SOLAR COMBISYSTEMS WITH FORECAST CONTROL TO INCREASE THE SOLAR FRACTION AND LOWER THE AUXILIARY ENERGY COST

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Abstract

Solar Combi systems still need quite a lot of auxiliary energy especially in small systems without seasonal storage possibilities. The control of the auxiliary energy input both in time and power is important to utilize as much as possible of the solar energy available from the collectors and also to use low backup energy prices during the day if electricity is used. The storage function and both stratified charging and extraction of heat, are very important, to separate different temperature zones in the storage. This paper describes a step towards forecast control for electricity based auxiliary energy sources. It can be either direct electric heating elements or a heat pump upgrading ambient energy in the air, ground, solar collector or waste heat from the house.

The paper describes system modeling and simulation results. Advanced laboratory experiments are also starting now with three different combisystems, operating in parallel. These systems will be briefly described too.

1. Introduction

In the deregulated electricity market situation in the Nordic countries, the electricity prices can vary dramatically from hour to hour. Therefore a smart control system that can use and adapt to these variations is very desirable, (Perers 2010, 2009). When a storage tank is available in the system, it can be used for storage of both solar thermal and auxiliary energy.

As more and more renewable energy sources are feeding into the electricity grid, the price variations will most probably be larger during the day. This happens now in Denmark where the wind power fraction in the grid is higher than 20%. This paper will present continued investigations for Danish conditions of climate, load, solar production, and electricity prices.

The work is done within a larger project with several Danish partners and the aim is to give the basis for a combisystem design that can be developed to a product on the market. The term combisystem means a solar heating system, that can deliver both heating and hot water to a house.The project is carried out in cooperation between Department of Civil Engineering, Technical University of Denmark, Danish Meteorological Institute (DMI), DTU Informatics, Technical University of Denmark, ENFOR A/S, AllSun A/S, Ohmatex ApS, Ajva ApS and COWI A/S.

Typically the electricity prices are higher during the day than in the night. This is good for solar heating systems that can reduce the use of backup electricity during peak hours of the day. Especially if the solar heating system inclusive the heat storage is well designed and properly sized. This happens partly automatically in existing combisystem with normal thermostatically controlled backup electric heating elements or a heat pump. Also the thermal load of a house has a daily variation, that match the price variations quite well, especially if the house has significant passive solar gains during the day. The problem toady is that the customer is not given credit to this as variable electricity prices are very uncommon yet on the market. But the project assumes that this will come soon for most customers as this is an important possibility to make it easier to introduce more renewable energy in the electric grid.

A normal control system in a combisystem does not have information about the weather and prices for the next day. Therefore the auxiliary charge can not be optimized for high solar production by minimizing the auxiliary charge and optimizing the power and time point, in the night before. If this was possible it would allow more solar input to the store and less use of backup energy at high electricity prices. In a normal combisystem a secure charging level in the store has to be maintained as if the next day will be rainy. Otherwise a lot of high cost electricity will be used during the peak hours of the next day to meet the load.

The paper describes further steps and progress in this area as well as describing the basic concept. The three test systems will also be described. The results can also be applicable to minimize the use of other backup energy sources and increase the solar fraction of a combisystem.

There are several control options for varying and thereby adapting the auxiliary charge of the storage. Figure 1 shows sketches of the main options. They can be divided into two main principles: Variable temperature and variable volume auxiliary charge. Both ways will open for advanced control of the auxiliary energy charge and thereby adaptation to the conditions of the electricity price variations, load and potential solar energy production the next day. To the left in figure 1 is the standard auxiliary charging method with a fixed volume and thermostat control and to the right the most advanced charging option with variable temperature and variable volume simultaneously.

In this paper these two extremes, traditional and advanced control, are compared to give a potential for improvement by smart tanks and smart control in a combisystem.

In this case a simplified calculation model has been chosen that can be implemented in Excel. The detailed TRNSYS system model described in previous papers (Perers 2010 and 2009) turned out to be problematic to use for the most advanced forecast control, with a combination of variable temperature and variable volume options. Therefore to be able to proceed and to find the maximum potential improvement level, a simplified model option was chosen as an intermediate step.

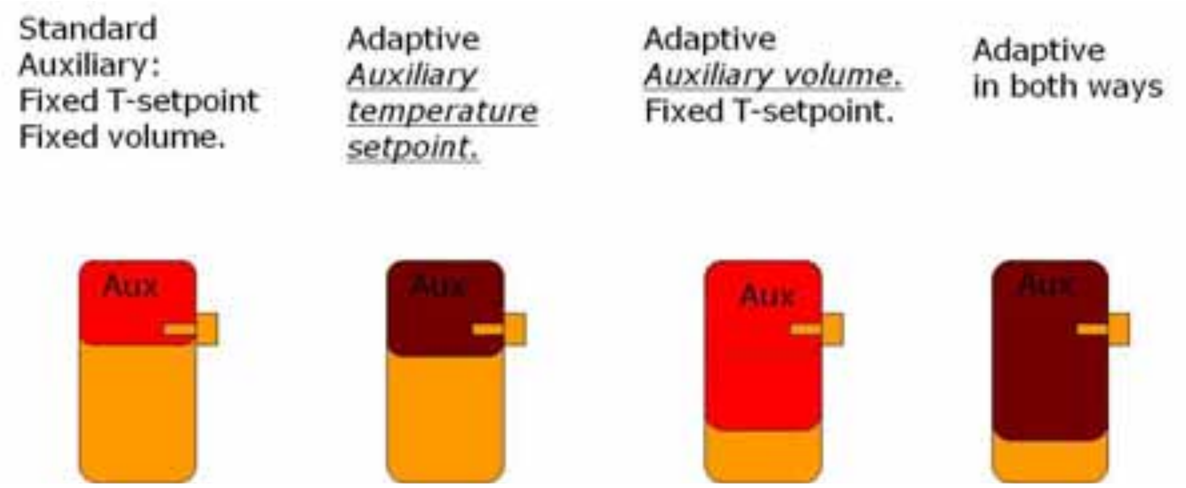

Fig. 1: Auxiliary charge control options for the storage in a combisystem. The standard solution to the left with fixed volume and thermostat control and the most advanced to the right with variable volume and temperature and forecast control.

In this study the forecast control is utilizing the known weather data for the next day in the measured weather data file that is available in the simulation. This was done to separate and eliminate, uncertainties in system modeling and control from inevitable uncertainties in the weather forecasts. DTU Informatics are working with the next step how to utilize real forecast data from DMI for smart control and handle these added uncertainties and still maintain an acceptable energy comfort in the house (Bacher 2011)

Experimental investigations are also an important part of this project. In figure 2 a description is given of the three laboratory combisystems and the three different tank designs, under monitoring at DTU Byg. These combisystems will be investigated to find an optimal tank configuration for this application. Tests of variable temperature and variable volume auxiliary charge and with extreme stratification measures, both during charge and discharge, in combined solar and auxiliary operation, are the main aims of the tests.

Fabric stratifiers will also be tested in the systems to keep the high temperatures in the top of the tank to meet the load and to have as low inlet temperature as possible in the bottom for the solar collectors and a possible heat pump as auxiliary source. The stratifiers are applied both in the load loops and in the collector loop.

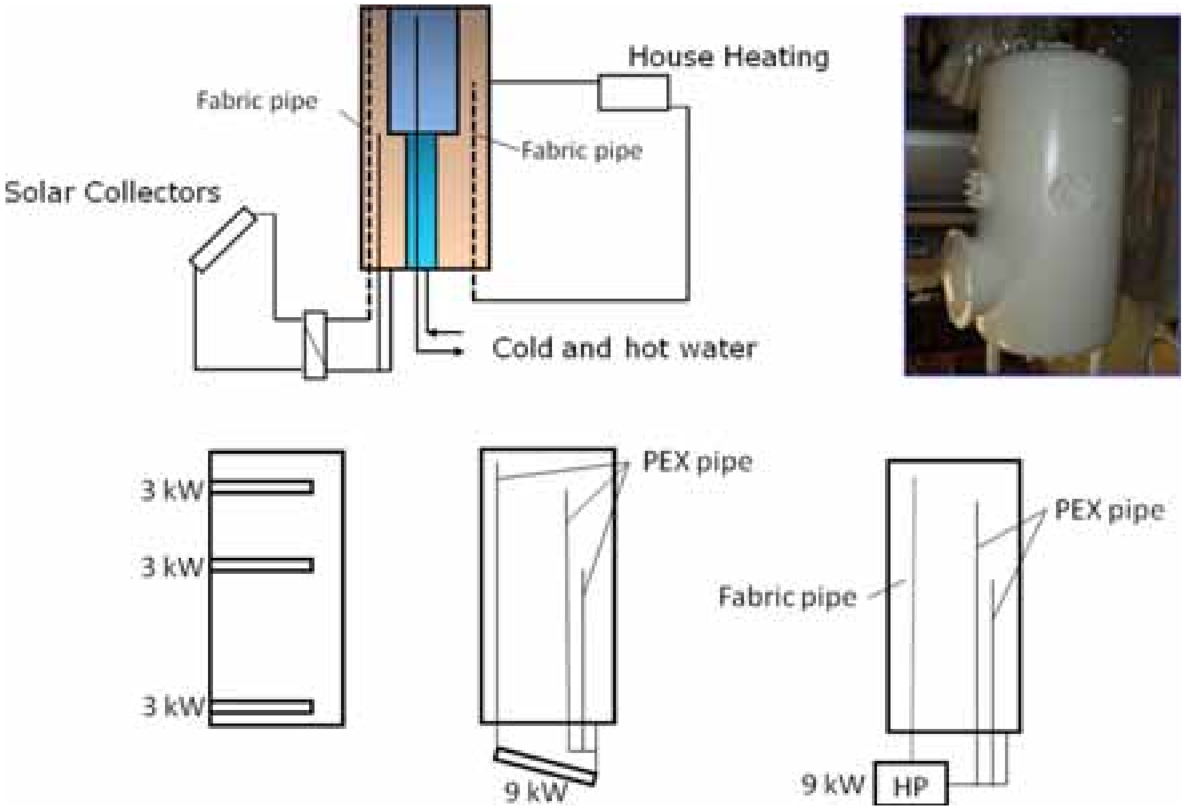

Fig. 2: Description of the system and the three tank designs in the system tests at DTU Byg. The combisystems will be investigated to find an optimal tank configuration for this application. Tests of variable auxiliary temperature and variable volume auxiliary charge and extreme stratification measures both during charge and discharge, are the main aims of the tests. Also a heat pump auxiliary solution is tested.

2. The simplified energy balance model

The simplified energy balance model, used here is shown in figure 3. This is also closer to the simplified system model that probably will be used in the controller. The full TRNSYS model in previously presented research work in this project Perers (2009, 2010) is probably too complicated with hundreds of parameters to be set for each system, to be implemented in a commercial controller.

Still all relevant energy flows in and out of the tank in the system are present, so no energy is neglected. In the figure also the very simple equation for the auxiliary energy need is shown. To be complete and realistic one also have to check the minimum and maximum charge level Q(t) so that the minimum load temperatures can be delivered and that the tank is not overheated or boiling of course.

The component models are also very much simplified to first order options, to make it easy to implement in Excel without the need for iterative procedures. Still also here the main effects are present. In a next step it can be possible to refine both the system model and component models in Excel, but the accuracy gain is limited for the aim of this study to find out the potential improvement level.

For future design optimization of the components together with manufacturers though, continued work with the full TRNSYS model can be very interesting and the idea is to validate the full TRNSYS model against the tests in the laboratory.

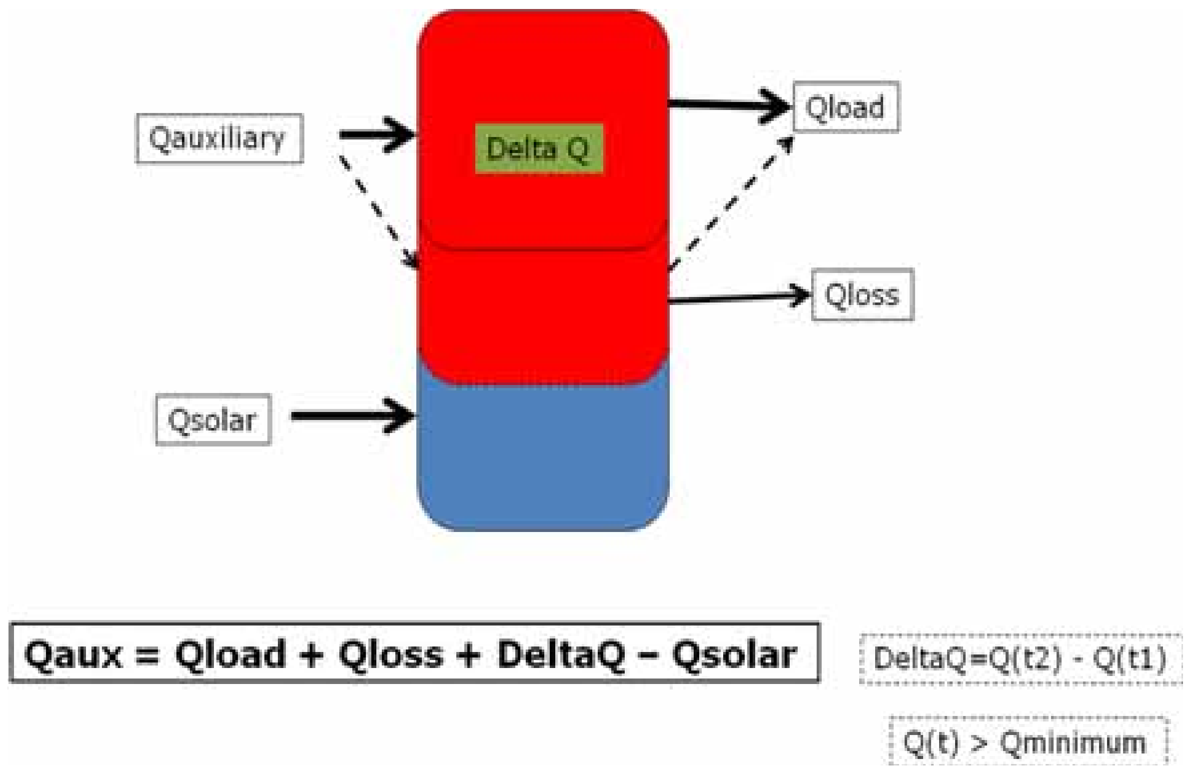

Fig. 3: The energy flows considered in the simplified model of the combisystem. The very simple equation for the required auxiliary charge is also given, together with limits for the energy content Q(t) of the store.

3. Input data and calculations

The same detailed and carefully monitored climate data from the DTU Byg weather station for year 2008 are used here as in the previous detailed TRNSYS simulation studies. Also the same hourly electricity price data from Nordpool for year 2008 are used. The forecast calculations are based on known climate data the next day in the climate file and not forecast data from DMI to be able to separate different effects and uncertainties from each other.

The system model is extremely simple as shown in figure 3. The aim here is to make a potential study how much ideal forecast control and ideal tank behavior (working as a capacitor for heat) can reduce the annual auxiliary costs in combination with addition of energy from a solar collector.

The component models for solar collector and building are simplified to stationary first order models to avoid iterations in Excel. The storage tank is modeled according to the energy balance given in figure 3.

The collector is tilted 45 deg and oriented due south. The collector model is an extremely simple first order model with an effective zero loss efficiency of 0.75 and a total heat loss factor of 3.5 W/m²K including pipe losses. The mean operating temperature of the collector is assumed to be constant (set to 50C in the presented calculations). In a real system this temperature is of course varying with many other variables and parameters, in the system but here this is second order parameter and only affects the collector and pipe heat losses.

The tank is modeled as an ideal "themal capacitor" and only the energy flows are studied, with no mixing between the energy flows as solar and auxiliary. The load and heat losses are also just extracted as a change in energy content of the store. The heat losses are assumed to be constant (in this case set to 100 W total for the tank plus system outside the collector loop). In reality of course the losses are very dependent on the tank design and control. But as the charging and discharging powers are of a magnitude 10-100 times larger, this heat loss variation was neglected in the presented calculations. But of course to optimize the system and for component design this should be variable and determined by full system simulation like in the TRNSYS model. Low heat losses are really essential for a well performing combisystem.

The auxiliary volume and auxiliary temperature of the tank are variable (but not calculated explicitly). The tank size is automatically adapted and set to the worst winter day, when the store has to be able to store the forecasted auxiliary need for one day, with the whole tank used as auxiliary volume. At this time of the year the solar charge is small and this volume need is neglected at this stage.

In the normal reference system the auxiliary part for the store is kept at a constant minimum temperature of 60°C, but occasionally when there is a lot of solar radiation available the tank temperature will increase above this level. If the tank is heated above a max temperature of 95°C the solar and auxiliary charge is stopped.

In the advanced forecast control alternative the auxiliary energy charge is done in the night and in an amount that will exactly meet the total load during the next day including house heating, hot water consumption and heat losses, but minus the predicted solar charge during the next day.

The control timing of the auxiliary charge is simplified to a fixed time period each morning when the prices are at minimum around 3 o'clock very regularly in the Danish grid. This is due to the low load in the grid at the end of the night, when very little activities occur in the society. In the full forecast control also the time for charge should be optimized but this turned out to be too complicated in this simplified potential study. An estimate is therefore given for this case in the results, using the lowest price every day to calculate the annual auxiliary cost.

Figure 4 shows an example of the hourly energy flows and energy content in the store in two control options: 1) normal control and 2) forecast control. In the normal control case (1) the auxiliary energy is added all the day instantaneously when needed. In the case of forecast control (2) the auxiliary supply is done in the night to use the lowest possible electricity prices. The absolute level of the energy content curves Qstore=Q(t) (two upper ones) are not representative for the future system design. Then the tank with forecast control should be possible to discharge deeper each day. Here the energy content is shown relative to 0 °C with a minimum allowable temperature of 60°C in the store. In a real system the advanced auxiliary control can allow the store to go below the energy content of the normal storage, as the forecast information warrants the comfort for the next day. Also extreme stratification measures will work in this direction to allow a lower minimum charging level of the tank.

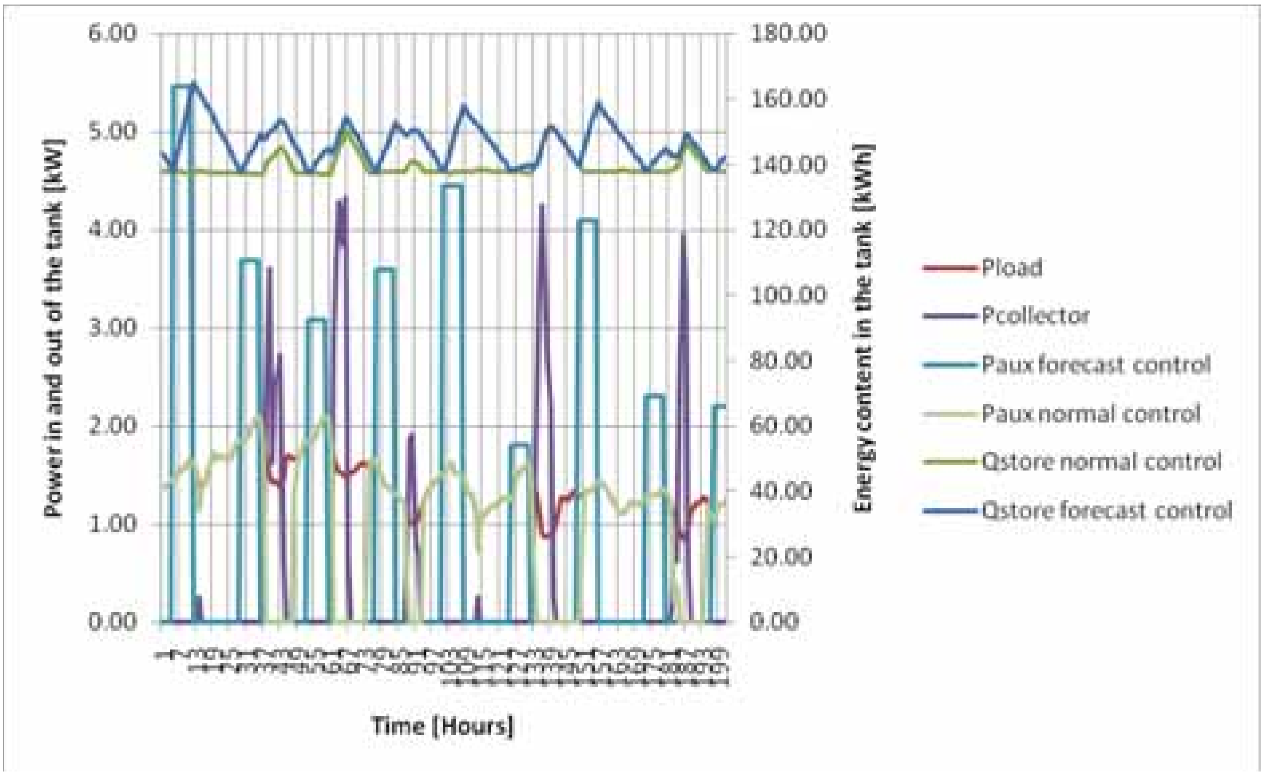

Fig. 4: Hourly energy flows in the system in kW, Pload, Pcoll and Paux (four lower curves) and energy content Qstore=Q(t) (the two upper curves) for the two control options. 100W/K house and 10 m² of collectors. The absolute level of the two upper energy content curves are not relevant for the auxiliary cost results, only the variations that reflect smart auxiliary charge at low prices.

4. Results

The results of the calculations for annual auxiliary costs in DKK (Nordpool cost level), have been summarized in figure 5, 6 and 7.

In figure 5 the costs are given for two different building insulation standards 200W/K and 100W/K, five different storage sizes and four different solar collector areas 5-20 m². The hot water load has been the same for all cases 100 litres/day.

The cost level is at the NORDPOOL electric stock exchange level http://www.nordpoolspot.com/
This is much lower than the final customer price level, so the potential savings in absolute numbers, in DKK per year, are much larger than shown in the diagrams.

The tank volume has been adapted to a minimum size needed to store enough energy for the different options. (The leftmost points on all curves represents a traditional tank design and a volume of 750 and 500 l has been set to be appropriate for the two house insulation standards).

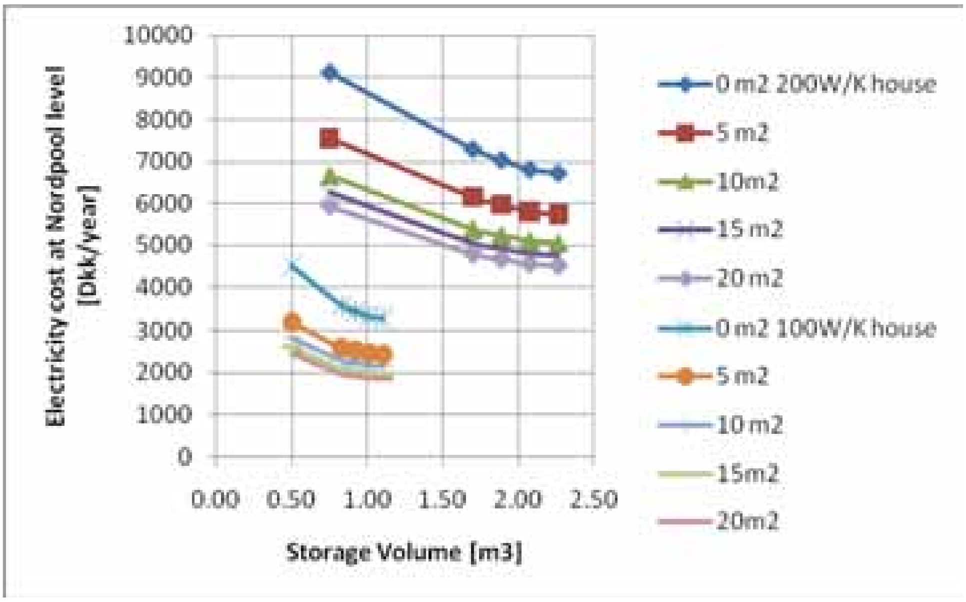

Fig. 5: Calculation results for ideal forecast control (the next days weather is known), compared to a standard auxiliary control where the thermostat decides when to use electricity instantaneously. Note in all cases a variable electricity cost is assumed for the system owner. The case of fixed price at the annual average level is only shown in figure 6.

In Figure 6 and 7 the same calculations are shown as a function of collector area. The tank volumes are also the same as in figure 5. Only the 200W/K house is shown in figure 6 to limit the number of curves. But here also the reference case is shown with constant electricity price all year (uppermost curve) and the extreme case of using the lowest price every day (24 hours) is shown too, as the lower curve giving the extreme improvement potential. (In figure 5 all curves are for the same variable electricity price conditions and only the auxiliary charging strategy/principle is changed.).

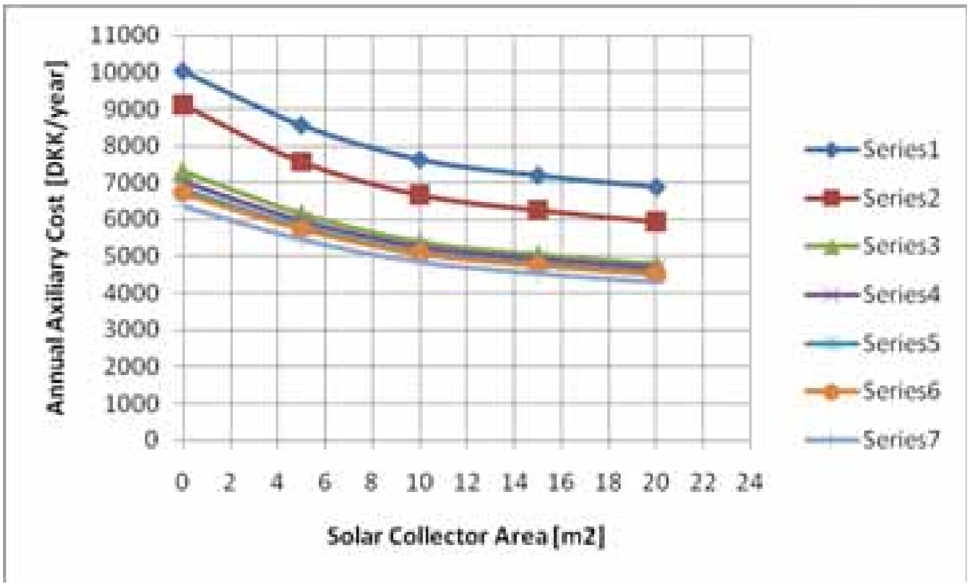

Fig. 6: Annual Auxiliary cost variation for a 200W/K house with different collector area and control option/pricing. Series 1 is the reference case with constant electricity price and normal thermostat aux control. Series 2 is the same thermostat control as series 1, but variable electricity price. Series 3 to 6 are shorter and shorter charging period and higher charging power around the minimum price time each day. Series 7 is the extreme case when the lowest electricity price each 24 hours is used.

In figure 7 below the same calculations and curves are given for a well insulated house 100W/K. It can be seen that the optimum collector area is smaller as expected closer to what is needed for the 100 l/day hotwater demand. Still the relative cost savings between a traditional system without solar collectors and an advanced system with solar is in the range of 50%.

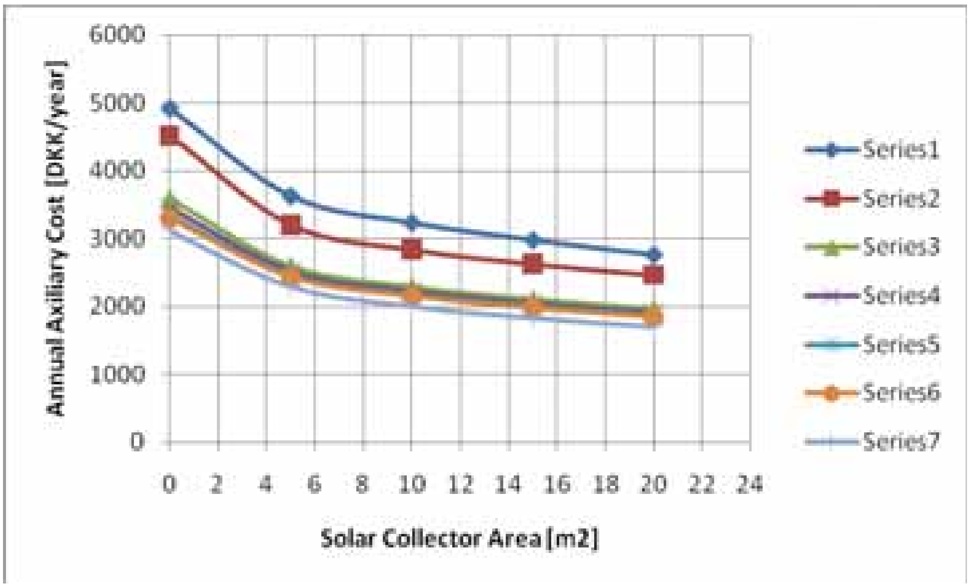

Fig. 7: Annual Auxiliary cost variation for a 100W/K house. Otherwise the same curves as in Figure 6.

The extra cost of receiving the maximum electric power level (max kW) needed to charge the tank in a short time span, is not included here, but this pricing may be adapted on the market in the future, as there is plenty of power available in the grid when the load is low and the electricity kWh cost is close to minimum. The curve series 3 in fig 6 with power needs of maximum 17 kW can be met by normal domestic electric connections of three phase 400V 25 A for the 200W/K house. For the 100W/K house series 3-5 can be covered with 16- 25 A three phase fuses at the final customer. The very lowest curves need special arrangements to meet the maximum load and are more shown as limiting curves with just 1 hour or less charging time per day. In case of a heat pump the electric power need, is at least halved, for normal conditions and the electric power need is no problem.

5. Conclusions

The combination of smart auxiliary control and addition of 10m² of solar collectors in a combisystem can reduce the auxiliary cost for a house by around 50% in an example for Danish conditions and a normal house.

The annual auxiliary cost savings is around 3000-5000 DKK on the Nordpool electricity cost level. The cost savings at the final customer price level is hard to predict, but can be estimated to two to three times larger depending on how the variable price structure will be and how energy and CO_2 tax will change in this case.

For the same collector area in the system a smart forecast auxiliary control has the potential of reducing the auxiliary electricity cost by 30-40% more alone.

From the results one can estimate that for a 200W/K house with 100l/day hot water load, 10m² of collectors is reasonable and for a well insulated house (100W/K) around 5m² can be recommended.

The very simple system model and forecast control shown here seems to give reasonable results and may be used as a template for commercial controller programming. Though a lot of refinements are possible.

This first order system modeling can give reasonable values for the potential value of smart forecast control and solar contribution in a solar combisystem. No energy flows are forgotten, but the exact levels are approximative in time and size. Compared to a full TRNSYS simulation the complexity and number of parameters needed are one or two orders of magnitude lower. For component design optimization and detailed control research the full TRNSYS model is needed and will be validated against measured data in the next step of the project.

6. References

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