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Sørensen, Bent

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MODELLING OF HYBRID PV-THERMAL SYSTEMS

Bent Sørensen
Roskilde University, Institute 2, tel: +45 4674 2028, fax: +45 4674 3020
mail address: Universitetsvej 1, POBox 260, DK-4000 Roskilde, Denmark,
email: bes@ruc.dk, web: http://mmf.ruc.dk/energy, http://www.danbbs.dk/~novator

ABSTRACT: The paper gives examples of modelling PV-T systems using the newly developed NSES software.
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1. PROBLEM OUTLINE

Systems involving solar thermal collection into a heat store have a complex dynamical behaviour, due to the influence of storage temperature on solar collector fluid inlet temperature, and on the other side the influence of load patterns on the variation of heat storage temperature. The photovoltaic part of a hybrid PVT (PV-thermal) system depends on the complex temperature behaviour only through the temperature dependence of collector performance, which is weaker than that of the thermal collection part [1]. This paper explores the dynamical behaviour of a number of PVT systems by use of the newly updated time simulation software NSES [2]. Details of the model is described in refs. [4] and more specifically in [5].

The collector model includes solar radiation capture through multiple layers of glazing, mediators and absorbers, with consideration of reflection and emittance. The absorbed radiation is converted to electricity with an efficiency that depends on temperature through a quadratic relationship determined from data for various photovoltaic materials. The further use of non-converted solar energy for heat production is achieved by thermalisation of electrons not converted to electricity, in either of the layers, followed by heat transfer by conduction and convection to a working fluid either passing behind the absorber or in front of it (typically water or air). The heat fluid circuit exchanges heat with a thermal store, from which building loads are covered through a secondary heat circuit.

The NSES model simulates the behaviour of such systems by an hourly time-step calculation using hourly data sets such as the Danish Reference Year [7] data for solar input (from which radiation upon tilted surfaces is calculated), wind speeds (affecting collector front losses) and ambient temperatures (determining building heat losses and collector long-wavelength radiative losses). Hourly behaviour of building loads of electricity and heat are considered, as well as heat storage losses depending on temperature stratification, insulation and geometry. If the set load temperatures for space heating and hot water cannot be met at all times, auxiliary energy is used, directly or through a heat pump operating with the heat store as its low-temperature reservoir.

1.1 Software verification

The NSES software has been tested on an experimental system studied as part of the project [6]. The parameters use are either measured or taken from conventional thermal simulation programs such as TRNSYS [8]. The resulting solar thermal efficiencies parametrised in terms of $T^* = (T_{collector\ inlet\ temperature} - T_{environment})/E_{incident\ shortwavelength\ energy\ flux}$ are shown in Figure 1.

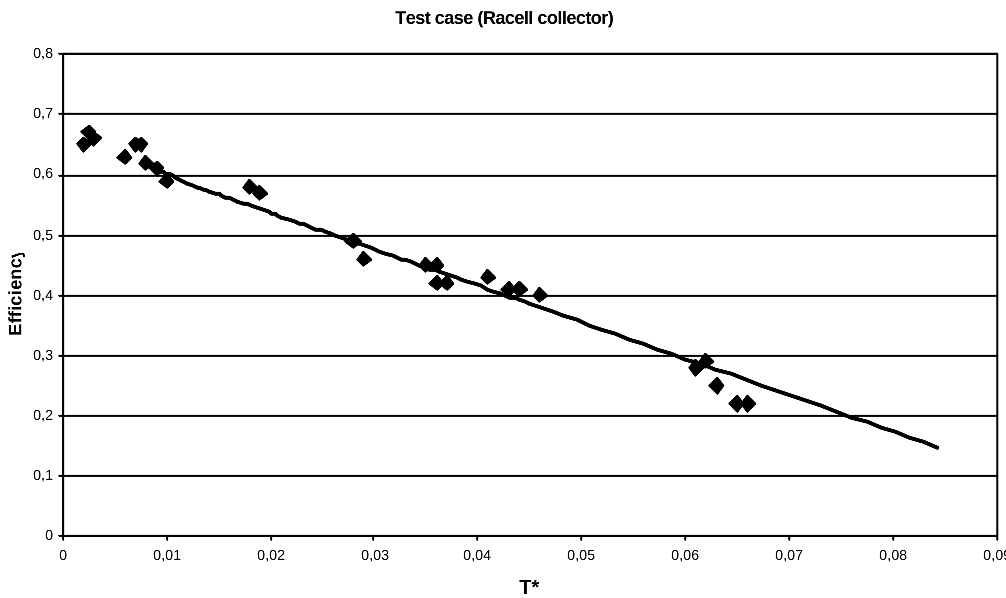

Figure 1. NSES efficiency results for test case (solid line) compared with measured data (♦), using $T^* = (T_{c,in} - T_e)/E_{sw}$

2. RESULTS OF SMALL PVT SYSTEM SIMULATION

The smallest system simulated is similar to the Racell prototype used for the verification shown in Fig. 1: The PV collecting panel is 2 m^2, and the thermal collection takes place under the PV panel by tubes attached to or part of a thermally conducting plate. The thermal storage tank is a mere 100 litres water container, with heat exchangers to collector and load circuits. The photovoltaic collection efficiency is taken as 15%, representing a state of the art commercial silicon module, and only a linear term is included in the thermal performance degradation of the PV efficiency (cf. the data presented in [1]).

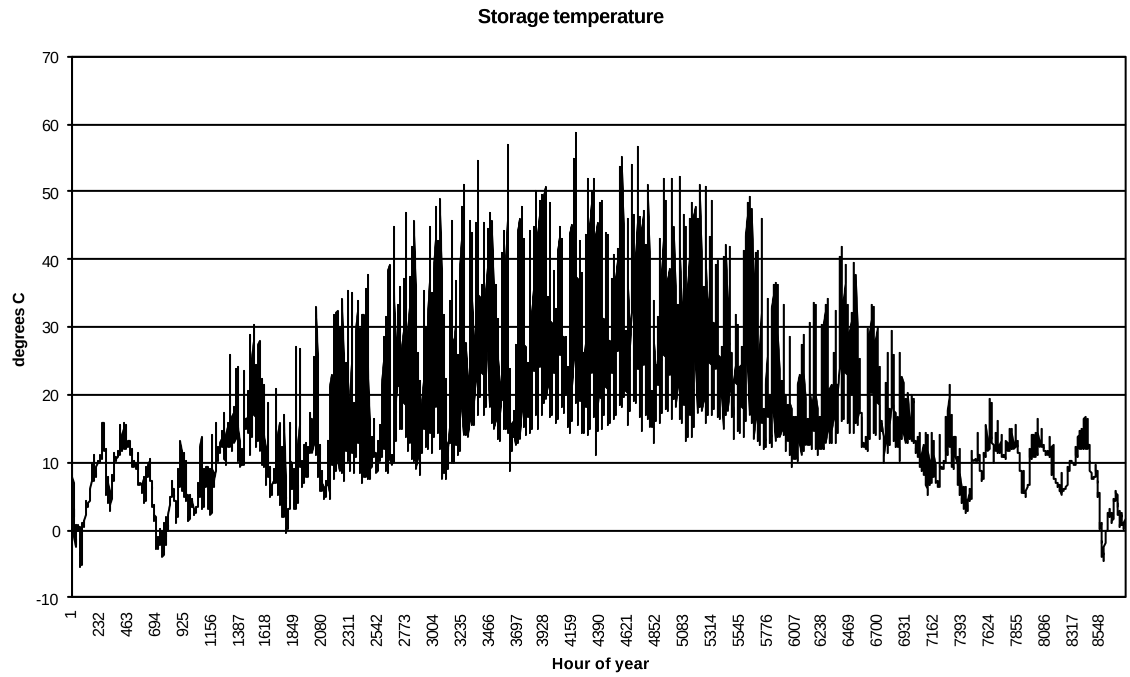

Figure 2. Hourly storage temperatures from NSES simulation of small PVT system.

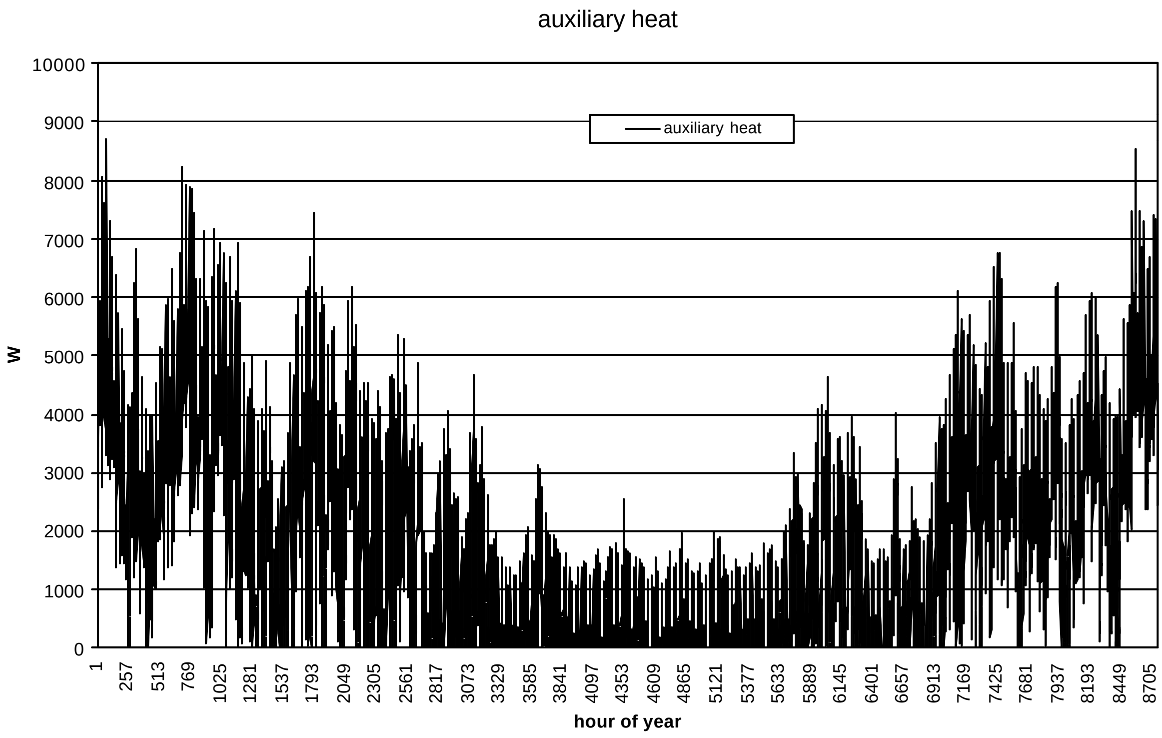

Figure 3. Hourly auxiliary heat requirements from NSES simulation of small PVT system.

The initial temperatures are for consistency taken in such a way that they resemble the temperatures at the end of the simulation period (here a year). This is not important for the small store considered here, because there is no long-term memory (Figure 2). Figure 3 shows the hour-by-hour behaviour of the requirement for auxiliary heat. The electric efficiency deviates a little from 15% in downward direction, due to the thermal effect during summer months. The thermal efficiency remains over 40% year round. The 1st law efficiency is the sum of electric and thermal efficiencies, while the second low efficiency is only slightly over the electric efficiency, due to the modest temperature rises accomplished by the solar system. The system covers about 5% of the annual electricity load and a similar percentage of overall heat load, but over 50% during summer.

The hourly course of storage temperatures (Figure 2) indicates that the solar system contributes to space heating during the period April through September (storage temperature above 28°C). The store temperature rarely exceeds 50°C, so some auxiliary energy is needed for hot water year round, as seen in Figure 3. This could be partially avoided by lowering the flow rate of the water passed through the collector circuit, with some associated decrease in thermal efficiency. It is seen that there are some hours even in winter where the system is able to cover the space heating need.

3. RESULTS OF LARGE PVT SYSTEM SIMULATION

The large system considered has 40 m^2 of PVT collectors and 40 m^3 of water storage. This may be divided into two, e.g. hemispherical parts with a common interface, to simulate stratification. The input to the collector is from the lower store and the heat to load is extracted from the upper part, provided it has a temperature higher than the lower one. The water passing through the solar collector is delivered at the top of the upper store, where a heat exchanger spiral is continuing down to the lower store. This means that if the temperature of the water heated by the solar collector exceeds that of the upper store, it delivers energy to that store and reaches the lower store at a diminished temperature, possibly allowing it to pass further heat to the lower part. This is not meant as a substitute for a more detailed simulation of stratification, which is not included in the present work.

The heat loss from the stores (U-value) is diminished to about a tenth of the value for a single store with 20-30 cm of insulation, because it is supposed that some 100 buildings share a common store, in which case the surface-to-volume advantage allows this kind of reduction, as demonstrated earlier in [4]. The average store temperatures are shown in Figure 4. It is seen that the mixing does not allow temperature differences between top and bottom to persist for very long.

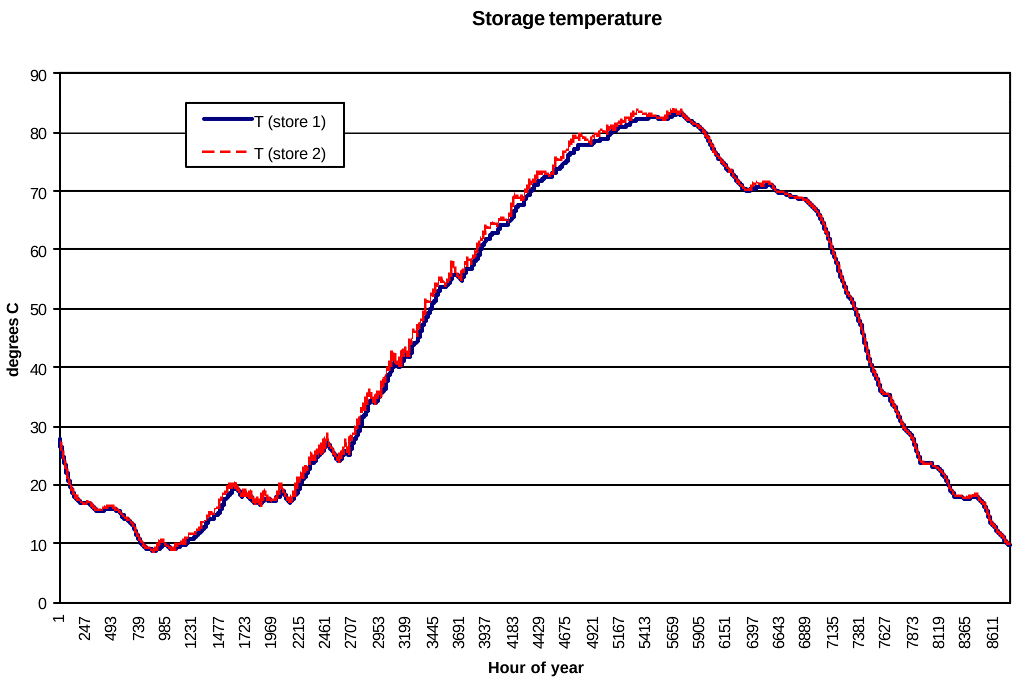

Figure 4. Hourly storage temperatures for the two-component store of the large PVT system simulated.

Electricity needs are covered 100% from late March to early September, and some 50% during the remaining part of the year. However, solar heat is only able to satisfy demand without assistance from late March to end of August. The annual heat coverage is about 65%. There is a strong asymmetry between the behaviour in spring and autumn, which is directly caused by the temperature variations of the store and thus the collector circuit inlet temperature. The store temperature remains high until November, which causes the thermal solar collection to perform poorly, while on the other hand the store is capable of satisfying heat demands from heat collected earlier. There is no need for auxiliary heat from May to November (Figure 5). This proves that the store is large enough to act as a seasonal store, but on the other hand there is a very negative effect on the solar thermal collection during the later months of the year. The hourly solar gain supports this interpretation, showing a clear asymmetry between spring and autumn, with a very poor performance towards the end of the year. The hourly course of storage temperature (1 is lower store, 2 upper) shown in Figure 4 peaks in August and has its minimum value in February, i.e.

displaced by 1-2 months relative to the solar radiation. Due to the size of the store, there are no rapid variations as for the store temperature of the smaller systems.

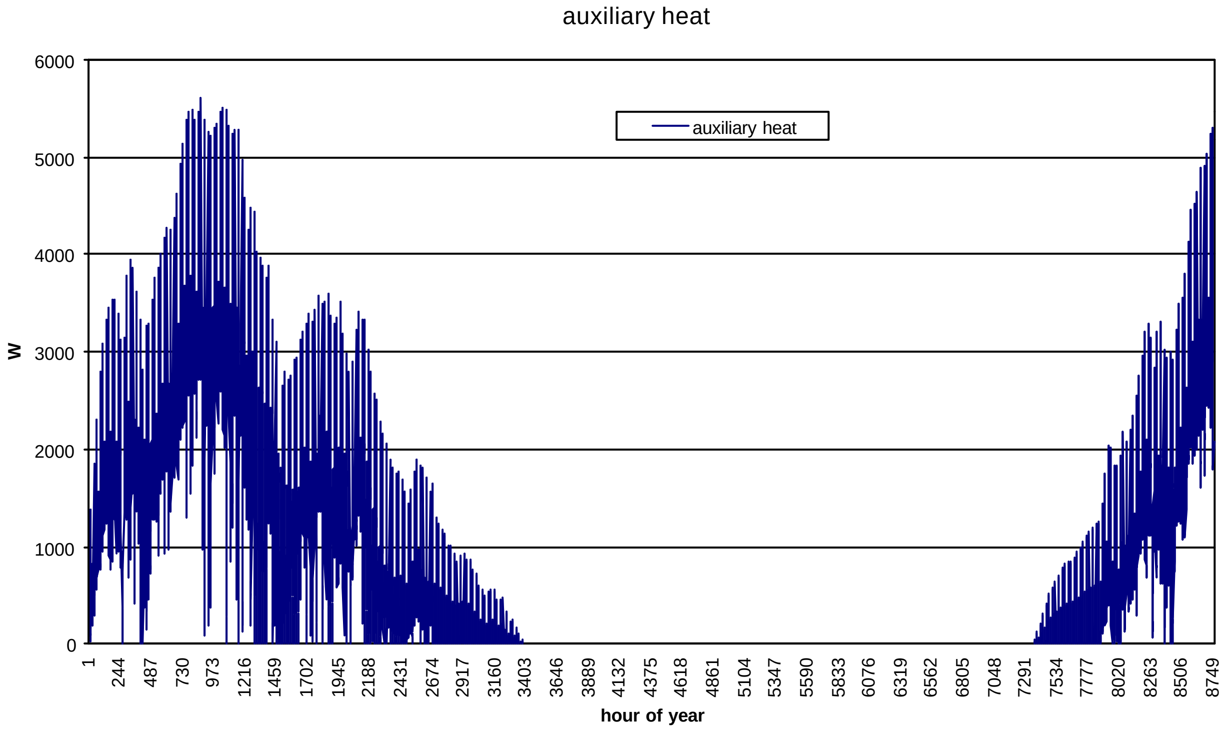

Figure 5. Hourly auxiliary heat requirements. NSES simulation of large PVT system.

The net heat drawn from the (two) stores occasionally becomes negative. This is because auxiliary energy must bring the load circuit temperature above a certain minimum value (here 28°C), and the return air from the load circuit thus heats the store, whenever its temperature is lower than that of the return air from the building ventilation system. This behaviour is confined to a few weeks in January and February. The necessary auxiliary heat inputs are still substantial during winter, although the solar heating system now satisfies all loads from May to November.

4. CONCLUSIONS

The simulations for a range of buildings with heat stores and PV-thermal panels of different size and located in Denmark (two examples being discussed above), show that the hybrid systems offers up to about 60% direct efficiency, as compared with 15% for the PV system considered, if it operated alone. Second law efficiencies are only modestly increased, and the effect of lowering PV collection temperatures by the extraction of heat turns out to be very small.

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