expressed in block 6.
18. *Heat loss* is the heat transfer from the return water to the ground causing temperature drop.
19. *Return water mixing* causes temperature changes. On one hand it takes place at sub-stations as flows from heating, ventilation and DHW heat exchangers are joined; on the other hand, mixing occurs in the nodes of the return pipeline. The mixed temperature of the flow is calculated as follows:

$$T_{mix} = \frac{T_1 \cdot c_{p1} \cdot \dot{m}_1 + T_2 \cdot c_{p2} \cdot \dot{m}_2 + T_3 \cdot c_{p3} \cdot \dot{m}_3 \ldots + T_n \cdot c_{pn} \cdot \dot{m}_n}{c_{p1} \cdot \dot{m}_1 + c_{p2} \cdot \dot{m}_2 + c_{p3} \cdot \dot{m}_3 \ldots + c_{pn} \cdot \dot{m}_n} \qquad [4.28]$$

where

T_{mix} is the temperature of the mixed flow, °C

$T_{1,2,3\ldots n}$ is the temperature of a given flow, °C

$c_{p1,2,3\ldots n}$ is the specific heat of a given flow, $\frac{kJ}{kg \cdot °C}$

$\dot{m}_{1,2,3\ldots n}$ is the mass flow of a given flow, $\frac{kg}{s}$

20. *Return water temperature* at a given point is calculated considering mixing and heat loss to ground as described in block 9.
21. *Supply water pressure at the plant* is the head produced by the circulating pump in the boiler plant.
22. *Return water pressure at the plant* is what is left from the pump head. In the application, it is supposed that the pressure difference between supply and return lines at the boiler plant is kept constant by means of a frequency converter that regulates the pump. The pressure difference is set by the user.
23. *Pressure drop in the supply line* is caused by the flow. It depends on flow rate, pipe size, pipe roughness, temperature, viscosity etc. In the application the user sets the nominal pressure drop (kPa) between the nodes at the nominal flow rate when all the control valves at sub-stations are fully open. The application then calculates the actual pressure drop as follows:

$$\Delta p_a = \left(\frac{\dot{m}_a}{\dot{m}_n} \right)^2 \cdot \Delta p_n \qquad [4.29]$$

where

Δp_a is the actual pressure drop, kPa

$\dot{m}_a$ is the actual mass flow, $\frac{kg}{s}$

$\dot{m}_n$ is the nominal mass flow, $\frac{kg}{s}$

Δp_n is the nominal pressure drop, kPa

It shall be noted that the actual pressure drop should be calculated by using volume flow rates instead of mass flow rates. The former have been used for the sake of saving computational capacity. The difference is almost negligible, nevertheless.

24. *Pressure drop in the return line* is caused by the flow. What has been said about block 23 goes for this one, too.
25. *Pressure drop in the sub-station* includes all pressure drop from nearest node to the sub-station and back except pressure drop over the control valve. The nominal pressure drop is set by the user and the application calculates the actual one the way described in connection with block 23.
26. *Pressure drop over the valve* needs to equal with the missing pressure drop when all the above pressure drops have been taken off from the pressure difference at the boiler plant. Only then the total pressure drop in every flow route of the district heating network equals with the available pressure difference.
27. *Regulating valve position* tells whether the control valve regulating the primary side flow through the heat exchanger is close, open or something between. It may have values between 0 and 100 %. The dependence of the flow rate on the control valve position and available pressure difference is discussed in connection with heating system, block 13.

4.5.5.6 Boiler plant

Figure 4.18 shows the calculation procedure in the boiler plant. It is a block diagram that includes the most significant parts of the calculation procedure and their relations to one another.

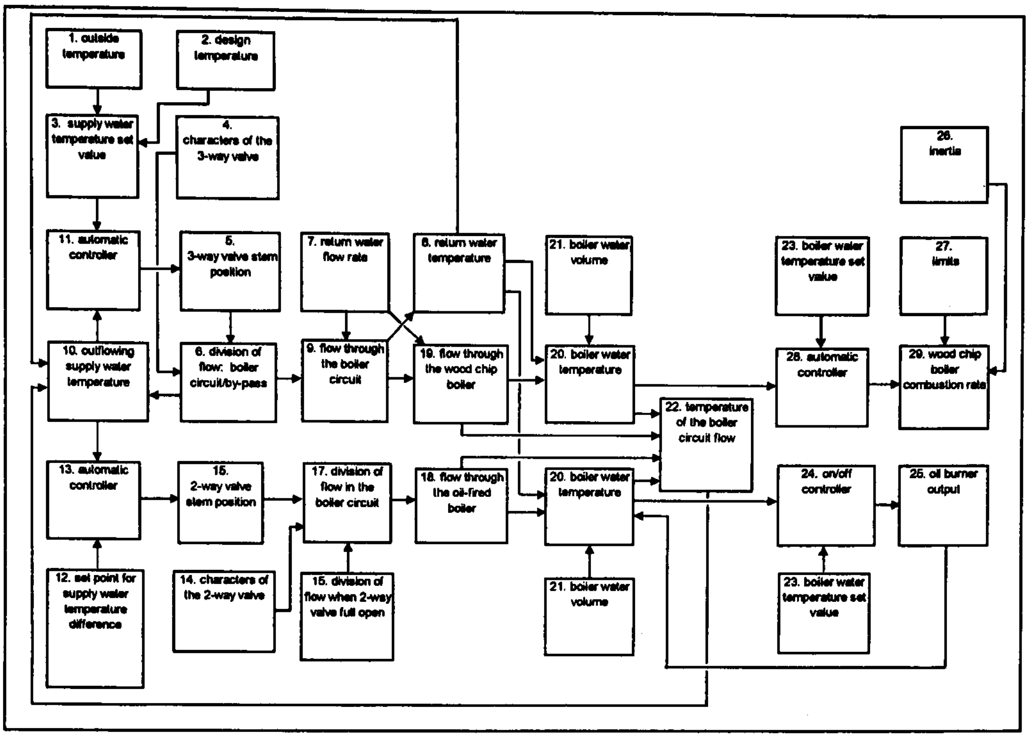

Figure 4.18. Boiler plant.

1. *Outside temperature* is set by the user.
2. *Design temperature* is set by the user. It is the outside temperature that results in the highest supply water temperature. There is also another limit value: the highest outside temperature when buildings are heated.
3. *Set value for supply water temperature* is calculated as follows:

When outside temperature is above the highest outside temperature when buildings are heated, the supply water temperature is constant, set by the user. Heat is used solely for domestic hot water preparation.

When outside temperature is at or below the highest temperature that buildings are heated, but not less than the design temperature:

$$T_s = \frac{T_h - T_o}{T_h - T_d} \cdot \left(T_{s,h} - T_{s,l}\right) + T_{s,l} \qquad [4.30]$$

where

T_s is the supply water temperature, °C

T_h is the highest outside temperature that buildings are heated, °C

T_o is the actual outside temperature, °C

T_d is the design outside temperature, °C

$T_{s,h}$ is the highest supply temperature, °C

$T_{s,l}$ is the lowest supply temperature, °C

When outside temperature is below the design temperature, the supply water temperature is at its highest value, $T_{s,h}$.

4. *Characters of the 3-way valve* determine the division of flow through the ports of the valve in different stem positions. The most significant feature is the inherent flow characteristic. In the application there are two different flow characteristic types to be chosen from: linear and equal percentage. Figure 4.19 shows how the flow relates to stem position with two above flow characteristics.

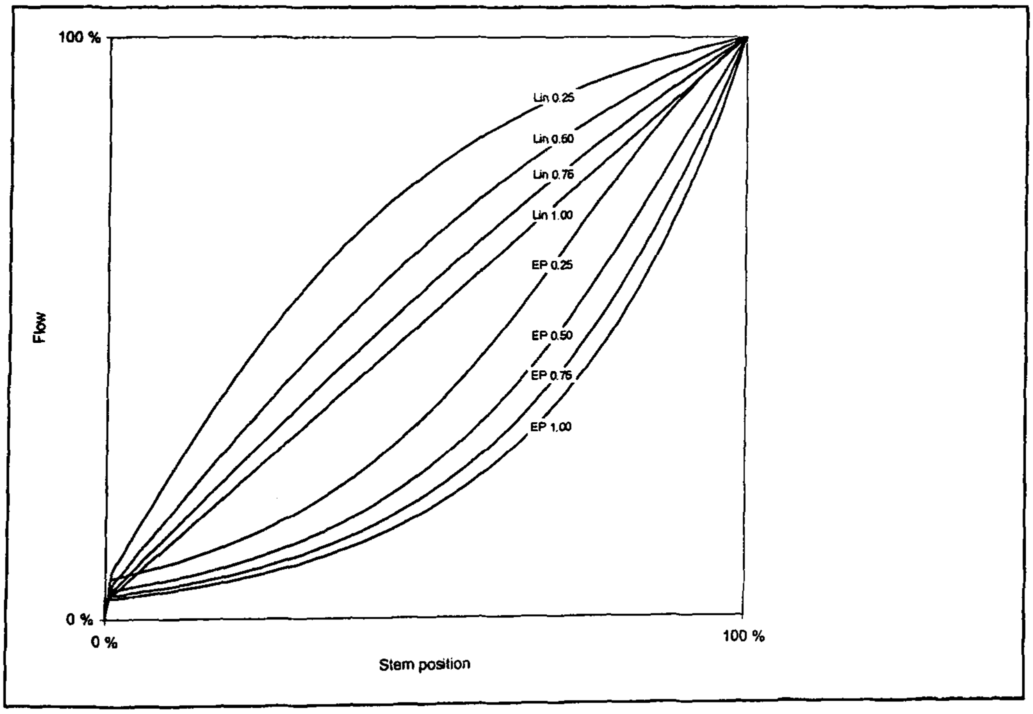

Figure 4.19. Flow rates against valve stem positions with four different authority values for linear and equal-percentage inherent flow characteristics.

As can be seen in figure 4.19, the flow rate depends strongly on the flow characteristic and the authority of the valve, which is the valve pressure-drop ratio:

$$p_r = \frac{\Delta p_v}{\Delta p_v + \Delta p_p} \qquad [4.31]$$

where

p_r is the pressure-drop ratio, authority of the valve

Δp_v is the pressure drop over the fully open valve

Δp_p is the pressure drop over the piping and boilers

5. *3-way valve stem position* tells about the travel of the valve stem: if the value is 100%, it is only boiler circuit water that passes through the valve; if the value is 0 %, only by-pass water flows through it. When intermediate values are concerned, also valve characters have an affect on the flow division.

6. *Division of flow boiler circuit/by-pass* is calculated so that both flow through the boiler circuit port and flow through the by-pass port are modelled.

In parallel connection, the authority of the boiler circuit port of the 3-way valve depends on the pressure drop in the boiler circuit which, in turn, depends on the flow rate and the flow route. If the 2-way valve is closed separating the oil-fired boiler from the boiler circuit, the authority of the boiler circuit port of the 3-way valve remains constant and is set by the user, who also sets the pressure difference values for the flow through the wood chip boiler and its pipe work and, on the other hand, for the pipe work that is common for both boilers. As the 2-way valve opens, the total pressure drop in the boiler circuit decreases which changes the authority of the boiler circuit port of the 3-way valve. Both pressure-drop values are given at the nominal flow rate. The authority of the by-pass port of the 3-way valve is not related to the stroke of the 2-way valve but it remains constant. Its value is set by the user. If boilers are connected in series, there is no

2-way valve that could interfere with the authority of the 3-way valve. In that case, the authority of both ports of the 3-way valve are constant and set by the user.

The authority of the boiler circuit port of the 3-way valve is calculated as follows:

$$p_r = \frac{\dfrac{1}{2\cdot\left(1-p_{r,n}\right)}}{\dfrac{1}{2\cdot\left(1-p_{r,n}\right)}+\dfrac{1}{2\cdot p_{r,n}}\cdot\dfrac{\left(\dfrac{\dot{m}_w}{\dot{m}_n}\right)^2\cdot\Delta p_w+\left(\dfrac{\dot{m}_b}{\dot{m}_n}\right)^2\cdot\Delta p_b}{\left(\dfrac{\dot{m}_b}{\dot{m}_n}\right)^2\cdot\left(\Delta p_w+\Delta p_b\right)}} \qquad [4.32]$$

where

p_r is the authority of the boiler circuit port of the 3-way valve

$p_{r,n}$ is the authority of the port with nominal flow rate in the boiler circuit, the 2-way valve closed

$\dot{m}_w$ is the mass flow through the wood chip boiler, $\frac{kg}{s}$

$\dot{m}_n$ is the nominal mass flow through the boiler circuit and through the wood chip boiler, $\frac{kg}{s}$

$\dot{m}_b$ is the mass flow through the boiler circuit, $\frac{kg}{s}$

p_w is the pressure drop in the wood chip boiler circuit with nominal flow rate, kPa

p_b is the pressure drop in the boiler circuit with nominal flow rate, kPa

For a linear inherent characteristic, the division of flows in the 3-way valve is calculated as follows [20]:

$$\frac{\dot{m}_{boiler}}{\dot{m}_{bypass}} = \frac{1}{\sqrt{\left(\dfrac{\dfrac{1}{\left(\dfrac{\dfrac{1}{p_{r,boiler}}}{\dfrac{1}{p_{r,boiler}} - 1 + \dfrac{1}{L_{boiler}^2}} \right)}}{\dfrac{1}{\left(\dfrac{\dfrac{1}{p_{r,bypass}}}{\dfrac{1}{p_{r,bypass}} - 1 + \dfrac{1}{L_{bypass}^2}} \right)}} \right)}} \qquad [4.33]$$

where

$p_{r,boiler}$ is the authority of the boiler circuit port of the 3-way valve

L_{boiler} is the stroke of the boiler circuit port of the 3-way valve; 0 corresponds with fully closed and 1 with fully open, respectively

$p_{r,bypass}$ is the authority of the by-pass port of the 3-way valve

L_{bypass} is the stroke of the by-pass port of the 3-way valve; 0 corresponds with fully closed and 1 with fully open, respectively

For an equal percentage inherent characteristic, the division of flows is calculated as follows [20]:

$$\frac{\dot{m}_{boiler}}{\dot{m}_{bypass}} = \frac{1}{\sqrt{\left(\dfrac{\dfrac{1}{\left(\dfrac{\dfrac{1}{p_{r,boiler}}}{\dfrac{1}{p_{r,boiler}} - 1 + \dfrac{1}{\left(R^{(L-1)}\right)^2}} \right)}}{\dfrac{1}{\left(\dfrac{\dfrac{1}{p_{r,bypass}}}{\dfrac{1}{p_{r,bypass}} - 1 + \dfrac{1}{\left(R^{(1-L-1)}\right)^2}} \right)}} \right)}} \qquad [4.34]$$

where

$p_{r,boiler}$ is the authority of the boiler circuit port of the 3-way valve

L is the stroke of the 3-way valve; 0 corresponds with boiler circuit port fully closed (by-pass port fully open) and 1 with boiler circuit port fully open (by-pass port fully closed), respectively.

$p_{r,bypass}$ is the authority of the by-pass port of the 3-way valve.

R is the rangeability of the control valve. It is the ratio between the maximum flow and the smallest controllable flow through the valve. It depends on the composition and the size of the valve. A typical value is in the order of 25. As the definition brings out, very low relative flow rates cannot be controlled successfully neither with the application nor in real installations.

7. *Return water flow rate* depends on the rate of heat consumption: it is the total flow rate through all the control valves, heat exchangers and potential by-pass lines at consumers' sub-stations.
8. *Return water temperature* is the temperature of the return water as it enters the boiler plant.

9. *Flow through the boiler circuit* is calculated, as the division of flows is known, as follows:

$$\dot{m}_{boiler} = \frac{\dfrac{\dot{m}_{boiler}}{\dot{m}_{bypass}}}{1+\dfrac{\dot{m}_{boiler}}{\dot{m}_{bypass}}} \cdot \dot{m}_s \qquad [4.35]$$

where

$\dot{m}_{boiler}$ is the flow through the boiler circuit, $\frac{kg}{s}$

$\dot{m}_{bypass}$ is the flow through the by-pass port of the 3-way valve, $\frac{kg}{s}$

$\dot{m}_s$ is the supply water outflow from the plant, $\frac{kg}{s}$

10. *Out flowing supply water temperature* is regulated by the 3-way valve. It is calculated as follows:

$$T_s = \frac{T_{boiler} \cdot c_{p_{boiler}} \cdot \dot{m}_{boiler} + T_{bypass} \cdot c_{p_{bypass}} \cdot \dot{m}_{bypass}}{c_{p_s} \cdot \dot{m}_s} \qquad [4.36]$$

where

T_s is the supply water temperature, °C

T_{boiler} is the temperature of water in boiler circuit, °C

$c_{p_{boiler}}$ is the specific heat of boiler circuit water, $\frac{kJ}{kg \cdot °C}$

$\dot{m}_{boiler}$ is the flow through the boiler circuit, $\frac{kg}{s}$

T_{bypass} is the by-pass (return) water temperature, °C

$c_{p_{bypass}}$ is the specific heat of by-pass (return) water, $\frac{kJ}{kg \cdot °C}$

$\dot{m}_{bypass}$ is the by-pass water flow rate, $\frac{kg}{s}$

c_{p_s} is the specific heat of supply water, $\frac{kJ}{kg \cdot °C}$

$\dot{m}_s$ is the supply water flow rate, $\frac{kg}{s}$

11. *Automatic controller* compares the desired supply water temperature to the actual one and regulates the 3-way valve if there is need for such an operation. The user sets the time it takes from the valve stem to move from one extreme position to the other one.
12. *Set point for supply water temperature difference* is a value set by the user. It determines how much the actual supply water temperature must be below the set point so that the 2-way valve starts to open and oil-fired boiler joins the boiler circuit.
13. *Automatic controller* compares the desired supply water temperature to the actual one and regulates the 2-way valve if there is need for such an operation. The user sets the time it takes from the valve stem to move from one extreme position to the other one. The temperature difference described above ensures that the oil-fired boiler is disconnected from the boiler circuit as the desired value of supply water is approached.
14. *Characters of the 2-way valve* include the inherent flow characteristics (linear and equal-percentage available) and the authority of the valve. The calculation of combined flow coefficient is described at block 6 and the flow rate at block 8.
15. *2–way valve stem position* is regulated by the automatic controller.
16. *Division of flow when 2-way valve full open* is set by the user. It is a percentage value giving the flow through the oil-fired boiler divided by the total flow in the boiler circuit.
17. *Division of flow in the boiler circuit* tells which part of the total flow passes through the oil-fired boiler and which through the wood chip boiler.
18. *Flow through the oil-fired boiler* is calculated as follows [21]:

$$\dot{m}_{oil} = \dot{m}_{boiler} \cdot \frac{\dot{m}_{oil,open}}{\dot{m}_{boiler,total}} \cdot \frac{C_o}{C_{100\%}} \qquad [4.37]$$

where

$\dot{m}_{oil}$ is the flow rate through the oil-fired boiler, $\frac{kg}{s}$

$\dot{m}_{boiler}$ is the flow rate through the boiler circuit, $\frac{kg}{s}$

$\frac{\dot{m}_{oil,open}}{\dot{m}_{boiler,total}}$ is the division of flow when 2-way valve is full open

$$C_o = \frac{n \cdot C_v}{\sqrt{\left(\left(\frac{n}{m}\right)^2 + 1\right)}} \qquad [4.38]$$

where, for a linear inherent characteristic:

$$m = 0{,}96 \cdot X + 0{,}03 \qquad [4.39]$$

and for equal percentage:

$$m = 30^{X-1} \qquad [4.40]$$

where

C_v is valve flow coefficient at full lift (full open position)
X is valve lift, fraction of full open
C_o is combined flow coefficient for valve and piping
$C_{100\%}$ is above coefficient when the valve is full open

$$n = \sqrt{\frac{\Delta p_v}{\Delta p_p}} \qquad [4.41]$$

where

Δp_v is pressure drop across the valve

Δp_p is pressure drop across the piping and boilers

19. *Flow through the wood chip boiler* is calculated as follows:

$$\dot{m}_{wc} = \dot{m}_{boiler} - \dot{m}_{oil} \qquad [4.42]$$

where

$\dot{m}_{wc}$ is the flow rate through the wood chip boiler, $\frac{kg}{s}$

$\dot{m}_{boiler}$ is the flow rate through the boiler circuit, $\frac{kg}{s}$

$\dot{m}_{oil}$ is the flow rate through the oil-fired boiler, $\frac{kg}{s}$

20. *Boiler water temperature* is calculated for both boilers as follows:

$$\Delta T = \frac{(q_i - q_o) \cdot t}{V \cdot \rho \cdot c_p} \qquad [4.43]$$

where

ΔT is the change in boiler water temperature, °C

q_i is the thermal input to the boiler, kW

q_o is the output from the boiler, kW, calculated as follows:

$q_o = \dot{m} \cdot c_p \cdot (T_o - T_i)$

$\dot{m}$ is the mass flow rate through the boiler, $\frac{kg}{s}$

c_p is the specific heat of boiler water, $\frac{kJ}{kg \cdot °C}$

T_o is the out flowing water temperature, °C

T_i is the inflowing water temperature, °C

t is the period of time (time step), s

V is the volume of the boiler, dm^3

ρ is the density of the boiler water, $\frac{kg}{dm^3}$

21. *Boiler water volume* is set by the user.

22. *Temperature of the boiler circuit flow* is calculated as follows:

$$T_{boiler} = \frac{T_{wc} \cdot c_{p_{wc}} \cdot \dot{m}_{wc} + T_{oil} \cdot c_{p_{oil}} \cdot \dot{m}_{oil}}{c_{p_{wc}} \cdot \dot{m}_{wc} + c_{p_{oil}} \cdot \dot{m}_{oil}} \qquad [4.44]$$

where

T_{boiler} is the boiler circuit water temperature, °C

T_{wc} is the wood chip boiler water temperature, °C

$c_{p_{wc}}$ is the specific heat of wood chip boiler water, $\frac{kJ}{kg \cdot °C}$

$\dot{m}_{wc}$ is the mass flow of the wood chip boiler water, $\frac{kg}{s}$

T_{oil} is the oil-fired boiler water temperature, °C

$c_{p_{oil}}$ is the specific heat of oil-fired boiler water, $\frac{kJ}{kg \cdot °C}$

$\dot{m}_{oil}$ is the mass flow of the oil-fired boiler water, $\frac{kg}{s}$

23. *Boiler water temperature set value* is set by the user for both boilers separately
24. *On/off controller* checks whether the oil-fired boiler temperature is below the limit that allows to start the burner. Once started, the burner continues to work until the set value has been reached. There has to be a difference of at least a couple of degrees between the boiler water set value and the limit that allows to start the burner.
25. *Oil-burner output* depends on its capacity, which is constant, kW, set by the user and on whether the controller keeps it on or off.
26. *Inertia.* There is definitely some kind of sluggishness in the control of combustion rate. Contrary to an oil burner which is able to reach its full capacity almost instantly, changes in the combustion rate of wood chips take some time. Obviously, there are several reasons that have an influence on it: Structure of the grate and the combustion chamber, temperature in the chamber, wood chip particle size and moisture content etc. In the application, it has been assumed that the biggest possible change in the combustion rate depends linearly on the starting value. Therefore the user sets a value for the biggest possible change in

combustion rate (kW/min) at the lowest limit and at the highest limit of the boiler capacity respectively. Separate values are given for increasing and decreasing combustion rates. As the boiler is practically always operating between above limits, the biggest possible change in the combustion rate is calculated at every calculation step linearly based on the relevant starting value.

27. *Limits*. There are two limit values set by the user that determine the capacity of the boiler: the maximum combustion rate that can be achieved with the fuel in question and the minimum combustion rate.
28. *Automatic controller* regulates the combustion rate of the wood chip boiler. Depending on whether the boiler water temperature is below or over the set value it increases or decreases the combustion rate. The controller operates nearly as a PI-controller; the P-action is calculated as follows:

$$q_P = -\frac{\Delta T_w}{T_w} \cdot K \cdot q_{init} + q_{init} \qquad [4.45]$$

where

q_p is the preferred rate of combustion, kW, according to the P-action

ΔT_w is the difference between the set value and the actual value of boiler water temperature, °C

T_w is the actual value of boiler water temperature, °C

K is a coefficient set by the user

q_{init} is the initial combustion rate, kW

As the proportional (P) action only works when the difference between the set value and the actual one changes, it tends to leave a constant deviation between said values. Increasing merely the coefficient K is not a solution as the control becomes unstable if the coefficient is too big. So there has to be another operator that gradually brings the actual value closer to the desired one. The problem is described in figure 4.20. There is a vessel from which water is flowing out. To compensate for the loss, the control valve lets water flow in the vessel. The stem of the control valve is connected to a lever. The other end of the lever is connected to a joint at point C. There is a float that is connected to the lever at point A. If the water level in the vessel starts going down due to increased outflow, the float follows the water surface and makes the lever come down, too. That movement is transferred to the stem of the control valve which makes the flow through the valve increase as well. As soon as the outflow equals the inflow, the stem stops moving. It may happen that the water surface is not at its set point any more, even though an equilibrium exists. If it seems that the valve did not react strongly enough to the change in the water surface, the float can be moved towards the joint e.g. to point B. That makes the stem of the valve move more rapidly whenever the water surface is starting to go up or down. This is what a proportional control is about. By moving the float from A to B one actually changes the amplification coefficient .

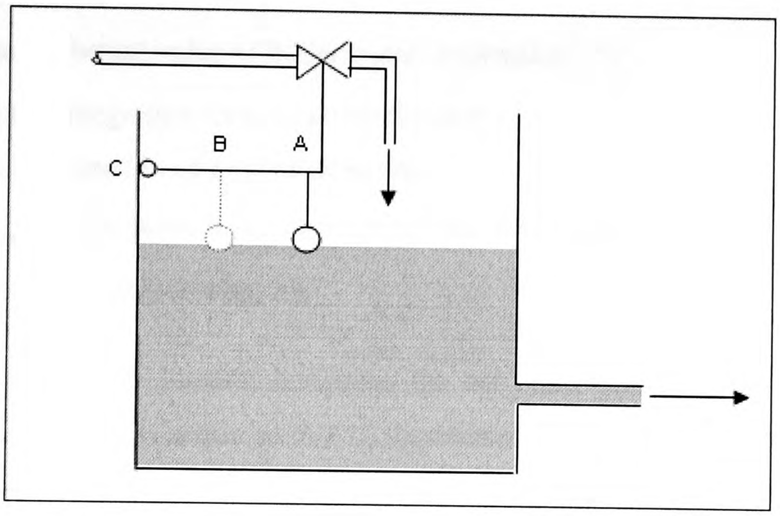

Figure 4.20. Control over water level.

As was mentioned before, with a proportional controller there is almost always a deviation from the set point, in this case the water surface is either too high or too low compared with the set value. The deviation can be reduced to a certain extent by increasing the amplification coefficient but it cannot be removed that way. In the case of figure 4.20, one could adjust the water level by moving the joint point C either up or down. This would make it possible to remove the deviation. The problem is that the adjustment would have to be done every time the flow rate from the vessel changes. It is also obvious that changes in point C should be done gradually and one should monitor the effects before further adjustments. An integral (I) control action works that way. It removes the deviation slowly but surely.

In the application, the I-action is calculated as follows:

$$q_{init2} = -\frac{\Delta T_w}{T_w} \cdot q_{init1} \cdot \frac{t_{cs}}{t_I} + q_{prev.init2} \qquad [4.46]$$

where

q_{init2} is the new initial value for the P controller, kW

q_{init1} is the original rate of combustion, kW

ΔT_w is the difference between the set value and the actual value of boiler water temperature, °C

T_w is the actual value of boiler water temperature, °C

t_I is the integration time, s, set by the user

t_{cs} is the duration of a calculation step, s

$q_{prev.init2}$ is the cumulative combustion rate according to the I-controller at the previous calculation step, kW

In the application, the I-action compares the set point with the actual value and if difference exists, it takes action so that if, for example, the boiler water is 10 % too cold, it tries to elevate the rate of combustion by the same 10 % during the set integration period. At the next calculation step it checks the deviation again. If it has reduced to, say, 8 % it now only tries to elevate the combustion rate by 8 % during the set integration period. As the calculation step is typically a lot shorter than the set integration period, only small changes take place before the following calculation step starts.

29. *Wood chip boiler combustion rate* is practically the same as the rate the automatic controller sets provided that the coefficients of the controller are properly set and the controller is not able to make swift changes. Nevertheless, it may happen that the combustion rate does not follow immediately changes set by the controller. For example, if the combustion rate has been going up for a while and the controller tries to cut it down, there are probably quite a lot wood chips on the

grate and the combustion chamber temperature is high so that heat transfer to boiler water will most obviously go on for some time regardless of what the automatic controller wishes. Another example could be a situation where the boiler water temperature has risen too high for some reason and the controller has cut down the fuel feeding for a lengthy period. During that time almost all the wood chips would have burnt out and the grate would be practically bare. Temperature in the combustion chamber would have sunk rather low. If the controller wanted, in that kind of situation, to increase the combustion rate, it would probably take some time before the heat transfer to boiler water would increase at all, despite increased fuel and combustion air supply rates.

In the application, it is possible to set some coefficients that take the aforementioned situations into consideration so that the actual combustion rate remains constant for some time before it changes its direction. It is just extremely difficult to know what kind of inertia effects actually exist in different situations. Therefore the user should be cautious about utilising above coefficients.

4.5.6. Simplifications in the model

Some simplifications have been made in the application. Their significance is discussed at this point.

4.5.6.1 Geometry of the network

The geometry of the network has been restricted to not more than seven nodes. In real installations the amount of nodes may quite easily be ten times that, even in rather small district heating systems. Nevertheless, in small DH systems the nodes have to be quite close to one another and the error resulting from bunching up some adjacent nodes is acceptable, especially when the idea is not to study any particular place in the network but the whole system including heat production, transfer and consumption. A study has been made in Denmark, revealing that the amount of separate pipes and nodes can be reduced drastically and the accuracy of simulation remains still at an acceptable level [3].

4.5.6.2 Flow calculations

It has been supposed that flow in the piping is always of turbulent nature. Laminar flow does not exist in the application. In real installations it is basically always that way: Laminar flow occurs rarely in heating systems where water is the heat carrier. Only in small pipes or other flow routes with a small cross-sectional area and with slow flow rate may the flow have a laminar nature. The nature of the flow affects on the one hand the heat transfer coefficient and on the other hand the pressure drop in the piping. Neither of above things is particularly interesting when flow rate is close to zero, so the flow is obviously turbulent in all situations of any interest.

The flow through the control valves and by-pass lines is calculated by using mass flow rate relations instead of volume flow rate relations. As the temperatures do not vary much in the calculation procedure, the density of water is almost constant. It is also important to notice that the user feeds in quite a lot information that is not accurate. On the contrary, the user most probably utilises typical values for pressure drops over sub-stations or pipelines instead of calculating them accurately. That makes the deviation caused by using mass flow rates of minor importance.

Pressure drop calculations are carried out so that there is an initial pressure drop with a given flow rate. (This is known by the user; it is the design flow rate and the one who has sized the pipes must have found out what the pressure drop would be). With all other flow rates the pressure drop is calculated based on the approximate relation between flow rate and pressure drop. This kind of calculation does not take into account changes in the physical properties of water as temperature varies. Notably viscosity relates to water temperature which means that the pressure drop in the supply line is different from the pressure drop in the return line even though the size, length, shape and mass flow rates are the same. Of course, variations in density lead to variations in volume flows, as well. However, as the shape of the district heating grid has been simplified somewhat, errors due to simplifications in the pressure drop calculation are negligible, having in mind that the application is not meant for dimensioning pipe work or pumps; its purpose is to help find relationships between certain things.

Control valves at the sub-stations are supposed to have strictly linear flow characteristics, which does not exist in real installations. However, as can be seen in figure 4.19, if the authority of the valve is around 0.7...0.8 and it has a linear characteristic, the actual relation between stem position and flow rate is almost linear. On the other hand, it has nothing to do with the eventual flow rate (which depends on temperatures and the heat exchanger), it is just how long it takes until the eventual flow rate is achieved.

4.5.6.3 Heat transfer calculations

In the calculation of heat loss from the pipes to the ground some simplifications have been done:

1. The length of the pipe between two given nodes is not strictly the same as the user has set. The procedure checks at every calculation step if the water that departed the previous node (at a given temperature) has already arrived. As the calculation step may be e.g. 30 seconds, the water may have flown say 50 metres during the calculation step. If it was quite close to the node at the previous calculation step, it may happen that at the following check point it has already passed by the node. It is the distance it has flown from the previous node that is used as the length of the pipe between the nodes. If the actual distance is short and the time step is long, a notable error may take place. If, as usually is the case, the distance is lengthy, flow rate moderate as well as the calculation step, the deviation is negligible.
2. The temperature of the water between two given nodes is considered constant by the application. This leads to too the heat loss rates being too high. Nevertheless, some calculations have been made to compare the results with above method to results with a more accurate model that takes the temperature drop into account. The comparison showed that the results were practically identical if the flow rates were moderate or high and the distance between the nodes was not extremely long. When it comes to low flow rates (actually the velocity is significant) the difference becomes visible. Of course, with poor thermal insulation the deviation increases.

3. Heat transfer between the supply and the return lines has not been taken into account at all. It can be seen quite easily that it is the insulation of the pipe that dominates the heat loss; the thermal resistance of the ground is of minor importance. (That is why the thermal resistance of the steel pipe and the plastic jacket on the insulation have also been ignored.) Therefore it is quite logical not to care what happens to the heat once it has left the insulation; some amount of it obviously comes across the return pipe but the insulation works in both directions. In general, as the pipes are not in common insulation but are insulated separately, the heat transfer between them can be regarded as negligible.
4. The specific heat capacity and the density of water are constant in the heat loss calculation. This leads to a certain deviation, depending on the temperature of the flow. Considering that the geometry of the network is simplified and the pipe sizes and distances are not strictly the same as they would be in a real installation, the significance of using constant values instead of accurate ones becomes remote.

4.5.6.4 Secondary side constants

Temperature of the secondary side flow is considered to be linearly proportional to the outside temperature. As the latter remains constant during the simulation period, the same goes for the secondary side flow, too. The model does not include heat transfer from the secondary side flow to the inside. Massiveness of the building, volume of the secondary side system, heating method (radiators, floor slab heating...) have an influence on how stable the return water temperature is. The flow rate is supposed to be constant. It is obvious that the secondary side return water temperatures are on average close to their design values just as the calculation expects, but undoubtedly situations occur when the temperatures fluctuate for some reason; and the same may happen to the flow rates. To include these fluctuations to the calculation would require modelling of the consumers, which would increase the size of the application drastically.

It is supposed at this point that above fluctuations do not last long and the secondary side values equal in general with the design values. It is also obvious that the fluctuations propagated from the secondary side to the primary side would level off as the separate flows would join in the main pipe.

Linear proportionality between the secondary side temperatures and outside temperature does not occur in reality. If the heat exchangers have been properly sized, secondary side temperatures are at their design values at the design outside temperature. On the other hand, as outside temperature is elevated so that there is practically no need at all for heating, and the control system works properly, there is no observable temperature difference in radiators and heating coils between supply and return temperatures. If the radiators and coils are not supposed to transfer heat to the interior, but flow circulation is still on, the temperature of both supply and return waters has to be very close to the room temperature. So, it can be considered that flow temperatures at the design outside temperature and at the need for heat ends outside temperature are known. The application calculates intermediate values linearly. In real installations, depending on sizing of radiators and coils, intermediate values are somewhat higher than linear proportionality would suggest. The maximum difference is in the region of 2 to 5 °C, in the return water even less. If the temperature is close to either design or heating ends outside temperature, the deviation is next to nothing. Secondary side return temperature is needed for calculating the primary side return temperature. Should there be a deviation of a couple of degrees in the secondary side return temperature, it would cause an error in the primary side return temperature in the region of one or two °C.

4.5.6.5 Heat exchangers

To calculate the effectiveness of the heat exchanger with different flow rates would require knowledge on the shape and size of the flow routes in the heat exchanger, so that the Reynolds number characterising the nature of the flow could be calculated. This kind of information is very seldom available when the heat exchangers have not been even purchased yet. On the other hand, it is known that the heat transfer coefficients in the heat exchanger are related to the flow rate, so that they cannot be just ignored.

An equation was found in the literature approximating the relation between the change in the flow rate in one side of the exchanger and the overall heat transfer coefficient [19]. Experiments were made with above equation and an heat exchanger sizing program [22] to see if the results match. The aforementioned sizing program is made by a heat exchanger manufacturer and is used in sizing heat exchangers for customers. It takes into account temperatures and flow rates, nature of flow, thermal properties of water and several convection coefficients.

Figure 4.21 shows the primary side return water temperature, which is the interesting variable, calculated with the sizing program and by using the aforementioned approximating equation. The design heat transfer rate is 20 kilowatts and the design primary side temperatures are 115 °C (inflow) and 45 °C (outflow) and in the secondary side respectively, 40 °C (inflow) and 70 °C (outflow). These are in accordance with typical Finnish installations. Heat transfer rate is proportional to outside temperature and the primary side supply water temperature and the secondary side return water temperature are calculated according to the outside temperature the way discussed previously.

It can be seen in figure 4.21 that the difference between the results is negligible. This is mainly due to high effectiveness which, in turn, results from design values (45 °C and 40 °C) which are quite close to each other.

Figure 4.22. Shows the comparison with a 50 kW heat exchanger. The design temperatures are the same as with the previous heat exchanger.

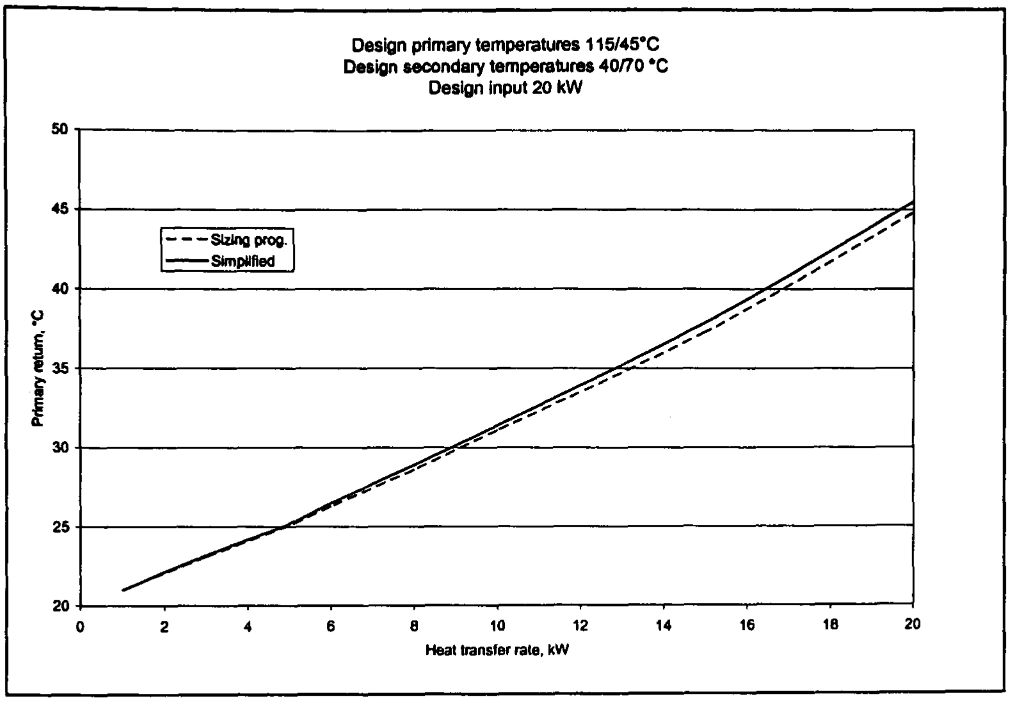

Figure 4.21. Primary return temperatures.

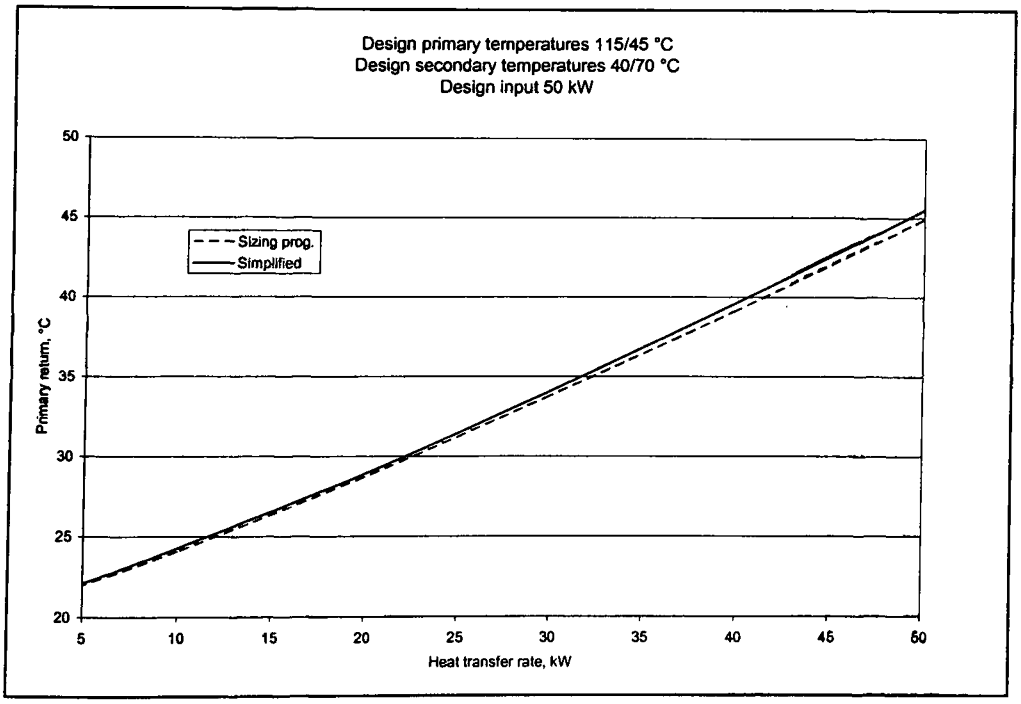

Figure 4.22. Primary return temperatures.

It can be seen in figure 4.22 that the design heat transfer rate is of no importance; the results go well with figure 4.21.

Figure 4.23 shows the comparison with a 50 kW heat exchanger but the primary side design supply temperature being 95 °C instead of 115 °C as it was in previous examples. This kind of heat exchanger could be installed to the farthest point of the DH network where the temperature loss to the ground could be significant.

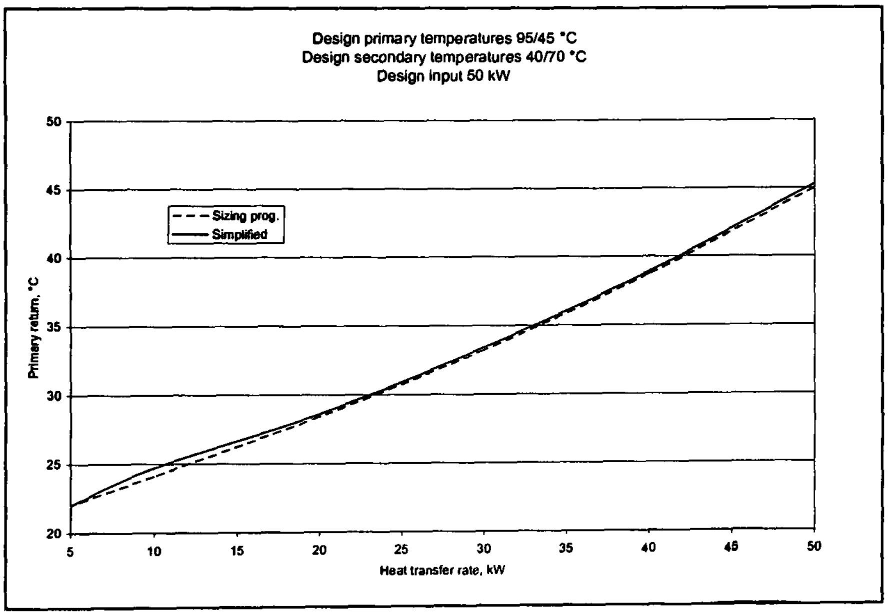

Figure 4.23. Primary return temperatures.

Again, it can be seen that the results are almost identical. As the design temperatures in the ventilation systems are generally either the same or at least close to the ones used in heating systems, it may be assumed that the simplifying equation gives results that are accurate enough as far as heating and ventilation heat exchangers are concerned.

Domestic hot water heat exchangers differ somewhat from the ones used for heating and ventilation. For one thing, the secondary side temperatures do not depend on outside temperature; in the application they are constant. For another thing, the secondary side flow rate is by no means constant. The most challenging situation occurs when the outside temperature is high and, thus, the supply water temperature is low: The exchanger should be capable of transferring the designed heat rate from the primary side to the secondary side even then. As the supply water temperature is elevated, the situation becomes easier. In figure 4.24 the operation of a 100 kW DHW heat exchanger is shown. The primary side design supply water temperature is 70 °C, return temperature 25 °C, secondary side cold water temperature 8 °C and hot water 55 °C. These values are well in accordance with typical Finnish installations. The hot water consumption rate is 100 kW through the calculation; the variables being the primary side supply water temperature and the return water temperature.

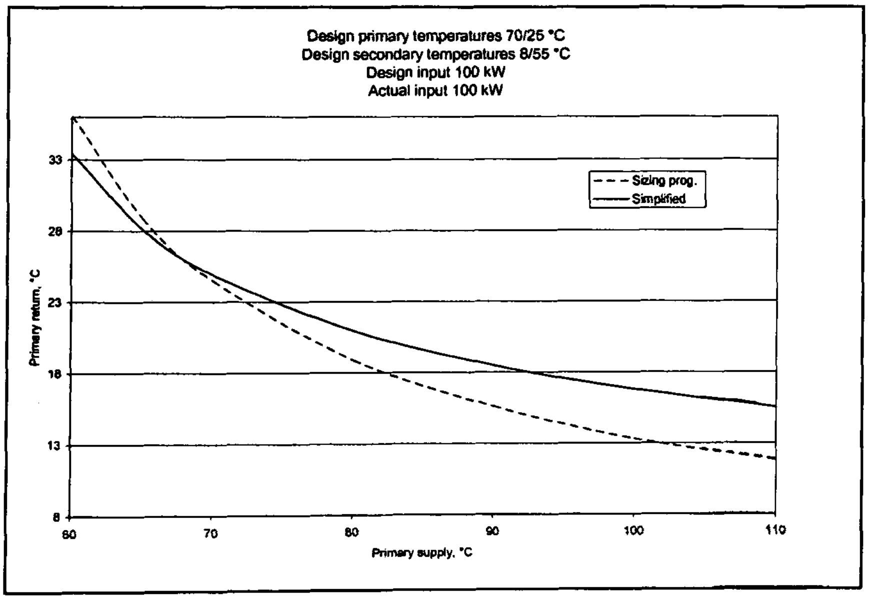

Figure 4.24. Primary return temperatures of a DHW heat exchanger.

It can be seen that even though the difference is evident, the shape of the simplified curve is satisfactory. Figure 4.25 gives the results of the same heat exchanger with a 70 kW hot water consumption rate.

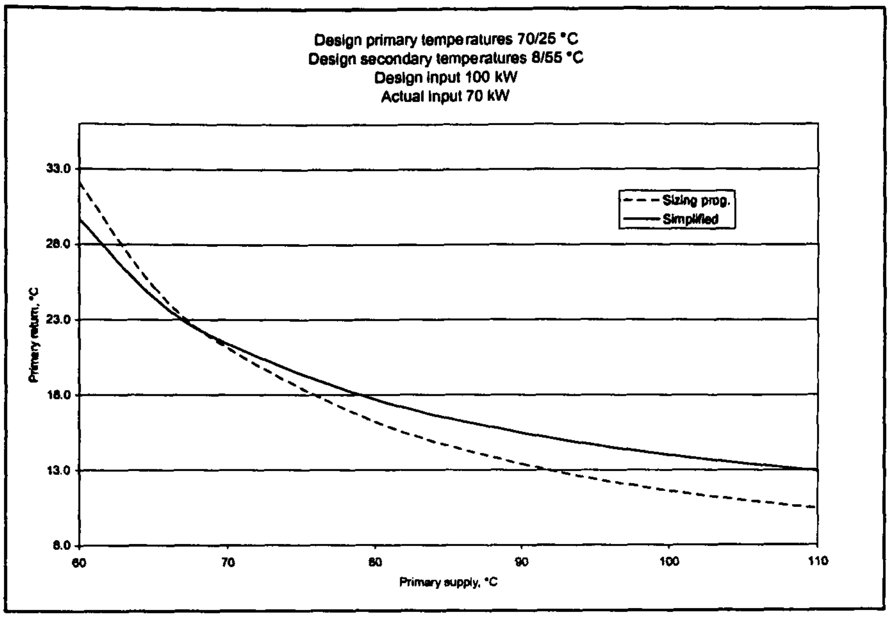

Figure 4.25. Primary return temperatures of a DHW heat exchanger.

Figure 4.26 gives the results of the same heat exchanger with a 30 kW hot water consumption rate.

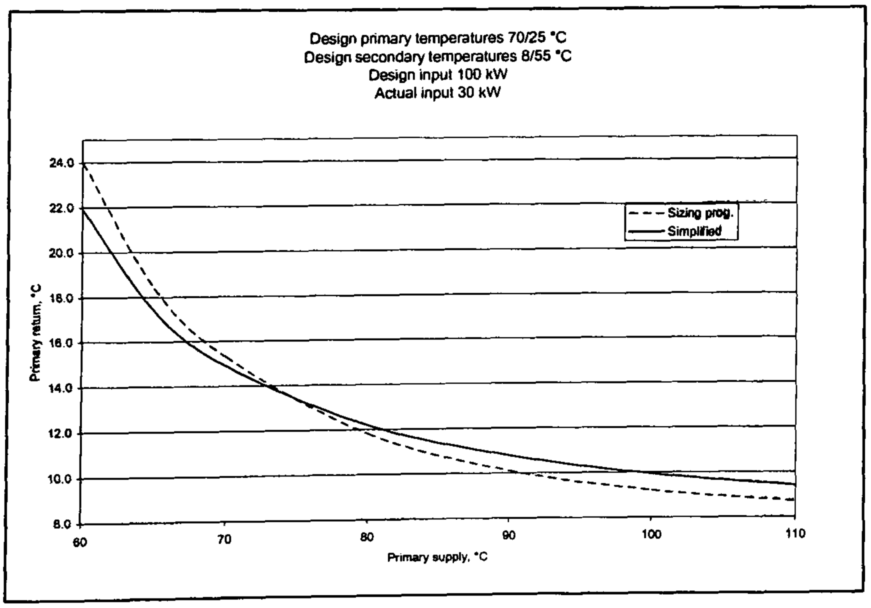

Figure 4.26. Primary return temperatures of a DHW heat exchanger.

Figure 4.27 gives the results of the same heat exchanger with a 10 kW hot water consumption rate.

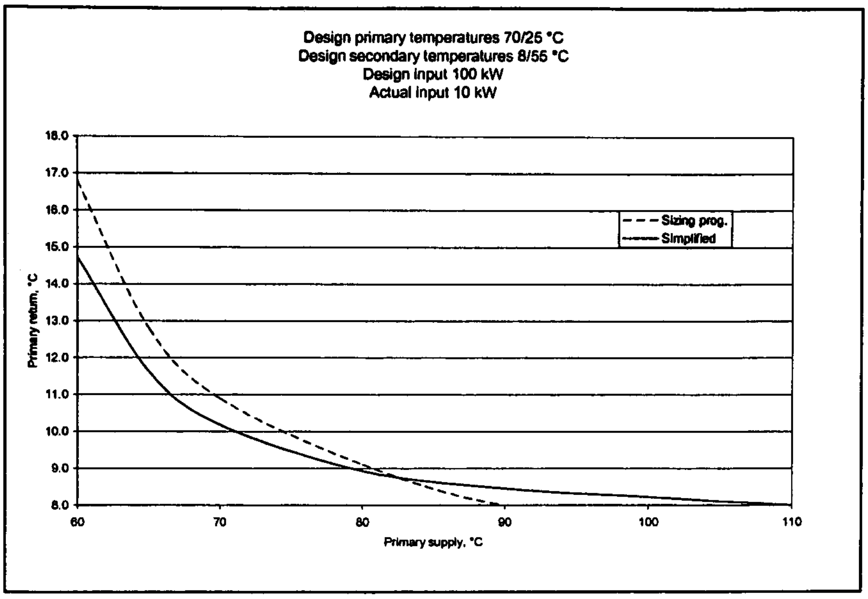

Figure 4.27. Primary return temperatures of a DHW heat exchanger.

As can be seen in figures 4.25 – 4.27 the difference between the return temperatures becomes smaller as the domestic hot water consumption rate decreases. It is rather obvious, because the effectiveness goes up with decreasing flow rates.

5. Application of the dynamic models

5.1 Introduction

In Chapter 3, an application of the steady state model was introduced. In this chapter, the same case will be studied again, but this time with the dynamic models introduced in Chapter 4. As has been said before, the initial data is essentially the same. Should there be miscalculations e.g. in the annual heat consumption of a particular building, it would be reflected in both calculation procedures. The annual heat consumption of each building is the same regardless of the calculation method. The difference, if any appears, will relate to the division of heat consumption through the year and its implications.

The annual heat consumption of each building is known. It consists of heat losses through the envelope, heat losses due to natural filtration, heat losses due to ventilation and heat consumed for domestic hot water preparation. There are also several heat gains that have an influence on the need for heat: Solar radiation, heat recovery, occupants' attendance and the usage of electric power decrease the need for heat from the DH network. It is extremely difficult to get detailed information on practically all the aforementioned heat gains. Solar radiation is a partial exception: The intensity of direct and scattered radiation through the test year are known, still there may be several variables which are difficult to predict but have a significant influence on solar radiation entering the room. An example of such things are Venetian blinds and curtains in general.

Even though it is most likely difficult to calculate exactly the availability of heat gains, this does not mean that such a calculation would be meaningless. If one, for instance, considers a day in April or in September, it is in this authors experience that even though the outside temperature may be pretty low, solar radiation is so intense that there is no need for heating in rooms whose windows are facing the sun. On the contrary, room temperature tends to rise too high so that curtains or Venetian blinds need to be adjusted. What is more, it is easy to believe that in schools and office buildings the internal heat gains are emphasized in the day-time when a lot of people not only occupy there but also use electrical appliances. The same goes vice versa for residential buildings: People return to their homes after work and start using electric power for many purposes probably more than has been the case in the day-time. All this is to say that depending on the purpose of use there is a definite and more or less regular variation in the intensity of internal heat gains in each building. What is not known exactly is the degree of the variation, but the overall picture can well be predicted.

5.2. DHW consumption

Another thing that is obviously significant when calculating the heat demand from the DH network is the usage of domestic hot water. It is known that the usage does not occur at a constant rate; on the contrary, there are a few peaks during which a great deal of domestic hot water is consumed. The hourly division is one thing and the total is another thing. If one has a good estimation on both of them, it is possible to determine the need for heat for this purpose from the DH network at any moment. Again, it is probable that one is not able to tell exactly how much domestic hot water is consumed in different buildings. Even more difficult is to find out how the total consumption is divided through the day and week. Nevertheless, some things are so obvious that they can be considered as facts. People tend to sleep at night, so no hot water usage then. People do not go to schools or offices in weekends, no hot water usage in those buildings then. Most people are not at home in the daytime except at weekends. There are obviously three peaks in the hot water consumption: When people wake up and prepare themselves for the day, at lunchtime and when people come back home and start making food and take showers etc.

In the Technical University of Chalmers, in Sweden, they have investigated the consumption of domestic hot water in a vast study made in the city of Gothenburg [2]. According to that study, the consumption of domestic hot water varied the way shown in figure 5.1. In the night from midnight till 5 o'clock in the morning there is no hot water consumption at all. From that point on the average consumption varied like figure 5.1 shows. In the study, there were many types of buildings, the majority were residential ones, however.

It can be seen that according to the study the highest peak takes place between 7 and 8 in the morning. The next peak is around midday and then in the evening there is no definite moment when the consumption would be particularly high, but it remains at a relatively high level between 5 and 9. In general, this kind of consumption profile looks plausible and would be easy to adopt. It is, thus, used in this application, too. The drawback is that the study did not bring out differences between weekdays and weekends. That is why the same profile has been used for each day in the week, in the application. Only the total consumption varies according to the period of week so that if there are 7 DHW consumption days a week, they are all similar. If there are only 5 days when DHW is consumed, weekdays from Monday to Friday are similar and on Saturday and Sunday there is no DHW consumption.

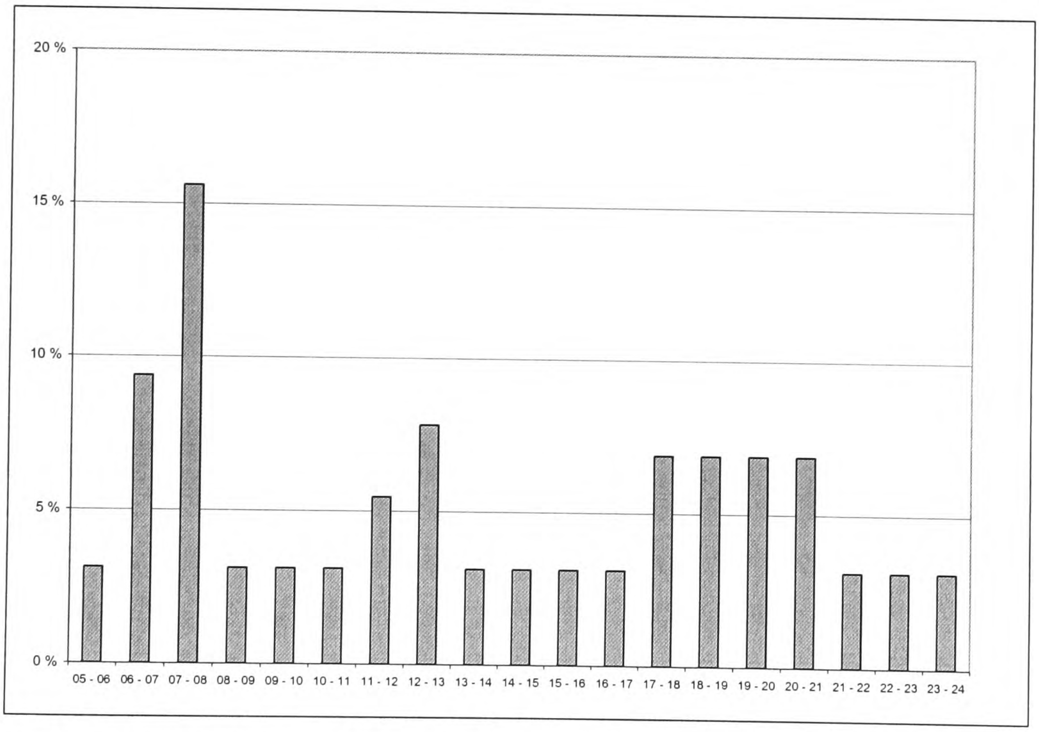

Figure 5.1. The average division of domestic hot water consumption during the day and night.

The total domestic hot water consumption of buildings has been estimated. For residential buildings, a statistical value for hot water consumption per square metre was found in the above Swedish survey. Almost all the other buildings are more or less one of a kind, since there are combinations of different purposes of use. That is why the value for hot water consumption per square metre of those buildings has solely been estimated by comparing it with residential buildings. For instance, it is probable that hot water consumption of a library or an office is significantly less than in a residential building. On the other hand, there a some buildings where people make rather large amounts of food. That would suggest a higher hot water consumption compared with residences. Table 5.1 shows the estimated hot water consumptions per square metre (in kilowatt-hours), the total annual consumption where it leads to, what is the domestic hot water percentage of the total heat consumption of the building and whether there are 5 or 7 days of DHW consumption a week.

When comparing table 5.1 to table 3.1 in Chapter 3, one can see that table 5.1 includes more items: The same building number may stand on several lines. This is due to the more accurate approach: Each building has been handled separately whereas with the steady state model several buildings were considered as one unit, as the initial data made that kind of approach convenient.

It can be seen that the estimated total annual heat consumed for domestic hot water preparation is 725 MWh. As the total heat consumption is 5920 MWh, it means that 12 % of all the heat these buildings draw from the DH network is used for domestic hot water preparation. If that figure is compared with the estimation that was used in the application of the steady state model, it can be seen that the new approach leads to a somewhat lower value. It was 20 % in the previous calculation.

Table 5.1. Domestic hot water consumption figures used in the study.

Nr	Building	DHW kWh/m^{2}a	DHW kWh/a	DHW/total heat cons.	Consumption days/week
1/1	Terraced house 1	31	13950	18 %	7
½	Terraced house 2	31	13950	18 %	7
1/3	Upper Secondary School	15	51750	9 %	5
2	Gymnasium and fire	12	51317	17 %	5
3	Library	7	3938	5 %	5
4	Annankoti OPH	35	80500	16 %	7
5/1	Rest home 1	31	10850	22 %	7
5/2	Rest home 2	31	6200	22 %	7
5/3	Rest home 3	31	10850	22 %	7
6	Iltarusko TH	31	10850	7 %	7
7	Day Centre living quarters	35	35000	29 %	7
8	Day Centre	25	8750	10 %	7
9/1	Clinic	18	11520	10 %	5
9/2	Doctor's residence	31	9300	13 %	7
10	Clinic	31	37200	17 %	7
11	Lower Secondary School	10	10133	9 %	5
12	City Hall	12	23232	8 %	5
13	Old City Hall	18	10029	15 %	5
16	Karvian Konepaja works	0	0	0 %	0
17/1	TH Leppipelto 1	31	17438	14 %	7
17/2	TH Leppipelto 2	31	15258	14 %	7
17/3	TH Leppipelto 3	31	13805	14 %	7
18/1	TH Kaari 1	31	24800	17 %	7
18/2	TH Kaari 2	31	24800	17 %	7
18/3	TH Kaari 3	31	16517	17 %	7
19/1	TH Yläsatakuntatie 1	31	57627	18 %	7
19/2	TH Yläsatakuntatie 2	31	57627	18 %	7
20/1	TH Haapa 1	31	9300	19 %	7
20/2	TH Haapa 2	31	7750	19 %	7
20/3	TH Haapa 3	31	7750	19 %	7
20/4	TH Haapa 4	31	10850	19 %	7
33	Shop Kyläkarviantie 14	15	6000	6 %	5
34/1	Bank building	10	6900	7 %	5
34/2	Cafeteria Hellun Herkku	40	22800	19 %	7
40	Church office building	10	5000	7 %	5
44	Shop Pankkitalo	25	12500	16 %	7
45	Cafeteria Nassukka	30	9000	23 %	7
			725039		

It is obvious that some items in table 5.1 require closer inspection:

Building number 6, Iltarusko terraced houses, gives only 7 % of total heat consumption to DHW preparation in spite of using the 'standard' DHW consumption per square metre. The reason for this is that the total annual heat consumption is as high as 159 MWh even though the area is only 350 m^2. It became evident during this study that either the area or the annual consumption has to be false. It could be so that heat that has been recorded for this building has actually been used by some other building. The error does not seem significant for the whole, however, and it would be difficult to say which building has actually used more heat than the records tell.

Building 16, Karvian Konepaja works, does not use domestic hot water at all, according to table 5.1. The reason is that as the DHW consumption is probably low in this type building (occasional hand washing), it is easier to leave it out from the calculation than to consider what the consumption and the profile of consumption could be. At present, there are only a few small electric hot water heaters installed, so the consumption cannot be significant.

In the library and all the shops and offices it has been considered that the hot water consumption is much less than in residential buildings. If there are several types of activities in the same building, that has been taken into account. For instance, a building may be partly residential and partly used as an office or a shop.

5.3. Electricity consumption

There are basically two values that have been used for electricity consumption of buildings. For residential buildings 13 kWh/m^3 per annum and for other type of buildings 8 kWh/m^3 respectively. With partly residential buildings the value is 10 kWh/m^3 per annum. Furthermore, is has been estimated what is the division of electricity consumption between day and night. Naturally, the durations of daytime and night-time periods have been estimated according to the purpose of use of the building. The division of electricity consumption between lighting and other purposes has also been estimated. The results can be seen in the Appendix, table III.

The same way as was the case with domestic hot water consumption, also at this point building number 16 has been left out of calculations. The reason is obvious: A machinery works consumes huge amounts of electric power compared with other buildings in the survey. It also operates in a completely different manner: Huge doors may be open even in the middle of winter if there is a need to transport something in or out. That makes heat gain calculations pointless for this particular building.

5.4. Occupancy

Table IV in the Appendix brings out how people are expected to stay in buildings or keep away of them. Some general rules have been applied when estimating the amount of occupants in residential buildings: There are four occupants per 100 m^2. Furthermore, it has been suspected that all the occupants are present in the night but only half of them in daytime. Schools and offices are occupied during daytime except weekends. The amount of people in those buildings has been estimated according to the size and purpose of use of the building.

5.5. The effect of heat gains

In the application, there are some heat gains that follow a similar pattern from day to day. Occupancy is one of them; there is one profile for weekdays and another one for weekends. Consumption of electric power for other purposes than lighting includes also a repetitive nature. On the other hand, the intensity of solar radiation does not follow any constant pattern; the heat recovery rate – if equipment for such exists – is not constant either. Heat liberated from lighting depends on what time the sun sets, something that changes every day.

Figure 5.2 shows variations in the demand for heat and the available heat gains for building 1/1 (a terraced house) during the January of the test year. The upper graph illustrates the need for heat for radiators and ventilation coils. The lower shows variations in available heat gains in the same period.

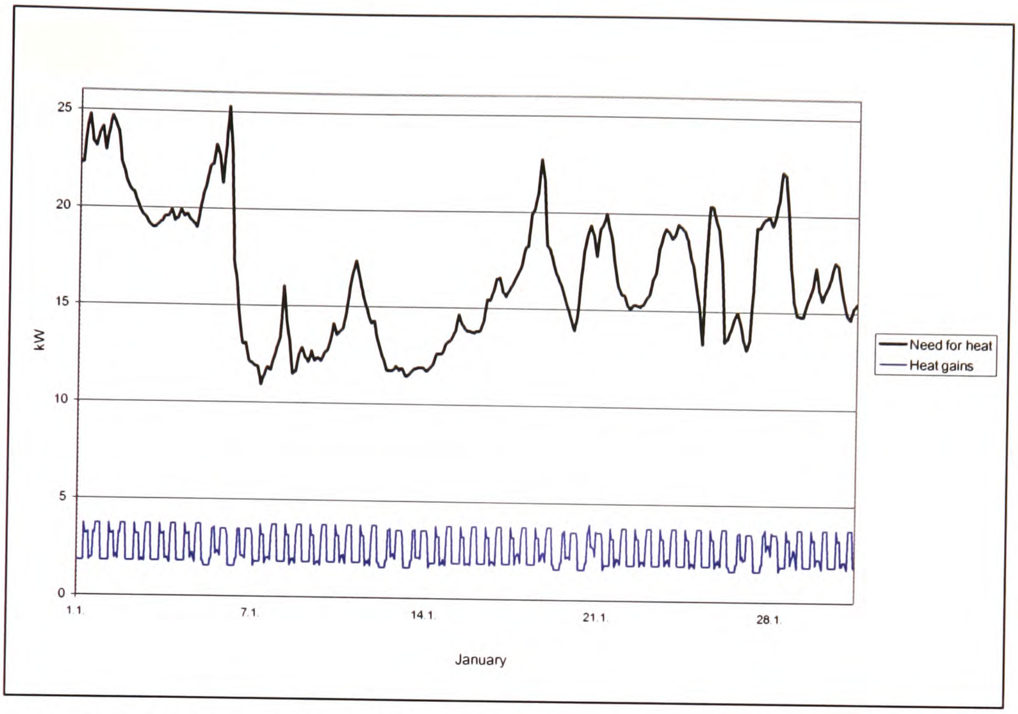

Figure 5.2. Demand for heat (the upper curve) and the available heat gains (the lower curve) of building 1/1 in the January of the test year.

The average need for heat in January is about 17 kW whereas the average heat gain during the same period is 2.5 kW which makes some 15 % of the total need, excluding domestic hot water preparation. Figure 5.3 illustrates further where this 2.5 kilowatts comes from. It brings out the division of heat gains during the first week in January. Solar radiation increases a little, otherwise virtually the same pattern is repeated through the whole of January.

It can be seen that at the beginning of January solar radiation is almost negligible; the highest transient value is a bit over 0.5 kilowatts. Occupants make a heat gain that oscillates between 0.5 (in daytime) and 1.1 kilowatts (in the night). Electricity consumption, including lighting, causes a heat gain which oscillates between 0.7 and 2.6 kilowatts. There are two peaks a day; the first in the morning and the second in the evening. During the night the output is at its lowest.

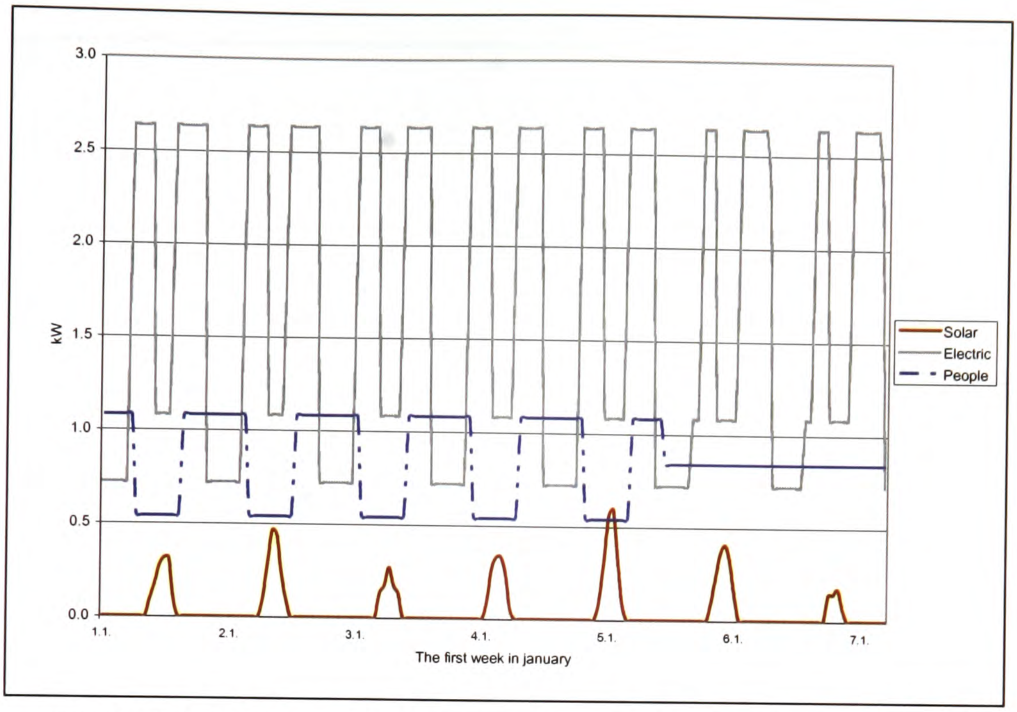

Figure 5.3. Division of heat gains during the first week in the January of the test year.

Two months later the picture is a bit different. Figure 5.4 brings out variations in the demand for heat and the available heat gains for the same building during the March of the test year. The upper graph illustrates the need for heat for radiators and ventilation coils. The lower shows variations in available heat gains. In the middle of the month there seems to have been a remarkably cold period compared with the rest of the month. The month begins with a Thursday.

The average need for heat in March is about 12.8 kW whereas the average heat gain during the same period is 2.7 kW which makes some 21 % of the total need, excluding domestic hot water preparation. Figure 5.5 illustrates further where this 2.7 kilowatts comes from. It brings out the division of heat gains during the first whole week (Monday – Sunday) in March.

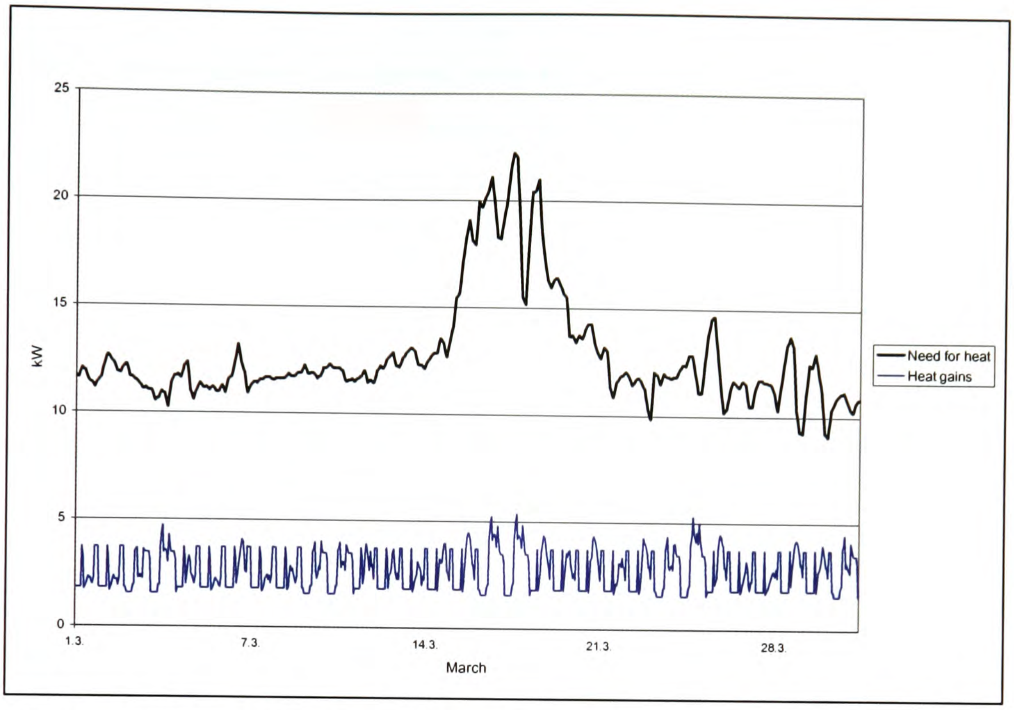

Figure 5.4. Demand for heat (the upper curve) and the available heat gains (the lower curve) of building 1/1 in the March of the test year.

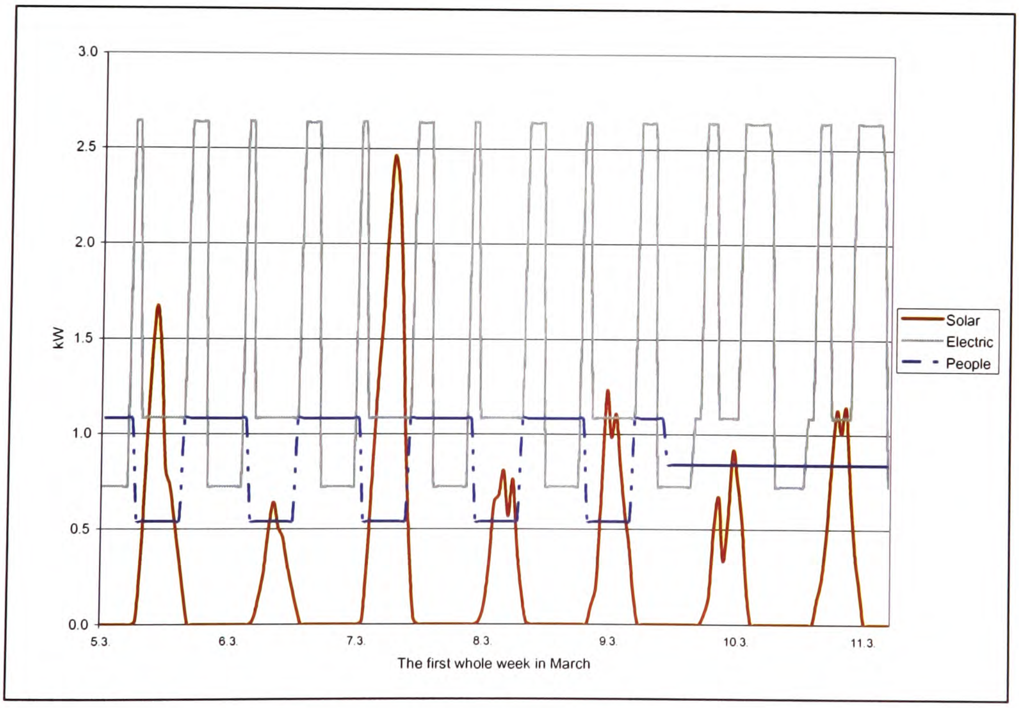

Figure 5.5. Division of heat gains during the first whole week in the March of the test year.

Heat gain from occupation is identical with the situation in January. Heat gain from electricity consumption oscillates between the same minimum and maximum but durations of maximum heat output are shorter, which is due to increased sunshine and, thus, decreased usage of artificial illumination. Solar radiation has increased considerably; the highest peak is close to 2.5 kilowatts.

Another two months will change the pattern even more. As can be seen in figure 5.6, in May solar radiation is very intense, and there are moments when heat gains exceed the need for heat. The average need for heat in May is about 6 kW whereas the average heat gain during the same period is 2.5 kW which makes some 43 % of the total need, excluding domestic hot water preparation. There are, however, periods (notably in the latter part of the month) when the need for heat is so scanty that all the available heat gains cannot be utilised. The month begins with a Thursday.

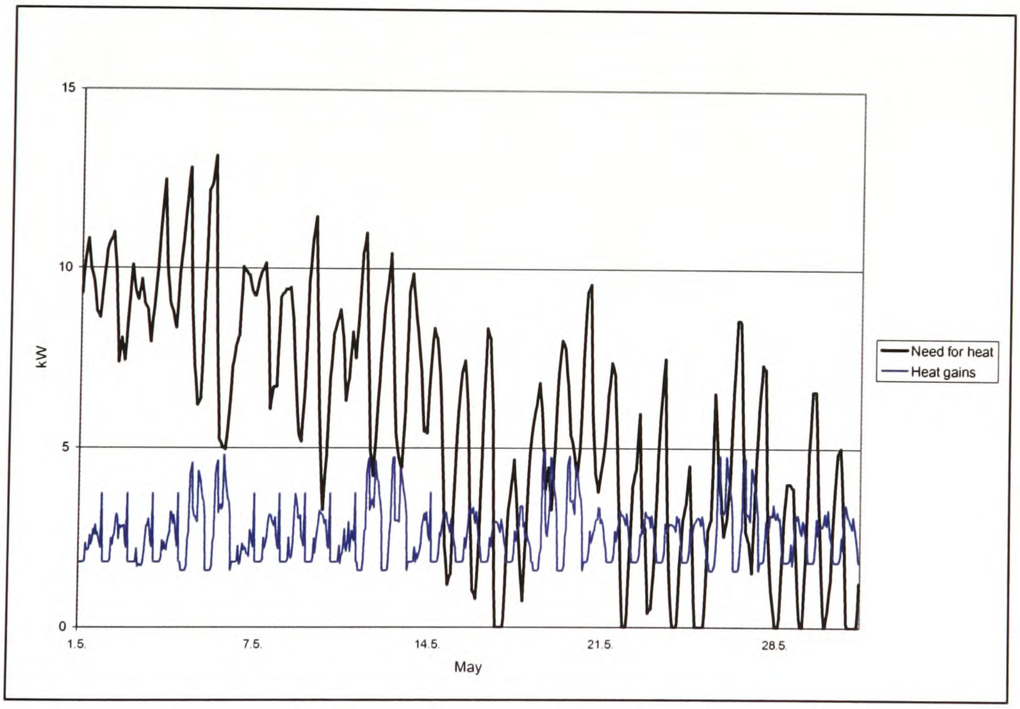

Figure 5.6. Demand for heat (the upper curve) and the available heat gains (the lower curve) of building 1/1 in the May of the test year.

As the summer comes closer, solar radiation becomes more and more important as a heat gain whereas the consumption of electricity loses its weight. Figure 5.7 illustrates the division of heat gains during the first whole week (Monday – Sunday) in May. The application considers that on a weekend people use more electricity than in a weekday (in a residential building). The increased consumption is due to staying awake late and having the lights on. It is probable that the application gives too high electricity consumption rates for lighting, as it only has two alternatives; all lights on or all lights off, but the electricity consumption could as well go that way: People tend to watch TV on weekends, for example.

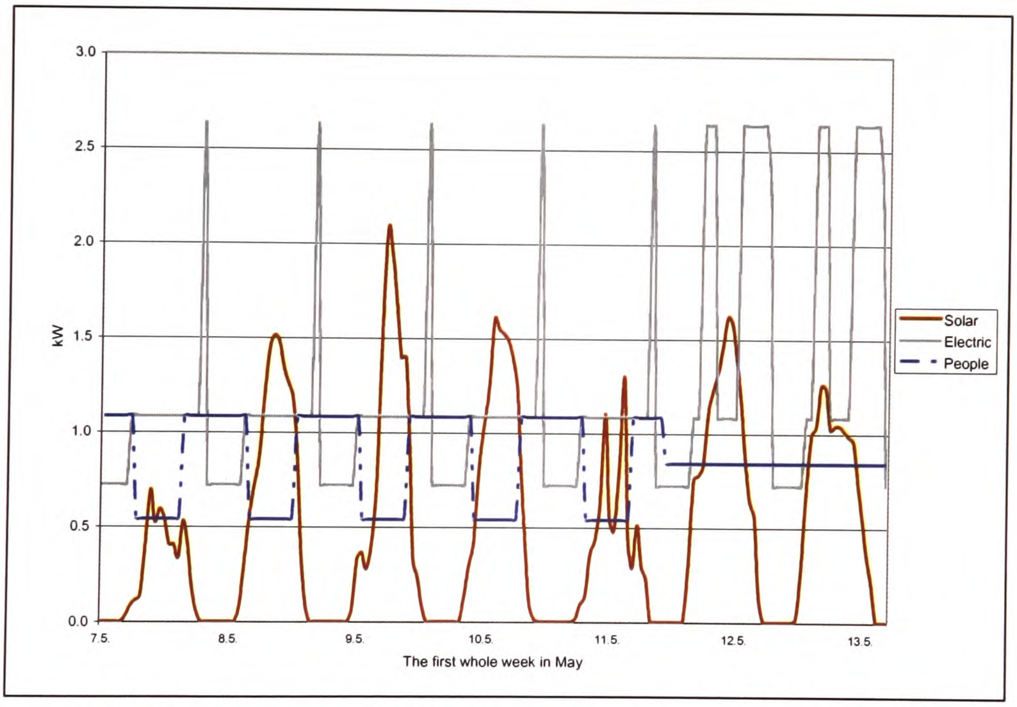

Figure 5.7. Division of heat gains during the first whole week in the May of the test year.

Figures 5.2 – 5.7 were shown just to give an idea of the significance of estimating the heat gains and their timing correctly. It can be seen, that in the colder period of the year heat gains are of minor importance compared with the need for heat. That would lead to a conclusion that even considerable miscalculations of the output or duration of heat gains would not ruin the calculation. Heat gains become important as the outside temperature rises. One of the main functions of the application is to gain data of diurnal variations in the need for heat from the DH network as the period of year is turning either from spring to summer or from summer to autumn. That kind of data would help to estimate how long a pause would be expected in the use of wood chip boiler in the summer. During late spring and early autumn daytime temperatures are often considerably higher than at night-time. Solar radiation exists, naturally, only in daytime. So, there is no doubt about it that there are periods when there is no need at all for space heating during day time, but some heat is required during the night. The consumption of domestic hot water changes this pattern to some extent, of course.

When evaluating the plausibility of heat gain calculations in the application, it must be said that there are definitely deviations due to so many estimations and generalisations. The pattern seems, though, credible as the heat gain from electricity consumption is at the highest during the winter, whereas heat gain from occupation reaches its maximum in houses during the evening and night and in schools and offices during the day. Solar radiation dominates from spring to autumn.

5.6. Heat consumption of the buildings

Heat drawn from the district heating system has been calculated for each building. The results can be seen on a monthly basis in the Appendix, table V, which brings out that some buildings are much more significant than some others when it comes to heat consumption of the whole network That is why only a few of them will be examined further. There will be graphs showing the need for heat (for space heating and ventilation) through the year, on buildings that draw more than 200 MWh per year for space heating and ventilation. Heat required for domestic hot water preparation is not shown in these graphs because it would make them extremely fuzzy. It is, though, shown in the figure which brings out the monthly heat consumption. In these figures, heat consumed by the ventilation system is included in 'Heating', so they match with table V.

The first building the heat consumption of which is presented, is the upper secondary school, building number 1/3.

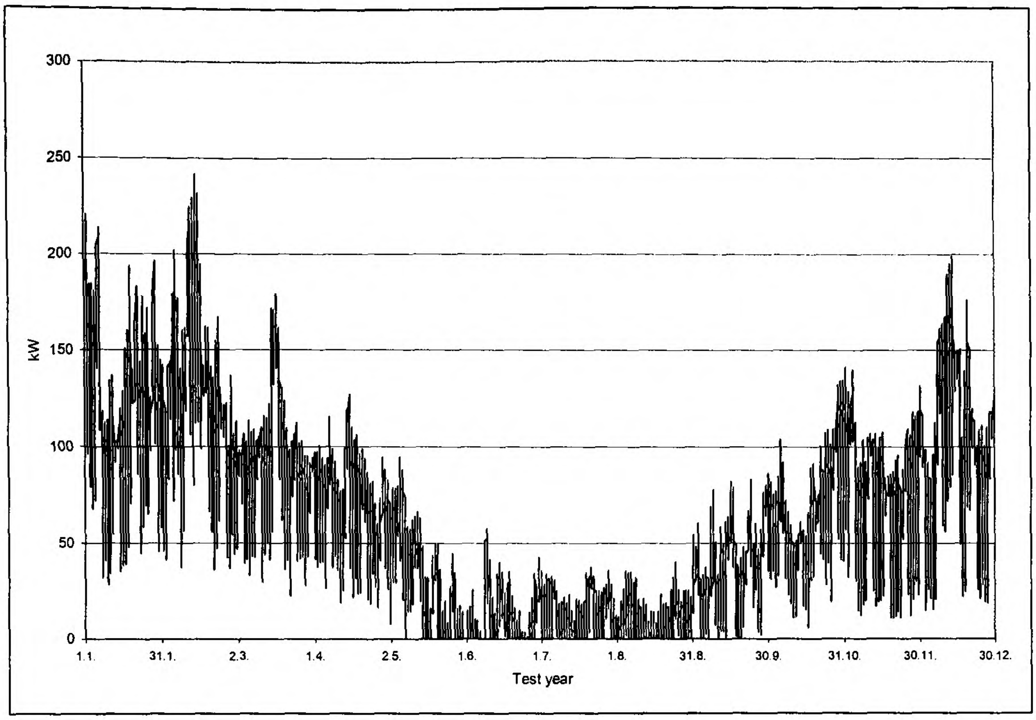

Figure 5.8. Heat building 1/3 draws from the DH network for heating and ventilation.

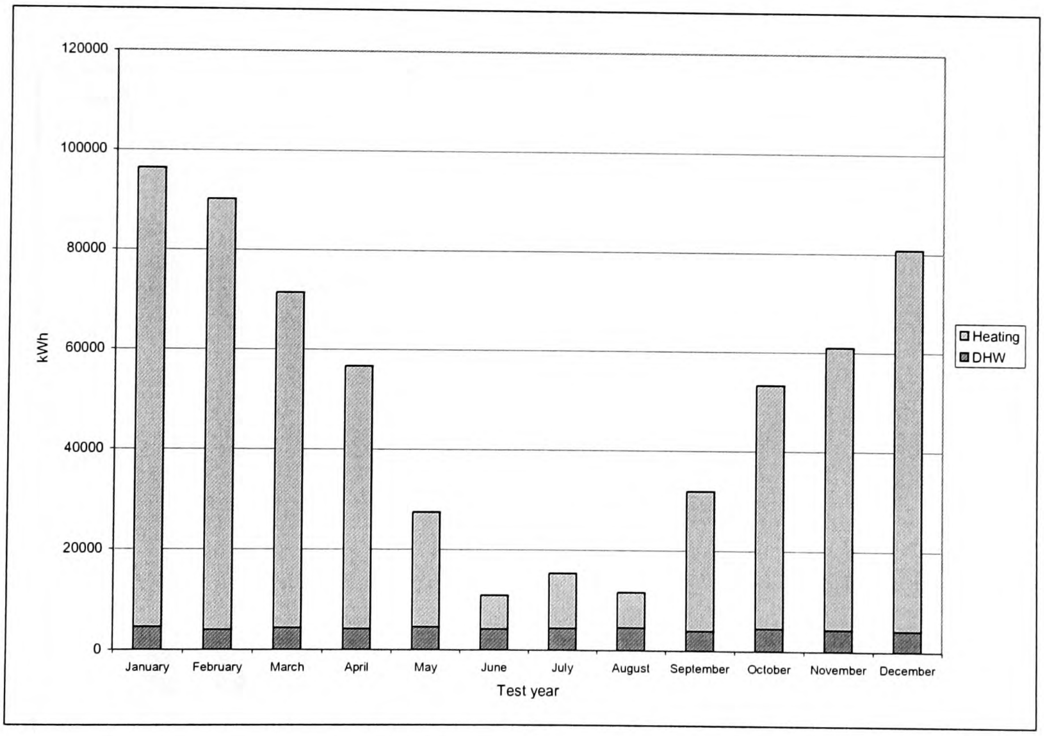

Figure 5.9. Division of heat consumption of building 1/3 on monthly basis.

Building number two is the gymnasium and fire station. First the consumption of heat for heating and ventilation, and then the monthly division:

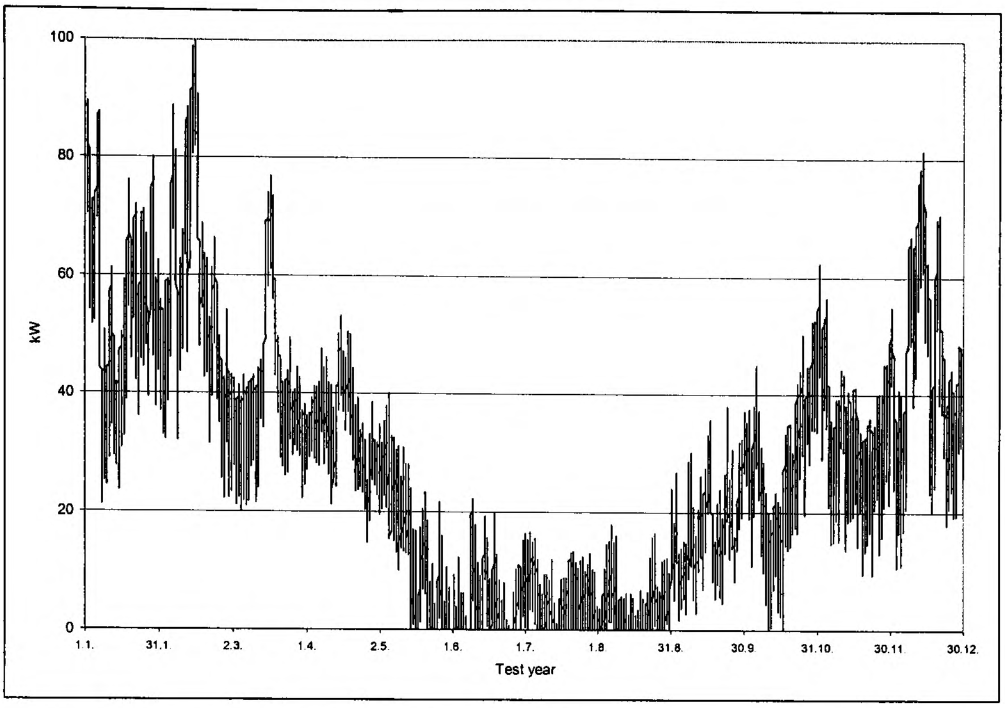

Figure 5.10. Heat building 2 draws from the DH network for heating and ventilation.

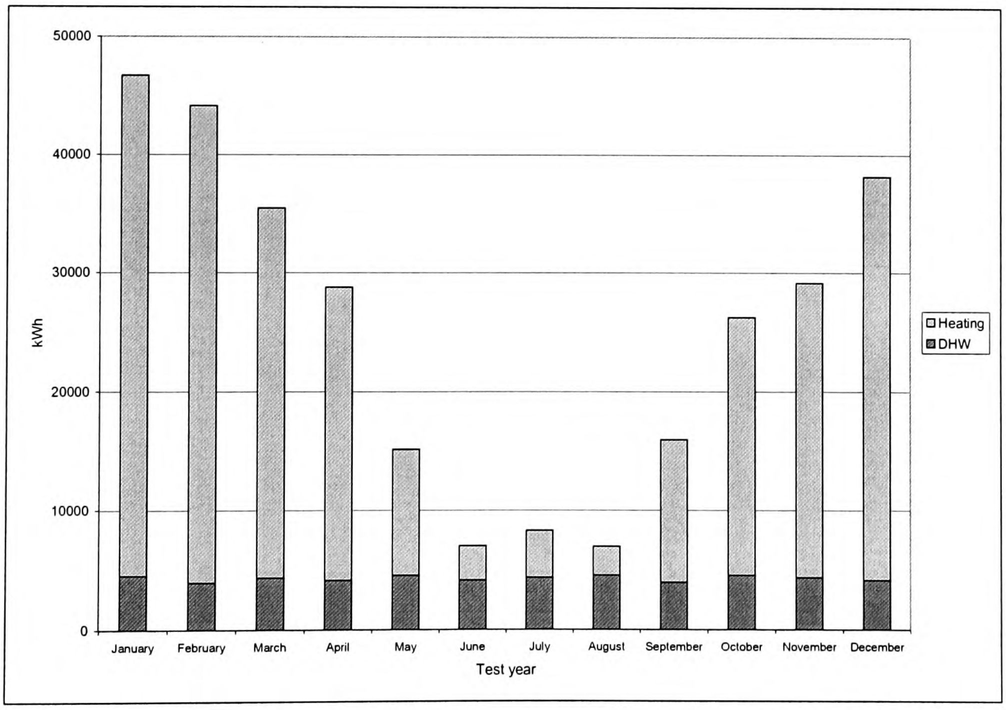

Figure 5.11. Division of heat consumption of building 2 on monthly basis.

Building number four, Annankoti old people's home:

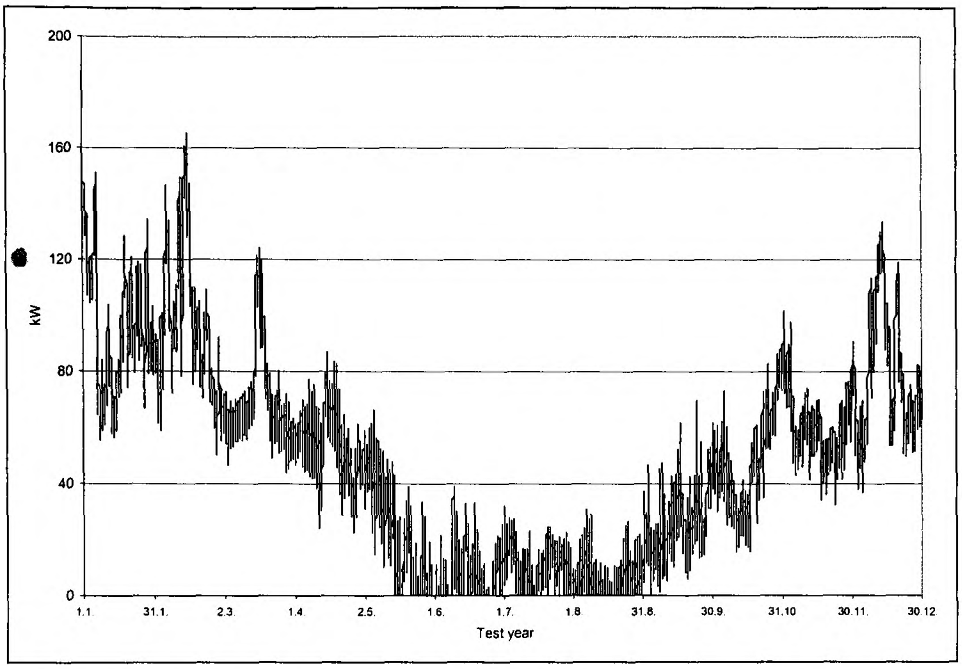

Figure 5.12. Heat building 4 draws from the DH network for heating and ventilation.

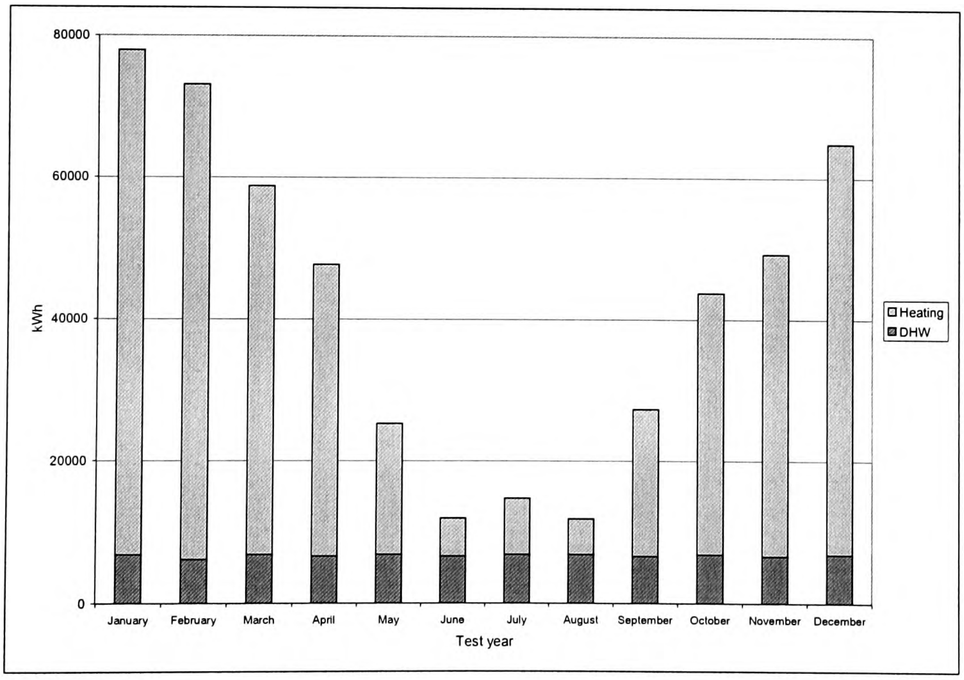

Figure 5.13. Division of heat consumption of building 4 on monthly basis.

Building number twelve, City hall:

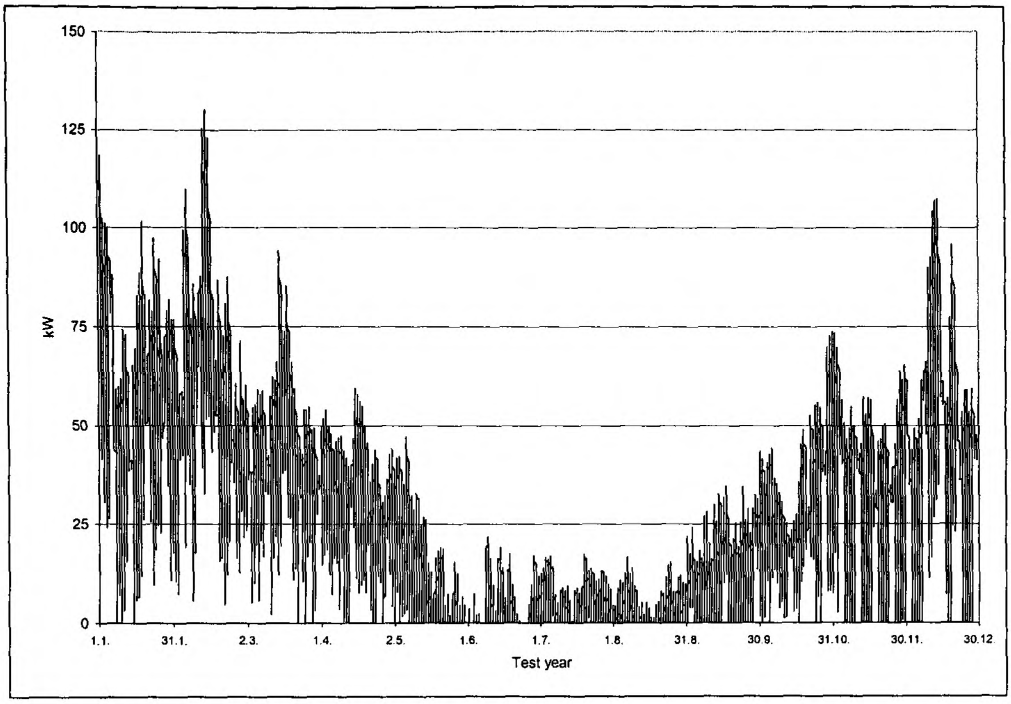

Figure 5.14. Heat building 12 draws from the DH network for heating and ventilation.

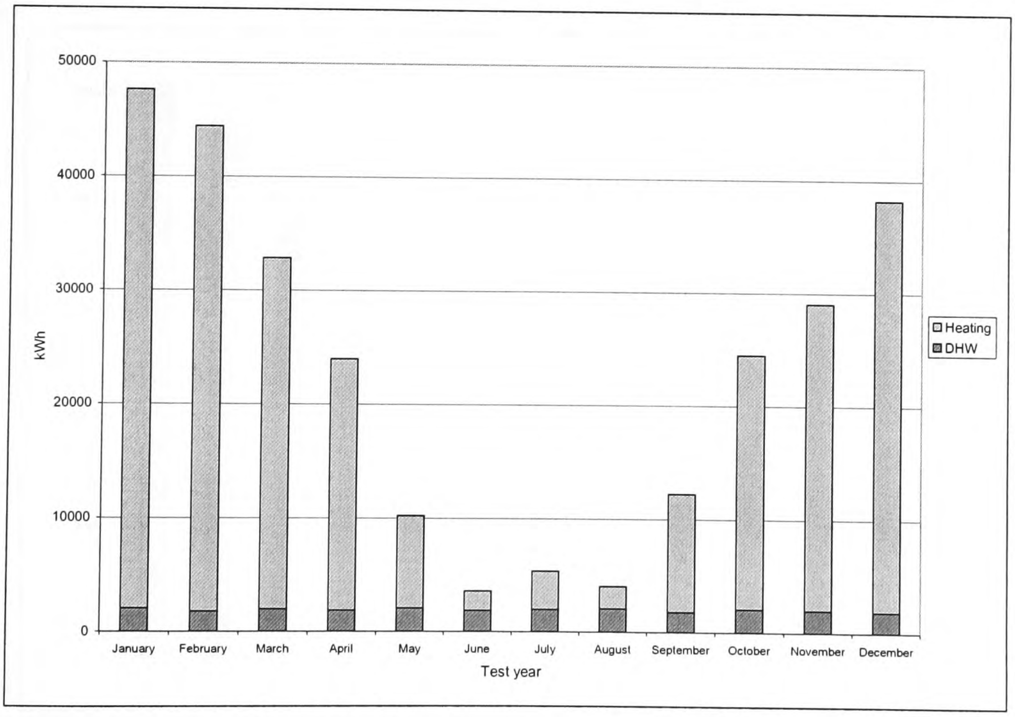

Figure 5.15. Division of heat consumption of building 12 on monthly basis.

Building number sixteen, Karvian Konepaja works:

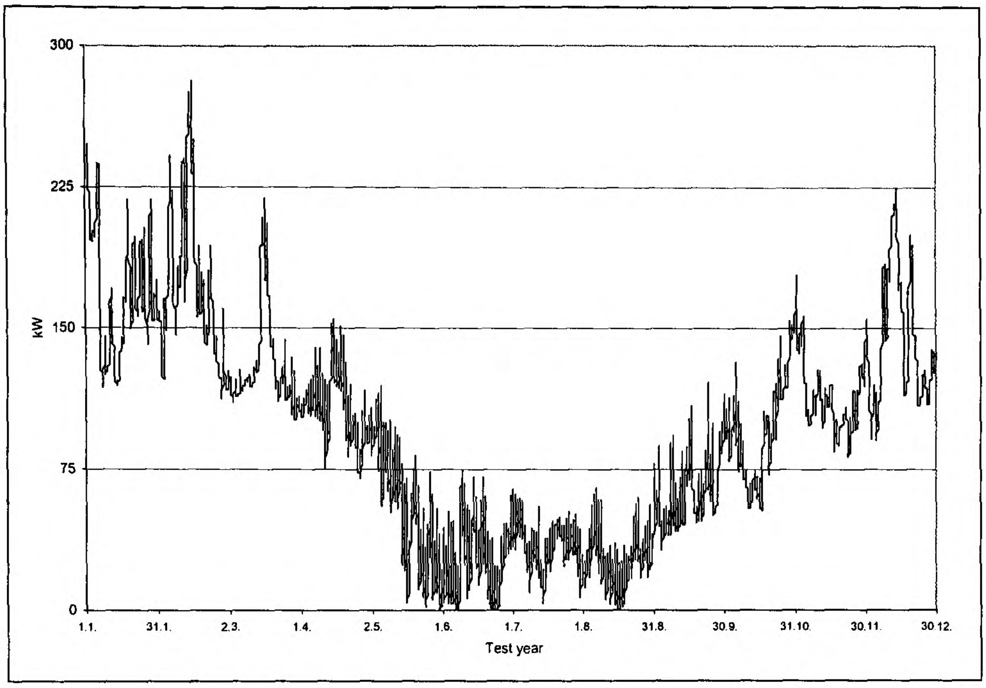

Figure 5.16. Heat building 16 draws from the DH network for heating and ventilation.

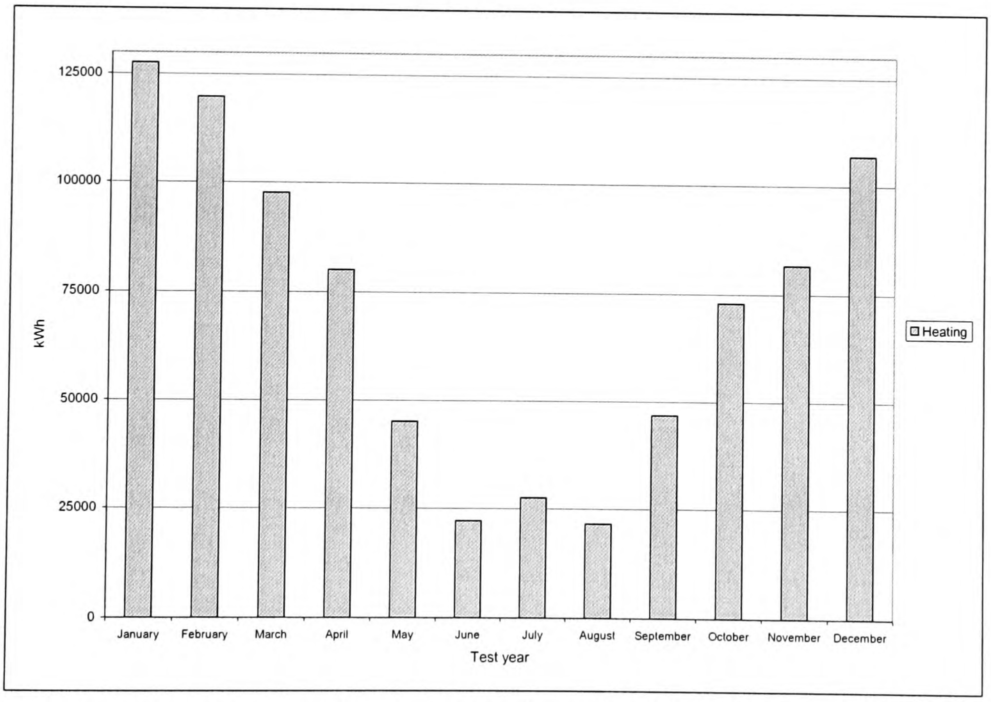

Figure 5.17. Division of heat consumption of building 16 on monthly basis.

Building number nineteen, terraced houses Yläsatakuntatie (1/2):

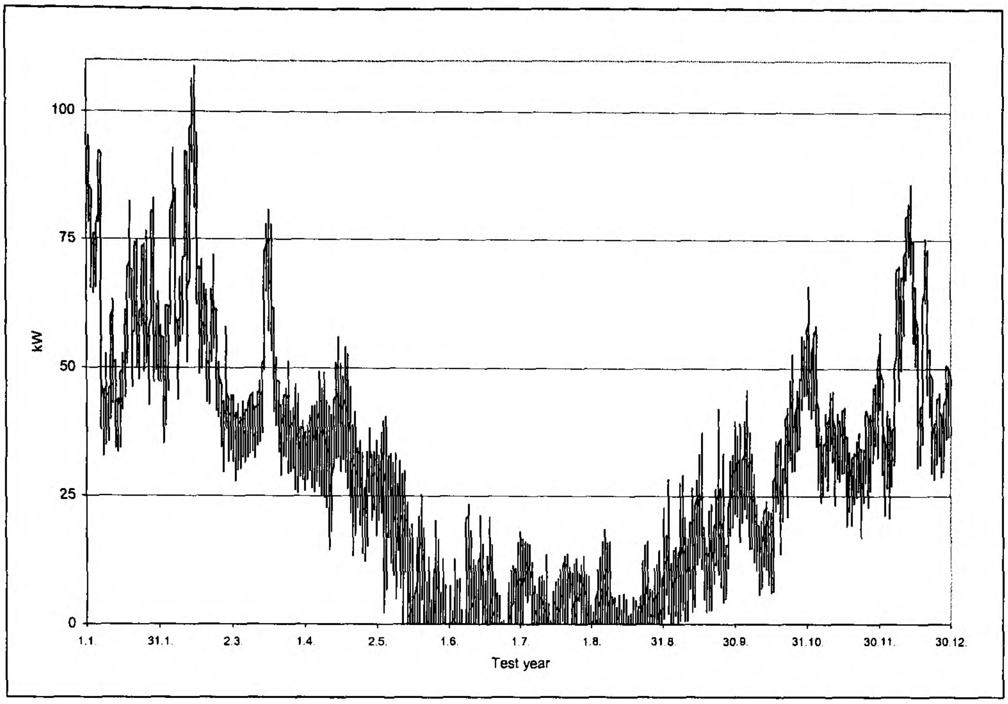

Figure 5.18. Heat building 19/1 draws from the DH network for heating and ventilation

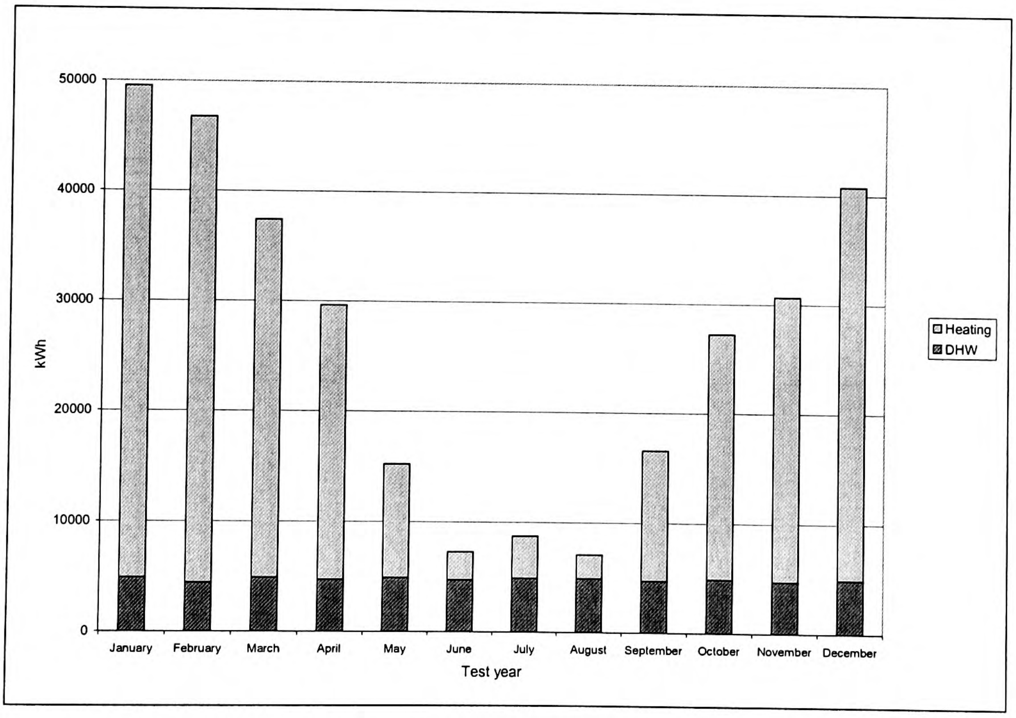

Figure 5.19. Division of heat consumption of building 19/1 on monthly basis.

And then terraced houses Yläsatakuntatie (2/2):

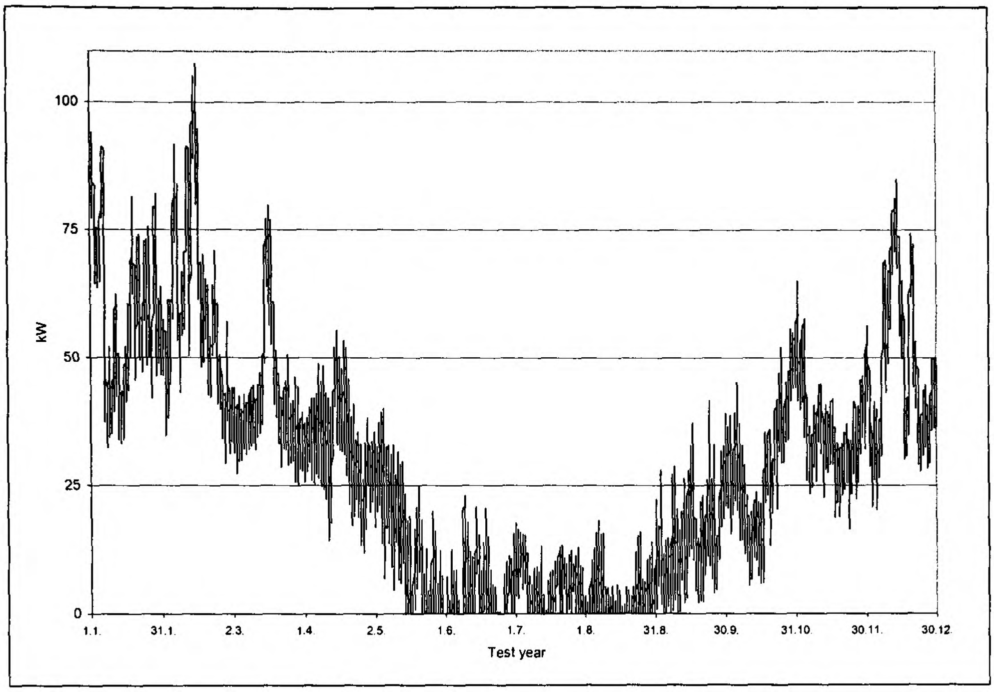

Figure 5.20. Heat building 19/2 draws from the DH network for heating and ventilation.

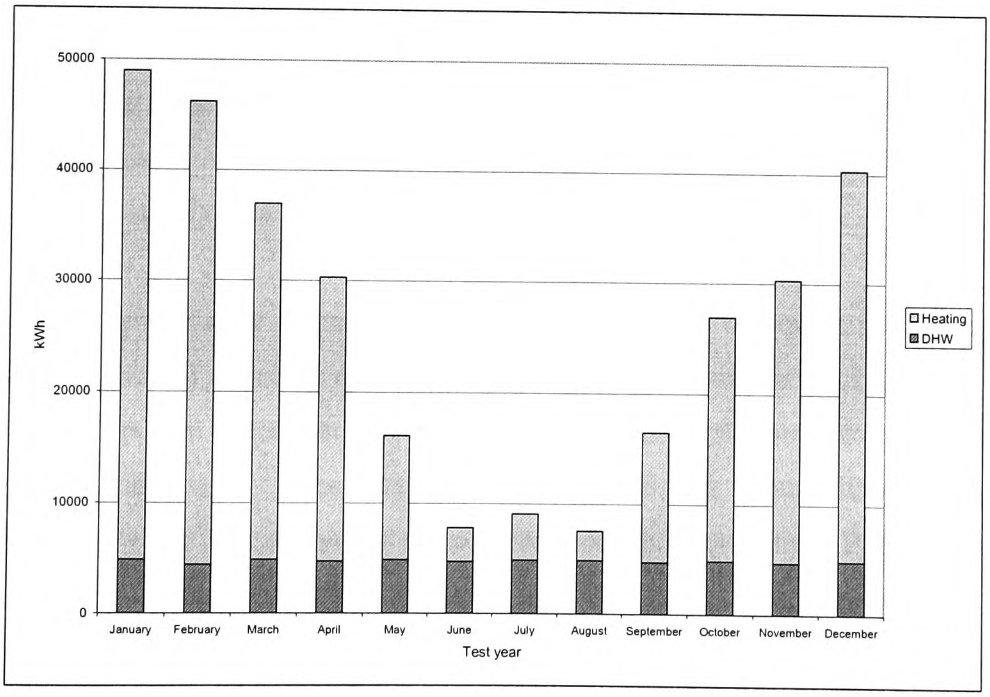

Figure 5.21. Division of heat consumption of building 19/2 on monthly basis.

5.7. Connecting the buildings

5.7.1. Total consumption

In Chapter 4, heat consumptions of separate buildings (or groups of buildings) were presented. To be able to compare the results with those from the steady state model calculation, simultaneous heat consumptions need to be added up. What is more, heat losses from the district heating network have to be taken into account.

As can be seen in table V in the Appendix, all the buildings together draw 5919 MWh per annum from the district heating system. The corresponding figure with the steady state model was 5920 MWh/a, so they virtually equal with each other.

Heat loss from the district heating network varies as temperatures of the fluids and ambient ground vary. The length of the supply line equals with the length of the return line. As the temperature difference between the fluid and the ground is, on average, a lot bigger when supply pipe is concerned it is truly good news that variations in supply water temperature are well known. The supply water temperature is adjusted to outside temperature as it leaves the boiler plant. Naturally, there will be some cooling in the network so that supply water coming to a customer's sub-station is at somewhat lower temperature than it was at the plant. Cooling is, though, the only factor that affects irregularly the supply water temperature.

Return water temperature is more complex. For one thing, it enters the network in many places simultaneously, and for another thing, initial temperatures are not uniform. It does not make things any better that these flows at different temperatures mix in junction or node points and cooling takes place all the time. All this means that calculation of average return water temperature is not possible with the application. Probably the only good thing related to return water temperature is that it is not as significant as supply water temperature.

At this point, return water temperature and average temperature drops due to cooling are simply given. Later in this study we will return to the question where did they come from. Supply water temperature, as it leaves the boiler plant, is adjusted to outside temperature so that it is 115 °C at the design temperature (-26 °C) and 70 °C as the outside temperature is 15 °C. Intermediate values are calculated linearly. It is supposed that the supply water temperature, on average, is at 5 % lower temperature than it is as it leaves the plant and enters the network. The average return water temperature is constant, 43 °C. Ground temperature is the average of preceding 24 hours' outside temperature.

Figure 5.22 shows the variations in heat output and heat loss through the year. It brings out that heat output in the boiler plant varies so that the maximum value is about 2200 kilowatts and in the summer it falls frequently close to zero. Heat loss is in the winter around 150 kW and in the summer about a half of that. The total heat loss is 943 MWh. The variations can be seen better in figure 5.23 which shows that the minimum heat loss is approximately 65 kW. With the steady state model calculation, the heat loss was approximated by using pipe manufacturer's data. The value used in calculations was 1086 MWh, which is 15 % higher than the result from this calculation.

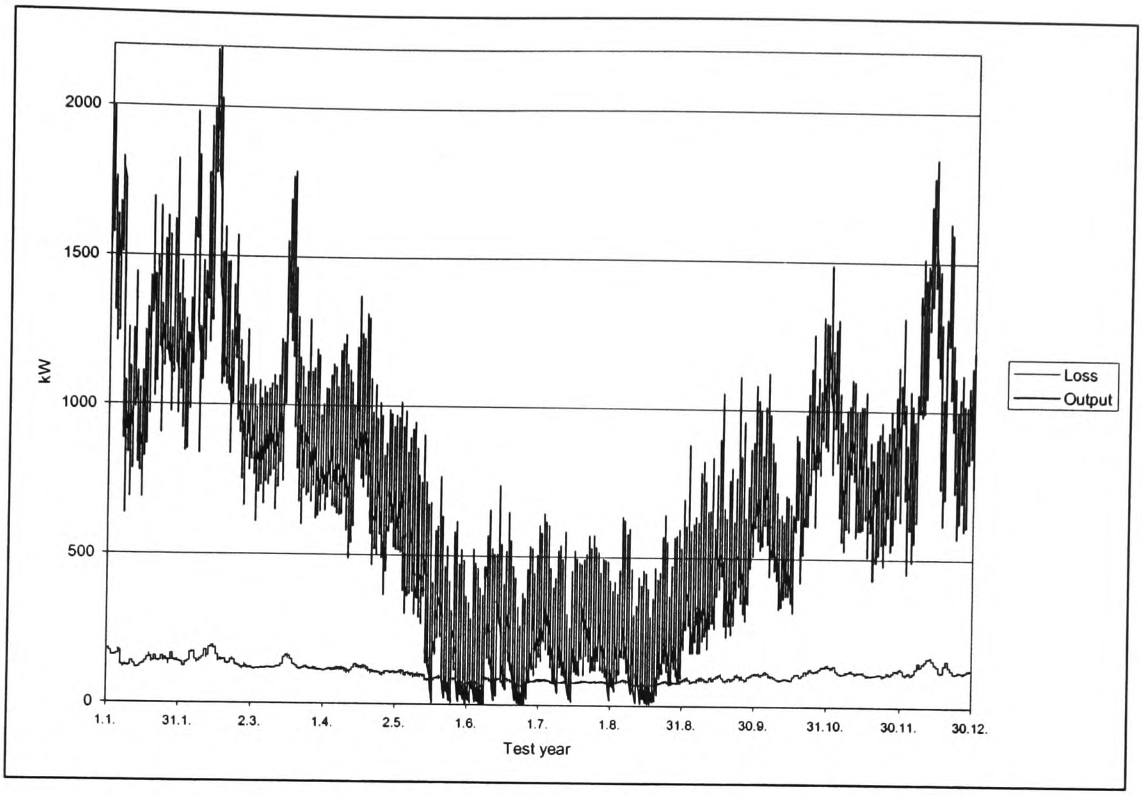

Figure 5.22. Heat output from the boiler plant and heat loss in the network.

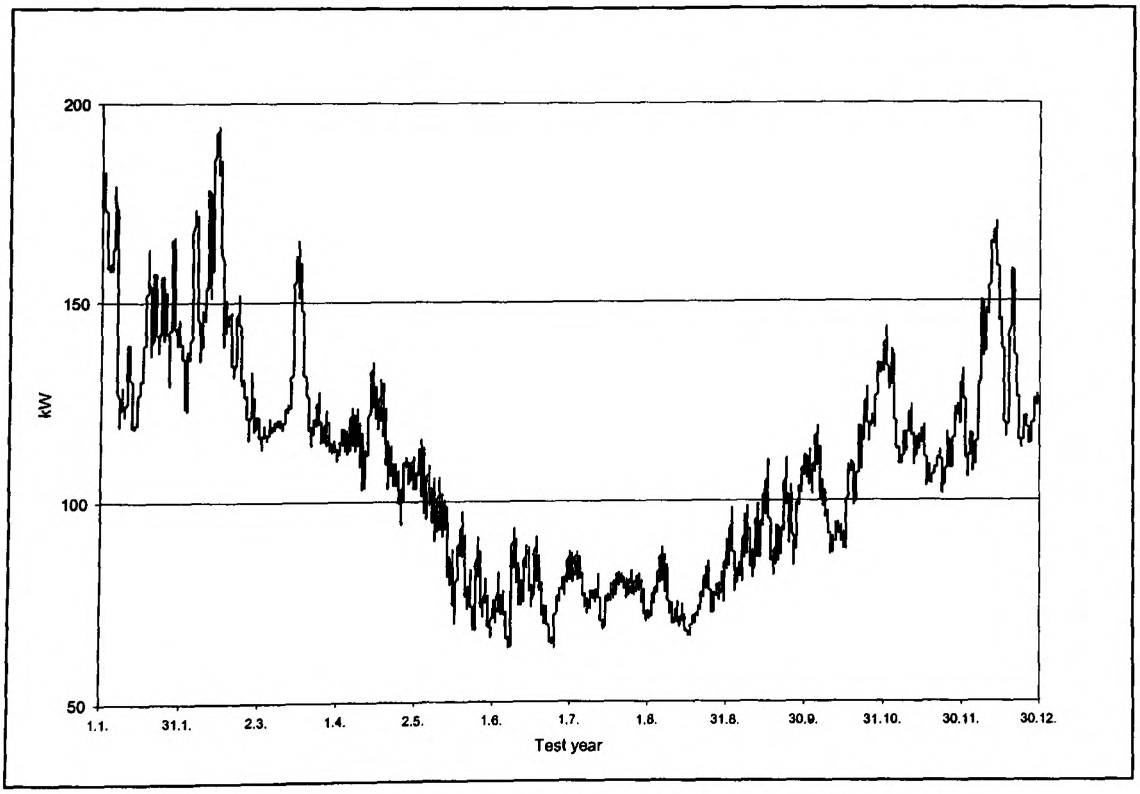

Figure 5.23. Heat loss from the DH network through the year.

The maximum output of the selected wood chip boiler was 1200 kW and the minimum sustainable output 240 kW according to the steady state survey. Below are presented the monthly outputs of the boiler plant. Not all of them are equally interesting, but as either the maximum or minimum limit of the boiler is reached in most of them, each are presented.

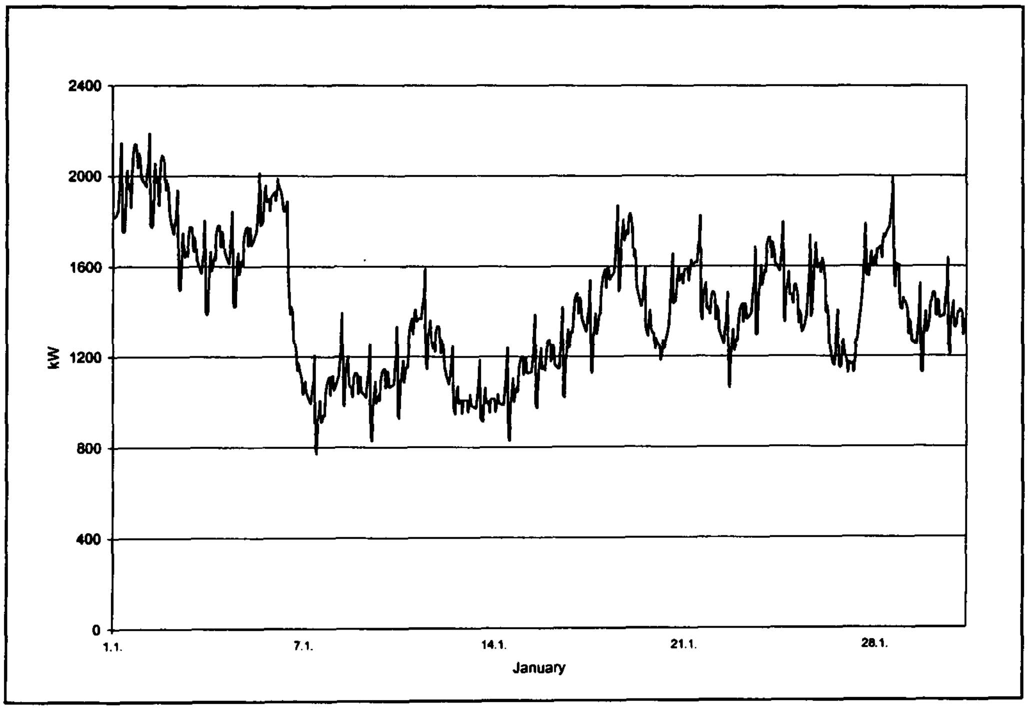

Figure 5.24. Heat output in January

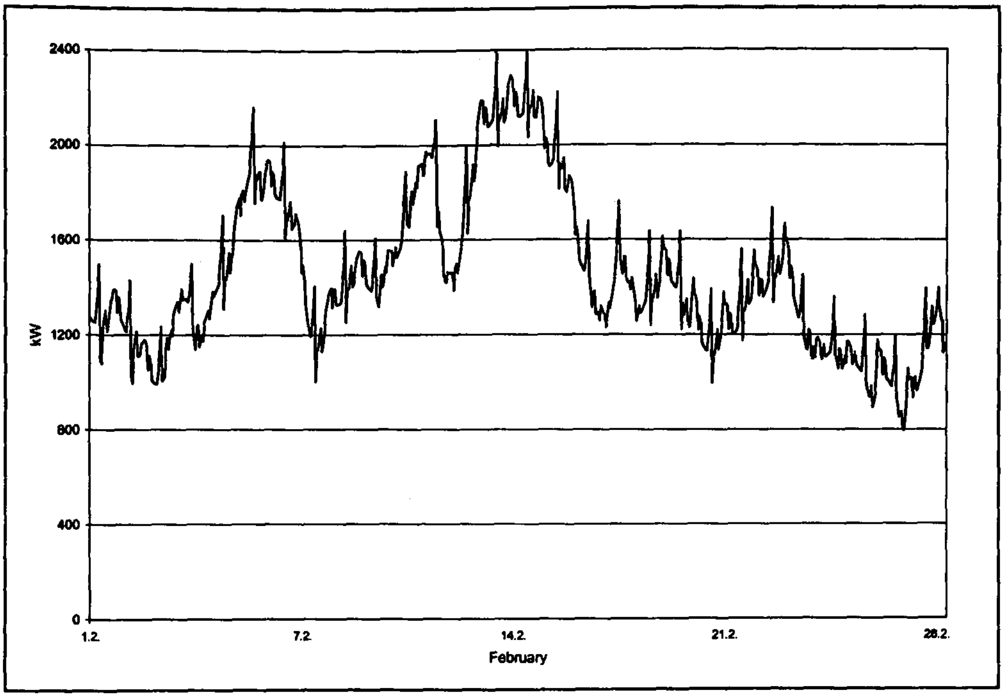

Figure 5.25. Heat output in February

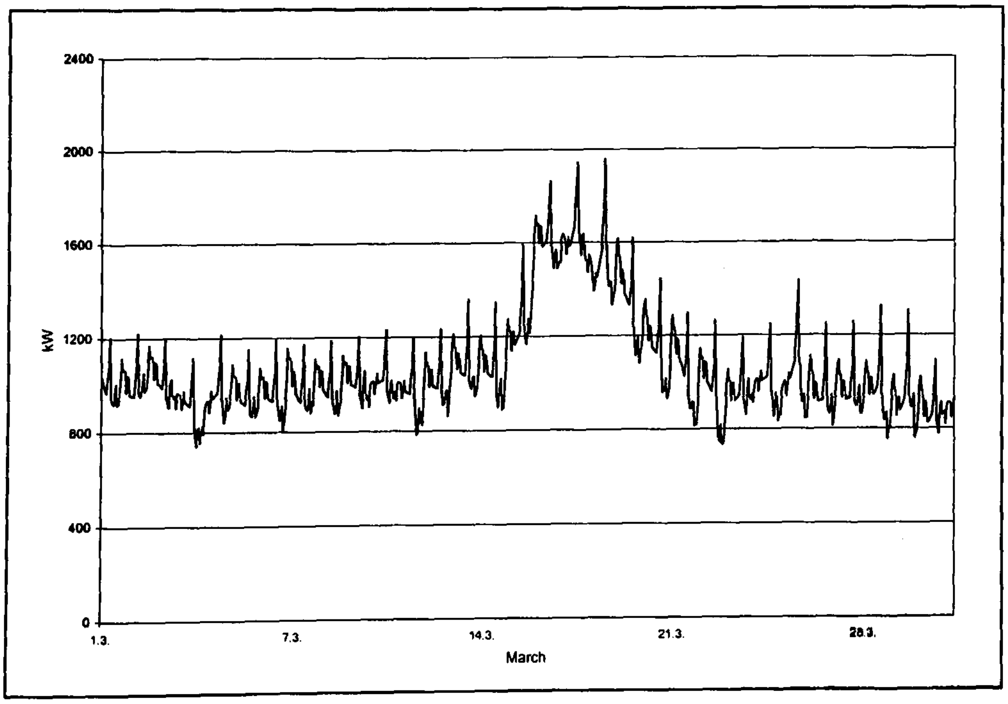

Figure 5.26. Heat output in March.

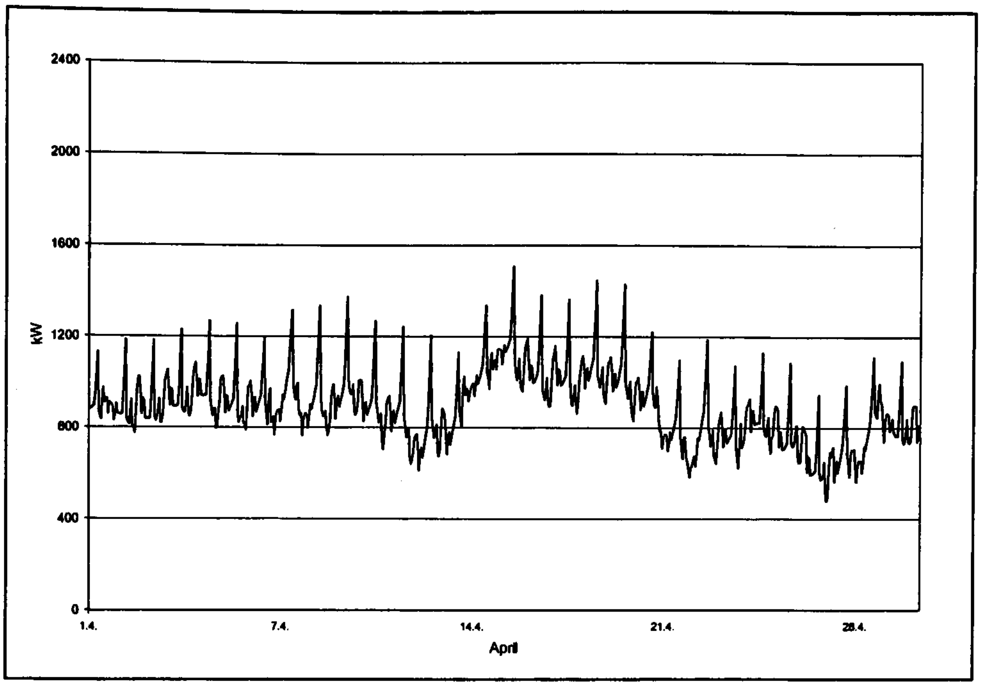

Figure 5.27. Heat output in April.

As the lower limit becomes more interesting, the scale is changed.

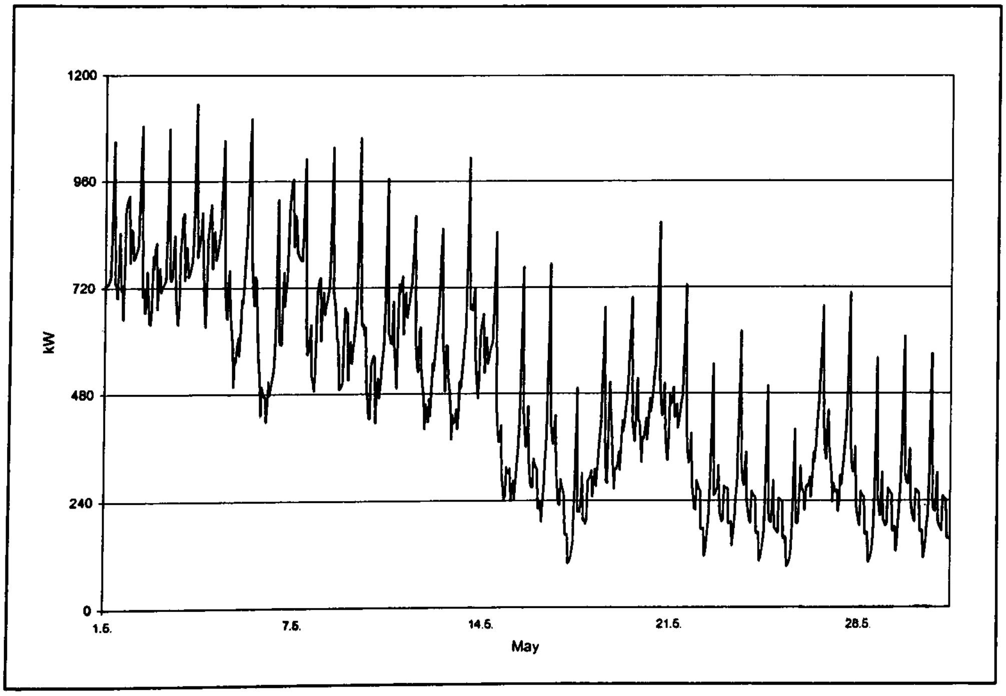

Figure 5.28. Heat output in May.

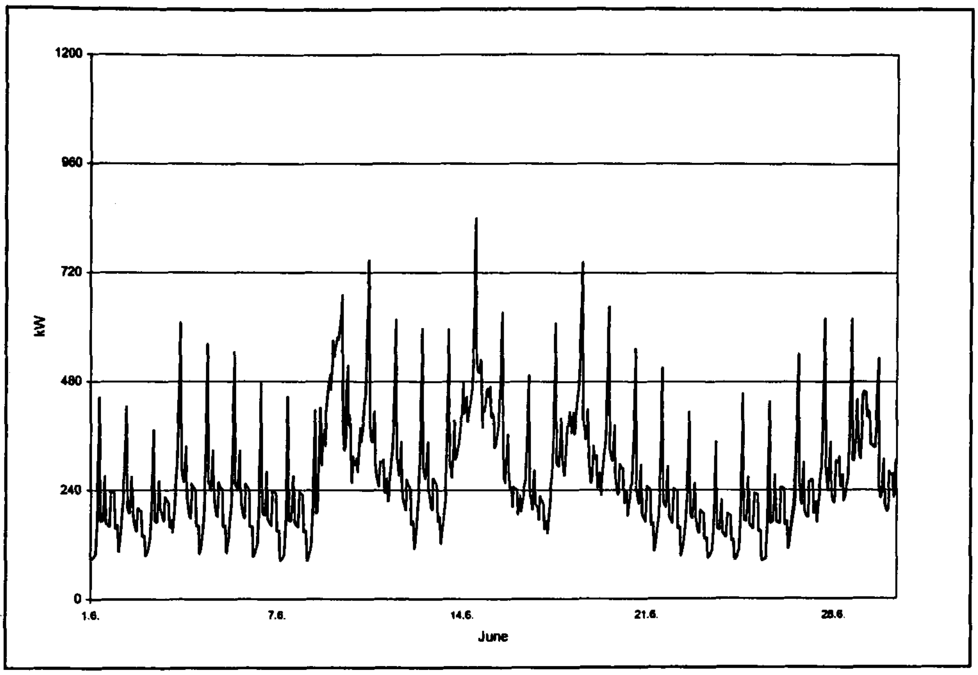

Figure 5.29. Heat output in June.

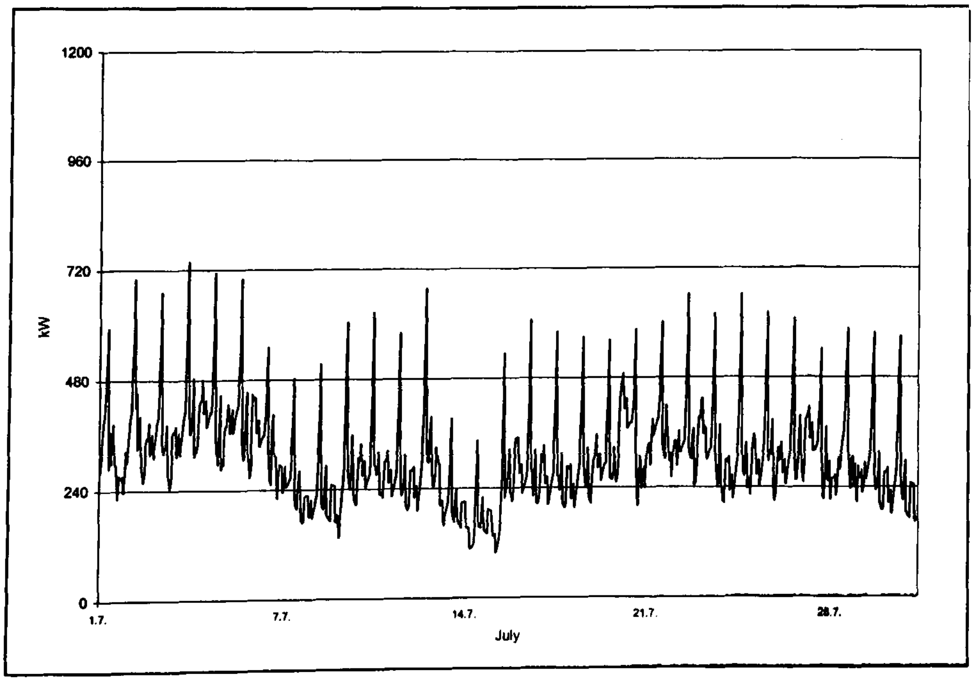

Figure 5.30. Heat output in July.

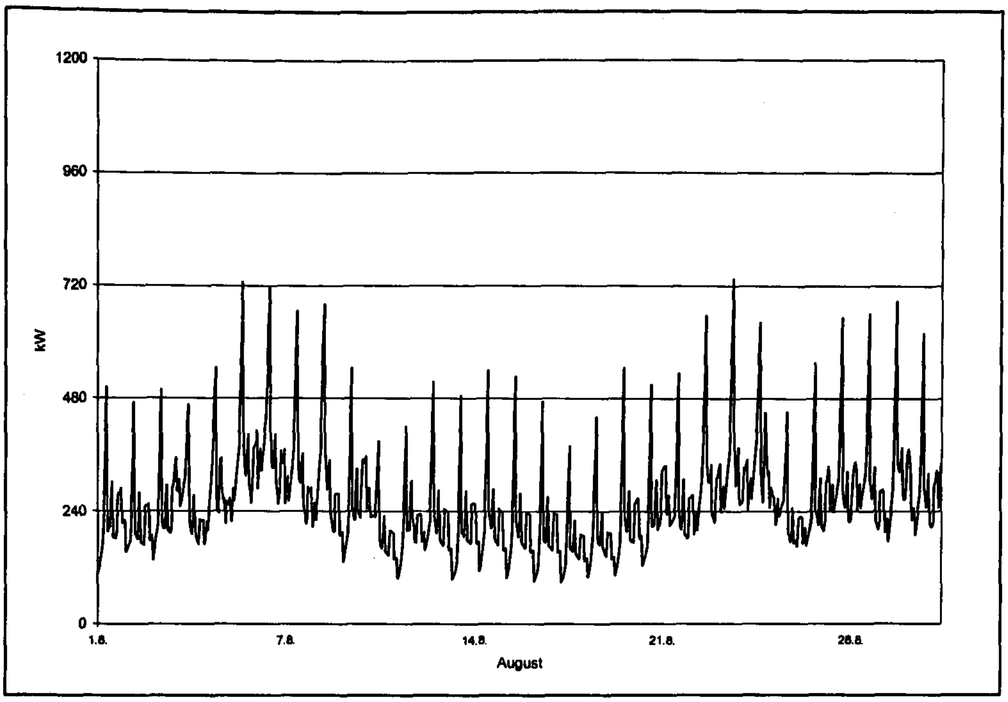

Figure 5.31. Heat output in August.

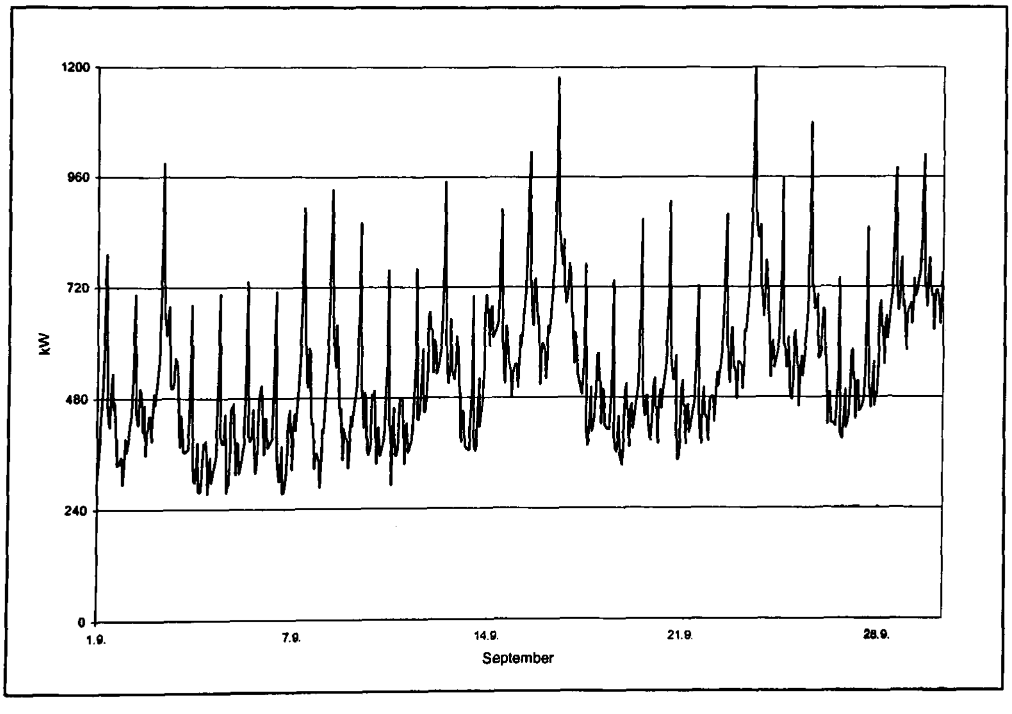

Figure 5.32. Heat output in September.

Time to change the scale again.

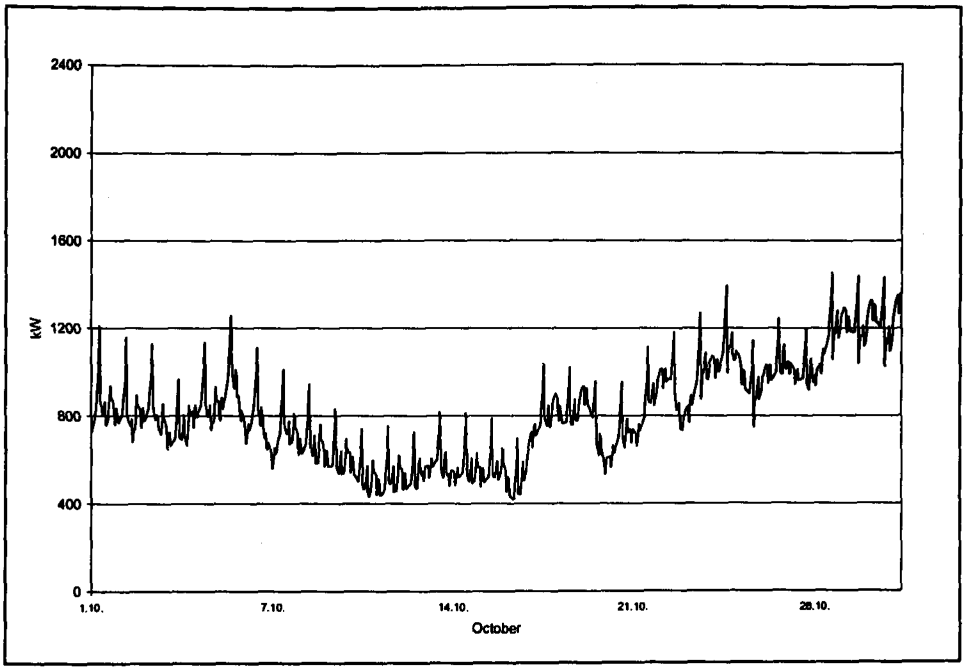

Figure 5.33. Heat output in October.

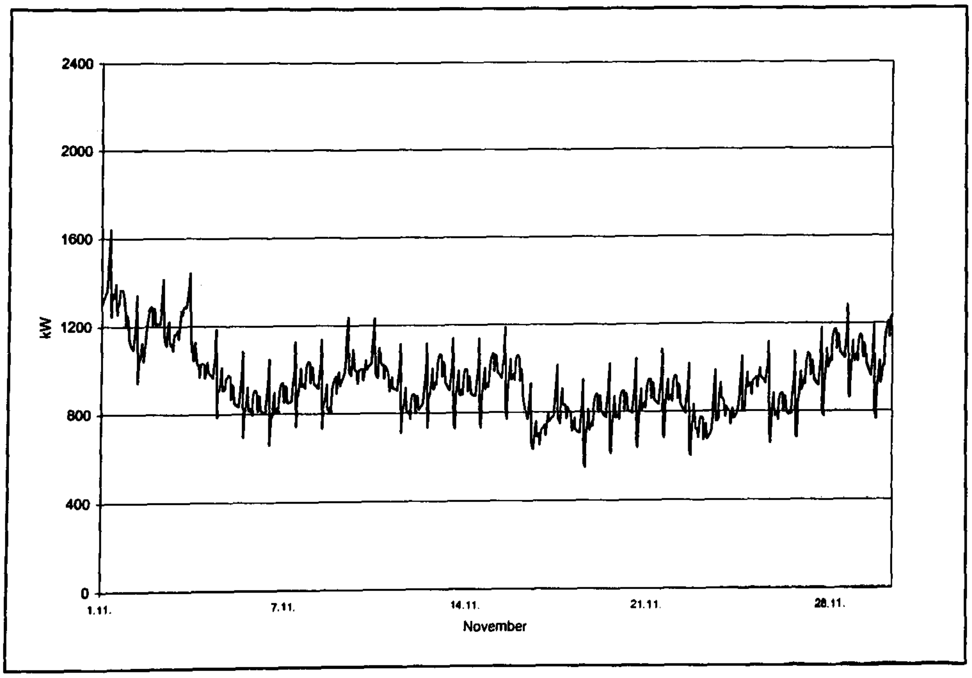

Figure 5.34. Heat output in November.

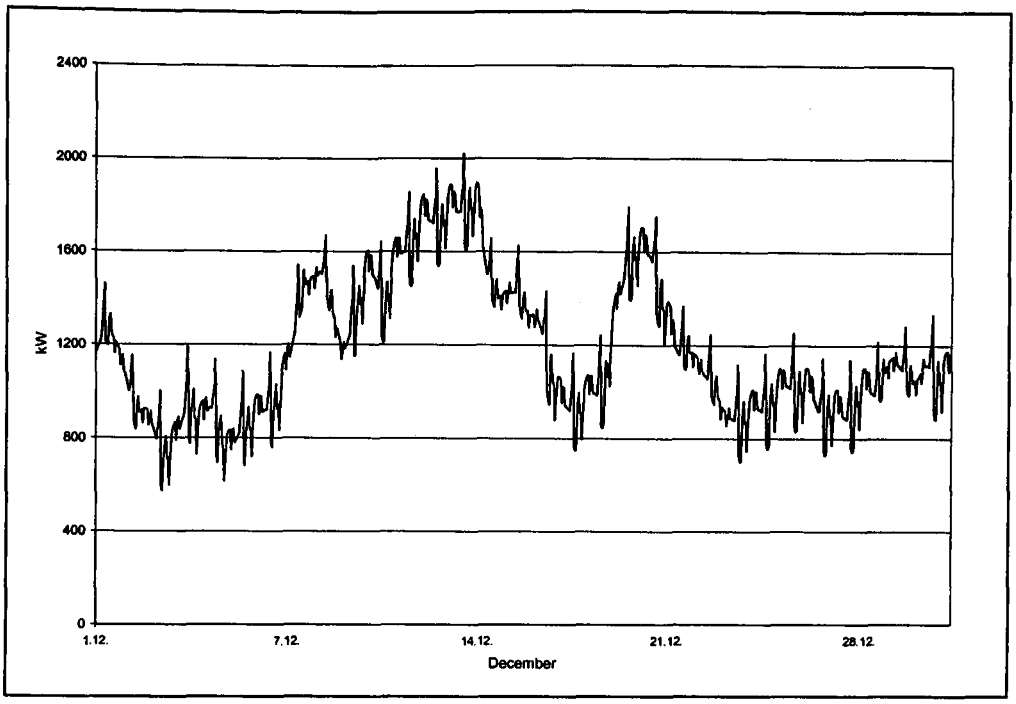

Figure 5.35. Heat output in December.

There is a general character related to short term fluctuation: During the summer relative variations in the need for heat are much bigger than in the cold period. That is easy to explain. In the summer, the base load is pretty low and a momentary domestic hot water consumption peak causes a huge increase in the need for heat, whereas in the winter the same peak does not have such an effect as the base load is higher.

Even a quick look at figures 5.24 – 5.35 shows that in January and February the back-up boiler is needed for most of the time. In March and December the usage of oil would be more moderate. In the summer time, it would seem that from the middle of May till the end of August it would be difficult to maintain the wood chip boiler in operation, even though in the latter part of July the consumption would seem to be a bit higher.

The crucial question when estimating the length of the pause in wood chip boiler's operation is how exact would the lowest sustainable output be. It can be seen that the required input goes below the lower limit (240 kW) frequently in the summer period, still it will not stay there for a long time until the need for heat increases again, mainly owing to DHW consumption peaks. If it is considered that the limit is exact and strict, this would mean that as the input goes below the limit, the boiler is switched off. As the ignition does not take place automatically, it would require the operator to do it manually. Obviously, the operator would become tired pretty soon if he tried to bring the boiler back into operation each time the input had gone below the limit, causing the boiler to have been switched off. Furthermore, figures 5.24 – 5.35 would not be available for the operator, so he would have to predict how the need for heat changes and what would be the reasonable point to switch the boiler on again. In practice, this is something the operator learns during some of the first summer periods. In this calculation, it is convenient to consider a situation where the operator has already learned, from experience, what is the right moment to switch the boiler off and when should it be taken into operation again. Prevailing temperatures vary from year to year, but as we have the data on the test year, it can be considered as a typical one.

The utilisation degree and the amount of heat generated with the wood chip boiler are calculated firstly so that as the heat input declines rather permanently below the lower limit around May 21st, it is taken that the wood chip boiler would be switched off then and the pause would continue till August 27th. The monthly division of heat generation between the wood chip boiler and the oil-fired back-up boiler can be seen in figure 5.36. According to it, only in April would it be possible to produce all the heat with the wood chip boiler. However, short peaks exceeding the capacity of the wood chip boiler would most probably be covered by the wood chip boiler alone; the supply water temperature would simply fall below its set value for a while.

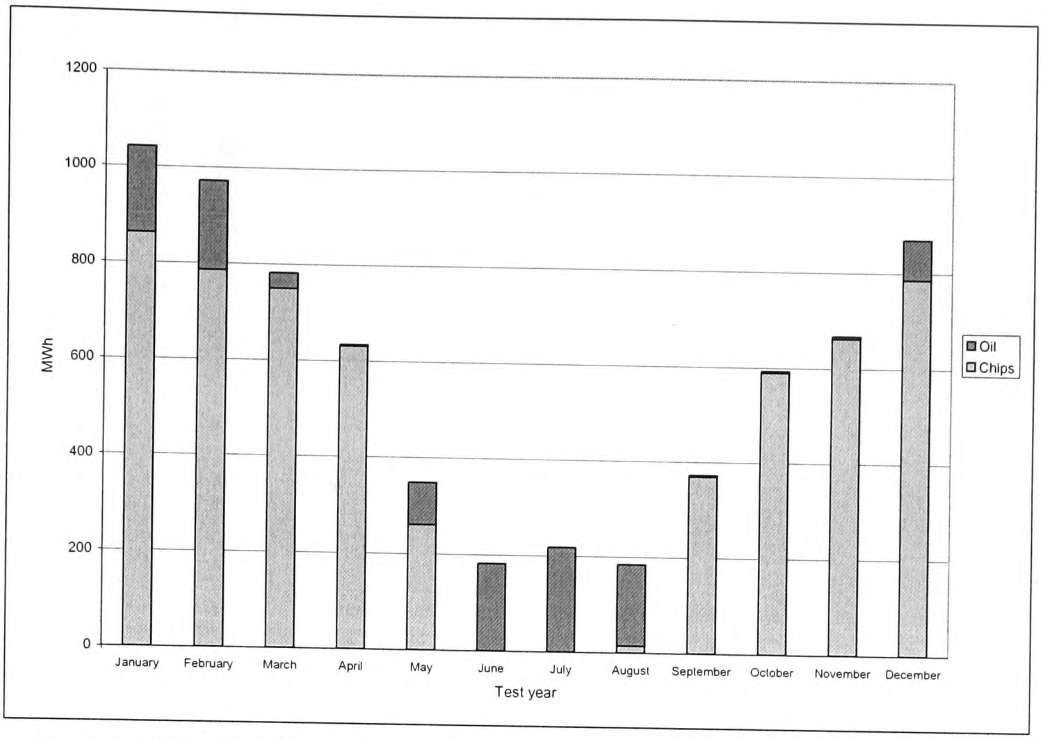

Figure 5.36. Division of heat generation between the wood chip boiler and the back-up boiler.

Figure 5.37 compares the total heat production on monthly basis with the results from steady state model calculation. DM stands for dynamic model and SSM for steady state model. The figure brings out that the steady state model gives a somewhat bigger variation in heat consumption between winter and summer.

Table 5.2 tells the division of heat production and heat consumption on annual basis. As for the share of DHW, the value in table 5.2 is a percentage of total heat consumption, including heat loss. The division of heat consumption in all the buildings together is that 87.7 % is used for heating and ventilation and 12.3 % is needed for domestic hot water consumption. These values can be compared with the estimation that was used in the steady state model calculation. It was then supposed that 20 % of all the heat buildings draw from the DH network is used for domestic hot water preparation.

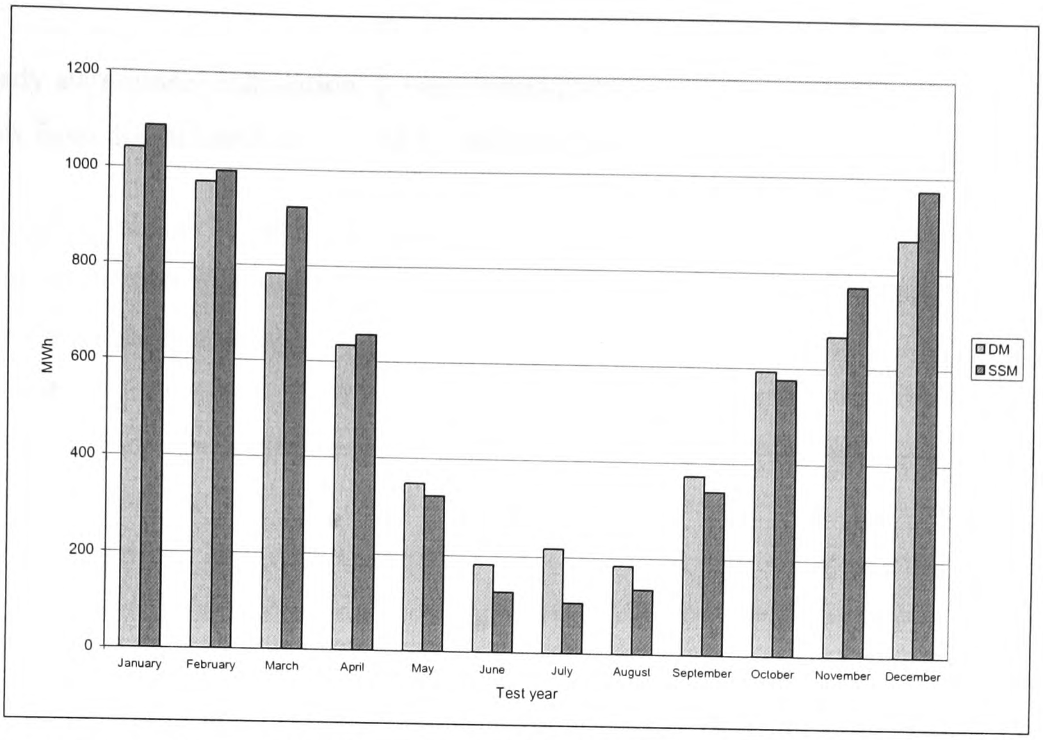

Figure 5.37. Comparison of heat production calculations with different approaches. DM stands for dynamic model and SSM for steady state model.

Table 5.2. Annual division of heat production and consumption.

	MWh	%
Wood Chip Boiler	5709.6	83.2 %
Oil fired Boiler	1151.8	16.8 %
Total	6861.4	
Heating and ventilation	5193.5	75.7 %
Domestic Hot Water	725.3	10.6 %
Loss	942.6	13.7 %

Table 5.2 tells the division of heat production and heat consumption on annual basis. As for the share of DHW, the value in table 5.2 is a percentage of total heat consumption, including heat loss. The division of heat consumption in all the buildings together is that 87.7 % is used for heating and ventilation and 12.3 % is needed for domestic hot water consumption. These values can be compared with the estimation that was used in the

steady state model calculation. It was then supposed that 20 % of all the heat buildings draw from the DH network is used for domestic hot water preparation.

Comparing results in table 5.2 with the results from the steady state model calculation would show that they are not far from one another. The previous calculation gave the wood chip boiler a share of 86 % (6028 MWh) of all the heat production (7006 MWh). The difference between the total productions stems from slightly different heat losses. The peak load would take place in February 15th between 7 and 8 in the morning, as the output required for DHW is 340 kW and for heat losses 194 kW. Total output at that moment would be 2407 kW. Comparing it with the peak load resulting from steady state model calculation would not bring out any major difference; with the steady state model, the peak load was 2406 + 135 = 2541 kW.

5.7.2. Heat production without a pause in the summer

The following calculation has been carried out so that there is no strict period when the wood chip boiler would be out of operation. Instead, there are some conditions that need to be fulfilled in order to keep the wood chip boiler in operation. If the heat demand remains for 4 hours below the lowest sustainable output level (240 kW) or the average output during above 4 hours is not more than 75 % of the said level (180 kW), the heat production of the wood chip boiler ends. There will have to be a period of 24 hours during which the average output is not less than 240 kW + 25 % = 300 kW and the lowest momentary output during the same period is not less than 240 kW – 25 % = 180 kW. What is more, this period of 24 hours begins in the morning at 7, 8 or 9 o'clock. The explanation for using so many conditions is that the operator would obviously be capable of finding out what the weather conditions during the following 24 hours would be. He would also be able to predict when the DHW peaks take place. With this information, he would make the decision whether or not to put the boiler back into operation in the morning, if it were not already. If it seemed out that either the average output of following 24 hours would be close to the lower limit or there would be a period (for one hour or longer) when the output would be clearly below the lower limit, the operator would probably not light up the chips, because the flames would soon die, anyway.

This type of calculation would describe the operation of the boilers if the operator were rather hardworking. The results can be seen in figure 5.38 and table 5.3.

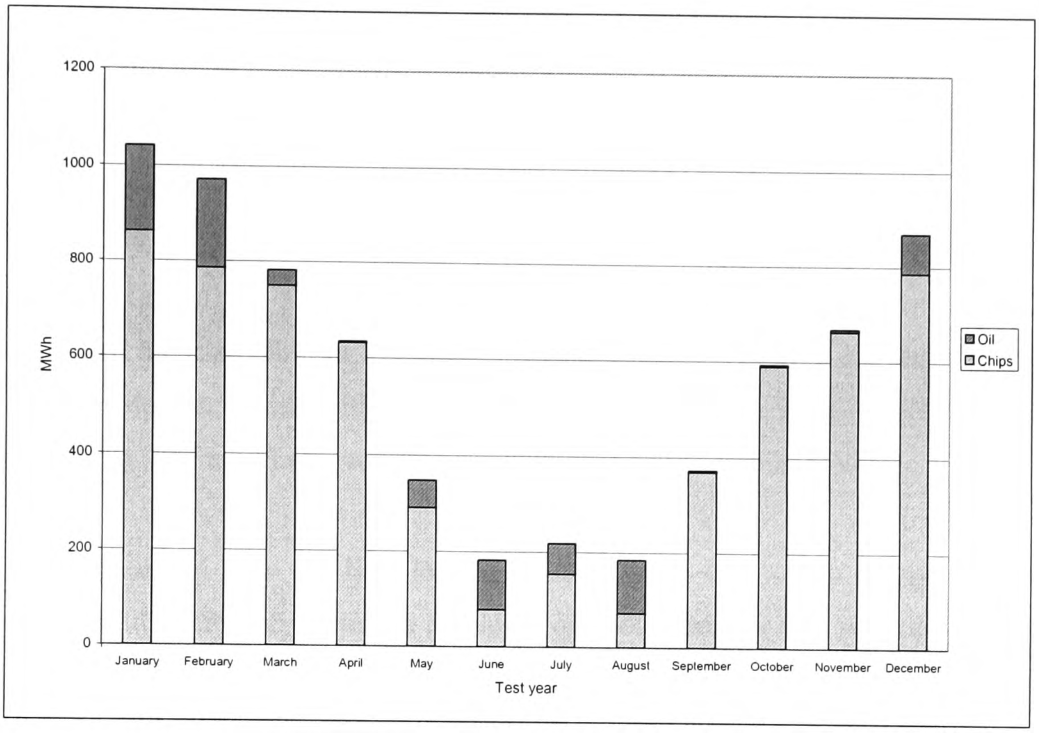

Figure 5.38. Division of heat generation between the wood chip boiler and the back-up boiler; without a summer pause in the use of the wood chip boiler.

Table 5.3. Annual division of heat production; without a summer pause in the use of the wood chip boiler.

	MWh	%
Wood Chip Boiler	6028.4	87.9 %
Oil fired Boiler	833.1	12.1 %
Total	6861.4	

What figure 5.38 and table 5.3 bring out is probably the best that could be achieved with the wood chip boiler if the operator were eagerly searching for a high degree of utilisation and the lower limit of the output of the boiler were estimated the right way. Figure 5.36 and table 5.2 tell what might be realistic to expect.

Obviously, there are two things that make comparing the results with these two models difficult, at least to a certain extent. The first thing is that the heat loss is slightly different: There is a difference of about 15 %, the significance of which is difficult to say. The other thing is that in the steady state model calculation, it was supposed that 20 % of the heat buildings need is used for domestic hot water preparation, whereas the corresponding figure with the dynamic model was approximately 12 per cent. To find out, how these items affect the final results, the average return water temperature is elevated to 58.2 °C (from 43 °C) and the average temperature of the supply water is now only 2.5 % (initially 5 %) lower than its initial temperature at the boiler plant. These changes will increase the heat loss so that it is annually 1087 MWh (initially 943 MWh) which corresponds well with the figure used in steady state model calculation (1086 MWh). The total heat production is with both models 7006 MWh.

Figure 5.39 shows how the heat loss division changes due to the change. The lower graph shows the initial division and the upper one describes the new situation.

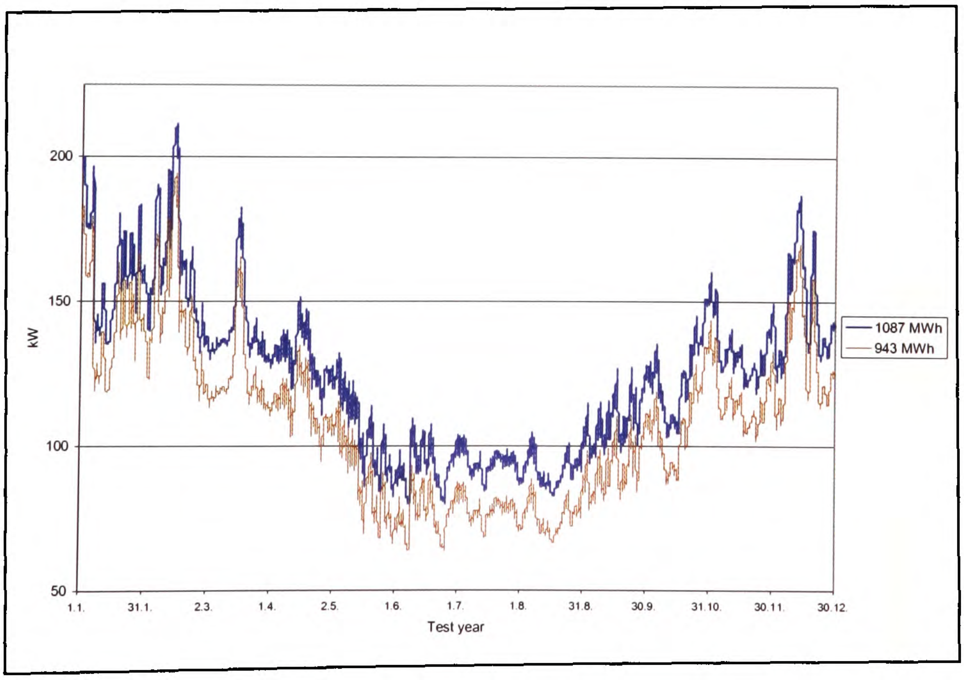

Figure 5.39. Division of heat loss with two different total values.

Figures 5.40 to 5.43 show how the monthly output changes from May to August. The upper graph illustrates the new output and the lower one shows the difference between the new output and the previous one.

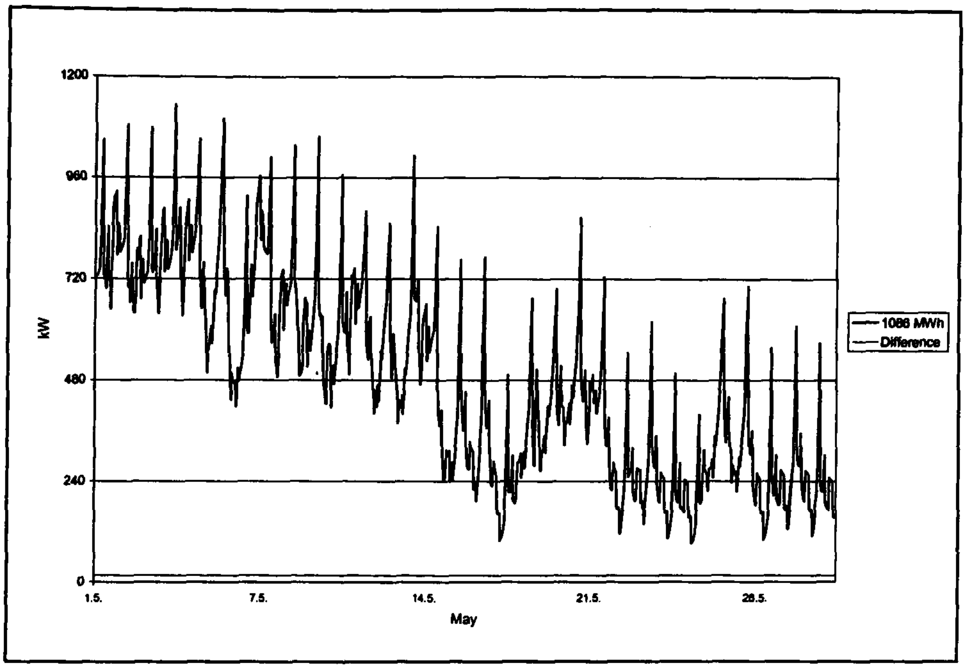

Figure 5.40. Change in the output in May.

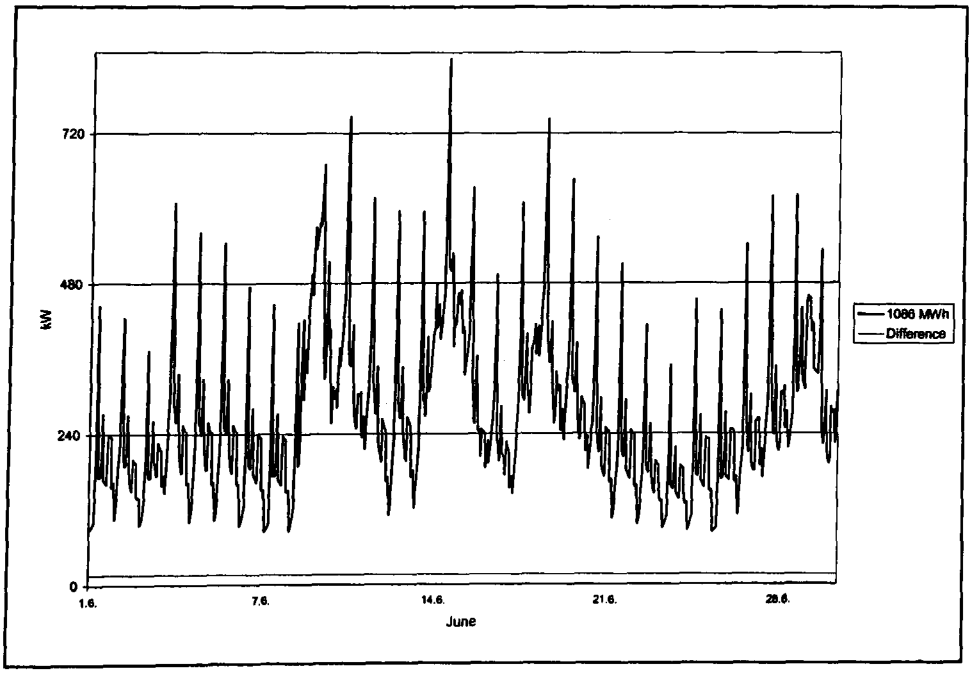

Figure 5.41. Change in the output in June.

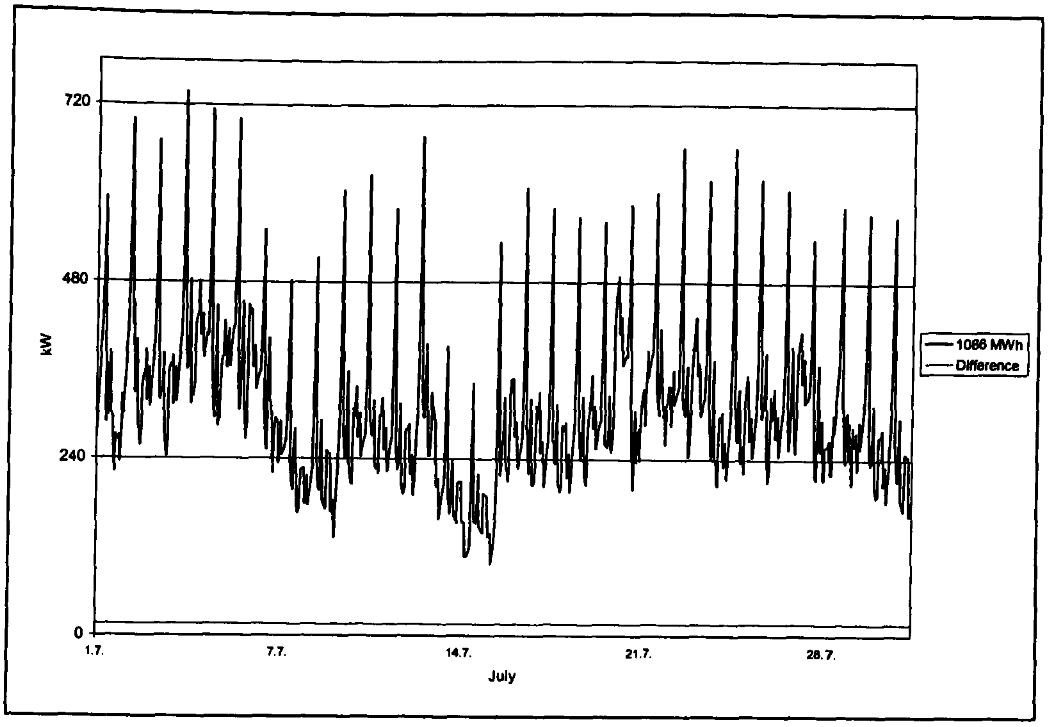

Figure 5.42. Change in the output in July.

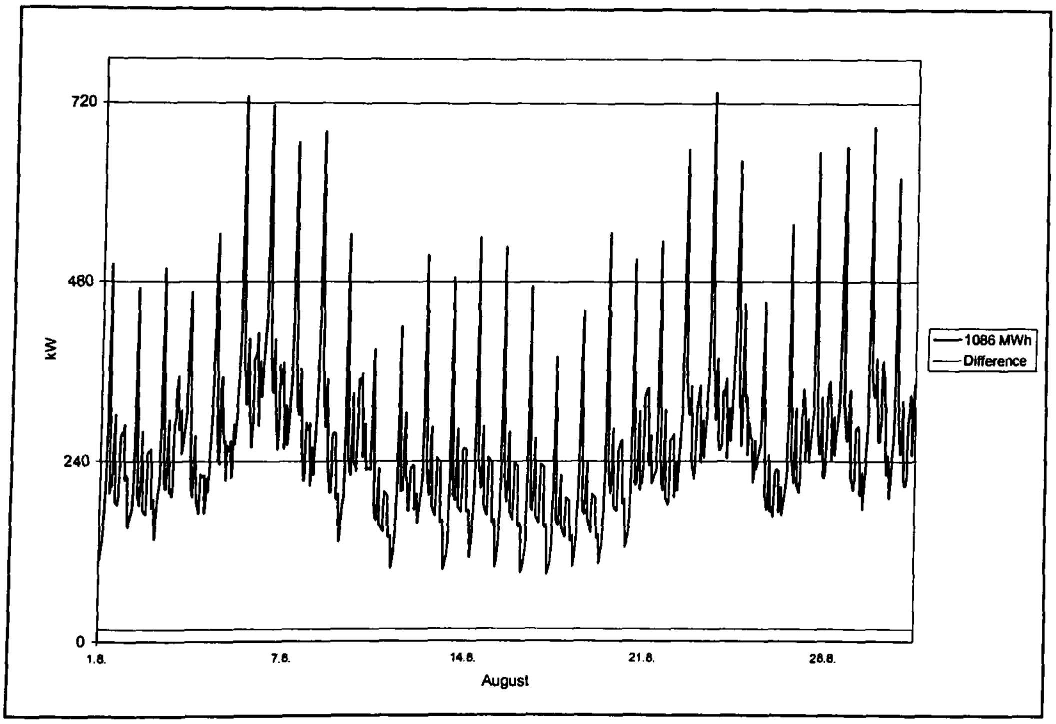

Figure 5.43. Change in the output in August.

It can be seen that the difference in the output is almost constant. It varies between 16.2 and 16.6 kilowatts during the summer period. The peak output, on February 15th, would be 2425 kW of which 211 kW would be lost with heat losses. The corresponding figures with the previous calculation were 2407 kW and 194 kW.

In conclusion, it can be seen that increasing the heat loss from 943 kW to 1087 kW would not change the result significantly. The output declines frequently below the lower limit during the probable pause from May 21st to August 27th, although in July there are several days when the boiler could be in operation.

If the new situation is calculated without a summer pause, the result is an estimation of what could be achieved. Again, if the heat demand remains for 4 hours below 240 kW or the average output during above 4 hours is not more than 180 kW, the heat production of the wood chip boiler ends, and there will have to be a period of 24 hours during which the average output is not less than 300 kW and the lowest momentary output during the same period is not less than 180 kW before the wood chip boiler starts again. Figure 5.44 illustrates the division of heat generation on monthly basis.

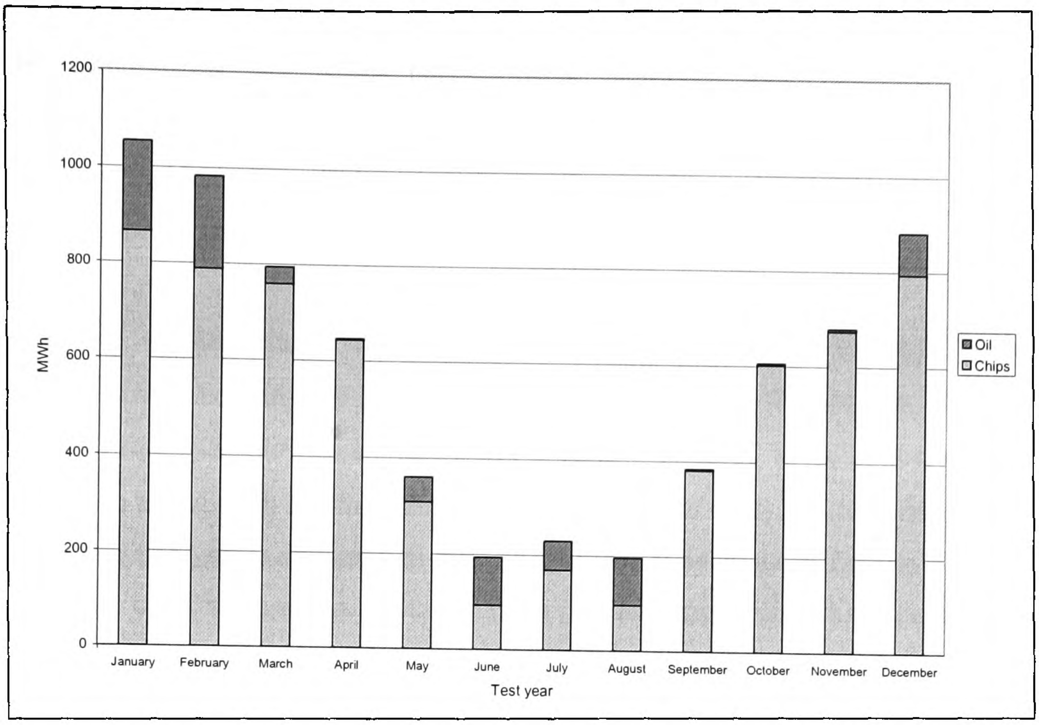

Figure 5.44. Division of heat generation between the wood chip boiler and the back-up boiler; without a summer pause in the use of the wood chip boiler. The total annual heat loss 1087 MWh.

Table 5.4 gives the figures.

Table 5.4. Annual division of heat production; without a summer pause in the use of the wood chip boiler. The total annual heat loss 1087 MWh.

	MWh	%
Wood Chip Boiler	6171.8	88.1 %
Oil fired Boiler	834.0	11.9 %
Total	7005.8	

It can be seen that the biggest part of oil is consumed during the winter and even though the wood chip boiler could produce a bit more heat in the summer if the heat losses were higher, this would be compensated by increased consumption of oil during the winter.

5.7.3 Re-evaluation of the boiler size

The size of the wood chip boiler has been, so far, the same as that used in steady state model calculations (1.2 MW). There were, however, other capacities that were considered, namely 0.7 MW, 0.9 MW and 1.5 MW. With all of them, it was thought that the minimum sustainable output is 20 % of the nominal. Let us start with the 0.7 MW wood chip boiler. Its lower limit would thus be 140 kW.

Figures 5.45 – 5.48 indicate that the boiler could be in operation through the summer. Most of the time the output is well above the lower limit and the periods it is not do not last long. These periods occur sometimes around midnight, when domestic hot water consumption has ceased, but the temperature is still rather high. Sometimes the minimum is reached in the afternoon between the DHW peaks. The scale in figures 5.45 – 5.48 is from zero to 500 kW, because the lower limit is interesting and it can be observed better this way. The same figures can be used with all the boiler capacities under survey.

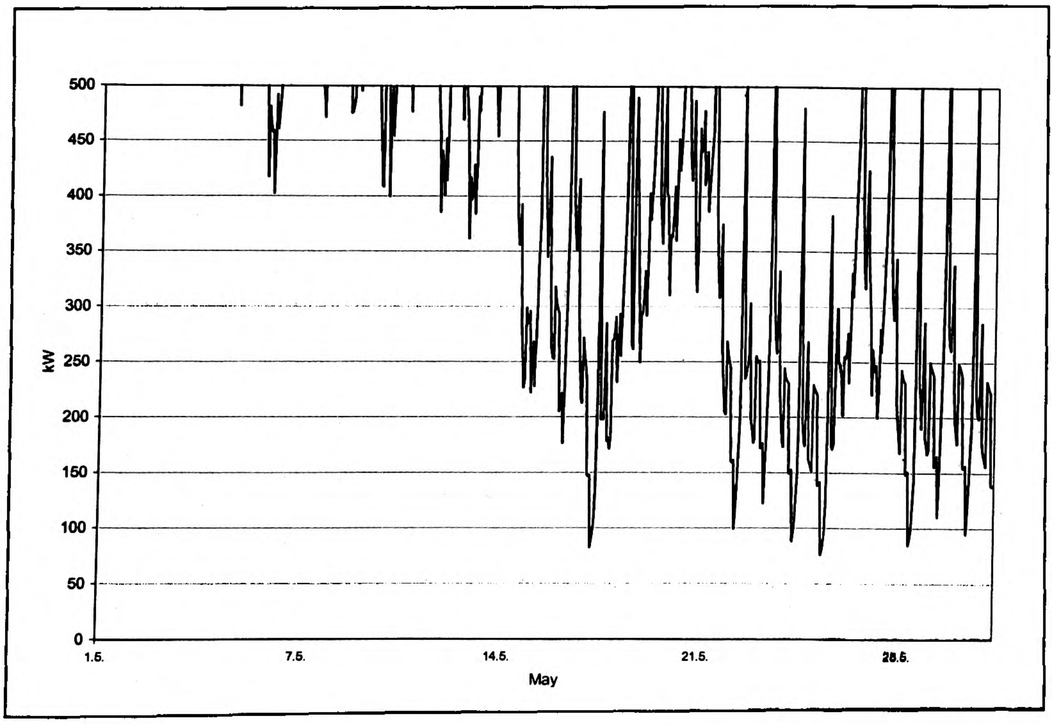

Figure. 5.45. Heat output in May.

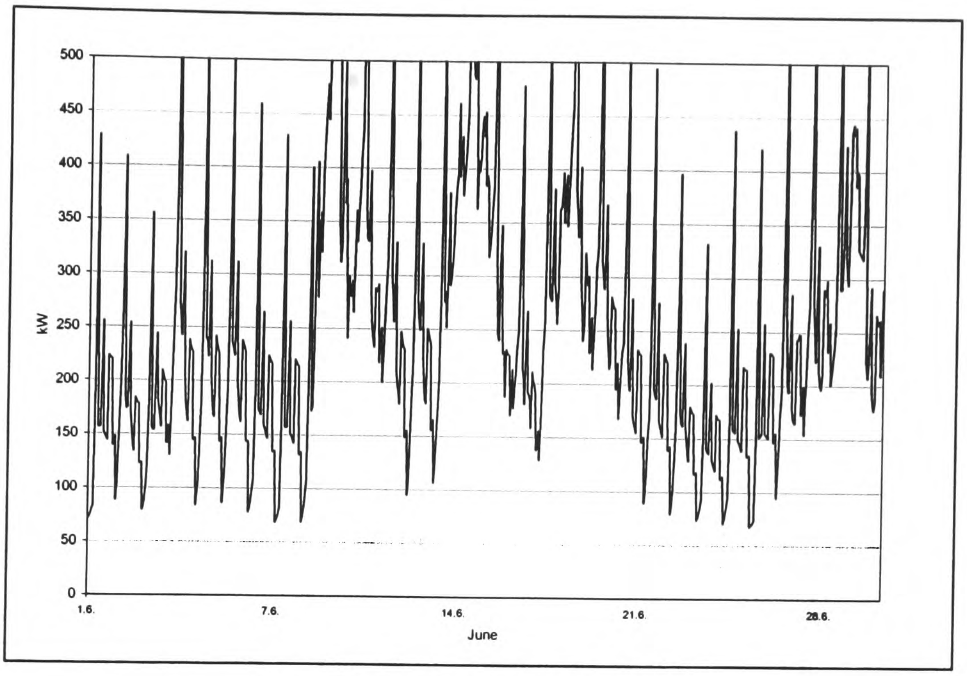

Figure. 5.46. Heat output in June.

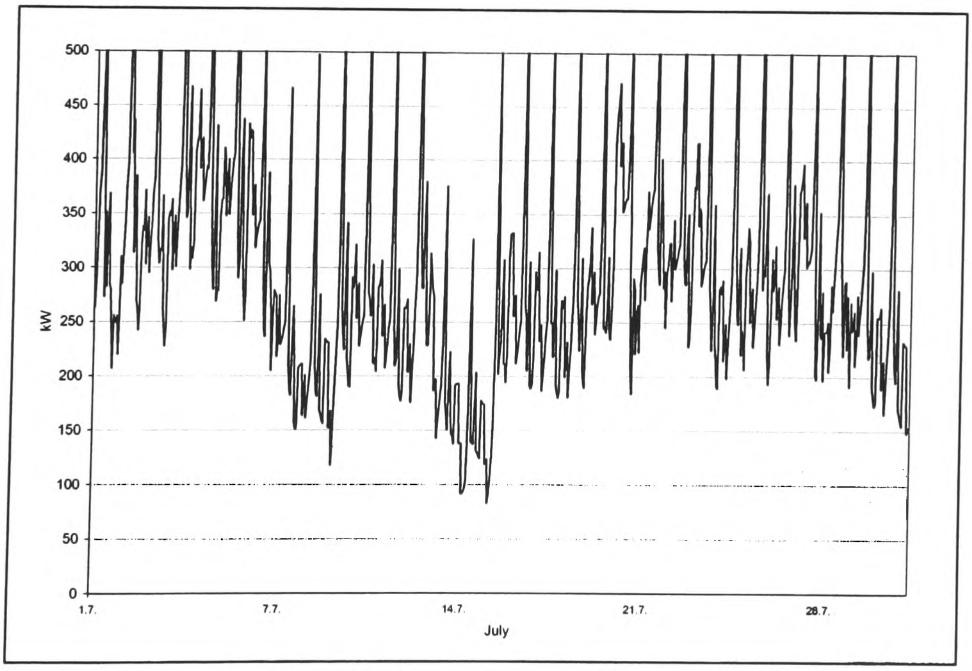

Figure. 5.47. Heat output in July.

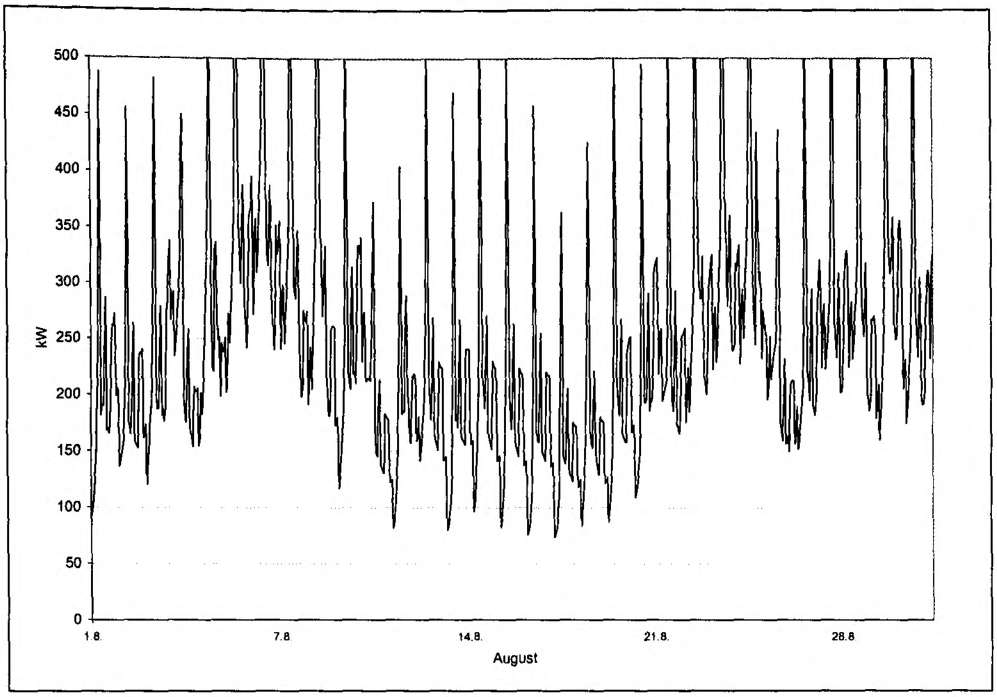

Figure. 5.48. Heat output in August.

The monthly division of heat generation is shown in figure 5.49.

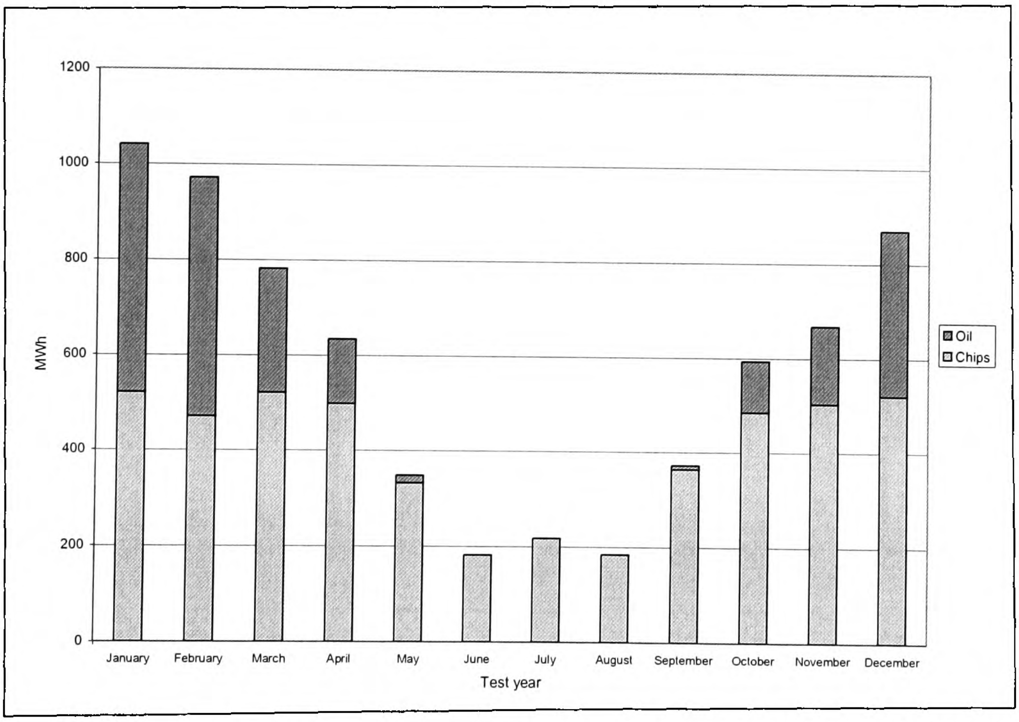

Figure 5.49. Monthly division of heat production with a 700 kW wood chip boiler.

The annual division is 69.9 % with chips and 30.1 % with oil. By using the 4 hours and 24 hours limits for the operation, the division would be 68.6 % versus 31.4 %.

The next boiler capacity for calculation is 0.9 MW with a lower limit of 180 kW. By taking a look at figures 5.45 – 5.48, one can see that heat consumption in May would probably be taken care by the wood chip boiler, although at the end of the month the input goes frequently below the 180 kW limit. In June it would be difficult to keep the wood chip boiler in operation, whereas in July it would seem to be possible. It could be possible in August, too although in the mid-August there is a period when the input is about half of the time below 180 kW. If the break of five weeks is considered to start at May 28th and continue till July 1st, the monthly division would be as follows:

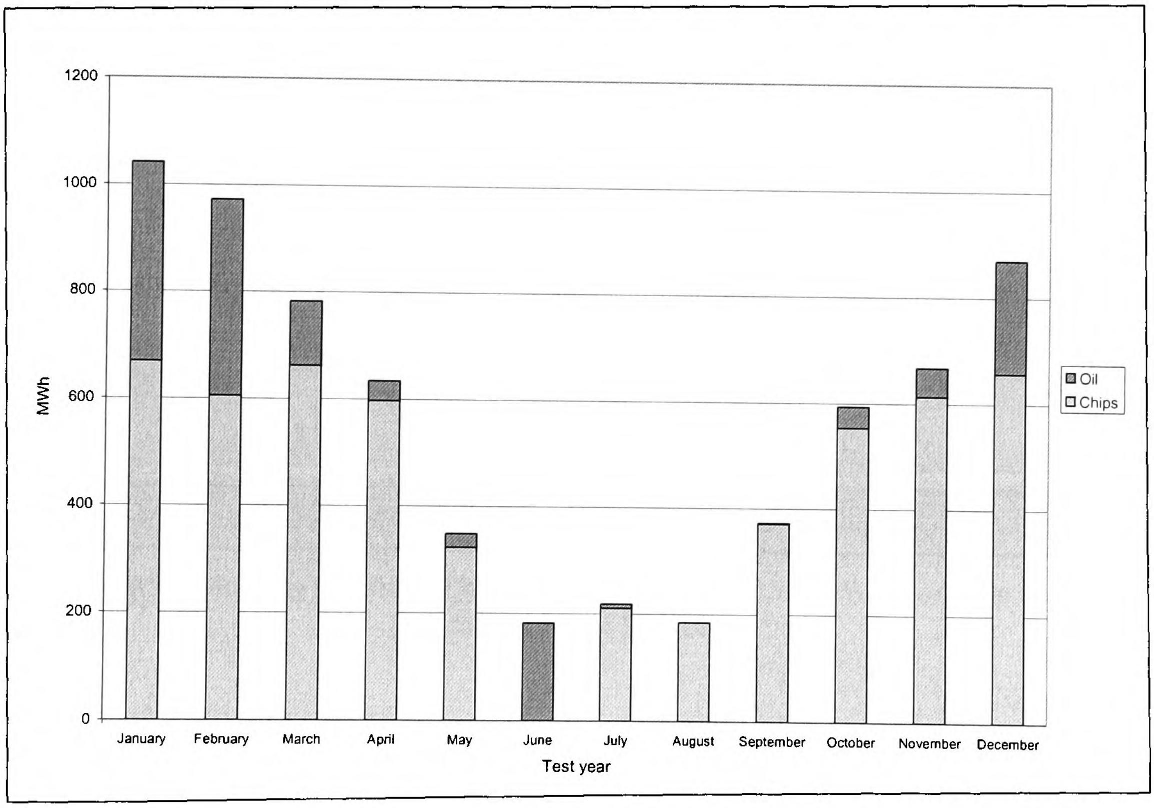

Figure 5.50. Monthly division of heat production with a 900 kW wood chip boiler. Summer pause of 5 weeks.

The annual division is 79.3 % with chips and 20.7 % with oil. By using the 4 hours and 24 hours limits for the operation, the annual division would be 79.9 % versus 20.1 %. The next boiler capacity for calculation is 1.5 MW with a lower limit of 300 kW. By taking a look at figures 5.45 – 5.48, one can see that the pause in heat production from wood chips would start in mid-May and continue till the end of August. In September the heat consumption is elevated rapidly above the 300 kW limit. The following monthly division is based on a summer pause between May 14th and September 3rd.

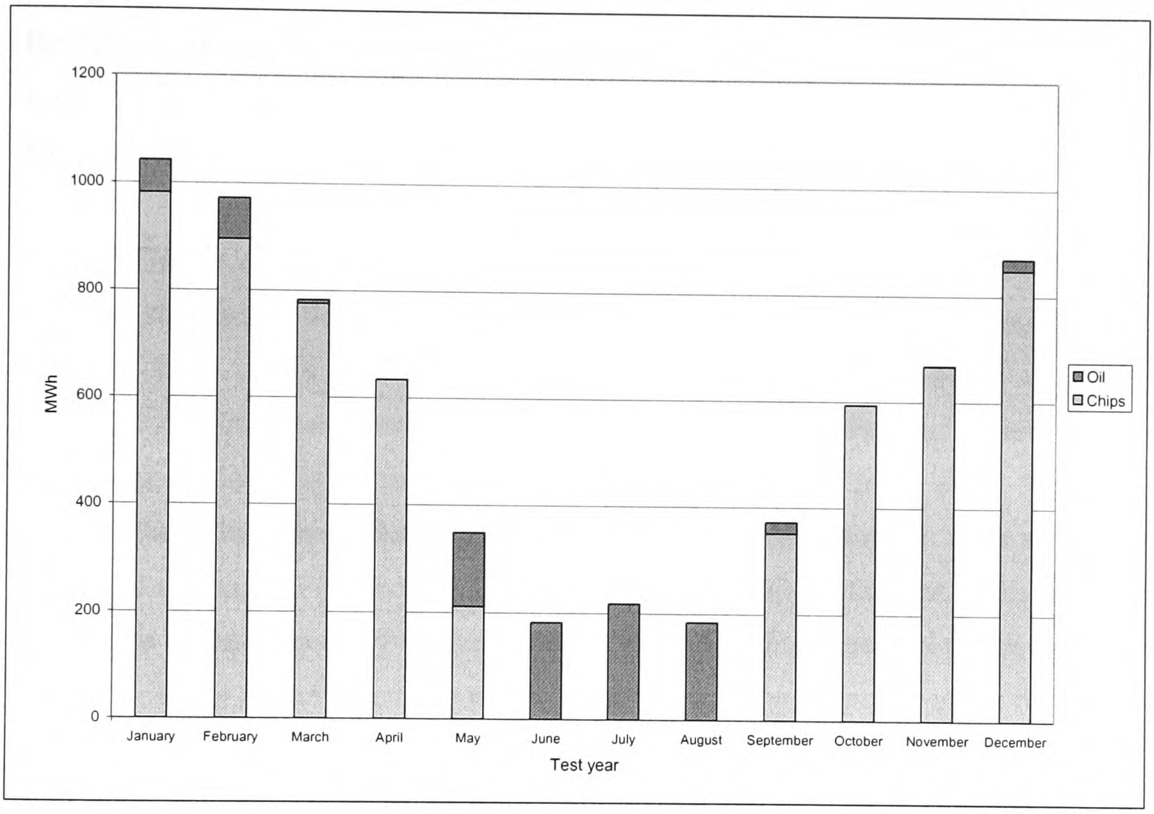

Figure 5.51. Monthly division of heat production with a 1500 kW wood chip boiler. Summer pause of 16 weeks.

The annual division is 86.8 % with chips and 13.2 % with oil. By using the 4 hours and 24 hours limits for the operation, the annual division would be 89.3 % versus 10.7 %. The results of above calculations are discussed in Chapter 7.

6. Short term calculations

6.1 Introduction

The previous dynamic model calculations have been carried out on annual basis. There are, however, many situations that should be studied more in detail and in shorter periods. Water temperatures in the network, the boiler's capability to handle rapid changes in the heat consumption and the co-operation between the wood chip boiler and the back-up boiler are considered to be the most significant items which, thus, deserve some further study. This is done with the model of the operation of the boiler plant and the district heating network.

Figure II in the Appendix shows the shape of the initial district heating network. Table IX in the Appendix tells details of the pipe dimensions and lengths between nodes.

Details of the simplified network that the application uses are presented in table 6.1. The shape of the network is the same as in figure 4.6. Node 0 is the boiler plant, then node 1 follows after which are nodes 1.1 and 2. After node 2 comes node 3. Also node 2.2 is connected to node 2. From node 3 the network continues to the farthest nodes 3.1 and 4. D_{pipe} is the outer diameter of the pipe without insulation. In general, N stands for 'node' when it does not matter whether we talk about nodes in the supply or in the return pipe. If there is a difference, N will be replaced by either 'S' (supply) or 'R' (return).

Table 6.1. The DH network.

Nodes	Distance, m	D_{pipe}, mm	Wall thickness, mm	Insulation, mm
0- 1	365	139.7	3.6	66.2
1-1.1	350	76.1	2.9	48.0
1-2	785	139.7	3.6	66.2
2-2.1	360	76.1	2.9	48.0
2-3	330	114.3	3.6	64.0
3-3.1	595	60.3	2.9	46.0
3-4	970	88.9	3.2	51.6

Table 6.2 tells to which node the buildings belong to.

Table 6.2. Connection of buildings to the nodes.

Node	Buildings
1	18 and 19
1.1	16
2	20, 33, 45, 40 and 44
2.1	1
3	2, 3, 11, 12, and 13
3.1	17 and 34
4	4, 7, 5, 6, 8, 9 and 10

6.2. Dimensioning the heat exchangers

The first thing to be found out are the design values for heat exchangers at different points in the network. The question is to what extent does the temperature of the supply water decrease during its journey from the boiler plant to a sub-station. It is evident that sub-stations located near the boiler plant are able to receive hotter supply water than their counterparts located farther away. This will be studied by setting the outside temperature to the design value (-26 °C) so that all the heating systems at different points of the network will operate at their full output. The same goes for most of the ventilation systems, too. There are, though some buildings that are equipped with a ventilation rate regulation system which switches the ventilation from full rate to the lower one for the night-time, and as this first calculation tries to simulate the situation in the night, these buildings will take less heat for ventilation than would be the case in daytime. The ground temperature equals the ambient air temperature.

In this calculation, the consumption of DHW is ignored. The idea is to simulate the night time situation, when heat is consumed solely for heating and ventilation systems. The time step is 1.5 minutes, which leads to a simulation period of 6 hours. Supply water temperatures can be seen in figure 6.1.

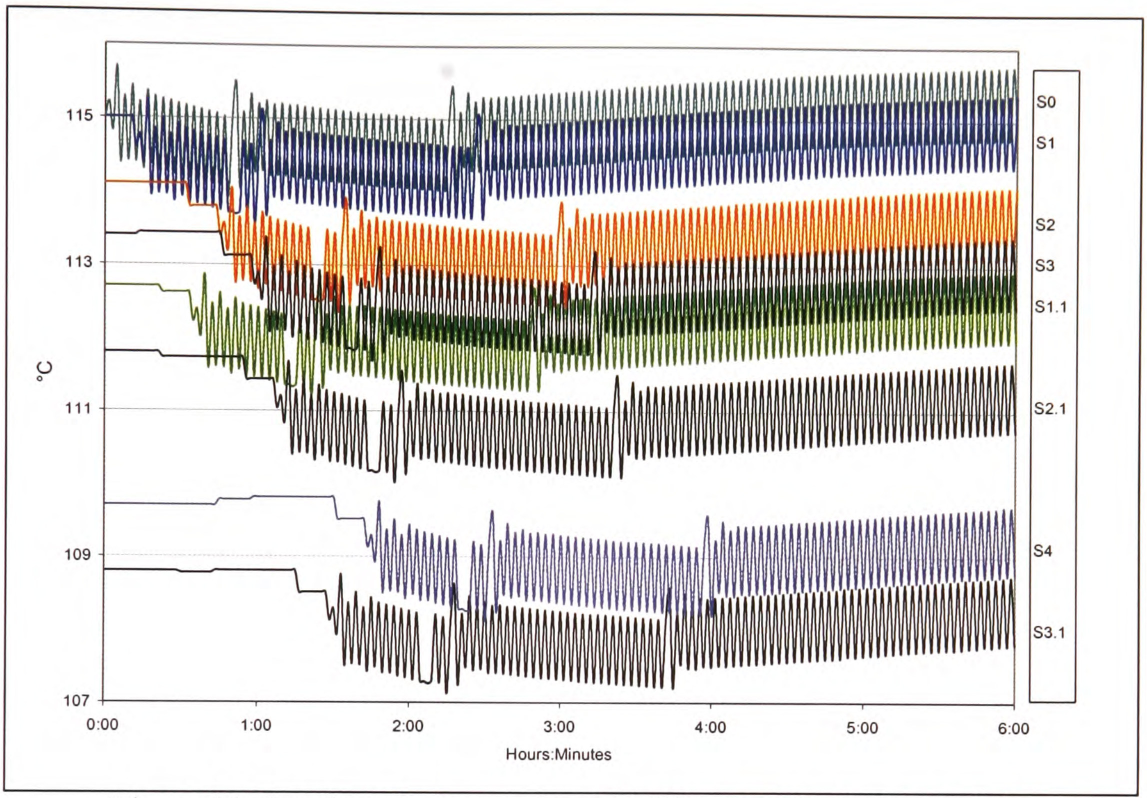

Figure 6.1. Supply water temperatures at different nodes in the network.

Even though the temperatures are fluctuating and some of them are close to one another, sufficient information can be obtained from figure 6.1: The out flowing temperature (S0) is close to 115 °C just like is the temperatures in node S1. The next group is nodes S2, S3 and S1.1. They receive their supply water between 112 and 114 °C. The lowest supply water temperatures can be found in the farthest nodes, S3.1 and S4 where it is around 109 °C. Figure 6.1 also shows that it takes almost two hours the water to flow from the boiler plant to the farthest nodes. Due to relatively long time step, the out flowing supply water temperature (S0) fluctuates somewhat. Naturally, this indigenous fluctuation can be seen through the water's passage to the customer and probably, to a certain extent, in its way back to the boiler plant, too. It takes some time, before the fluctuation starts at different points of the network. This is the time it takes the water to flow from the boiler plant to a particular node. Until that point, the temperature is based on what are supposed to be the initial temperatures in different points of the network. In this calculation, the initial values have been set based on a previous calculation with 2 minutes time steps.

This calculation would suggest that design primary side supply water temperatures for heating and ventilation heat exchangers should be as follows:

S1	114 °C
S1.1	112 °C
S2	113 °C
S2.1	111 °C
S3	113 °C
S3.1	108 °C
S4	109 °C

Above design values are set for heat exchangers and they are used in this chapter from this point on.

The flow rate is not constant during the calculation period since as the supply water temperature at a sub-station changes, the control valves will compensate the change by re-adjusting the flow so that the required input is gained. This can be seen in figure 6.2.

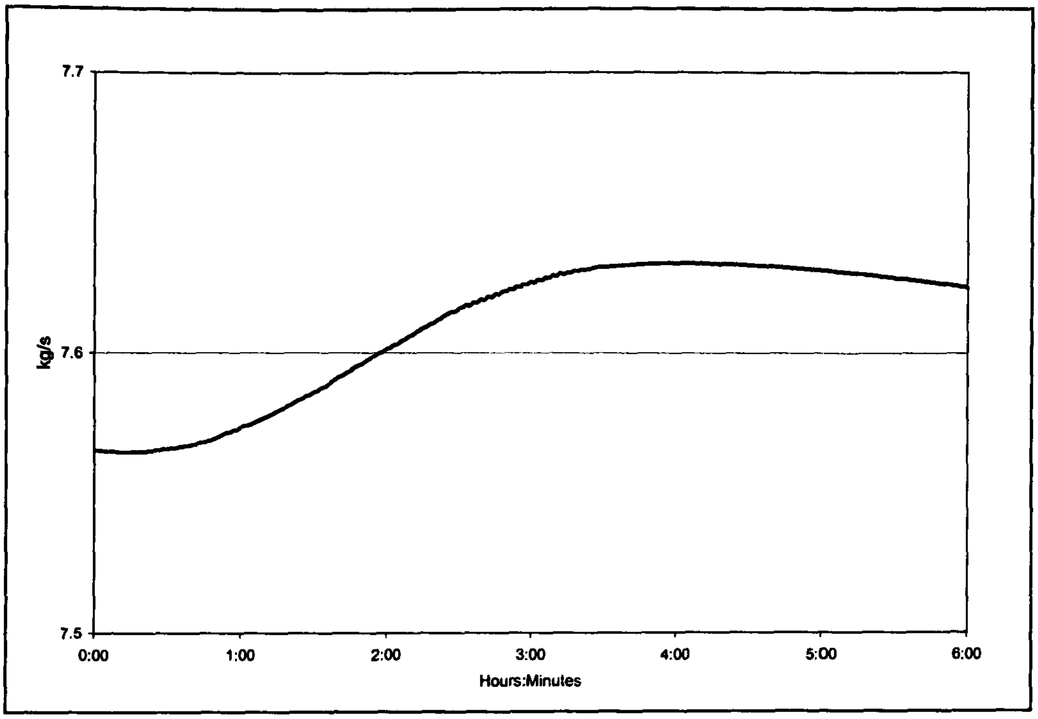

Figure 6.2. Flow rate during the calculation period.

In this calculation, there is no by-pass flow, but all the flow goes through heat exchangers. Average flow velocities between 2 and 6 hours are as follows:

S0 → S1	0.58 m/s
S1 → S1.1	0.26 m/s
S1 → S2	0.41 m/s
S2→ S2.1	0.28 m/s
S2 → S3	0.43 m/s
S3 → S3.1	0.34 m/s
S3 → S4	0.36 m/s

Return water temperatures during the calculation period can be seen in figure 6.3. When it comes to return water, it is not so clear, where the water comes from. That is why the origin nodes are given in parentheses.

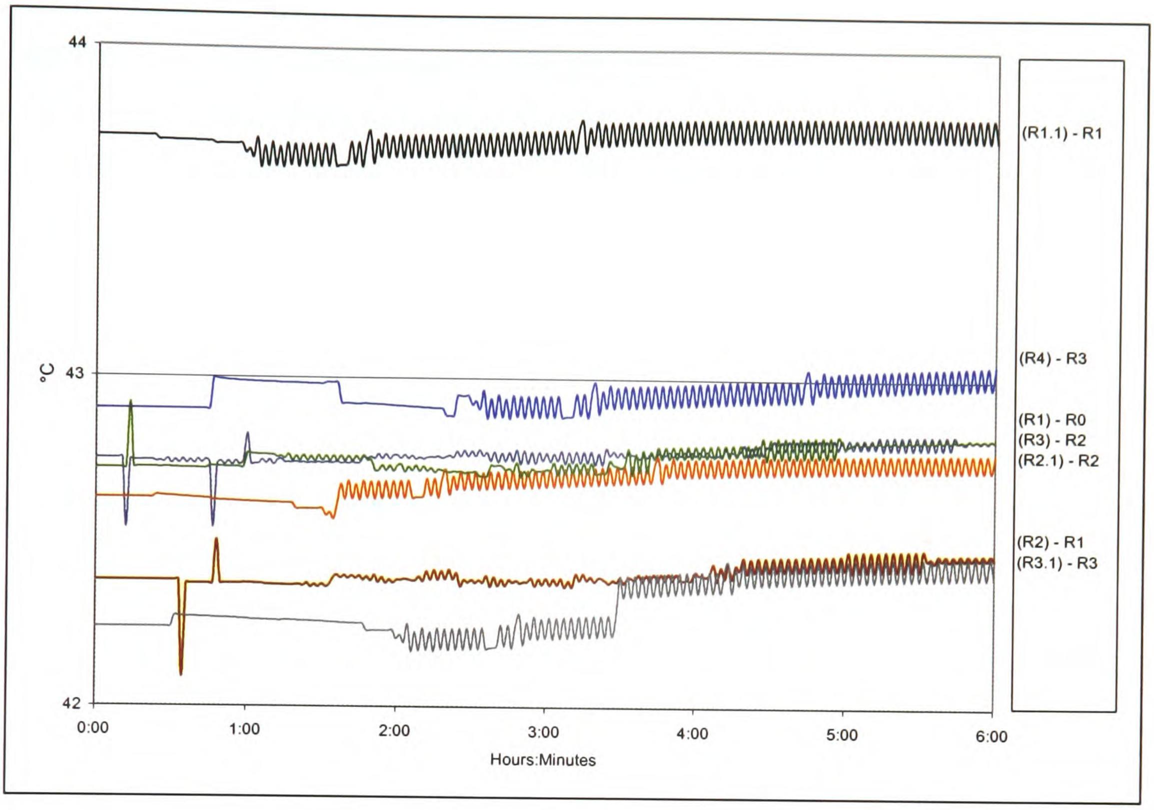

Figure 6.3. Return water temperatures.

As figure 6.3 brings out, the temperature range within return waters is distinctively narrower than with supply waters. It is less than two °C. The fluctuation in temperatures is also slighter due to mixing in the network. Heat exchangers obviously level the fluctuation down, too.

6.3. Heat loss

To have an idea of the heat losses at design temperature, it is better to shorten the time step, so that the calculation becomes more accurate. The calculation procedure is that after each time step the application checks whether or not water at a given initial temperature has reached the following node. With a long time step and relatively short distances, a considerable error may occur; in particular, if the flow velocities are high. For example, if the distance between two adjacent nodes is 250 m, the velocity of the flow is 1.0 m/s and the time step two minutes, after four minutes the water has flown 240 metres, and the application notices that the water has not reached the node yet. After six minutes it definitely has, but it has actually travelled 360 metres by that time. The application is aware of the distance being 250 metres. It considers that it took 6 minutes for the travel. Calculating the average speed for the flow would result 0.7 m/s instead of 1.0 m/s which is the actual value. So, the heat capacity flow would be only 70 % of the actual and, thus, the calculated temperature drop would be too big. This error can, naturally, be mitigated by using shorter time steps.

Since the previous calculation showed that the system started to be in a relatively steady condition at the end of the calculation period, initial values for the next calculation are transferred from the previous one. These initial values are temperatures at every supply and return node plus control valve positions and the output of the boiler. The next time step is 15 seconds.

The output of the wood chip boiler and the total input during the calculation period can be seen in figure 6.4. The desired value for the total input is 2137 kW. Excluding the hiccup at the beginning of the calculation period, the average output of the boiler plant is 2308 kW and the average input 2139 kW respectively. That makes the average heat loss 169 kW, which is well in accordance with the results from the calculation of the whole year. That application gave a heat loss of 193 kW as the outside temperature was -26 °C. The pipe work was, however, longer; the total length being 4.7 km whereas in this application it is only 3.8 km. The total overall hear transfer coefficient multiplied by the total length of the pipe work describes in a better way the difference between the pipe work in these two applications: In the former it is 1910 W/°C whereas in the latter it is 1646 W/°C, so the first one is 16 % greater than the other one. The difference in calculated heat losses is 14 % respectively. This residual difference (2 %) is probably due to different ground temperatures: The application for the whole year considers that ground temperature equals the prevailing 24 hours mean outside temperature, whereas the application for short term simulation takes that the ground temperature is constant, in this case it equals with the outside temperature (-26 °C).

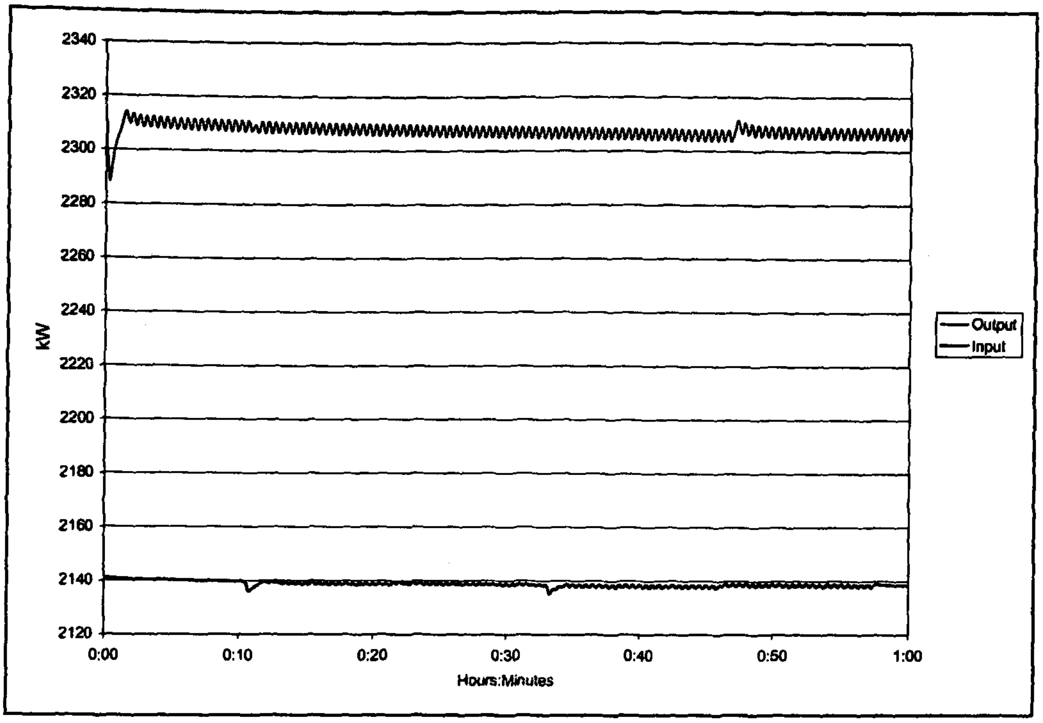

Figure 6.4. The output of the boiler plant and the input to the buildings.

To make the temperature drop smaller in a given network and with a given outside temperature, would require higher flow rates. This could be achieved by increasing the by-pass flow rate. In the previous calculation, there was no by-pass flow at all. It can be seen that the flow velocities are quite moderate and the velocity, on average, could easily be doubled without problems related to too high pressure drop. However, by-pass is something that should be avoided, in general. Besides increasing heat loss, it causes additional pressure drop leading to higher pumping costs.

6.4. Re-dimensioning of the pipes

In the application, the by-pass flow at each sub-station is determined with a given pressure difference. Increasing it would in practice mean increasing the size of the by-pass pipe or re-adjusting the regulating valve if such equipment exists. This kind of change would not, though, increase the flow very much in a situation where the need for heat, and the flow rate too, is high. The explanation for this is that high flow rates cause high pressure loss in the pipe work, so the available pressure difference at the end of the network is rather low and increasing the size of the by-pass pipe does not have any dramatic effect. When the need for heat decreases, leading to lower flow rates, a bigger share of the pump head is available for the sub-stations and, the by-pass pipes. This is the actual reason for installing by-pass pipes at least to certain points in the network: When the need for heat is close to zero, supply water would practically cease to flow in the pipe work. This would mean a lot of cooled water in the system, which would be a nasty surprise for the one who would like to take a shower in the morning. It might take hours until domestic hot water would be available at the end of the pipe work.

The other way to increase the flow rates is to reduce the pipe size. That leads to smaller heat loss and increased velocity in the pipe work. Of course, the price is increased pumping cost. To find out the significance of pipe sizing, all the pipe sizes in the network, except the first one from point 0 to node 1, were reduced by two dimensions, the first one by one dimension the way table 6.3 shows. Then the same calculation was carried out again. At first the time step was 30 seconds, because it was estimated that it would be enough for the flow to get from the boiler plant to the farthest node by that time. From that calculation, initial values for the next one, with a time step of 15 seconds, were transferred. The results in supply water temperatures are illustrated in figure 6.5.

Table 6.3. Reduced sizes of the pipes.

Nodes	D_{pipe} previous, mm	D_{pipe} new, mm	Wall thickness new, mm	Insulation new, mm
0- 1	139.7	114.3	3.6	64.0
1-1.1	76.1	48.3	2.9	41.9
1-2	139.7	88.9	3.2	51.6
2-2.1	76.1	48.3	2.9	41.9
2-3	114.3	88.9	3.2	51.6
3-3.1	60.3	42.4	2.9	44.8
3-4	88.9	60.3	2.9	46.0

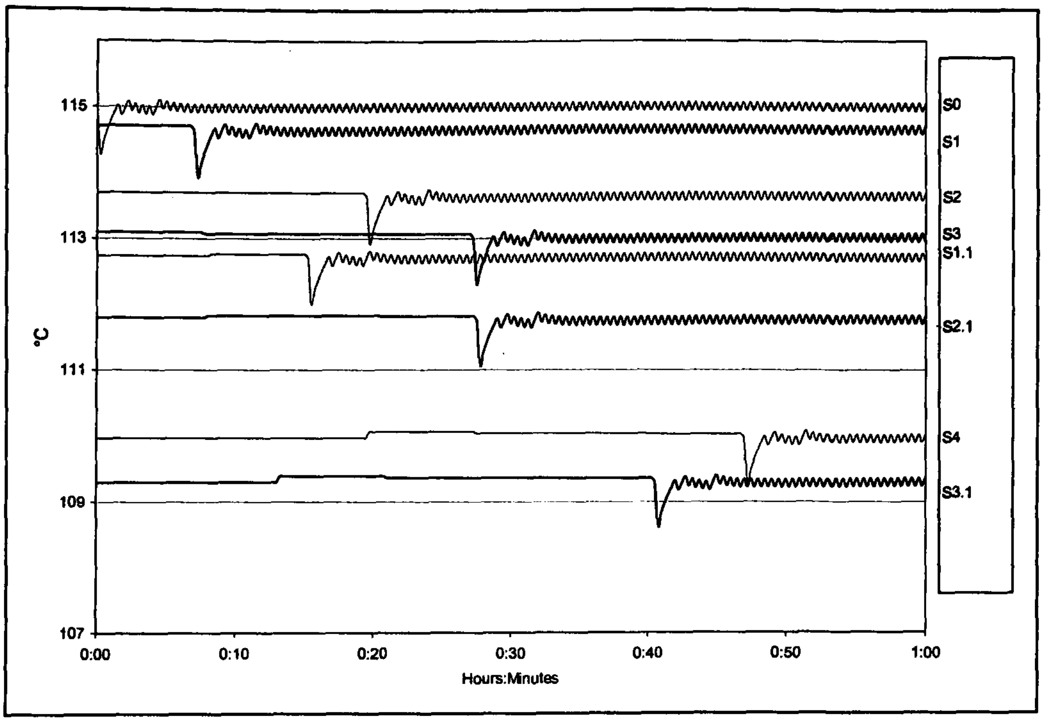

Figure 6.5. Supply water temperatures with the reduced pipe work.

The calculation step being only 15 seconds results in almost non-existent fluctuation in the temperatures. Compared with results from calculation with original pipe sizes and 15 seconds time step in Chapter 6.2 the differences are:

Table 6.4. Comparison of supply water temperatures and flow velocities with different pipe sizes.

Node	Temperature original pipe size, °C	Temperature reduced pipe size, °C	Velocity original pipe size, m/s	Velocity reduced pipe size, m/s
S1	114.6	114.7	0.58	0.89
S1.1	112.3	112.8	0.26	0.71
S2	113.5	113.7	0.41	1.06
S2.1	111.2	111.8	0.28	0.76
S3	112.9	113.0	0.43	0.72
S3.1	108.4	109.4	0.34	0.75
S4	109.1	110.0	0.36	0.83

6.4.1 DHW peaks with the reduced pipe work

Table 6.4 shows that changes in the supply temperatures are fairly moderate notwithstanding the pipe sizes have been reduced significantly. The average output is 2282 kW and the average input 2139 kW respectively. That makes 143 kW for heat losses. Compared with the original size network, the peak heat loss came down by 15 % (from 169 kW to 143 kW).

As domestic hot water consumption creates momentary peak loads, it would be good to find out how the size-reduced pipe work would cope with these situations. With the application that calculates the heat consumption of the whole network through the year, it was calculated that the mean peak for DHW was 340 kW, between 7 and 8 o'clock in the morning. As this is just a mean value, one might suspect that there are peaks when the desired input for domestic hot water preparation is in the order of 500 kW. What is more, different buildings consume DHW at different times. For, example schools and offices that are unoccupied at 7 o'clock do not consume any DHW then. In the following calculation, it has been suspected that all the residential buildings consume DHW so that the total heat consumption for that purpose is 500 kW. This amount has been divided between the buildings so that each uses the same percentage of total DHW heat exchanger capacity. Flow rates per building are shown in the Appendix, table X.

Flow velocities, during the DHW peak are as follows:

S0 → S1	0.99 m/s
S1 → S1.1	0.71 m/s
S1 → S2	1.18 m/s
S2→ S2.1	0.82 m/s
S2 → S3	0.79 m/s
S3 → S3.1	0.84 m/s
S3 → S4	0.96 m/s

Velocities are still at a clearly acceptable level. Water temperatures are not fully comparable with the previous calculation due to different time steps.

The calculation has been carried out with a 30 seconds time step which results in a calculation period of 2 hours. This is because it takes some time to reach the new water temperatures at different nodes with this new flow rate. As the situation starts, the input exceeds the output, because the return water temperature at sub-stations goes rapidly down whereas the boiler plant still receives water at a higher temperature. Naturally, as time goes on, this cooler return water reaches the boiler plant and the boilers, eventually, have to pay the loan back. In Finland, the design return water temperature from a DHW heat exchanger is typically 25 °C whereas from a heating or ventilation heat exchanger it is 45 °C.

The next calculation includes DHW consumption starting five minutes from the beginning of the calculation period and continuing for 30 minutes. Then DHW consumption abruptly ceases and heat is consumed solely for heating and ventilation plus heat losses. The total DHW input is still 500 kW and the calculation period is 2 hours that is the calculation step is 30 seconds. Figure 6.6 shows the behaviour of return water temperatures. The most interesting temperature is the one returning to the boiler plant. It is the thick black curve.

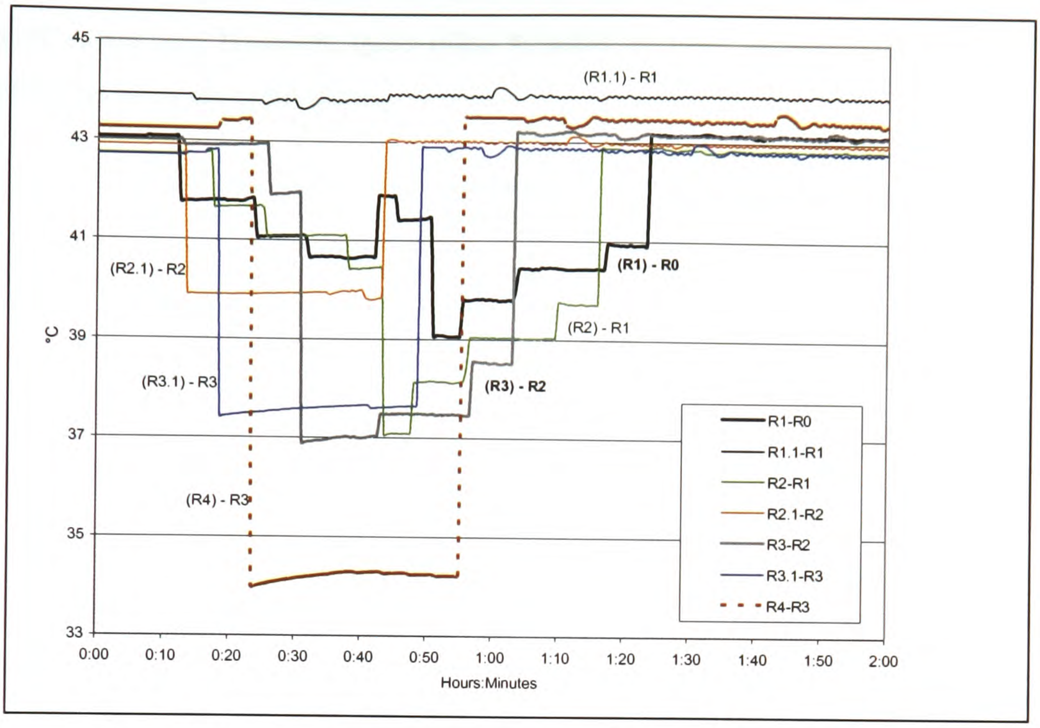

Figure 6.6. Return water temperatures with the reduced pipe work.

As can be seen, it takes almost 1 hour after the DHW consumption has ceased (at 35 minutes) until the temperature of the water that returns to the boiler plant has stopped fluctuating. The final temperatures are practically constant and at the same level they were at the beginning. Return flow from node R4 to node R3 experiences the largest temperature drop owing to the relatively biggest DHW consumption compared with heat input for heating and ventilation. This results from the fact that effectively all the buildings at node 4 are residential ones.

Figure 6.7 shows how abrupt the change in the total flow rate was. The decrease in the flow rate continued after the DHW had ceased. This is because the pump head at the boiler plant is constant and, consequently, when the total flow rate comes down, the available pressure difference at sub-stations increases, owing to lesser pressure drop in the pipe work. Increased available pressure difference leads to increased flow through heat exchangers and, of course, increased input. The control valves at sub-stations counteract this by closing gradually. Their movement is, though, retarded so that it takes some time before they reach their new positions. This retardation is necessary in the application to avoid increasing fluctuation. In real installations, the movement of the control valves are, however, quite often retarded as well, though probably not to the same extent as in the application.

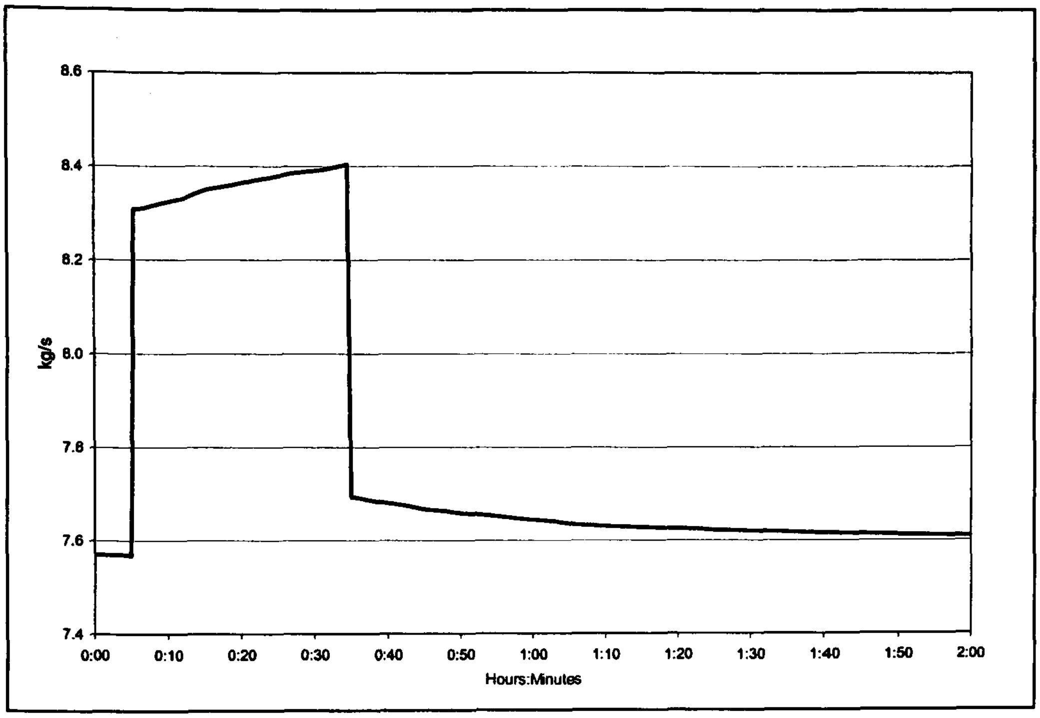

Figure 6.7. The flow rate during the simulation period, with the reduced pipe work.

In this kind of situation, there are two things that immediately affect the need for output from the boiler plant; the flow rate and the return water temperature. As figure 6.6 brings out, the return water temperature drops drastically after some 12 minutes from the start. Figure 6.7, on the other hand, shows that the peaks continues for 30 minutes. It is, thus, no surprise that the boiler plant has very little time to adapt to the new situation. This is illustrated in figure 6.8.

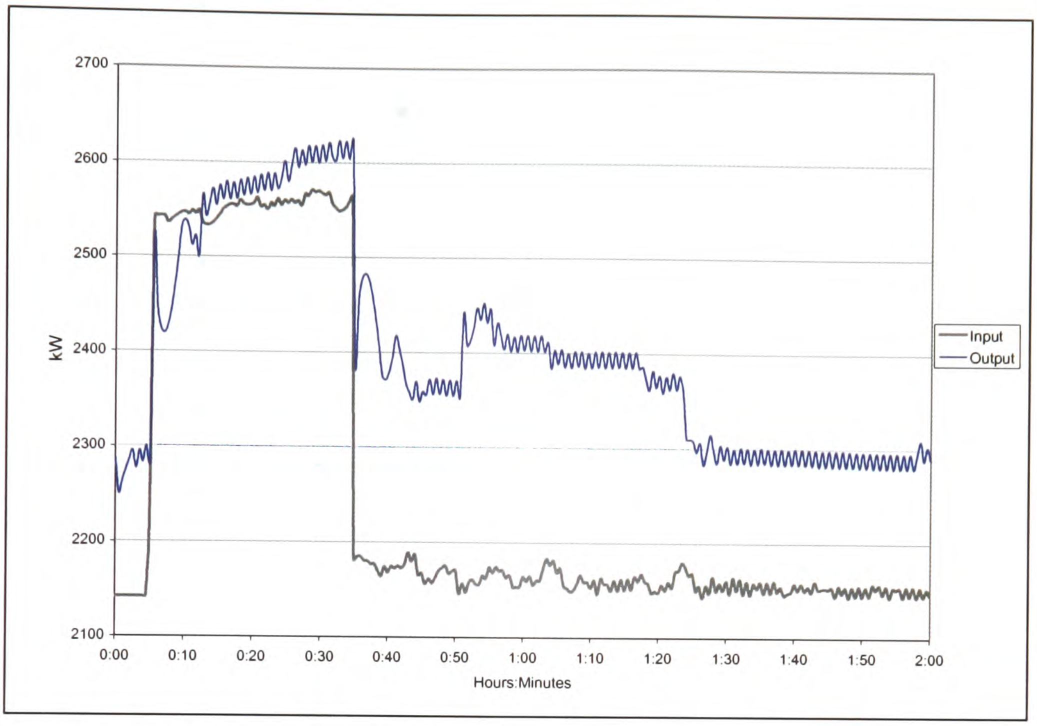

Figure 6.8. The output of the boiler plant and the input to the buildings with the reduced pipe work.

In the output graph there are two U-shape mirror images; the first one from five to ten minutes and the next one upside down from 35 to 40 minutes. They come from the abrupt changes in the flow rate that cannot be instantly compensated by the control system. The smaller deviations after the aforementioned ones origin from the same reason.

It is only some 7 minutes from the point the DHW usage begins the boiler plant can benefit from the accumulative effect of the network. Then it needs to increase its output above the input level. After an hour or so from the end of the peak, both input and output are relatively steady. The output is fluctuating through the calculation because of relatively long time step (30 seconds) and relatively fast moving control valves. Fluctuation in the supply water temperature causes then fluctuation in the input, too.

Figure 6.8 goes well with figure 6.6 suggesting that as the return water temperature has levelled off, some kind of steady state condition has been reached. Until that point the boiler has to operate at a higher output even though the peak is over. It would seem that the accumulative effect of the pipe work could be taken into account when sizing the boilers: At the end of the calculation period, it can be seen that the difference between the output and input is something like 139 kW. This needs to be the heat loss. The mean input, during the latter half of the peak, is 2547 kW. The total need for heat would then logically be 2686 kW. The highest output was, though, 2624 kW just at the end of the peak. The mean output during the latter half of the peak was 2592 kW. A kind of conclusion could be that short peaks can be handled by the network, but the more the duration increases, the more capable must the boiler be to meet the need for heat. One thing that is significant, is that in which part of the network does the peak take place. The longer from the boiler plant the more time it takes until the cooled return water reaches the plant.

6.4.2. DHW peaks with the original pipe work

The accumulative effect of the pipe work probably increases if the pipe sizes are bigger. The next calculation is exactly the same as the previous one, but the pipe sizes have been changed back to the original ones again. Because, as table 6.3 shows, the flow velocities are less than half of the previous ones, the calculation period needs to be extended. The new time step is 35 seconds leading to a calculation period of 2 hours 20 minutes.

Figure 6.9 shows the return water temperatures with the original size network. The black and thick graph is, again, the water coming back to the boiler plant that is R1 – R0. It can be seen that it now takes about 2 hours and a quarter from the beginning of the peak, until the temperature of the water returning to the boiler plant has come back to the initial value again. It takes some 10 minutes from the beginning of the peak until temperature of this water goes abruptly down. With the previous calculation, the time was some 7 minutes. But the pipe between the boiler plant and node 1 was only changed by one dimension.

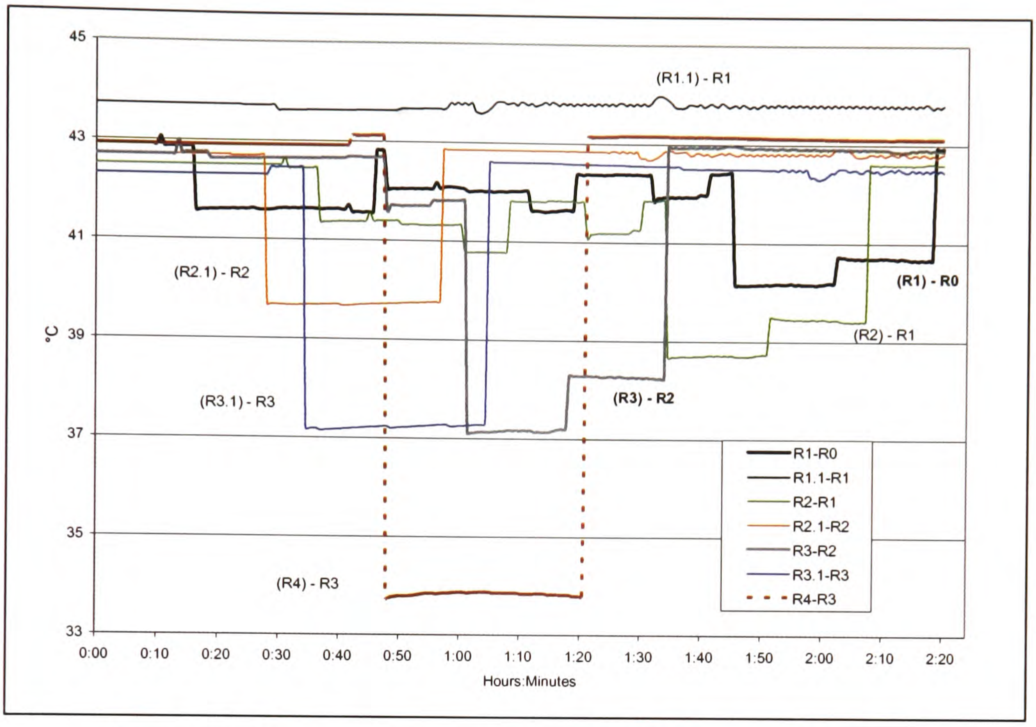

Figure 6.9. Return water temperatures with the original pipe work.

The accumulative effect of the network can be seen in figure 6.10. The output and input from the previous calculation can be seen, too. The thick line illustrates the situation with larger pipe sizes and the thin one with smaller ones, respectively. The boiler plant will be able to maintain the output below the input for some 5 minutes longer than with the smaller pipe work, from the beginning of the peak. There is a minor difference between the maximum outputs, 2608 versus 2624 kilowatts. The fluctuations of return water temperature continue about one hour longer with the larger pipe work.

In both previous calculations, the DHW consumption starts exactly at five minutes from the beginning of the calculation period. The boiler output increases then instantaneously from 2137 kW to a little over 2500 kW, due to the increased flow rate. So rapid changes are, of course, something that cannot be found in real installations. The idea at this point, though, is to study what the accumulative effect *could be.* With smoother changes in the flow rate and output it would be more difficult too see how the pulses move in the network.

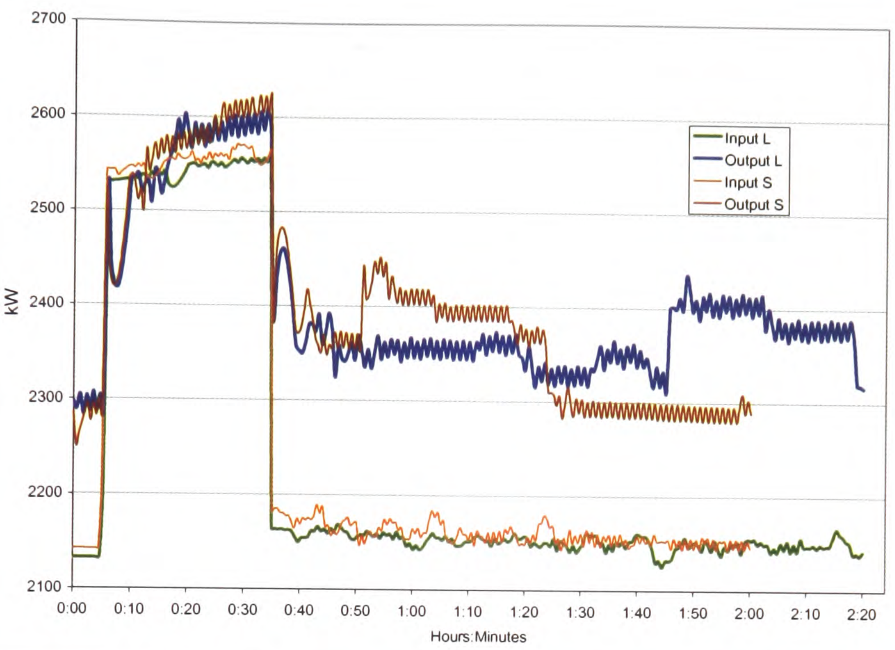

Figure 6.10. The output of the boiler plant and the input to the buildings with the original pipe work.

6.5. By-pass

All the previous calculations illustrate the situation at outside temperature -26 °C which is the design temperature in this case. Another interesting situation is when the outside temperature is so high that the need for heat is close to the lower limit of the boiler. It has been estimated earlier that the lowest sustainable output of the wood chip boiler could be 20 % of the maximum that is 240 kW. With the larger size (original) network, the flow velocities will be so low that for one thing the calculation period would have to be more than 8 hours, which would require a time step longer than 2 minutes, and for another thing, the heat loss would cause a temperature drop beyond the acceptable range. For these reasons, the by-pass flow has been introduced. The biggest by-pass is at the end of the network, i.e. at nodes 3.1 and 4. A bit smaller by-pass takes place at node 2.1 and an even smaller one at node 1.1. It has been thought that nodes situated along the mains do not require any by-pass of their own.

The following calculation simulates a situation where the outside temperature (and the ground temperature as well) is 12 °C. The initial values for temperatures at different nodes and control valve positions plus boiler output have been found with a longer calculation period. The time step is now 30 seconds leading to a period of 2 hours. The essential data of the results are collected in table 8.5. Velocity is practically the same in supply and return pipes and mass flow rate is exactly the same in both pipes. That is why they are shown only once. In table 6.5, by-pass flow is the flow that passes by heat exchangers at a particular node, so even though by-pass makes 61 % of the total flow, it has not been detached from the total flow at nodes without a by-pass connection.

Table 6.5. By-pass flow rates.

Nodes	Temperature °C	Velocity m/s	Total flow kg/s	By-pass flow kg/s	By-pass flow %
S0	77.9	0.14	1.81		
S1	77.2	0.13	1.81		
S1.1	70.5	0.04	0.16	0.07	40.2 %
S2	75.3	0.11	1.54		
S2.1	71.3	0.08	0.29	0.19	64.7 %
S3	74.4	0.13	1.18		
S3.1	69.5	0.15	0.33	0.26	77.8 %
S4	70.0	0.14	0.75	0.58	76.5 %
R1-R0	46.3				
R1.1-R1	38.1				
R2-R1	49.5				
R2.1-R2	51.1				
R3-R2	52.0				
R3.1-R3	55.1				
R4-R3	55.5				
Total				1.09	

As table 6.5 shows, these by-pass flows give satisfactory results. The by-pass might, though be increased at node 3.1 because the supply water temperature goes a little below 70 °C which is the design temperature for the DHW heat exchangers. On the other hand, by-pass at node 2.1 could be decreased somewhat respectively. The deviations can be considered negligible, nevertheless. The output of the boiler plant during the calculation period is 240 kW and the total input 159 kW respectively. That makes 81 kW for the heat loss.

6.6. Summer time peaks

6.6.1. One peak with the original pipe work

If a DHW peak is made, one will find out the function of the pipe work in a summer situation. At this point, there is no doubt about the boiler plant being able to generate enough heat during the peak since the base load is very low. The interesting question relates to the accumulative and smoothing behaviour of the pipe work. The boiler is almost asleep and it needs to wake up very fast when consumers start to use domestic hot water. As was said before, the DHW peak could be something like 500 kilowatts. It is not in reality as abrupt with the start and the end as it was in previous calculations concerning winter time DHW peaks. In the following calculation, the DHW consumption starts at 5 minutes and continues an hour. The peak is in the middle of the consumption period. Figure 6.11 shows the change in the flow rate. The calculation period is 6 hours as the flow velocities are rather low.

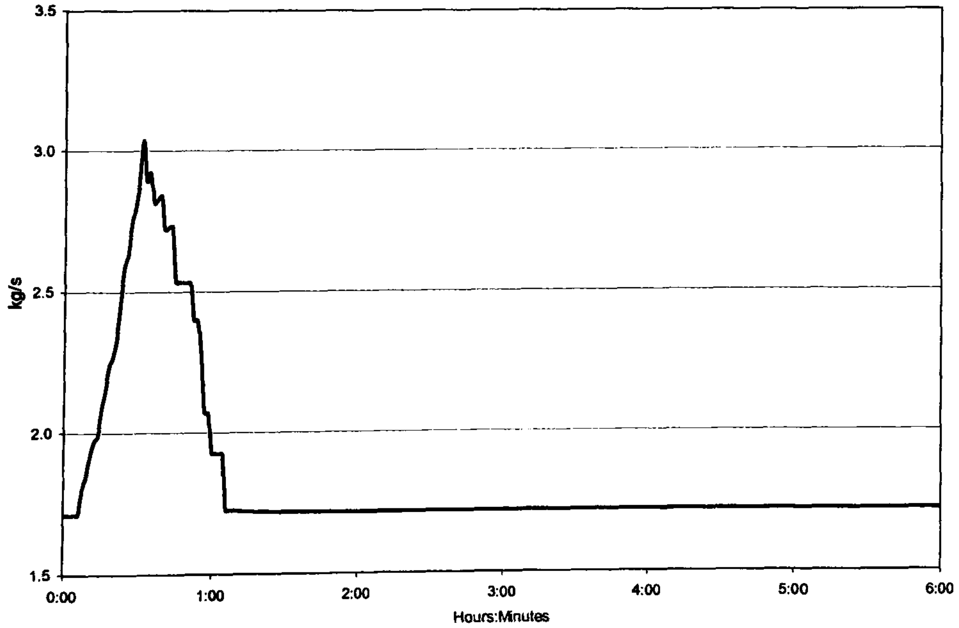

Figure 6.11. Peak in the flow rate (with the original size pipe work).

Figure 6.12 shows the input and output during the period. The average input for DHW is 208 kW. Figure 6.13 shows fluctuations in supply water temperatures.

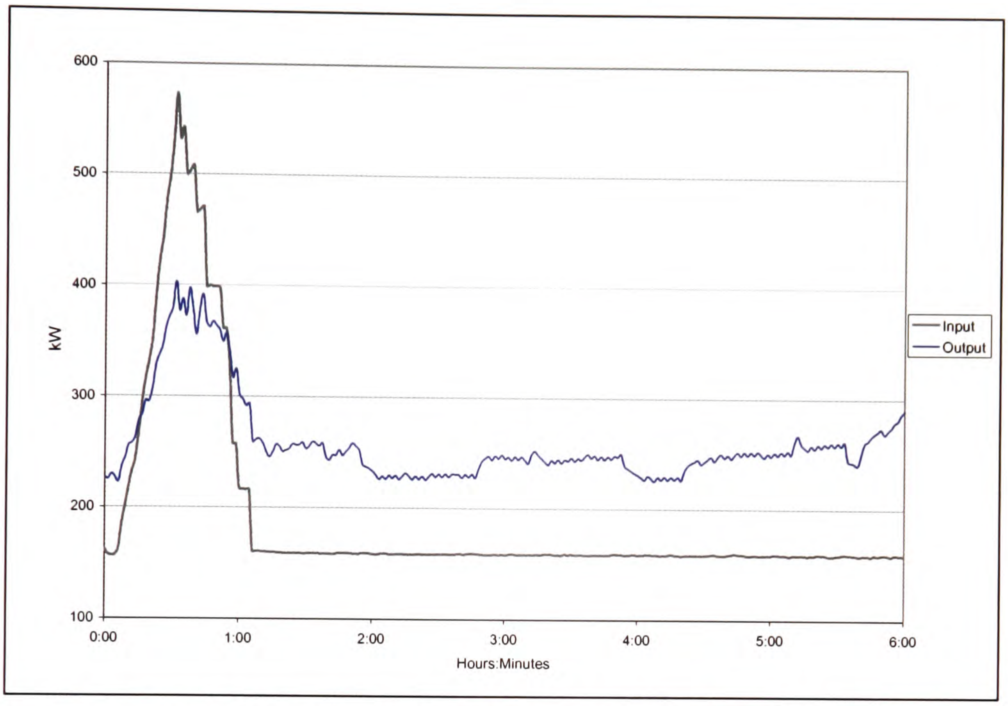

Figure 6.12. Input and output (with the original size pipe work).

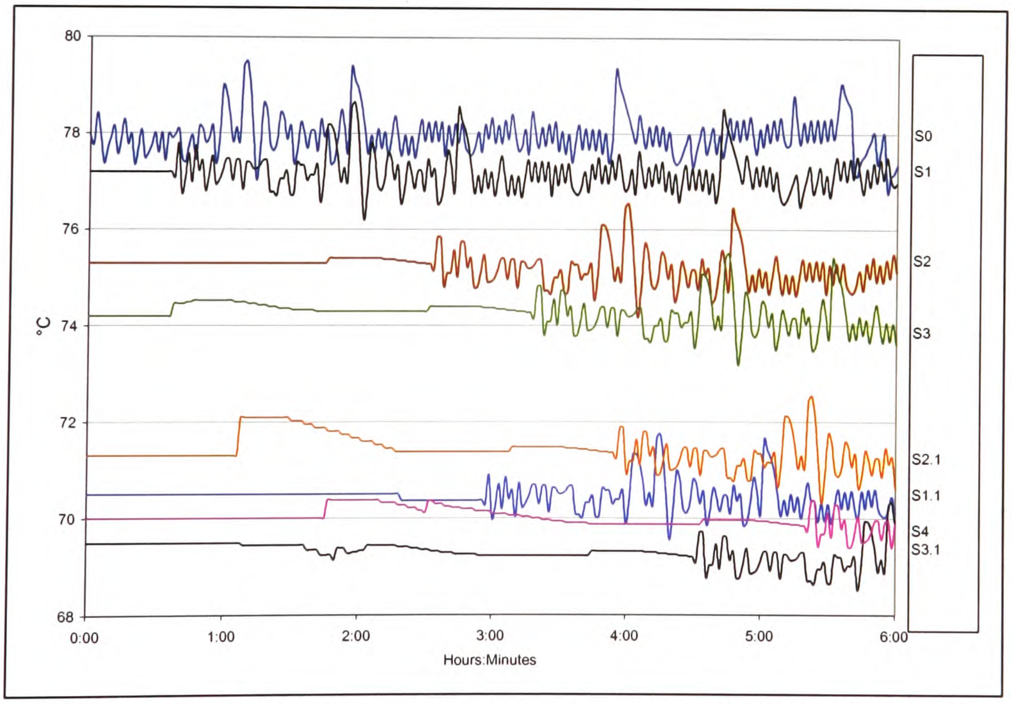

Figure 6.13. supply water temperatures (with the original size pipe work).

Figure 6.14 shows return water temperatures.

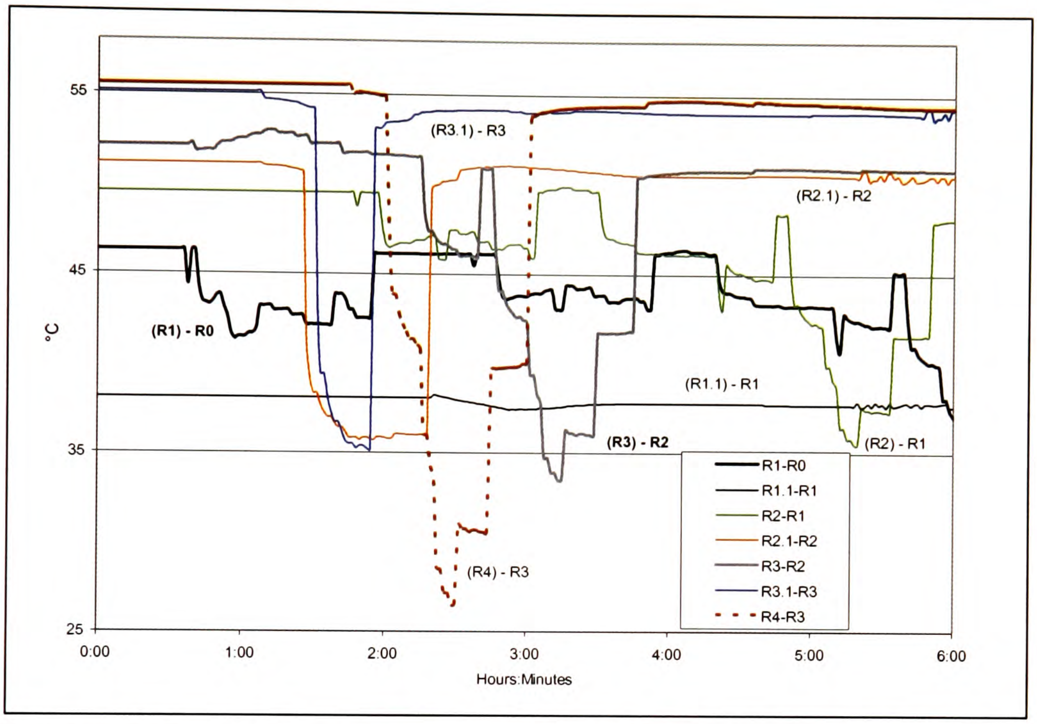

Figure 6.14. Return water temperatures (with the original size pipe work).

Figures 6.12 and 6.14 give probably the most interesting information. Figure 6.14 shows that the return water temperatures fluctuate quite a long time after the DHW consumption period. As a matter of fact, they still continue fluctuating after 6 hours' calculation period. It can be seen, for example that water returning to the boiler plant (R1 – R0) is still getting colder at 6 hours. That is why the output is going up at the end of the calculation period.

This could be the morning DHW consumption period. The next one would occur around noon. That is to say that fluctuations from the first period would not have levelled off before the next would begin. In plain words: The return water temperature would probably fluctuate the whole day and part of the night, as well.

6.6.2. Two peaks with the original pipe work

The next calculation includes two DHW consumption periods, the first of which is identical with the one in the previous calculation. The second takes place 3 hours after the first one. The consumption rate is 75 % of the previous one. The average input for DHW is 208 kW during the first consumption period and 163 kW during the next one. Figure 6.15 shows the input and output.

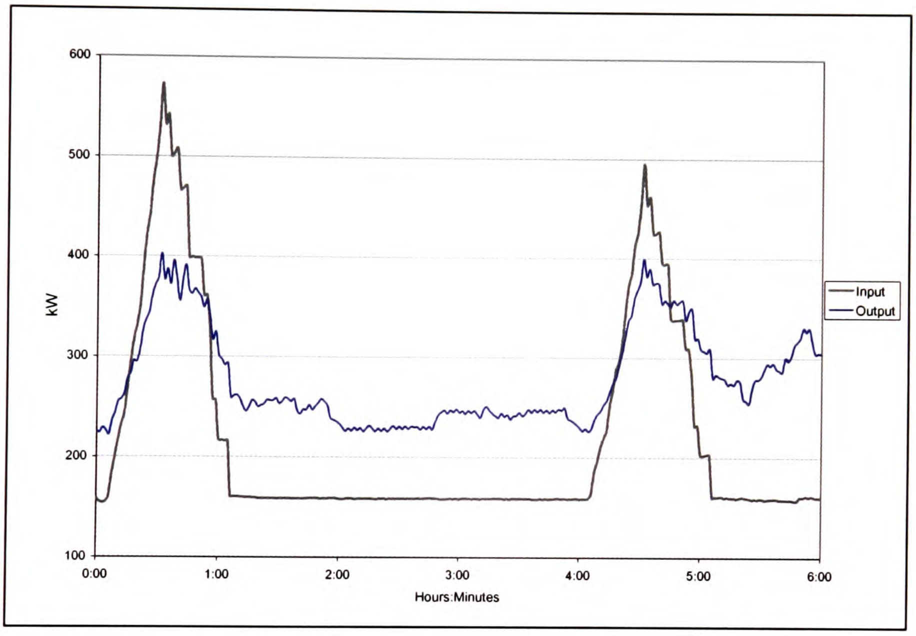

Figure 6.15. Input and output (with the original size pipe work).

Figure 6.15 brings out that even though the peak input is some 80 kW higher at the first consumption period, the peak outputs are practically identical. That is due to the colder return water at the second DHW consumption period. The output seems also to be climbing higher at the end of the calculation period. It is easy to understand if one looks at figure 6.16 which shows the return water temperatures. Temperature of return water (R1)-R0 is around 36 °C at the end of the calculation period.

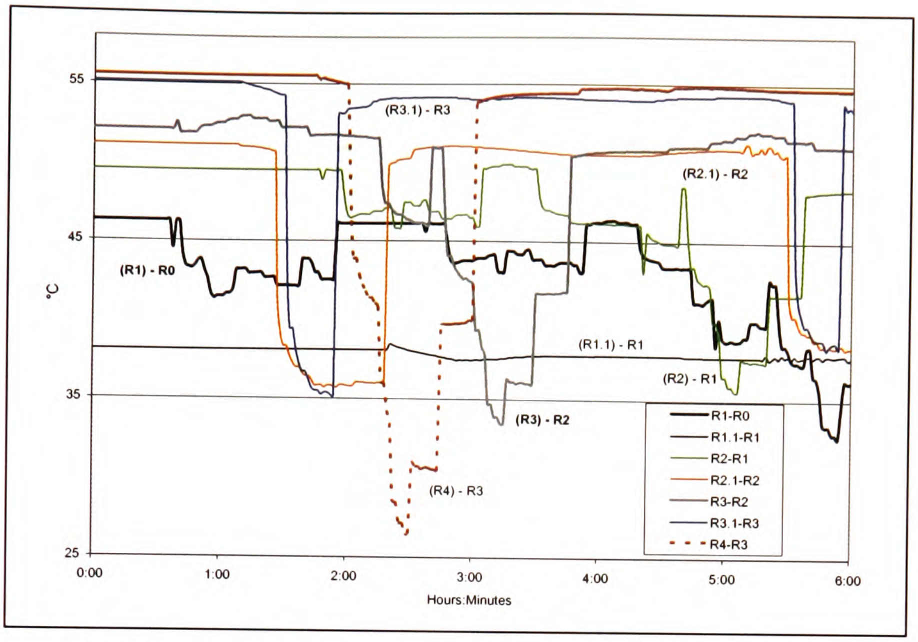

Figure 6.16. Return water temperatures (with the original size pipe work).

6.6.3. Two peaks with the reduced pipe work

The next calculation is almost identical with the previous one. The only exception is that pipe sizes have been reduced to the same that was used in winter time calculations. Figure 6.17 shows the input and output. Output with the larger pipe work can also be seen, in broken line. Figure 6.18 brings out the return water temperatures.

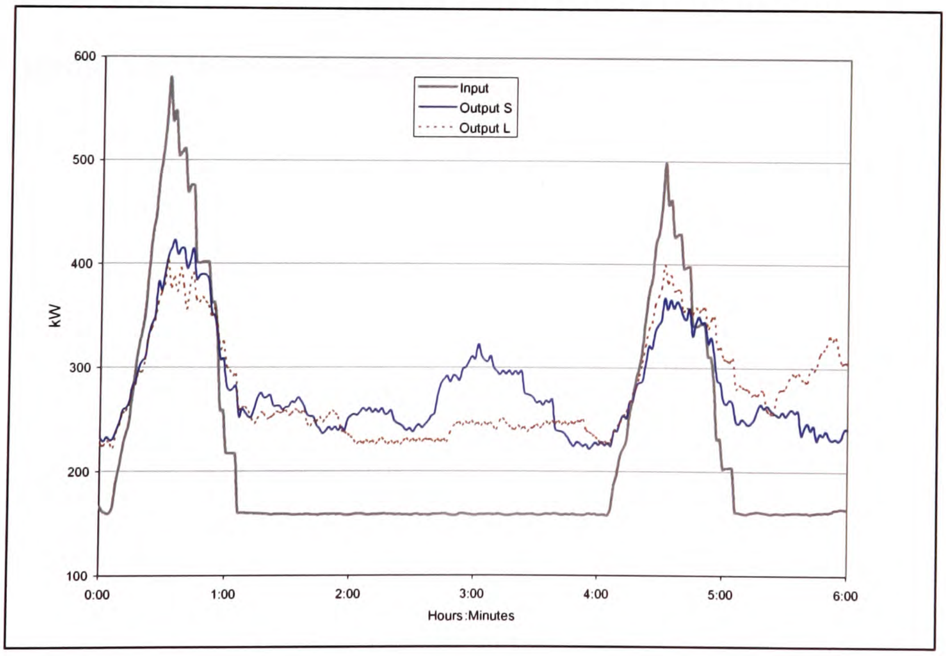

Figure 6.17. Input and output (with the reduced pipe work).

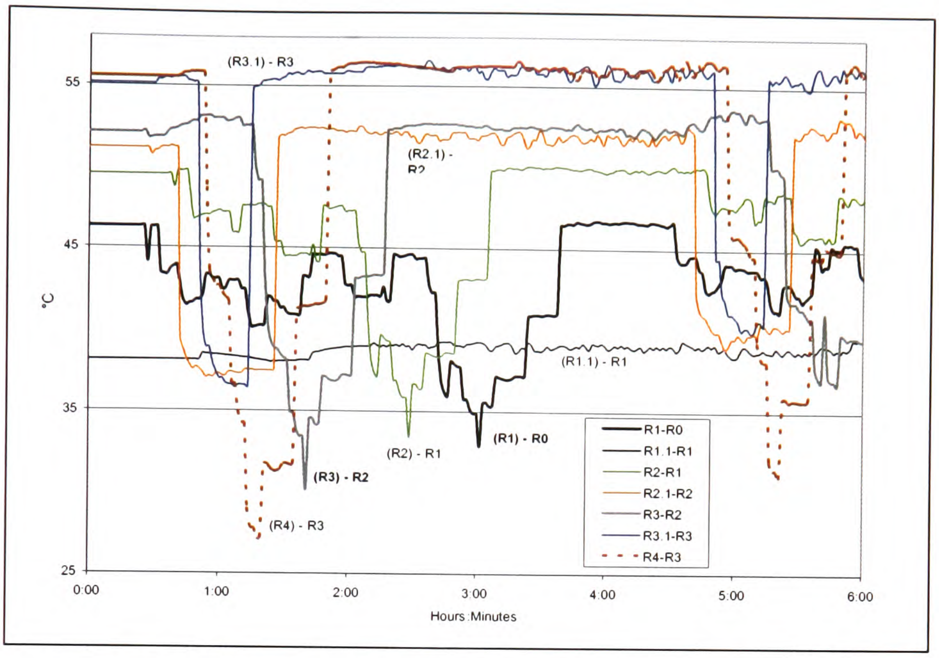

Figure 6.18. Return water temperatures (with the reduced pipe work).

Figure 6.18 shows that fluctuations due to the first consumption period are over about 2.5 hours after it ends.

6.7. Dynamics of the wood chip boiler

6.7.1. Volume

The following calculations will focus more on the boiler plant. A typical difficult situation for a wood chip boiler is the morning when one large consumer or many consumers simultaneously start using hot water. Notably if the base load is low, will it be difficult for the boiler to respond for the rapid change in the need for heat. In previous calculations the parameters for the boilers were set so that the out flowing supply water temperature did not drop practically at all when the DHW consumption started. In reality, it probably would do so and that is what will be studied next.

A summer time morning situation could be something like what is shown in figure 6.19. The steady low need for heat abruptly increases as some buildings start to consume domestic hot water. The consumption periods lasts for a while and then rather abruptly ends. This kind of consumption pictures do exist, as there are often buildings that use rather large amounts of hot water in a short period of time, for instance for cleaning. In large DH networks they do no harm, but in small ones they are sometimes troublesome. The consumption period has now been restricted to half an hour to be able to use shorter time steps (20 seconds) so that there is still enough calculation time after the consumption period to see if any fluctuation appears. The DHW consumption starts at 5 minutes and ends at 35 minutes. The larger size (original) network is introduced. The outside temperature is 12 °C.

The calculation has been carried out so that the boiler water temperature has been kept practically constant; the total deviation is less than one degree. It has been calculated what would the boiler output have to be through the calculation period so that the boiler water temperature would not change. The boiler water volume has not, however, been kept constant. The calculation has been done with several boiler water volumes: 2000, 4000, 8000 and 16000 litres. A typical volume for a boiler with an output around 1 MW is a bit more than 2000 litres. So, the larger volumes would in practice mean installing external vessels in connection with the boiler. An important thing to notice in the calculation is that it has been taken that the boiler water mixes with the return water fully. That is, there is no stratification of different temperatures. A 100 per cent mixing is probably the least efficient way to take advantage of an external buffer tank. The most efficient way would be the one with a 100 per cent stratification, where hot water would remain hot and colder return water would be separated from it completely, so that the whole hot water reserve could be utilised. The real installations are something between these two extreme examples. As the degree of stratification or mixing is difficult to estimate, the calculations have been done by using complete mixing.

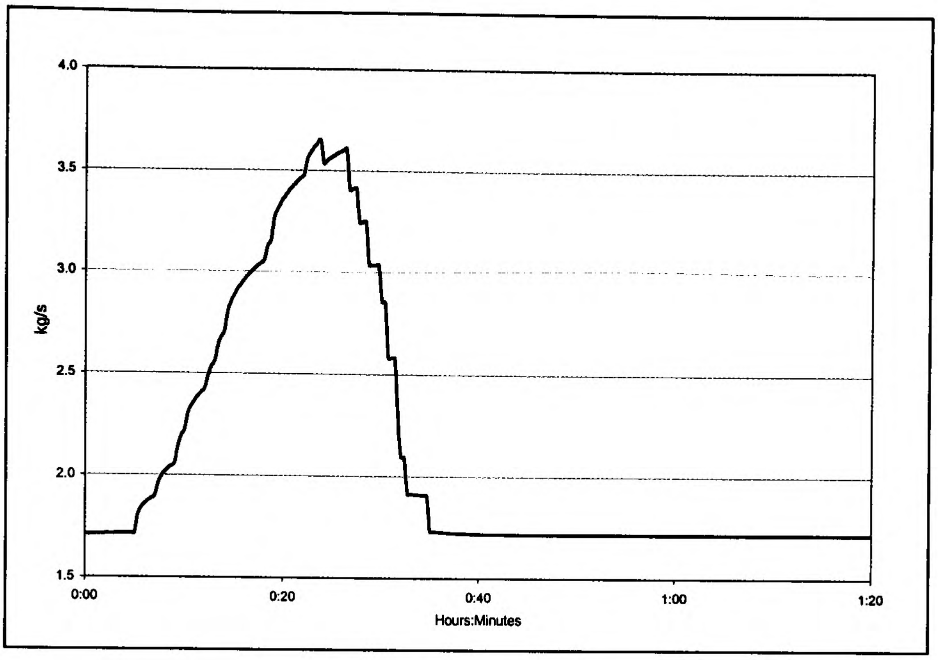

Figure 6.19. Flow rate.

Figure 6.20 illustrates the input and boiler outputs with different boiler water volumes. It brings out that, the larger the volume the more time the boiler has to respond to the change in the need for heat. The maximum required output is, though, practically the same with all above boiler water volumes.

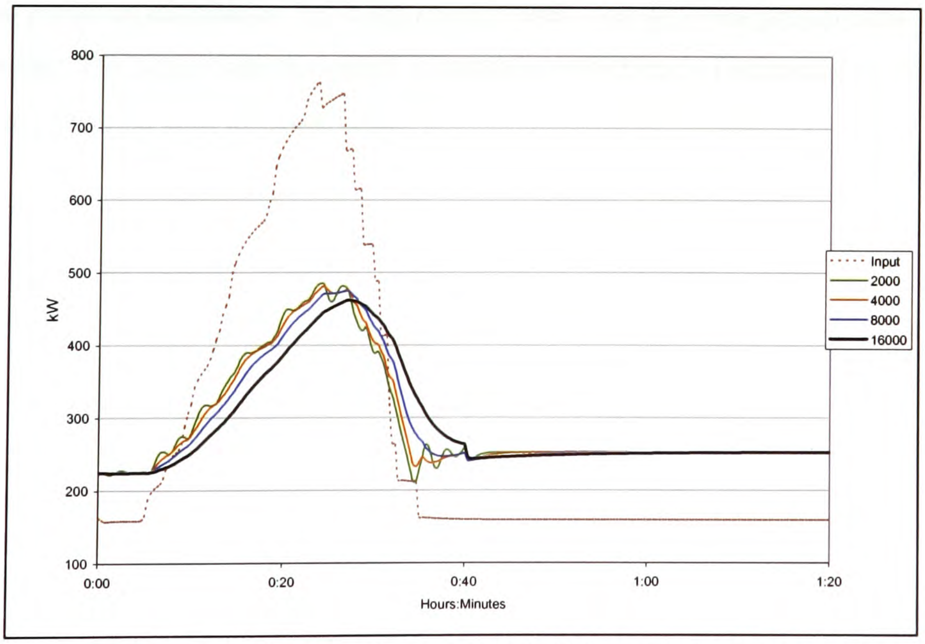

Figure 6.20. Input and required output with different boiler water volumes.

As the previous calculation showed what the effective output of the boiler should be to keep the boiler water temperature at its desired value (100 °C in this case) it did not actually match with real occasions. When a wood chip boiler operates at its lower output limit, it takes quite a lot time to increase the output significantly. On the other hand, when the boiler has been increasing its output for some time as fast as possible, it simply cannot change the direction and start going down with the same rate. The combustion chamber is full of burning chips and all the brick-linings, grate and other material are at high temperature which means that heat transfer goes on for some time. What is more, the control system is typically rather sluggish to avoid hunting.

6.7.2. Automatic controller

In the following calculation, it has been assumed that the minimum temporary output of the boiler is 50 kW and the maximum 1000 kW respectively. Furthermore, it has been assumed that at 50 kW the boiler is only capable of increasing its output by 1 kW per minute. On the other hand, when the output of the boiler is very close to 1000 kW, the corresponding acceleration is 50 kW/min. The intermediate values come linearly, so that at 225 kW, which is the initial output, the value is almost 10 kW/min. The boiler's capacity to decrease its output has been assumed to be constant, in this calculation 20 kW/min. Exactly the same situation, with a DHW consumption period of 30 minutes, as in the previous calculation has been studied with four different proportional controller coefficients. The larger size (original) network is introduced. The results in boiler water temperature can be seen in figure 6.21.

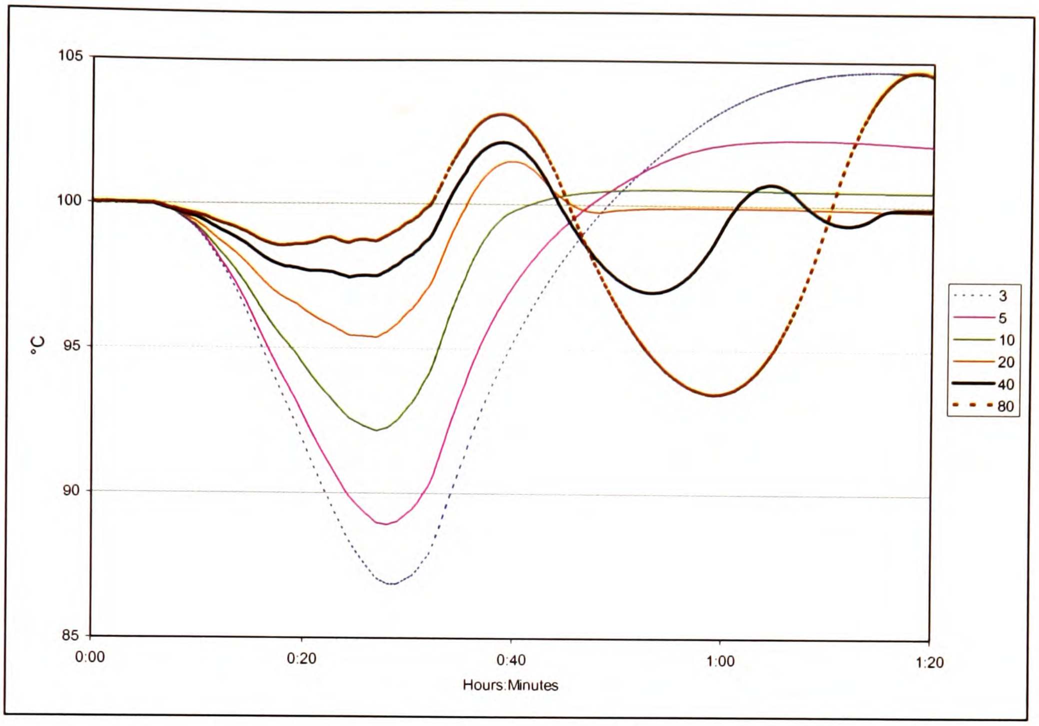

Figure 6.21. The significance of the P controller amplification coefficient.

Notwithstanding the dynamic behaviour of the boiler is purely estimated, some general interdependences can be found in figure 6.21. The thin broken line illustrates rather moderate amplification coefficient (3). It lets the boiler water drop down as the need for heat increases and it seems to be levelling off after the flow rate has settled down. There is, however, a considerable deviation between the desired value (100 °C) and the actual one. The integral operator has been set to work rather slowly in this calculation.

If the coefficient is 5, the temperature drop is less and the actual value comes closer to the desired value after the peak.

With a coefficient of 10 the deviation after the peak is around 0.5 °C.

When the amplification coefficient is 20, there is a distinctive overshoot after the undershoot. The temperature levels rapidly off, though. The next value for the amplification coefficient in this calculation was 40. It is a bit too large a value for the system as there are several under- and overshoots before the temperature calms down. However, the system seems not to be unstable as the fluctuation is fading.

The greatest value, 80, is distinctively too large a value for the system as the over- and undershoots are getting bigger. The system is unstable.

In real installations, rather big fluctuations are not an exception. Even though the fluctuation may seem rather bad in the graph, it needs to be born in mind that the cycle is often rather long. Few people are able to notice this kind of fluctuation if they visit the boiler plant. In some cases the range may be more than 10 °C with a cycle of 15 minutes. Figure 8.22 is based on measurements at an existing boiler plant. It shows how the boiler water temperature was fluctuating in a 700 kW boiler as it was operating around its full capacity. During the later half of the measuring period, the range of the fluctuation was about 10 degrees and the cycle 20 to 25 minutes. The operator of the plant considered the fluctuation to be normal.

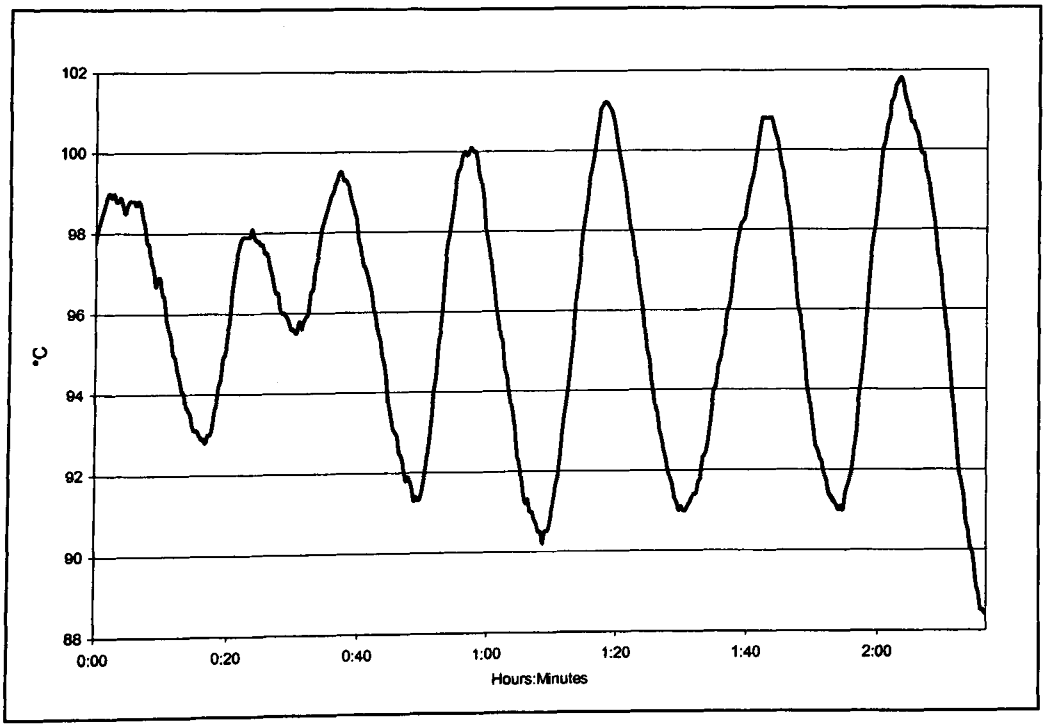

Figure 6.22. Fluctuation in the boiler water temperature.

6.8. Boiler co-operation

The co-operation between the wood chip boiler and the oil-fired back-up boiler has not been studied so far. When the outside temperature is close to the design temperature, it is evident that the back-up boiler operates continuously in addition to the wood chip boiler operating with full capacity. Variations in the need for heat are then taken care of by the back-up boiler, the wood chip boiler operates at a constant rate if the control system works as it should.

An interesting situation takes place when the base load is close to the upper limit of the wood chip boiler and a consumption peak occurs. Depending on the control arrangement, the back-up boiler will assist the wood chip boiler to a certain extent during the peak. The following calculation brings out the significance of certain temperature limits. The outset is that the outside temperature is -2 °C, the steady input to the network is about 1070 kW and the maximum output of the boiler is 1200 kW. There will be a period of DHW consumption which starts at 5 minutes and continues till 45 minutes. It is otherwise similar to the DHW consumption period in previous calculations but it lasts for 10 minutes longer. The mean input for DHW during the consumption period is 438 kW and the maximum 680 kW respectively. The boilers are connected in parallel. The time step is one minute leading to a calculation period of 4 hours.

In the first calculation, the temperature difference set point for starting to open the 2-way valve and letting part of the flow through the back-up boiler, is 15 °C. That is, the temperature of the out flowing supply water needs to be 15 °C below its desired value, before the back-up boiler starts taking part of the heat generation. The two-way valve that separates the back-up boiler from the network moves at moderate speed: It would take 20 minutes to move it from one extreme position to another. The next calculation is otherwise similar, but the temperature difference set value is 10 °C. There are also calculations with 5 and 3 °C set values and, finally, with a set value of 1 °C.

Figure 6.23 shows the outputs from the boiler plant.

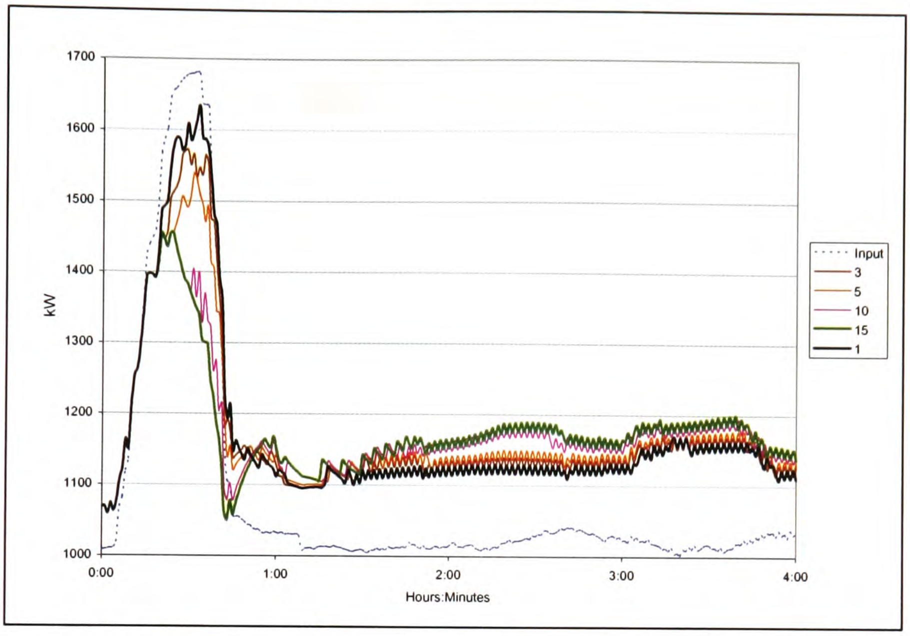

Figure 6.23. Output from the boiler plant with different back-up boiler set values.

As figure 6.23 is difficult to read after the peak, figure 6.24 shows the same data in different scale from 1 hours to 4 hours. Input is not seen. The highest graph is the 15 °C, then follow 10, 5 and 3 °C. The lowest one is the 1 °C.

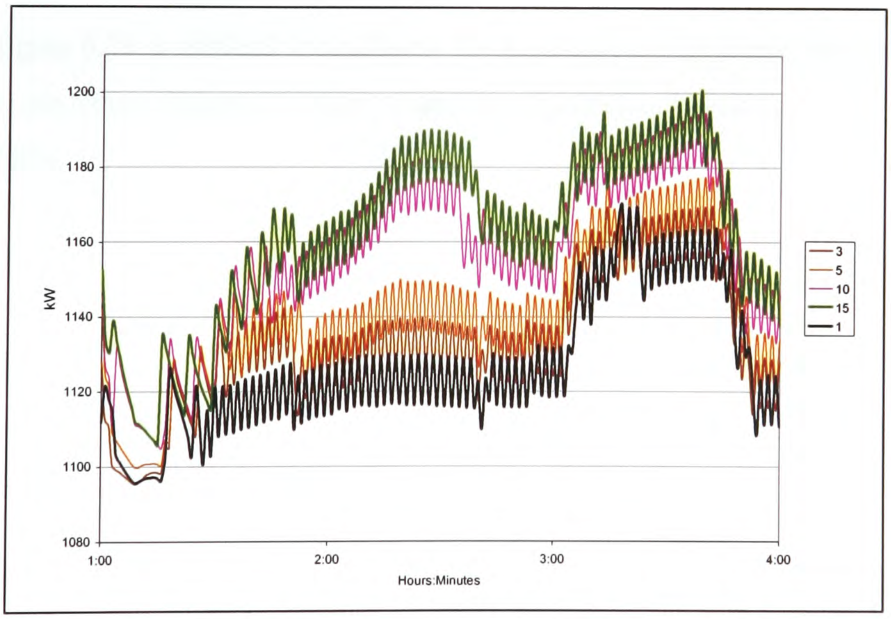

Figure 6.24. Output from the boiler plant with different back-up boiler set values. Scale changed.

The temperature of the out flowing supply water is the interesting thing. Figure 6.25 brings out, how it behaves with different set values.

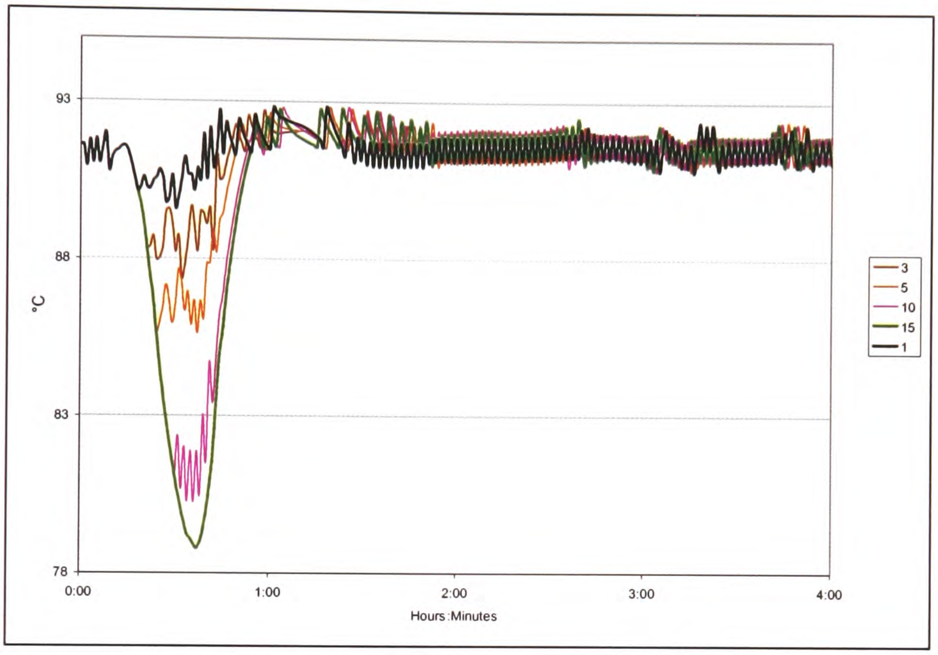

Figure 6.25.Temperature of the supply water outflow from the boiler plant with different back-up boiler set values.

Because figure 6.25 is difficult to read after the peak figure 6.26 shows the same data in different scale from 1 hours to 4 hours. Only two graphs are included to make the figure more readable.

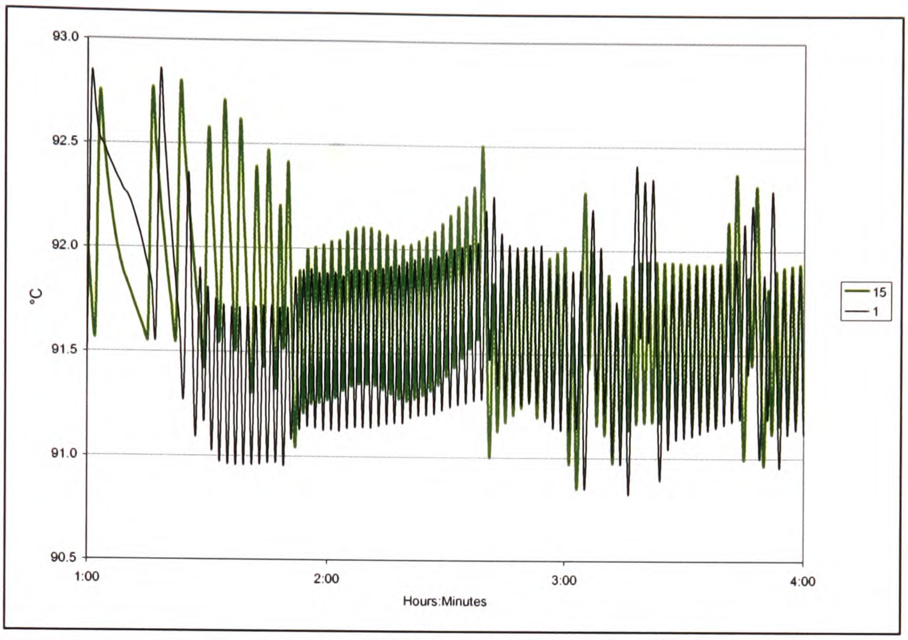

Figure 6.26.Temperature of the supply water outflow from the boiler plant with different back-up boiler set values. Scale changed.

Figure 6.26 brings out that the supply water temperatures half an hour after the peak are practically identical. The wood chip boiler water temperature drop is the main cause of fluctuation in the out flowing supply water temperature. Figure 6.27 shows how the boiler water relates to different set values.

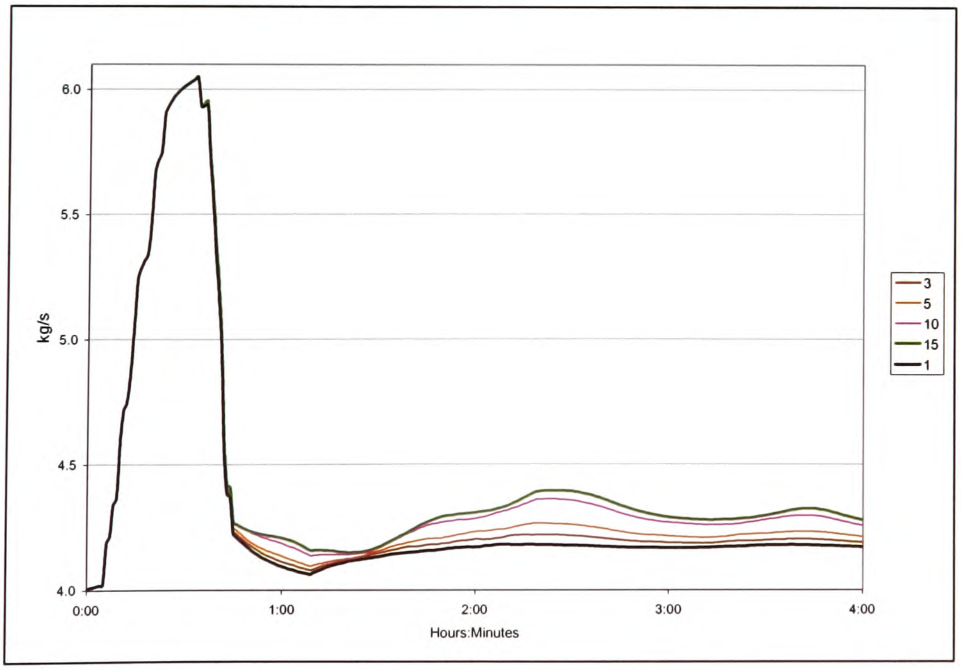

Figure 6.27. Boiler water temperature with different back-up boiler set values.

It can be seen that with a set value of 15 degrees temperature difference the wood chip boiler water temperature comes down by almost 40 degrees. Figure 6.28 illustrates the total outflow from the boiler plant during the whole calculation period and figure 6.29 from 1 hour to 4 hours respectively.

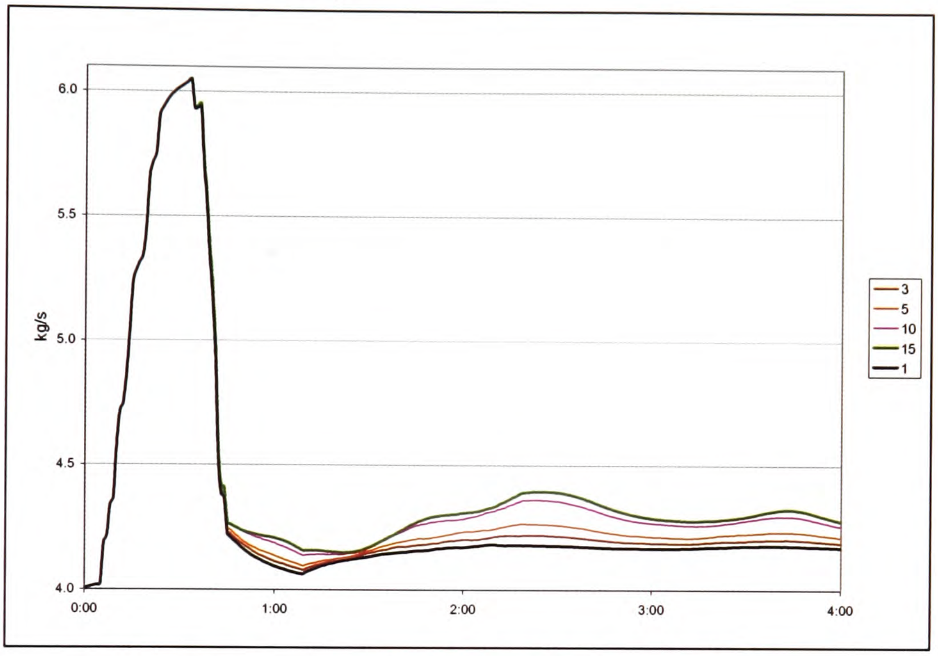

Figure 6.28. Flow rate with different back-up boiler set values.

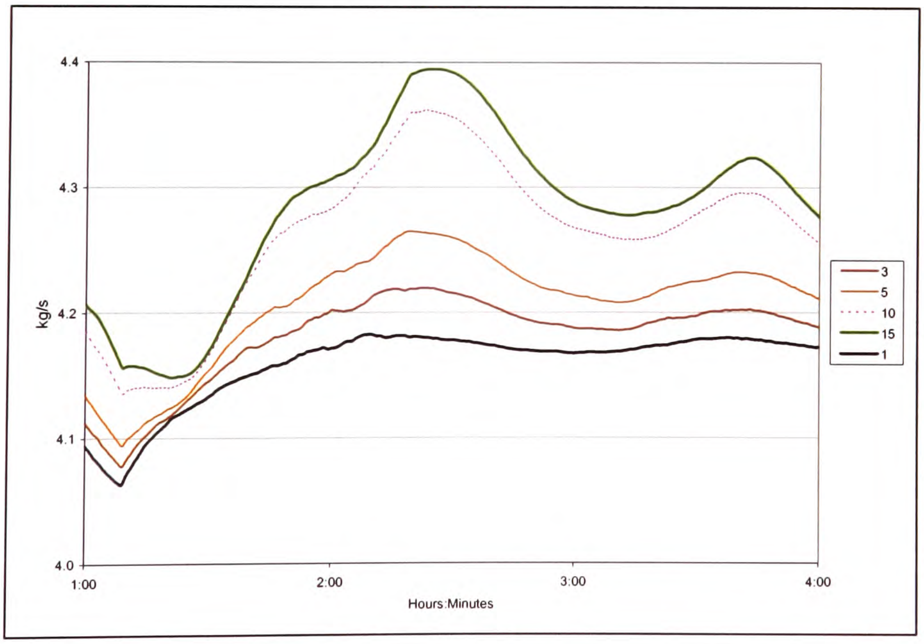

Figure 6.29. Flow rate with different back-up boiler set values. Scale changed.

The consumers should draw 1018 kW from the network after the DHW consumption period. The need is constant and control valves at sub-stations are trying to maintain it despite fluctuations in supply water temperature. Figure 6.30 shows how well they succeed. The period is from 1 hours to 4 hours.

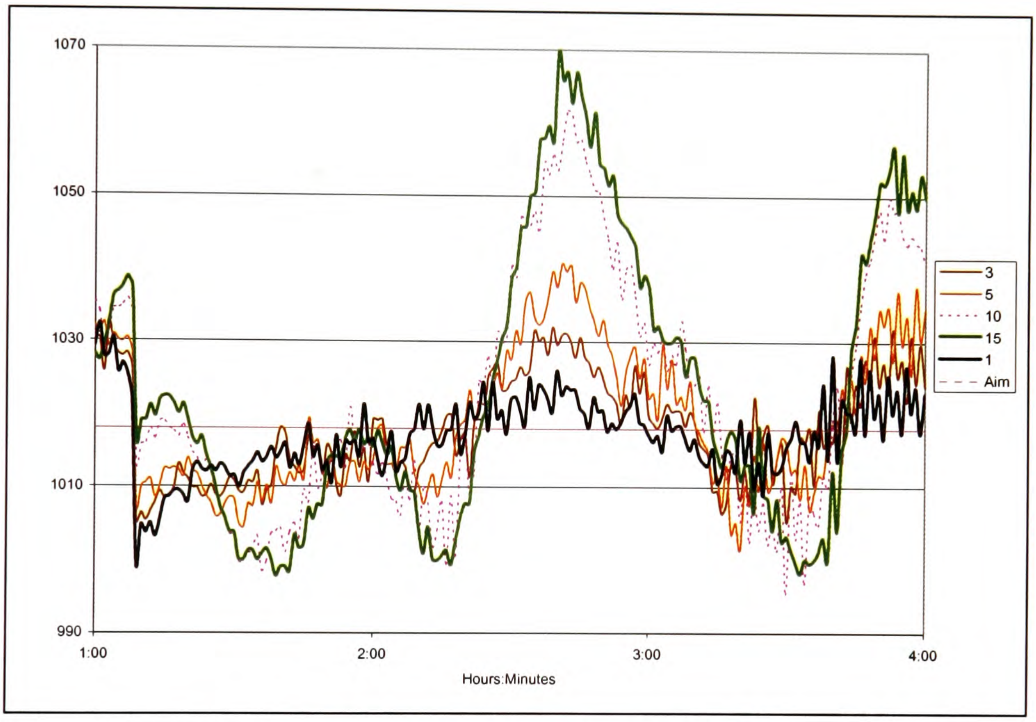

Figure 6.30. Consumer inputs with different back-up boiler set values.

It is clear that the temperature difference set value of 1 minute gives the most stable input of the consumers. With a set value of 15 °C the input is far from stable. Figure 6.31 clarifies the reason for this.

The fluctuation in the outflow temperature moves in the network and disturbs consumers at different points of the network for a long time. Figure 6.31 also brings out that the out flowing supply water drops some 13 °C during the peak. It means that the valve separating the back-up boiler did not open at all as the set value was 15 °C. With a set value of 10 °C it must have opened for a while.

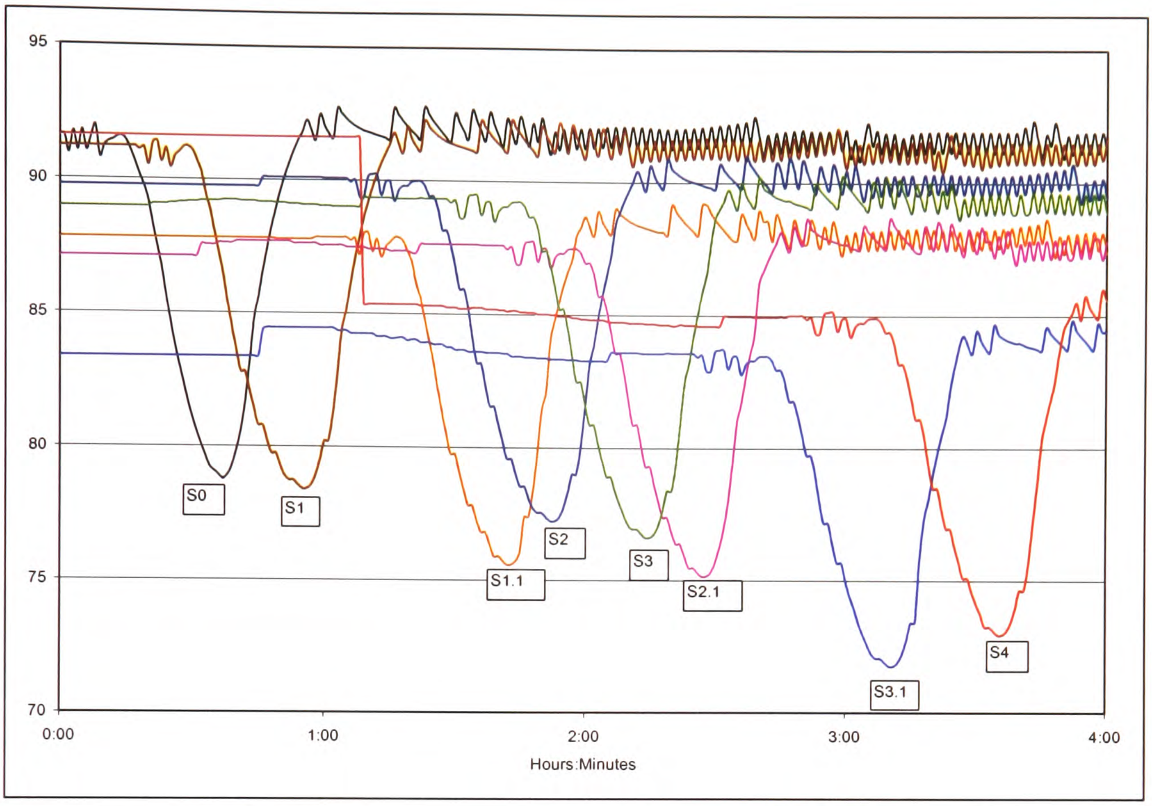

Figure 6.31. Supply water temperatures in the network with a back-up boiler set value of 15 °C.

7. Discussion

7.1. Annual consumption model

When comparing the heat losses between the steady state calculations and the dynamic model calculations, it is justifiable to notice that the starting points are not quite identical. In the steady state model, the temperatures were the typical average ones for a district heating system in Finland; supply 85 °C, return 55 °C and the ground 5 °C. In these systems, heat is quite often generated in large boilers as a by-product of electricity generation and temperatures are high. There is no problem in delivering supply water at a high temperature, but still in water phase. When it comes to smaller boiler plants, pressure limits are a lot lower, control of combustion is not as sophisticated and fluctuations in the need for heat in the DH network are more abrupt. All this leads to lower boiler water temperature set values which, in turn, leads to lower supply water temperatures, because the operators avoid using the back-up boilers if the wood chip boiler is able to generate enough heat to meet the consumption, even though the supply water temperature might not reach its set point. Just to compare the calculation procedure with the data from steady state calculations, the temperature of the supply water was elevated so that the annual average was 85 °C and return water was set to 55 °C. The ground temperature was not tampered with, its annual average was 4.3 °C. With these changes, the annual heat loss was 1099 MWh which is 1 per cent higher than the value from steady state calculation (1086 MWh). This negligible deviation results at least partly from the 0.7 °C difference in the ground temperature.

The other thing that is confused when comparing the results with the steady state model and the dynamic one was that the proportion of domestic hot water was 20 % in the steady state model calculation, whereas in the latter case it turned out to be 12.3 % of the total heat all buildings consume. To find out the significance of this deviation, it is necessary to return to the steady state model calculation. If the proportion of DHW is set to 12.3 %, it will result in an annual consumption of 728.6 MWh. This is well in accordance with 725.3 MWh which is the share of DHW in the dynamic model. The calculation can be seen in the Appendix, table VI, which brings out that the constant output for DHW would be 83 kW and the peak 2594 + 83 = 2677 kW respectively. This differs clearly from the peak that resulted from the dynamic model calculation (2407 kW or 2425 kW depending on heat loss) and the initial steady state model calculation (2541 kW). The new calculation with the steady state model would suggest that the annual heat generation of the wood chip boiler is 5926 MWh that is 84.6 % of the total production. These values result from the lower limit of the boiler being between 18 and 22 per cent of the maximum capacity (1200 kW). The initial calculation with the steady state model rated the wood chip boiler 6028 MWh, that is 86 % of the total.

The idea of the study was to compare the results from different sizing methods. This can be carried out most conveniently by tabulating the data. In table 7.1, SSM stands for steady state model and DM for dynamic model. With the dynamic model, one can determine the annual heat generation in two ways; what is possible and what is probable. With the steady state model, on the other hand, only one result is available.

Figure 7.1 shows the same data in graphic form. On the horizontal axis is the capacity of the wood chip boiler and vertically is its percentage of the total annual heat production. To make the graphs more continuous, intermediate values with 100 kW steps were calculated, and the maximum capacity was elevated from 1.5 MW to 2.0 MW. Steady state model calculations have been carried out with two different DHW shares: 12 % and 20 %. The dynamic model calculation has been carried out solely with the 4 h and 24 limits, as estimating the length of summer pause has been considered to be too approximate.

Table 7.1. Comparison of different calculation methods.

Method/ Size, kW	Identifier	Peak load, kW	Heat loss, %	Heat from chips, probable, %	Heat from chips, possible, %
SSM/700	DHW 20 %, lower level 20 – 27 %	2541	15.5 %	62.8 %	
SSM/700	DHW 20 %, lower level 0 – 20 %	2541	15.5 %	65.6 %	
SSM/900	DHW 20 %, lower level 16 – 21 %	2541	15.5 %	75.4 %	
SSM/1200	DHW 20 %, lower level 17 – 20 %	2541	15.5 %	86.0 %	
SSM/1200	DHW 20 %, lower level 21 – 25 %	2541	15.5 %	84.7 %	
SSM/1500	DHW 20 %, lower level 17 – 20 %	2541	15.5 %	90.5 %	
SSM/1500	DHW 20 %, lower level 21 – 24 %	2541	15.5 %	89.1 %	
SSM/700	DHW 12 %, lower level 12 – 20 %	2677	15.5 %	61.8 %	
SSM/700	DHW 12 %, lower level 21 – 29 %	2677	15.5 %	61.1 %	
SSM/900	DHW 12 %, lower level 17 – 22 %	2677	15.5 %	73.7 %	
SSM/1200	DHW 12 %, lower level 18 – 22 %	2677	15.5 %	84.6 %	
SSM/1500	DHW 12 %, lower level 18 – 22 %	2677	15.5 %	89.6 %	
DM/700	Heat loss 943 MWh	2407	13.7 %	69.0 %	68.6 %
DM/900	Heat loss 943 MWh	2407	13.7 %	79.3 %	79.9 %
DM/1200	Heat loss 943 MWh	2407	13.7 %	83.8 %	87.9 %
DM/1200	Heat loss 1087 MWh	2425	15.5 %	83.2 %	88.1 %
DM/1500	Heat loss 943 MWh	2407	13.7 %	86.8 %	89.3 %

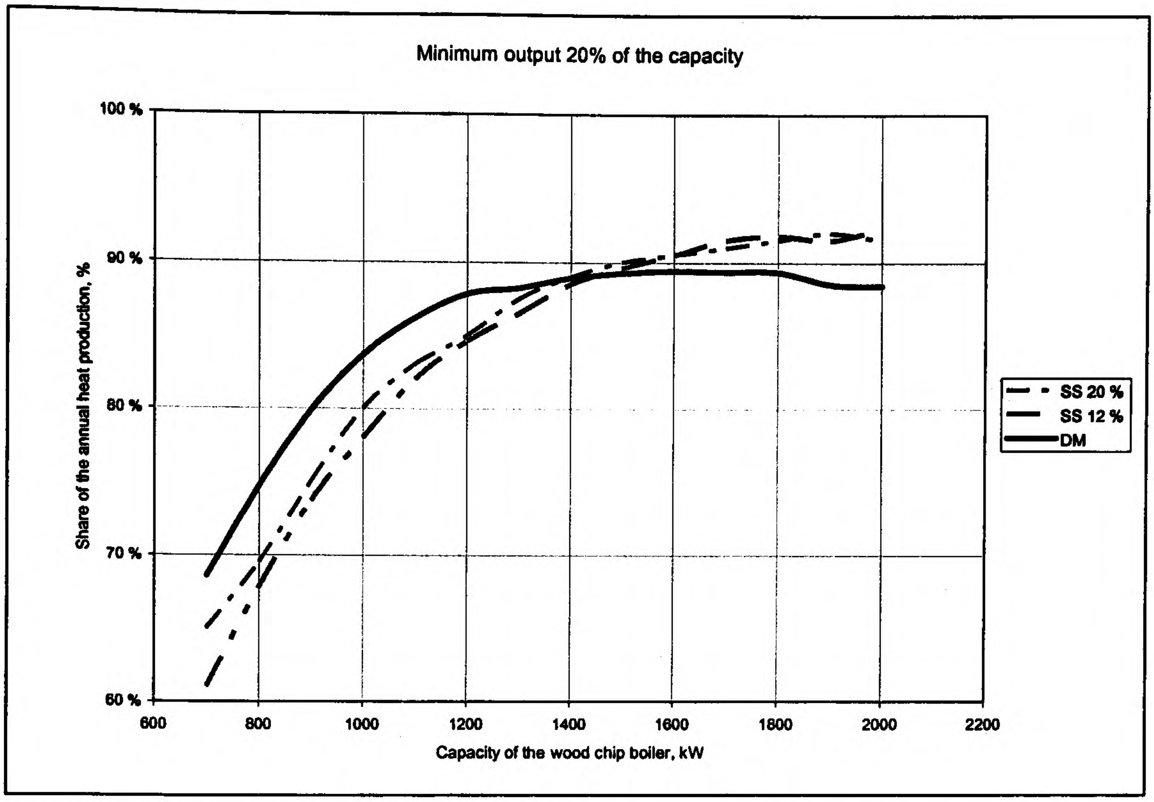

Figure 7.1. Wood chip boiler's share of total heat generation with different calculation methods. Minimum output of the wood chip boiler 20 % of the nominal output. The absolute capacity applied.

The picture illustrates the tendency better than pure figures: With a low capacity, the dynamic calculation gives a bigger share for the wood chip boiler. The slope of the dynamic model graph changes rather rapidly so that above 1200 kW it is almost horizontal. Above 1400 kW both steady state model calculations give a bigger share for the wood chip boiler than the dynamic model.

To find out the significance of the lowest sustainable output limit, the same calculations have been carried out so that the lower limit has been 15 % of the maximum output. The results can be seen in figure 7.2.

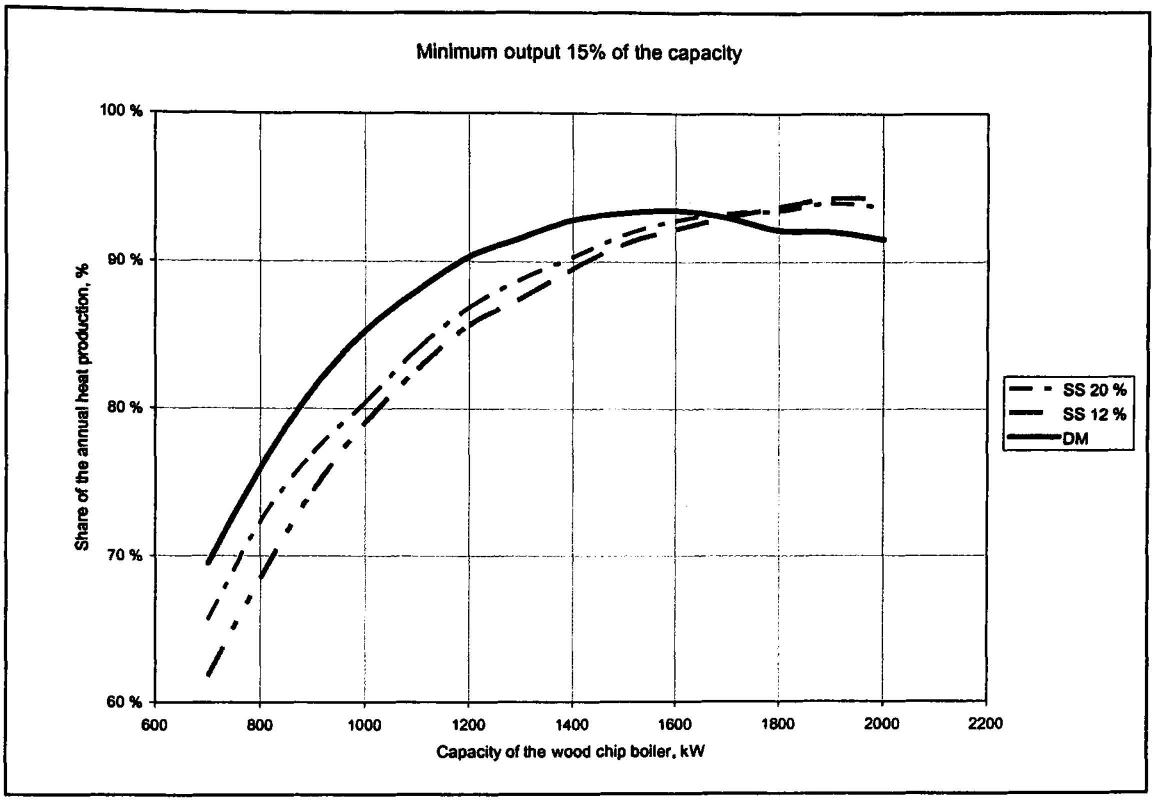

Figure 7.2. Wood chip boiler's share of total heat generation with different calculation methods. Minimum output of the wood chip boiler 15 % of the nominal output. The absolute capacity applied.

The dynamic model graph is not quite as flat now as it was when the lower level was 20 %. Nevertheless, the pattern is the same; with low capacities the dynamic model gives a higher share for the wood chip boiler than either of the steady state model calculations. With high capacities it is vice versa.

Figures 7.1 and 7.2 show the boiler capacity in kilowatts in the horizontal axis. If the relative capacity is substituted for the absolute one, the pattern becomes different. The relative capacity is the capacity of the wood chip boiler in proportion to peak load. It has been shown that different calculation methods give different values for the peak load: For the steady state model calculation DHW 12 % it was 2677 kW, with 20 % DHW it was 2541 kW and the dynamic model resulted in a peak load of 2407 kW. Figure 7.3 illustrates the situation with a lower limit of 20 % of the maximum output. Figure 7.4 is the same graph with a lower level of 15 % of the maximum.

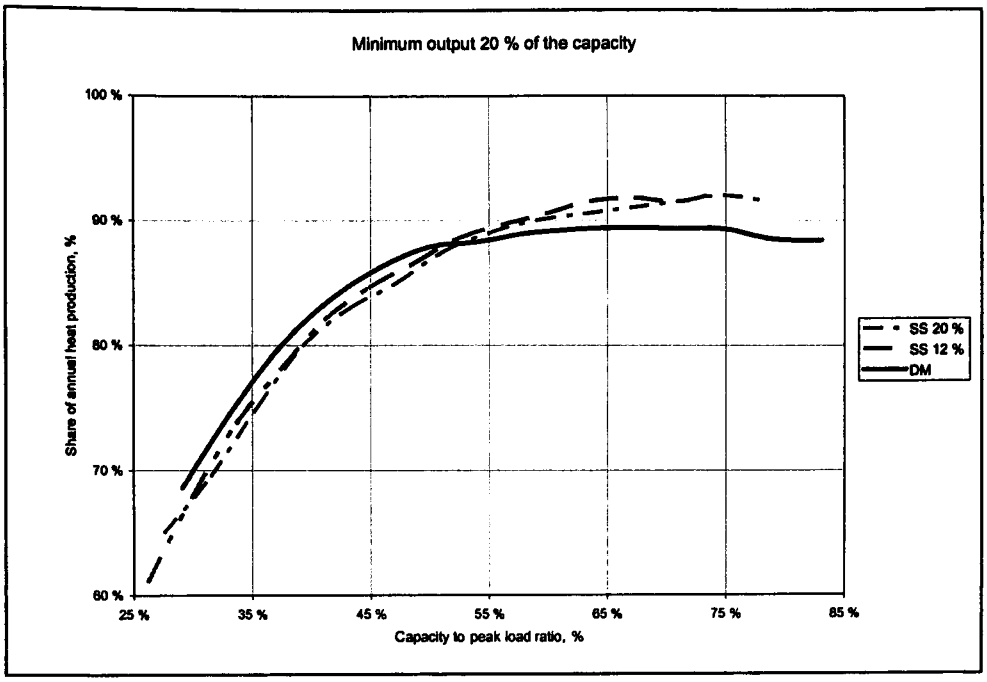

Figure 7.3. Wood chip boiler's share of total heat generation with different calculation methods. Minimum output of the wood chip boiler 20 % of the nominal output. The relative capacity applied.

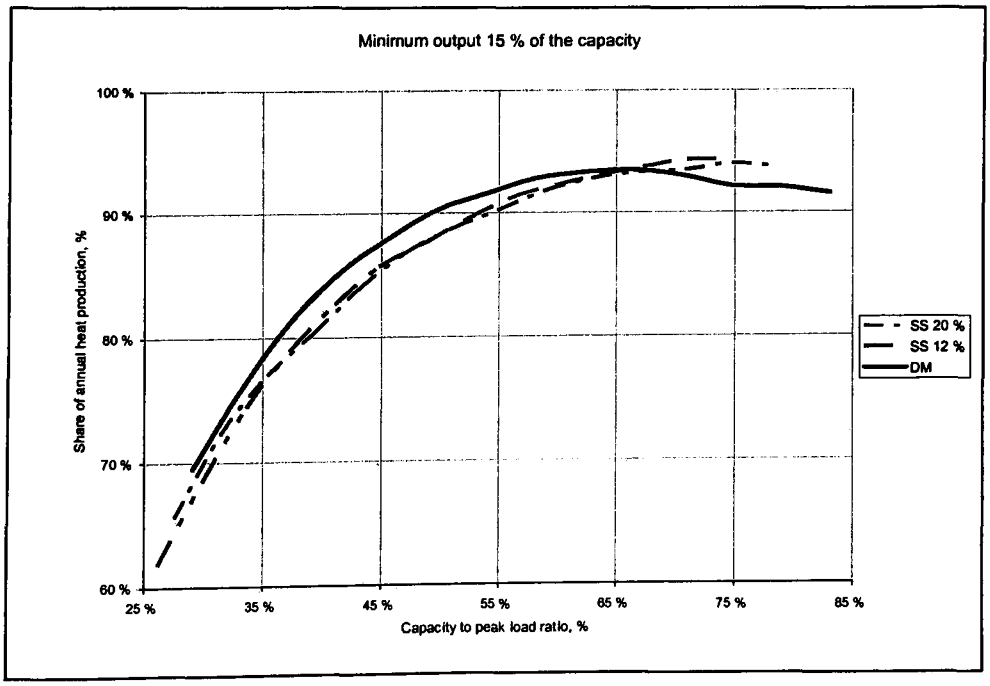

Figure 7.4. Wood chip boiler's share of total heat generation with different calculation methods. Minimum output of the wood chip boiler 15 % of the nominal output. The relative capacity applied.

It can be seen that in both relative capacity figures all the graphs are virtually identical. This would give the impression that these sizing methods give similar results. Nonetheless, the steady state model suggested that the peak load is distinctively higher than was the result from dynamic model calculation. With the same share for domestic hot water (12 %) the former gave a peak load of 2677 kW which is 11.2 % higher than the value from dynamic model calculation (2407 kW). With the selected wood chip boiler capacity (1200 kW) the steady state model gave an annual share for wood chips of 84.6 % whereas the dynamic model resulted in 87.9 % even though with a reasonable summer pause the result was 84 %. Figure 7.1 shows that the sizing would be more or less optimal if the lower limit were 20 % of the maximum output.

In the initial steady state model calculations the DHW share was 20 %. Compared with dynamic model calculations, the results are closer to one another as the DHW share is 20 % than with 12 %. This is the case with both the peak load and the annual share for wood chips. The peak load was 2541 kW which is 5.6 % higher than the corresponding figure from dynamic model calculation. With 12 % DHW share the difference was twice that much.

The essential question in previous calculations is what would the division of heat generation between the wood chip boiler and the back-up boiler be. Of course, this is not the final result, because the main question is: Does it make economic sense to purchase a wood chip boiler? The steady state model calculation suggested that 22.1 €/MWh would be the marginal price for produced heat, i.e. that much could be paid for the one who would supply the chips and run the boiler plant. With the dynamic model, considering that there would be a pause in the heat generation, the marginal price would be 22.0 €/MWh. If there were not any longer pause in the summer, the price would be 23.3 €/MWh. The boiler sizes and the capital cost plus all the unit prices are the same that were introduced in connection with the steady state model calculation. The calculation can be seen in the Appendix, tables VII and VIII.

7.2. Short term simulation model

The main purpose for carrying out calculations with the short term simulation model in Chapter 6 was to show that the model works logically right. There are no measured data nor results from other models available to compare the results with. The direction of the change is, though, easy to predict in most cases. For example, the increase in the need for heat surely increases the primary flow which, in turn, surely decreases the boiler water temperature if the boiler output does not go up along with the increase in the flow rate. In this respect, no contradictions between the calculated results and deduction came out. Another thing is the magnitude of the changes; without comparison material one can only rely on his experience. In a very simple scale, the results seemed more like credible than unbelievable; and even though there is uncertainty, it still makes sense to go the results through.

The first simulation related to the dimensioning of the heat exchangers. It is clear that the last building in the network gets the supply water at a lower temperature than the one that is located close to the boiler plant. With the original size pipe work without any by-pass flow the biggest temperature drop was about 7 °C in a cold winter night. The length of the supply pipe between the building and the boiler plant was a bit more than 2 kilometres. Flow velocities in the pipe work varied between 0.26 and 0.58 m/s. Temperatures of return waters from different sub-stations were rather uniform; the variation was less than 2 °C. The simulation emulated a night-time situation when there is no DHW consumption and all the space heating equipment work with their full output.

The heat loss from the network to ambient ground and further to air was calculated with the model. The most appropriate situation for this purpose is the same cold winter night as was used in the previous simulation. The results could be compared with results from the annual consumption model. It turned out that there was a difference of about 2 % in the results, and a reasonable explanation for even that rather small deviation could be found. On the other hand, the results from the annual consumption model were well in accordance with data given by the pipe manufacturer. In a network with a total length of about 4 kilometres, the maximum heat loss seemed to be around 170 kilowatts, as the total output was 2.3 megawatts. That makes a heat loss of 7 % of the production.

The pipe sizes in the network were chosen without dynamic simulation when the steady state application was carried out. However, during the dynamic simulation it turned out that flow velocities are rather low and the pipes might as well be somewhat smaller. Table 6.4 shows the comparison of supply water temperatures and flow velocities at different nodes in the network in a cold winter night. It came out that the velocities on average more than doubled but the effect on the heat loss was rather small. The coldest supply water temperature (about 2 kilometres from the boiler plant) was only one °C higher than it was with the original size pipe work. The heat loss came down to 6 % of the production. In this respect, it would seem that it is not necessary to reduce the pipe sizes to the minimum just to avoid heat losses.

Domestic hot water peaks were simulated to see how the smaller pipe work could cope with the maximum load situation with full space heating load plus a DHW peak. It turned out, that flow velocities would not cause problems, because the DHW peak (about 500 kW) is relatively small compared with space heating and heat losses (about 2300 kW). The simulation brought out also that the fluctuation in return water temperatures may go on a long time after the peak is over. The magnitude of the fluctuation depends strongly on, is it just one consumer that starts using large amounts of hot water or are there many of them, and the duration depends on how far from the boiler plant the consumers are. The explanation for the dependence on the amount of consumers is that if one consumer takes large amounts of hot water, the primary return water temperature at that point goes extremely low. In the case of several consumers dividing up the same consumption of hot water, the return temperatures stay higher as there is more heat exchange surface available.

It also came out during the DHW peak simulations that in particular the smaller pipe work was rather poor when it came to the accumulative effect of the network. It took only some 7 minutes after the beginning of the peak, until the return water temperature at the boiler plant came distinctly down. With the original size pipe work the time was about 10 minutes, with the same DHW peak. One reason for so fast a feedback is that there were rather large consumers connected to the first node in the network. The distance between the said node and the boiler plant was only 365 metres. Due to the cold winter situation, the flow rates were also at the maximum, which means that in warmer times of the year the accumulative capacity of the pipe work would be better. This was shown with the subsequent simulation which showed that on a summer day it took almost half an hour until the return water temperature started to go down with the original size network and some 25 minutes with the smaller network. With two DHW peaks the return water temperatures seemed to fluctuate several hours in a summer situation. This is something that should be considered when setting parameters for control valves at the boiler plant and consumer sub-stations.

The summer time simulations brought out that it would be necessary to have some by-pass flow at certain points of the network in the summer. Otherwise the flow rates would be so low that the temperature drop at the end of the network would be beyond an acceptable level. In the outside temperature of 12 °C, a suitable by-pass flow seemed to be in the region of 40 to 80 per cent of the total flow. That would guarantee the supply water to be warm enough for domestic hot water preparation.

All the above discussed summer time calculations relate to the stability of the output. The conclusion could be that domestic hot water consumption, despite being momentary, keeps the output higher for some hours after the consumption has ceased. This could help in keeping the wood chip boiler in operation during the daytime in spite of higher outside temperatures. During the night, the domestic hot water consumption being non-existent, the colder outside temperature could create enough load for the wood chip boiler.

The dynamics of the boiler plant was studied in several simulations. The effect of boiler water volume, parameters of the automatic controller and parameters of the back-up boiler were under inspection. These simulations are very case-dependent and it is difficult to generalise the results. They were carried out mainly to show how the model works. There are, though, some interesting points worth mentioning. One of them is that the effect of boiler water volume on the required combustion output during and after a DHW peak seemed to be smaller than one could have expected. Nevertheless, this would require further investigation since the dynamics of the combustion system are not known well enough at this point. Another interesting point resulting from the simulations is that the by-pass boiler parameters should be designed carefully. With proper set values the temperature of the out flowing supply water fluctuated a lot less than with poorly selected values, and if the out flowing temperature fluctuates, it causes more fluctuation in the network as control valves at consumer sub-stations try to counteract the change in the supply water temperature by altering the flow rate.

8. Conclusions and further research needs

8.1. Steady state model

The steady state model introduced in this study or some of its many variations is the most often used tool for carrying out feasibility studies on wood chip boilers. When it comes to the very smallest units, rules of thumb are preferred to calculation, but as the capital cost gets bigger, people begin to want more and more facts to support their decisions.

In the steady state model, prevailing temperature data is relied on. Other weather related factors such as wind and solar radiation are simply ignored. These kinds of energy consumption calculations have been carried out for such a long time that they just cannot be completely false. Years differ from one another but on the average, the steady state model gives satisfactory results. That is known from experience.

What is said above, relates to using the steady state model for calculating the monthly division of the known annual heat consumption or the amount of heat that could be produced by the wood chip boiler on an annual basis. It is known that the consumption of domestic hot water does not fit in the calculation procedure very well. But it has been thought that as some simplifications are anyhow made by ignoring the effect of the wind for example, one can as well consider that DHW consumption is of minor importance compared to outside temperature and let the latter dominate the calculation.

In the case studied with the two models, it came out that the steady state model gave smaller percentages of annual heat production for the wood chip boiler if its capacity was less than approximately half of the peak, compared with the dynamic model. As the capacity of the wood chip boiler was more than approximately half of the peak, the steady state model started to give bigger percentages for the wood chip boiler than the dynamic model. The turning point seemed to relate to the minimum sustainable output of the wood chip boiler so that as the minimum output came down the turning point went up. Since only one case was studied, it is difficult to generalise more than that. However, the difference seemed to be in the order of a few percentage units, notably if the share of DHW consumption of the total consumption was somewhat over-estimated.

One thing that may cause deviation is the accuracy of the prevailing temperature data: In this case the temperature durations were with 1 degree intervals; whereas sometimes the step is 2 degrees. That would make the graph illustrating the wood chip boiler's share of annual heat production against boiler capacity rather uneven. Anyway, since the minimum sustainable output of the wood chip boiler is very seldom known exactly, one should calculate with different values that are obviously in the right region instead of using a fixed value. It may happen that changing the minimum output value by one percentage unit results in a change in the wood chip boiler's annual share by several percentage units.

When it comes to finding out the peak that is dimensioning the boiler plant, the steady state model is not on a very steady ground because for one thing, the DHW peaks are handled rather poorly and, for another thing, the accumulative effect of the network is ignored. One might think that the steady state model would give smaller peak loads compared with the dynamic model as the true DHW peaks are definitely bigger than the average that is used in the steady state model. In the case studied, the difference between the peak loads was rather small, though. And it came out that the steady state model gave bigger peaks than the dynamic one. The difference was in the region of 5 to 10 per cent so that with an over-estimated DHW consumption in the steady state model calculation, the results were closer to each other.

8.2. Annual consumption model

The dynamic model introduced in this study relies on the same prevailing outside temperature data as the steady state model. That is the effect of wind is ignored in this model. Solar radiation, on the other hand, has been included in the model just like all the other predictable heat gains. The main difference between the two models is that the dynamic one takes into consideration the daily, weekly and yearly rhythm of the occupants and the sun.

The obvious weak point of the model is that items that need to be fed in the application are probably never known exactly, and they may not always be constants like the application considers. However, compared with the steady state model that ignores the heat gains completely, the dynamic model presented is surely a step in the right direction. If one is unsure about the heat gains, it is always possible to feed in rather moderate values so that the weighting of the heat gains becomes lesser.

Another weak point is that using the model is rather laborious. It takes quite a lot time to walk around all the buildings and write down all the necessary details. It is not effortless either to calculate for each building separately what the peak needs to be so that it results in desired annual heat consumption and what the DHW consumption rates at different buildings through the day and night have to be so that the total consumption equals with the desired. However, the model is not meant to be a tool for everyday analyses. The original idea was to create one, but it turned out that it needs to be a model that can be used for evaluating the accuracy of some less complex model which, in turn, can be used as an everyday tool. After the comparison of the results, it seems that the steady state model is a useful tool for the field.

There were actually two things in the steady state model that raised doubts in the first place and gave a reason to create another model: The cumulative handling of outside temperatures which does not take into account *when* the temperatures occur. Another thing was that the timing of DHW consumption is ignored in the steady state model. There would have to be more case studies before one could say for sure how it is, but this study suggests that the deviation between the results of the models is rather small. It also needs to be born in mind that accurate calculations will never be available: There are always aspects that cannot be predicted exactly, such as weather conditions, the behaviour of the heat consumers and the industriousness of the operator of the boiler plant.

There is still something that needs to be considered if the usage of the wood chip boiler in the summer is the aim. For one thing, if the boiler operates at a very low output, its efficiency is probably rather low, which should be taken into account in the viability calculations. For another thing, emissions in the flue gas tend to be many times higher when the output is low compared with nominal or even moderate output [23]. Additional problems relate to soot build-up, difficulties with the multi-cyclone type fuel gas precipitator (as the flow rate goes below its range) and back-fire problems. All this is to say that it does not eventually make either financial or technical sense to try to keep the wood chip boiler in operation when the need for heat declines frequently rather low.

8.3. Short term simulation model

The model for short term simulation of the heating system, the network and to a certain extent, the consumers of heat is by far the most complex application introduced in this study. The creation of it has taken several years. It has many features that have not been taken advantage of in this study, due to requirements to keep the thesis in a reasonable size. The idea, though, was to introduce the application and carry out calculations that relate closely to the rest of the study. Extensive simulation series would be another story.

The model is at its most useful if the setup is not a typical one. If there are just buildings that draw heat from the network at almost constant rate, there is no idea to study the dynamics of the system. In a case in which some large consumer rapidly changes its heat consumption, it would be interesting to find out in advance how these fluctuations are going to affect other consumers and the boiler plant. The results of the simulation could be taken advantage of when designing the plant and the network. There are several factors to be experimented with: Pipe sizes, boiler water volume and temperature, control valve authorities and types, set values for the back-up boiler, set value for the DH pump pressure difference etc.

The calculations carried out in this study gave an idea of the dynamics of the network. How long it takes, before a temperature pulse in the network reaches the farthest consumers? What is the order of magnitude of the cooling in the network? Should it be considered when dimensioning the heat exchangers? The relevance of sizing the network the right way: It seems not to be a simple question as over-sizing clearly gives the boiler plant more time to generate the heat that has been consumed during the peak. The drawback is increased capital cost. Larger pipe sizes also require more by-pass flow during summer. The heat loss, though, does not seem to change significantly along with different pipe sizes.

This study gives some general outlines about the dynamics of the system. Probably the most useful is the comprehension that a peak in the network causes immediately a certain load in the boiler plant, and another load takes place when the cooled water returns from the consumer to the boiler plant. If the consumer is located close to the boiler plant and the peak lasts for a while, these two loads may overlap. By proper sizing of crucial pipelines, the designer may impede the overlapping and, thus, size the boiler somewhat smaller. The potential for taking advantage of the accumulative effect of the network depends on the nature of the heat consumption; return water from a DHW heat exchanger comes in a different (usually lower) temperature compared with return water from a heating or ventilation heat exchanger.

8.4 Overall conclusions

The purpose of the study was to introduce the models and to compare their results with the same case study. As a conclusion, it could be said that the steady state model seems to give satisfactory results, notably if the DHW consumption is estimated to be somewhat more than it probably is. It needs, however, to be born in mind that the deviation in the calculated wood chip boiler's annual heat production may be several percentage units. That should be considered by carrying out a sensitivity analysis on the question.

Four models were introduced: A steady state model for the annual calculation of heat consumption, a dynamic model for annual heat consumption calculation in a single building, a dynamic model that enables connecting the consumptions of several buildings and makes them a district heating system to be studied on annual basis and, finally, a short term simulation model that makes it possible to study interactions in the district heating system including the boiler plant, the distribution network and the consumer sub-stations. Due to the limited amount of simulations and the lack of measured data or some other comparison material, it is not possible to give any clear design instructions based on this study. Nevertheless, the study brought out several interesting interactions in the district heating system, which, on the one hand, are good to realise when designing a DH system and, on the other hand, give a reason for further research.

8.5. Recommendations for further research

Validating the annual consumption model with an existing case would be necessary to find the correct parameters for different types of buildings. It would also give an idea of the accuracy that can be achieved with the model. Verification would, however, require extensive measurements through the whole year (or several years). These measurements would not necessarily be difficult to carry out as one probably could estimate which factors are worth measuring and which are not that significant. Nevertheless, it would require quite a lot measuring equipment, since at least heat and electricity consumption would have to be measured in all the buildings under survey. Alternately, or in addition to validating the model, it would be useful to carry out a few case studies more with the steady state model and the dynamic one so that one could get more diversified results.

When it comes to the short term simulation model, measurements would be needed to find out how rapidly the boiler can increase or decrease its output from different starting points. Of course, measurements would be needed from several boilers of different types and sizes and probably even different fuels, too. At least moisture content apparently affects the 'acceleration' of the boiler. In general, a lot of measured data covering the dynamics of different wood chip boilers would be useful. These data should include several variables such as boiler water temperatures, combustion air flow rates, flue gas temperatures, return water temperatures and the positions of the control valves at the boiler plant. Moreover, concentration of some harmful pollutants in the flue gas should be measured. Validating this model, too, with a real case, would be necessary. The main problems relating to validating are that flow rates and temperatures should be measured in many places at the same moment and that the position of the control valves should be measured too. Temperature measurements are not a problem, but flow rates are another thing. Logging the position of control valves has also proved not to be very easy. It is obvious that verification of the whole model would be practically impossible to be carried out, but a realistic approach could be to validate some parts, kind of sub-systems, of the model at a time.

The short-term simulation model could be developed further, so that pumps and fans would be included in order to simulate the electric power intake in different situations. That would be basically easy as the need for combustion air can be readily calculated if the boiler output, moisture content of the fuel and the excess air factor are known. The flue gas flow is not a problem either. Instead, a problem might be that the excess air factor is not constant but it relates to the output. Thus, at least data from measurements would be required to model the interdependence between these two factors. The same goes for the ratio between primary and secondary air: Even if the total combustion air requirement is known, the division might not be.

It would also be interesting to carry out several simulation calculations, concerning the dynamics of the system, with different DH networks and boiler connections so that one could get either simple equations or some rules of thumb for the design process of a small district heating system, which typically is carried out without any sophisticated network simulation software.

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Nomenclature

Abbreviations

CHP = Combined Heat and Power
DH = District Heating
DHW = Domestic Hot Water
DM = Dynamic Model
HVAC = Heating, Ventilation and Air-Conditioning
N = Node
NTU = Number of Transfer Units
PID = Proportional, Integral and Derivative (controller)
R = Return
S = Supply
SSM = Steady State Model
VAT = Value-Added Tax

Symbols

Latin letters:

A = Heat transfer area [m^2]
a = Altitude (of the sun) [°]
C = Heat capacity rate [kJ/(K s)]
C_γ = Ratio of heat capacity rates [-]
C_o = Flow coefficient [%]
c_p = Specific heat capacity [kJ/(kg K)]
C_v = Valve flow coefficient [%]
D = Diameter [m, mm]
d = Declination [°]
E = Time difference [min]
I = Incident radiation [W/m^2]
k = Thermal conductivity [W/(m K)]
L = Latitude, Stroke (of a valve) [°, %]
l = Thickness, Length [m, mm]

L_o = Longitude [°]

$\dot{m}$ = Mass flow [kg/s]

n = Day number [-]

p_r = Authority (of a valve) [%]

q = Heat transfer rate, Need for heat [kW]

R = Adjustability (of a valve) [-]

R_E = Thermal resistance of the insulated pipe per metre of pipe [(m K)/W]

R_M = Thermal resistance of the ground per metre of pipe [(m K)/W]

T = Temperature [°C]

t = Time [s, min, h]

U = Heat transfer coefficient [W/(m^2 K)]

U′ = Heat transfer coefficient of a pipeline per metre of pipe [W/(m K)]

V = Volume, diurnal water usage [dm^3, dm^3/day]

$\dot{V}$ = Volume flow [dm^3/s]

X = Valve lift [%]

Z = Azimuth (of the sun) [°]

Greek letters:

Δ = Difference, Change [-]

ε = Effectiveness [%]

ρ = Density [kg/dm^3]

Subscripts

a = Available
b = Boiler
c = Cold
d = Design
g = Ground
h = Hot, Highest
I = Inside, Insulation, In
j = Jacket
l = Lowest
lm = Log mean
loc = Locality
min = Minimum
n = Nominal
o = Outside, Out
off = Official
p = Pipe, Primary, Preferred
s = Secondary
v = Vertical
w = Wood chip boiler

Appendix

Table I. Temperature durations, output and energy generation for different purposes.

Outside temperature °C	Duration hours p.a.	Relative output %	Output for heating kW	Output for DHW kW	Heating energy generation MWh	DHW energy generation MWh	Total energy generation MWh
28,5	3	0,0 %	0	135	0,0	0,4	0,4
27,5	2	0,0 %	0	135	0,0	0,3	0,3
26,5	4	0,0 %	0	135	0,0	0,5	0,5
25,5	16	0,0 %	0	135	0,0	2,2	2,2
24,5	34	0,0 %	0	135	0,0	4,6	4,6
23,5	20	0,0 %	0	135	0,0	2,7	2,7
22,5	71	0,0 %	0	135	0,0	9,6	9,6
21,5	71	0,0 %	0	135	0,0	9,6	9,6
20,5	89	0,0 %	0	135	0,0	12,0	12,0
19,5	122	0,0 %	0	135	0,0	16,5	16,5
18,5	174	0,0 %	0	135	0,0	23,5	23,5
17,5	234	0,0 %	0	135	0,0	31,6	31,6
16,5	304	0,0 %	0	135	0,0	41,1	41,1
15,5	299	0,0 %	0	135	0,0	40,4	40,4
14,5	308	2,4 %	57	135	17,6	41,6	59,3
13,5	371	4,8 %	115	135	42,5	50,1	92,6
12,5	317	7,1 %	172	135	54,5	42,8	97,3
11,5	259	9,5 %	229	135	59,3	35,0	94,3
10,5	236	11,9 %	286	135	67,6	31,9	99,5
9,5	230	14,3 %	344	135	79,0	31,1	110,1
8,5	242	16,7 %	401	135	97,0	32,7	129,7
7,5	177	19,0 %	458	135	81,1	23,9	105,0
6,5	187	21,4 %	515	135	96,4	25,3	121,7
5,5	224	23,8 %	573	135	128,3	30,3	158,6
4,5	289	26,2 %	630	135	182,1	39,1	221,1
3,5	333	28,6 %	687	135	228,9	45,0	273,9
2,5	358	31,0 %	745	135	266,6	48,4	314,9
1,5	450	33,3 %	802	135	360,8	60,8	421,6
0,5	582	35,7 %	859	135	500,0	78,7	578,7
-0,5	423	38,1 %	916	135	387,6	57,2	444,8
-1,5	295	40,5 %	974	135	287,2	39,9	327,1
-2,5	192	42,9 %	1031	135	197,9	26,0	223,9
-3,5	213	45,2 %	1088	135	231,8	28,8	260,6
-4,5	189	47,6 %	1145	135	216,5	25,5	242,0
-5,5	164	50,0 %	1203	135	197,3	22,2	219,4
-6,5	159	52,4 %	1260	135	200,3	21,5	221,8
-7,5	108	54,8 %	1317	135	142,3	14,6	156,9
-8,5	129	57,1 %	1375	135	177,3	17,4	194,8
-9,5	113	59,5 %	1432	135	161,8	15,3	177,1
-10,5	90	61,9 %	1489	135	134,0	12,2	146,2
-11,5	74	64,3 %	1546	135	114,4	10,0	124,4
-12,5	98	66,7 %	1604	135	157,2	13,2	170,4
-13,5	112	69,0 %	1661	135	186,0	15,1	201,2
-14,5	65	71,4 %	1718	135	111,7	8,8	120,5
-15,5	49	73,8 %	1775	135	87,0	6,6	93,6
-16,5	60	76,2 %	1833	135	110,0	8,1	118,1
-17,5	34	78,6 %	1890	135	64,3	4,6	68,9
-18,5	42	81,0 %	1947	135	81,8	5,7	87,5
-19,5	23	83,3 %	2005	135	46,1	3,1	49,2
-20,5	23	85,7 %	2062	135	47,4	3,1	50,5
-21,5	30	88,1 %	2119	135	63,6	4,1	67,6
-22,5	27	90,5 %	2176	135	58,8	3,6	62,4
-23,5	11	92,9 %	2234	135	24,6	1,5	26,1
-24,5	5	95,2 %	2291	135	11,5	0,7	12,1

-25,5	8	97,6 %	2348	135	18,8	1,1	19,9
-26,5	8	100,0 %	2406	135	19,2	1,1	20,3
-27,5	5	100,0 %	2406	135	12,0	0,7	12,7
-28,5	2	100,0 %	2406	135	4,8	0,3	5,1
-29,5	3	100,0 %	2406	135	7,2	0,4	7,6
					5822	**1184**	**7006**

In table I, the outside temperature goes with 1 degree steps so that the value in the middle of the range is shown, e.g. 20.5 stands for temperatures between 20 and 21.

Table II. Calculation of the marginal price of produced heat. Minus sign indicates expenses to the municipality.

			subsidy, %	subsidy, €
Boiler plant	460000	€	15 %	69000
Foundation	30000	€	15 %	4500
DH pipework	803000	€	15 %	120450
Heat measuring	46000	€		0
DH sub-stations	91000	€		0
Subtotal	**1430000**	€		**193950**
Capital cost (1430000 € - 193950 €)	1236050	€		
Repayment period	20	a		
Interest rate	3,0	%		
Annual instalment (1236050 €, 20 a, 3 % interest rate)	-83082	€/a		
Heat for own buildings (municipality)	3019	MWh/a		
Heat for sale (other customers)	2901	MWh/a		
Fuel oil price	0,40	€/l		
Heat produced from wood chips	6028	MWh/a		
Heat produced from oil	978	MWh/a		
Price of sold heat (other customers)	42,4	€/MWh		
Saving in heating of own buildings because no oil is needed (municipality) 3019 MWh/0.85 x 0.40 €/l x 100 l/MWh	142080	€/a		
Income from selling of heat to other customers 2901 MWh x 42.4 €/MWh	122994	€/a		
Annual cost for using oil as back-up fuel 978 MWh/0.8 x 0.40 €/l x 100 l/MWh x (-1)	-48900	€/a		
Annual cost of produced heat (municipality pays to the co-operative)	-133092	€/a		
Marginal price for produced heat	**22,1**	€/MWh		
Expenses, total (to the municipality)	-265074	€/a		
Incomes and savings, total (to the municipality)	265074	€/a		

Table III. Calculation of electricity consumption.

Nr	Consumption kWh/m^3, a	Daytime consumption coefficient	Daytime hours	Night time hours	Lighting share, %	Lighting kWh/a	Other consumption kWh/a
1/1	13.0	1.5	16	8	25 %	3522	10567
1/2	13.0	1.5	16	8	25 %	3522	10567
1/3	8.0	4	8	16	5 %	4106	78019
2	8.0	2	10	14	10 %	8541	76869
3	8.0	4	10	14	10 %	1799	16195
4	13.0	2.5	16	8	20 %	17155	68620
5/1	13.0	1.5	16	8	25 %	2728	8185
5/2	13.0	1.5	16	8	25 %	1560	4681
5/3	13.0	1.5	16	8	25 %	2728	8185
6	13.0	1.5	16	8	25 %	9654	28963
7	13.0	1.5	16	8	25 %	8578	25733
8	10.0	3	8	16	10 %	1248	11235
9/1	8.0	4	8	16	5 %	819	15569
9/2	13.0	1.5	16	8	25 %	3121	9362
10	8.0	2	8	16	15 %	3865	21904
11	8.0	4	7	17	5 %	1215	23094
12	10.0	4	8	16	5 %	4842	91993
13	13.0	2.5	8	16	10 %	2026	18232
16	0.0					0	0
17/1	13.0	1.5	16	8	25 %	5849	17547
17/2	13.0	1.5	16	8	25 %	5119	15357
17/3	13.0	1.5	16	8	25 %	4626	13879
18/1	13.0	1.5	16	8	25 %	6497	19491
18/2	13.0	1.5	16	8	25 %	6497	19491
18/3	13.0	1.5	16	8	25 %	4325	12976
19/1	13.0	1.5	16	8	25 %	16918	50753
19/2	13.0	1.5	16	8	25 %	16918	50753
20/1	13.0	1.5	16	8	25 %	2719	8158
20/2	13.0	1.5	16	8	25 %	2272	6816
20/3	13.0	1.5	16	8	25 %	2272	6816
20/4	13.0	1.5	16	8	25 %	3176	9527
33	10.0	2.5	8	16	10 %	2040	18363
34/1	13.0	4	8	16	3 %	807	26093
34/2	13.0	3	8	16	10 %	2223	20006
40	8.0	4	8	16	5 %	675	12830
44	8.0	2	8	16	15 %	2163	12255
45	10.0	3	8	16	10 %	1000	9001
						167128	**858084**

In table III, the names of the buildings are not shown but the numbers match with table 5.1. *Consumption* shows how many kilowatt-hours per cubic metre the building is supposed to consume electric power per year. *Daytime consumption coefficient* tells the estimated relation between daytime and night time consumption. *Daytime hours* and *night-time hours* relate to the duration of above periods. *Lighting share* is estimation of which part of the total electricity consumption is used for internal lighting. The next column tells the same in kilowatt-hours per year. The last column shows how much electricity is used for other purposes than lighting, on annual basis.

Table IV. Occupancy in buildings.

Nr	People night time	Daytime period weekdays	Occupants daytime weekdays	Daytime period weekends	Occupants daytime weekends	Lights on weekdays	Lights on weekends
1/1	18	7-17	9	0-24	13.5	6-22	8-23
1/2	18	7-17	9	0-24	13.5	6-22	8-23
1/3	0	8-16	150		0	8-16	
2	5	7-17	15	0-24	3	7-18	9-16
3	0	9-19	10		0	9-19	
4	40	7-16	50	0-24	40	6-22	8-22
5/1	14	0-24	14	0-24	14	6-22	8-22
5/2	8	0-24	8	0-24	8	6-22	8-22
5/3	14	0-24	14	0-24	14	6-22	8-22
6	40	0-24	40	0-24	40	6-22	8-22
7	25	7-16	30	0-24	25	6-22	8-22
8	0	8-16	10	8-16	10	8-16	8-16
9/1	0	8-16	5		0	8-16	
9/2	6	7-17	3	0-24	4.5	6-22	8-23
10	6	8-16	10	0-24	4	6-22	8-23
11	0	8-15	50		0	8-15	
12	0	8-16	30		0	8-16	
13	5	8-16	15	0-24	4	6-22	8-23
16							
17/1	23	7-17	11	0-24	17	6-22	8-23
17/2	20	7-17	10	0-24	15	6-22	8-23
17/3	18	7-17	9	0-24	13	6-22	8-23
18/1	32	7-17	16	0-24	24	6-22	8-23
18/2	32	7-17	16	0-24	24	6-22	8-23
18/3	21	7-17	11	0-24	16	6-22	8-23
19/1	74	7-17	37	0-24	56	6-22	8-23
19/2	74	7-17	37	0-24	56	6-22	8-23
20/1	12	7-17	6	0-24	9	6-22	8-23
20/2	10	7-17	6	0-24	7.5	6-22	8-23
20/3	10	7-17	6	0-24	7.5	6-22	8-23
20/4	14	7-17	6	0-24	11	6-22	8-23
33	3	8-16	5	0-24	2	6-22	8-23
34/1	0	9-17	5	0-24	0	9-17	
34/2	3	9-17	6	9-17	6	6-22	8-23
40	0	8-16	3		0	8-16	
44	5	8-16	5	0-24	3	6-22	8-23
45	2	9-17	4	9-17	4	6-22	8-23

In table IV, *People night time* gives the number of people occupying a building in the night period. *Daytime period weekdays* tells the hours when people are supposed to leave and enter a residential building or enter and leave a non-residential building that is it defines the daytime period on weekdays. *Occupants daytime weekdays* tells the number of occupants in a building in above period. *Daytime period weekends* tells the hours when people are supposed to leave and enter a residential building or enter and leave a non-residential building that is it defines the daytime period on weekends. In most cases it is 24 hours, because it is difficult to say how people act on weekends. *Occupants daytime weekends* tells the number of occupants in a building in above period. In most cases it is the average of day and night occupation on weekdays. *Lights on weekdays* tells the hours when internal lights are supposed to be on, provided that people are present and the sun is below the horizon. *Lights on weekends* gives the same hours for weekends, respectively.

Building number 16 has been left out of calculations. There is no 'daytime' nor 'lights on' period on weekends in buildings which are supposed to be unoccupied then.

Table V. Monthly heat consumption of buildings.

Nr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
1/1	10553	9909	7527	6046	2607	688	942	590	2799	5285	6173	8528	61648
1/1	1185	1071	1185	1147	1185	1147	1185	1185	1147	1185	1147	1185	13956
1/2	10655	10005	7599	5992	2448	565	852	525	2813	5333	6237	8614	61638
1/2	1185	1071	1185	1147	1185	1147	1185	1185	1147	1185	1147	1185	13956
1/3	91795	86131	67027	52492	22878	6751	10948	7073	27890	48695	56618	76562	554860
1/3	4566	3970	4367	4169	4566	4169	4367	4566	3970	4566	4367	4169	51811
2	42182	40210	31151	24642	10636	2860	3969	2418	12026	21706	24806	34032	250638
2	4527	3937	4331	4134	4527	4134	4331	4527	3937	4527	4331	4134	51377
3	13948	12745	9130	6934	2572	601	1135	813	3438	6958	8408	11366	78046
3	348	302	333	317	348	317	333	348	302	348	333	317	3946
4	71114	66898	51938	41074	18407	5314	7918	5035	20663	36896	42637	57996	425891
4	6838	6176	6838	6618	6838	6618	6838	6838	6618	6838	6618	6838	80514
5/1	7103	6633	4874	3851	1462	287	387	229	1615	3379	4046	5692	39558
5/1	921	832	921	891	921	891	921	921	891	921	891	921	10847
5/2	4018	3767	2791	2217	871	182	242	140	938	1923	2287	3215	22590
5/2	527	476	527	510	527	510	527	527	510	527	510	527	6201
5/3	7451	6651	4776	3399	1327	288	420	235	1439	3323	4253	5982	39546
5/3	921	832	921	891	921	891	921	921	891	921	891	921	10847
6	25202	23972	18401	14660	6452	1782	2383	1460	6637	12495	14522	20196	148161
6	921	832	921	891	921	891	921	921	891	921	891	921	10847
7	15284	14521	10792	8342	3223	575	815	402	3391	7114	8475	12051	84986
7	2973	2685	2973	2877	2973	2877	2973	2973	2877	2973	2877	2973	35005
8	13311	12418	9642	7624	3432	1004	1598	1064	3992	7083	8183	10922	80273
8	742	671	742	718	742	718	742	742	718	742	718	742	8742
9/1	16775	15629	12108	9690	4350	1362	1977	1431	5089	8987	10341	13715	101453
9/1	1017	884	973	928	1017	928	973	1017	884	1017	973	928	11539
9/2	10513	9866	7616	6015	2632	742	1142	735	3037	5487	6327	8588	62700
9/2	791	714	791	765	791	765	791	791	765	791	765	791	9311
10	30447	28578	22375	17875	8606	3024	4352	2855	9447	16347	18752	25172	187831
10	3160	2854	3160	3058	3160	3058	3160	3160	3058	3160	3058	3160	37204
11	19074	17451	13015	9602	3763	914	1739	1107	4707	9493	11469	15532	107865
11	894	777	855	816	894	816	855	894	777	894	855	816	10142
12	45563	42643	30876	22090	8169	1710	3404	1995	10421	22431	27077	36366	252746
12	2049	1782	1960	1871	2049	1871	1960	2049	1782	2049	1960	1871	23254
13	10314	9605	7103	5435	2047	435	705	428	2462	5009	6003	8396	57942
13	885	770	847	808	885	808	847	885	770	885	847	808	10048
16	127598	119763	97669	80071	45108	22232	27519	21616	46828	72929	81676	107021	850031
16	0	0	0	0	0	0	0	0	0	0	0	0	0
17/1	17604	16493	12533	10014	4137	1049	1483	978	4724	8871	10380	14278	102543
17/1	1482	1338	1482	1434	1482	1434	1482	1482	1434	1482	1434	1482	17445
17/2	15747	14715	11077	8592	3411	772	1188	708	4056	7901	9299	12786	90251
17/2	1296	1171	1296	1255	1296	1255	1296	1296	1255	1296	1255	1296	15265
17/3	14096	13228	10044	7838	3218	766	1170	697	3726	7116	8325	11436	81661
17/3	1172	1059	1172	1135	1172	1135	1172	1172	1135	1172	1135	1172	13805
18/1	21426	19974	14816	11390	4510	1073	1634	949	5277	10692	12652	17408	121800
18/1	2107	1903	2107	2039	2107	2039	2107	2107	2039	2107	2039	2107	24803
18/2	21248	19849	14995	11346	4516	1141	1611	1057	5568	10681	12535	17254	121802
18/2	2107	1903	2107	2039	2107	2039	2107	2107	2039	2107	2039	2107	24803
18/3	13486	12800	9948	7974	3726	1208	1576	1019	3822	6884	7933	10900	81276
18/3	1403	1267	1403	1358	1403	1358	1403	1403	1358	1403	1358	1403	16516
19/1	44655	42347	32506	24889	10311	2564	3845	2197	11818	22350	25948	35916	259347
19/1	4894	4421	4894	4736	4894	4736	4894	4894	4736	4894	4736	4894	57627
19/2	44084	41791	32059	25566	11231	3050	4180	2640	11760	22009	25581	35440	259391
19/2	4894	4421	4894	4736	4894	4736	4894	4894	4736	4894	4736	4894	57627
20/1	6906	6508	4914	3675	1430	323	483	278	1726	3403	3993	5552	39191
20/1	791	714	791	765	791	765	791	791	765	791	765	791	9311
20/2	5738	5391	4048	3185	1258	266	386	236	1421	2811	3314	4612	32666
20/2	659	595	659	637	659	637	659	659	637	659	637	659	7756
20/3	5776	5415	4049	3174	1234	247	360	212	1407	2822	3338	4646	32680
20/3	659	595	659	637	659	637	659	659	637	659	637	659	7756
20/4	7917	7499	5704	4477	1871	444	642	368	2017	3909	4569	6351	45768
20/4	921	832	921	891	921	891	921	921	891	921	891	921	10847
33	16720	15403	11538	8724	3421	828	1412	893	4470	8577	10146	13813	95946

33	529	460	506	483	529	483	506	529	460	529	506	483	6007
34/1	16420	15421	11688	9129	3810	1006	1605	1077	4518	8493	9885	13297	96350
34/1	608	529	582	555	608	555	582	608	529	608	582	555	6902
34/2	16244	15074	11442	8960	3713	1017	1548	1059	4417	8334	9793	13339	94940
24/2	1937	1750	1937	1875	1937	1875	1937	1937	1875	1937	1875	1937	22812
40	12753	11293	8250	6155	2508	675	1099	782	3050	6333	7803	10303	71004
40	441	383	422	403	441	403	422	441	383	441	422	403	5003
44	11641	10793	8173	6277	2630	689	1084	645	3066	5924	7019	9567	67508
44	1061	959	1061	1027	1061	1027	1061	1061	1027	1061	1027	1061	12496
45	5636	5124	3640	2737	1008	238	396	279	1282	2718	3319	4608	30985
45	765	691	765	740	765	740	765	765	740	765	740	765	9007
Tot	933177	872141	689323	551458	281110	127978	159635	128403	306374	512877	584115	772251	5918842

Table VI. The division of annual heat generation.

Outside temperature °C	Duration hours p.a.	Relative output %	Output for heating kW	Output for DHW kW	Heating energy generation MWh	DHW energy generation MWh	Total energy generation MWh
28,5	3	0,0 %	0	83	0.0	0.2	0.2
27,5	2	0,0 %	0	83	0.0	0.2	0.2
26,5	4	0,0 %	0	83	0.0	0.3	0.3
25,5	16	0,0 %	0	83	0.0	1.3	1.3
24,5	34	0,0 %	0	83	0.0	2.8	2.8
23,5	20	0,0 %	0	83	0.0	1.7	1.7
22,5	71	0,0 %	0	83	0.0	5.9	5.9
21,5	71	0,0 %	0	83	0.0	5.9	5.9
20,5	89	0,0 %	0	83	0.0	7.4	7.4
19,5	122	0,0 %	0	83	0.0	10.1	10.1
18,5	174	0,0 %	0	83	0.0	14.5	14.5
17,5	234	0,0 %	0	83	0.0	19.5	19.5
16,5	304	0,0 %	0	83	0.0	25.3	25.3
15,5	299	0,0 %	0	83	0.0	24.9	24.9
14,5	308	2,4 %	62	83	19.0	25.6	44.6
13,5	371	4,8 %	124	83	45.8	30.9	76.7
12,5	317	7,1 %	185	83	58.7	26.4	85.1
11,5	259	9,5 %	247	83	64.0	21.5	85.5
10,5	236	11,9 %	309	83	72.9	19.6	92.5
9,5	230	14,3 %	371	83	85.2	19.1	104.3
8,5	242	16,7 %	432	83	104.6	20.1	124.7
7,5	177	19,0 %	494	83	87.4	14.7	102.2
6,5	187	21,4 %	556	83	103.9	15.6	119.5
5,5	224	23,8 %	618	83	138.3	18.6	157.0
4,5	289	26,2 %	679	83	196.3	24.0	220.3
3,5	333	28,6 %	741	83	246.8	27.7	274.5
2,5	358	31,0 %	803	83	287.4	29.8	317.2
1,5	450	33,3 %	865	83	389.0	37.4	426.5
0,5	582	35,7 %	926	83	539.1	48.4	587.5
-0,5	423	38,1 %	988	83	417.9	35.2	453.1
-1,5	295	40,5 %	1050	83	309.7	24.5	334.2
-2,5	192	42,9 %	1112	83	213.4	16.0	229.4
-3,5	213	45,2 %	1173	83	249.9	17.7	267.6
-4,5	189	47,6 %	1235	83	233.4	15.7	249.1
-5,5	164	50,0 %	1297	83	212.7	13.6	226.3
-6,5	159	52,4 %	1359	83	216.0	13.2	229.2
-7,5	108	54,8 %	1420	83	153.4	9.0	162.4
-8,5	129	57,1 %	1482	83	191.2	10.7	201.9
-9,5	113	59,5 %	1544	83	174.5	9.4	183.8
-10,5	90	61,9 %	1606	83	144.5	7.5	152.0
-11,5	74	64,3 %	1667	83	123.4	6.2	129.5
-12,5	98	66,7 %	1729	83	169.4	8.2	177.6
-13,5	112	69,0 %	1791	83	200.6	9.3	209.9
-14,5	65	71,4 %	1853	83	120.4	5.4	125.8
-15,5	49	73,8 %	1914	83	93.8	4.1	97.9
-16,5	60	76,2 %	1976	83	118.6	5.0	123.6
-17,5	34	78,6 %	2038	83	69.3	2.8	72.1
-18,5	42	81,0 %	2100	83	88.2	3.5	91.7
-19,5	23	83,3 %	2161	83	49.7	1.9	51.6
-20,5	23	85,7 %	2223	83	51.1	1.9	53.0
-21,5	30	88,1 %	2285	83	68.5	2.5	71.0
-22,5	27	90,5 %	2347	83	63.4	2.2	65.6
-23,5	11	92,9 %	2408	83	26.5	0.9	27.4
-24,5	5	95,2 %	2470	83	12.4	0.4	12.8
-25,5	8	97,6 %	2532	83	20.3	0.7	20.9
-26,5	8	100,0 %	2594	83	20.7	0.7	21.4
-27,5	5	100,0 %	2594	83	13.0	0.4	13.4
-28,5	2	100,0 %	2594	83	5.2	0.2	5.4
-29,5	3	100,0 %	2594	83	7.8	0.2	8.0
					6277	729	7006

Table VII. Calculation of marginal price. Summer pause included.

			subsidy, %	subsidy, €
Boiler plant	460000	€	15 %	69000
Foundation	30000	€	15 %	4500
DH pipe work	803000	€	15 %	120450
Heat measuring	46000	€		0
DH sub-stations	91000	€		0
Subtotal	**1430000**	€		**193950**
Capital cost	1236050	€		
Repayment period	20	a		
Interest rate	3.0	%		
Annual instalment	-83082	€		
Heat for own buildings	3019	MWh		
Heat for sale	2900	MWh		
Fuel oil price	0.40	€/l		
Heat produced from chips	5747	MWh		
Heat produced from oil	1114	MWh		
Price of sold heat	42.4	€/MWh		
Saving in heating of own buildings	142056	€/a		
Income from selling of heat	122973	€/a		
Annual oil cost	-55700	€/a		
Annual cost of produced heat	-126247	€/a		
Marginal price for produced heat	**22.0**	€/MWh		
Expenses, total	-265029	€/a		
Incomes and savings, total	265029	€/a		

Table VIII. Calculation of marginal price. Without a summer pause.

			subsidy, %	subsidy, €
Boiler plant	460000	€	15 %	69000
Foundation	30000	€	15 %	4500
DH pipework	803000	€	15 %	120450
Heat measuring	46000	€		0
DH sub-stations	91000	€		0
Subtotal	**1430000**	€		**193950**
Capital cost	1236050	€		
Repayment period	20	a		
Interest rate	3.0	%		
Annual instalment	-83082	€		
Heat for own buildings	3019	MWh		
Heat for sale	2900	MWh		
Fuel oil price	0.40	€/l		
Heat produced from chips	6028	MWh		
Heat produced from oil	833	MWh		
Price of sold heat	42.4	€/MWh		
Saving in heating of own buildings	142056	€/a		
Income from selling of heat	122973	€/a		
Annual oil cost	-41655	€/a		
Annual cost of produced heat	-140292	€/a		
Marginal price for produced heat	**23.3**	€/MWh		
Expenses, total	-265029	€/a		
Incomes and savings, total	265029	€/a		

Table IX. Description of the DH network.

From where	To where	Length, m	Size, DN
N1	N2	15	75
N2	B16	70	350
N2	N3	48	240
N3	B18	3	15
N3	N4	20	100
N4	B19	5	25
N4	N5	130	650
N5	N6	12	60
N6	B33	6	30
N6	N7	5	25
N7	B45	5	25
N7	N8	10	50
N8	B44	5	25
N8	B40	10	50
N5	N9	33	165
N9	B20	9	45
N9	N10	13	65
N10	N11	23	115
N11	B1b	5	25
N11	B1a	26	130
N10	N12	12	60
N12	N13	42	210
N13	B11	6	30
N13	N14	9	45
N14	B12	12	60
N14	B13	10	50
N12	N15	17	85
N15	B3	4	20
N15	N16	17	85
N16	B2	5	25
N16	N17	33	165
N17	N18	37	185
N18	B34	3	15
N18	B17	47	235
N17	N19	111	555
N19	B8	9	45
N19	N20	5	25
N20	B9	9	45
N20	N21	12	60
N21	B10	10	50

N21	N22	24	120
N22	B5	3	15
N22	N23	12	60
N23	B4+B5	13	65
N23	B7	28	140

N1 (= node 1) is the boiler plant. B refers to the relevant building number.

Table X. DHW consumption.

Building number	DHW consumption, dm^3/s
Building 18	0.282
Building 19/1	0.192
Building 19/2	0.192
Building 16	0.000
Building 20	0.206
Buildings 33 and 45	0.184
Buildings 40 and 44	0.000
Building 1 TH	0.184
Building 1 USS	0.000
Buildings 2 and 3	0.000
Building 11	0.000
Buildings 12 and 13	0.000
Building 17	0.235
Building 34 OP	0.000
Building 34 HH	0.000
Buildings 4 and 7	0.321
Buildings 5 and 6	0.354
Buildings 8, 9 and 10	0.415

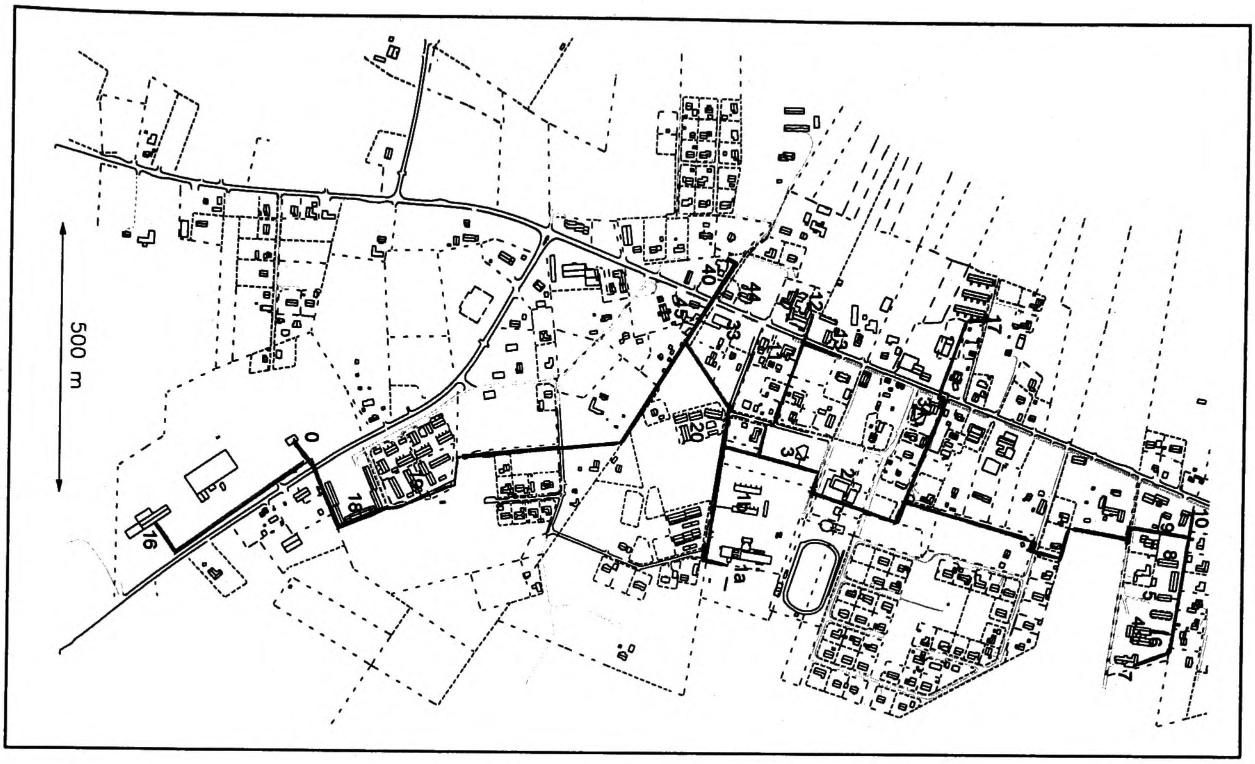

Figure I. Lay-out of the district heating network.

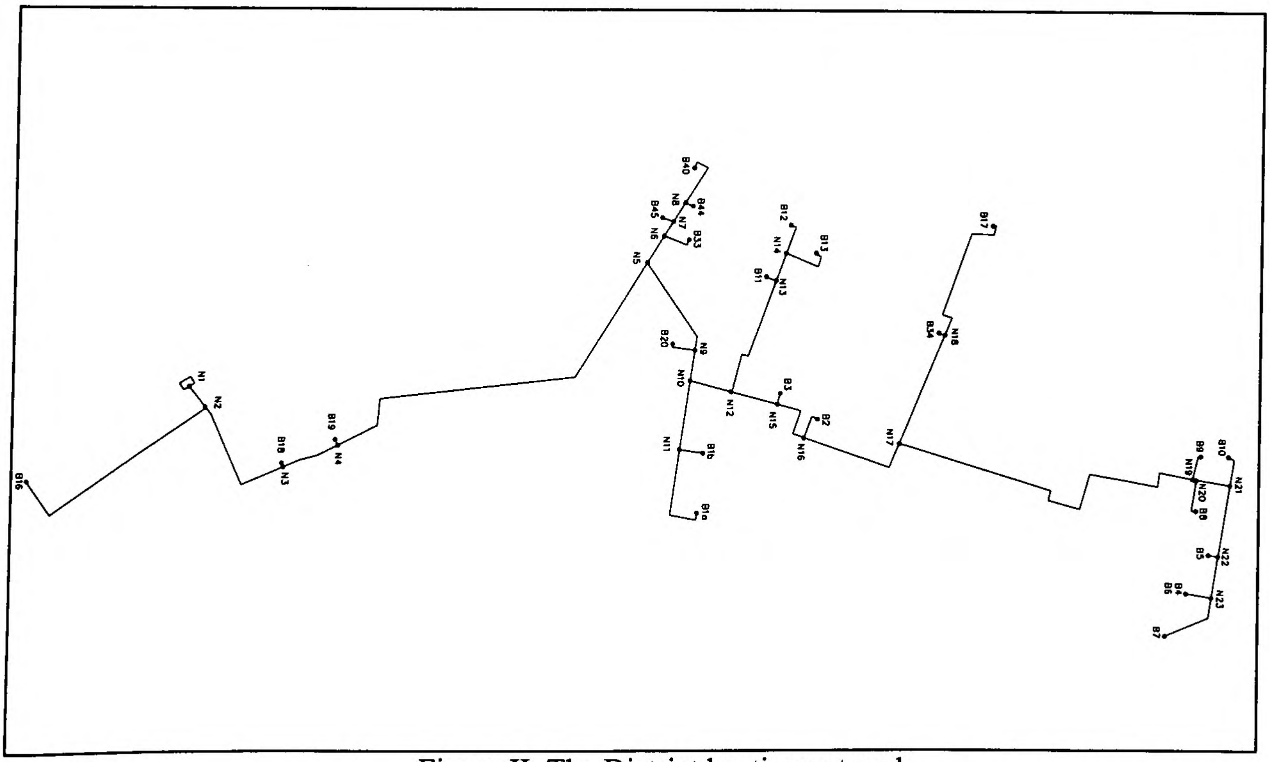

Figure II. The District heating network