USE OF WEATHER FORECASTS TO CONTROL NIGHT COOLING

Kim B. Wittchen[1], Ejvind Løgberg[2], Søren Pedersen[2], Rolf Djurtoft[2] & Jesper Thiesen[3]

[1]Danish Building Research Institute, Hørsholm, Denmark
+45 4574 2396, kbw@SBi.dk
[2]Birch & Krogboe A/S, Consultants and Planners, Virum, Denmark
[3]Vejr2 – Private Weather-service of Denmark, Roskilde, Denmark

ABSTRACT

Traditional night cooling control strategies relies on the knowledge of the current situation – indoor and outdoor. The building is ventilated – passive or as free cooling via a mechanical ventilation system - with cool night air, hoping that the building will warm up the following day due to excess of free gains. In cool or moderate climates this often results in a thermal discomfort the next morning due to under-cooled constructions. As a consequence the system is often turned off. Alternatively the control system is modified to provide a hot air boost in the morning to compensate for the cold constructions. The latter is the best solution as the boost only heats the air and leaves the stored cooling energy inside the constructions for subsequent release to the room.

No matter which solution, the result is increased energy consumption for space cooling or heating compared to an optimal situation where heating and cooling is minimised for the next day. This paper focus on a method taking advantage of forecasts issued by the local meteorological office as background for making an intelligent decision about how to control night ventilation – set-point and air flow rate.

INTRODUCTION

One way to reduce the energy consumption for conditioning spaces in a building is to cool down the constructions by letting cool night air flow into the building. The flow of cool night air can be obtained either as free cooling in a mechanical ventilation system or as ventilation driven by natural buoyancy. This control normally aims at cooling the building to a certain temperature, e.g. 18 °C, and thus start the next days heating up from this lower temperature level. The building will require less cooling energy during the next day, as cooling has been stored in the constructions during the previous night. The night ventilation will typically start when the night air has reached a temperature some degrees below the indoor temperature (Oestreicher et. al, 1996) and run until the room or the constructions have reached a certain temperature or until 1 hour before the work starts in the morning. The last hour, without night cooling ventilation, before start of the work will allow the building to gain a little of the temperature drop and increase the comfort level. Previous works have showed that this approach have a good potential for saving cooling energy (Braun, 1990), (Givoni, 1998).

In cold or moderate climates, this traditional night cooling strategies have a tendency to create indoor climate problems during the first hours of work. If the constructions are cooled to eliminate the cooling load of the next day, the indoor operative temperature will normally be too low to be acceptable (Fanger, 1972). To avoid this, a hot air boost is often introduced in the morning to compensate for the cool constructions.

In a recent research project (PSO ELFOR 2003, Project no. 335-006, *Optimising of night cooling in buildings using local weather forecasts*) this problem has been addressed and the potential energy savings estimated for office buildings. New possibilities for control strategies have been evaluated using detailed thermal building simulations in combination with forecasts for the upcoming next hours of outdoor conditions. The passive night cooling control strategies are thus dependent not only on the current conditions in the building and the environment, but also on a forecast of the conditions of the outdoor climate. The outdoor climate prediction can either come as forecasts from the local meteorological office via a network connection or as in-house predictions of the outdoor climate. In the present project the weather forecasts was foreseen being provided by a local meteorological office. It was thus of importance to gain confidence in the accuracy of these forecasts.

A prototype of an intelligent control strategy has been implemented in a thermal building simulation tool. Preliminary results indicates that the energy consumption for space cooling and heating can be decreased, while at the same time improving the thermal indoor climate.

RESEARCH PROJECT

A research project was set up to investigate the possible energy saving by having a better control strategy for night cooling in office buildings. The thesis of the research project was that having accurate knowledge of the weather (temperature and solar irradiation) for the coming day, it would be possible to control the night cooling in a more optimal way. The improved control should lead to energy savings and/or thermal comfort improvements. The energy saving is realised by: 1) avoiding/minimising the heated air boost in the morning to overcome thermal discomfort due to cold constructions, and 2) storing just the right amount of cooling in the constructions when the external loads of the next day are known.

Previous projects indicate that use of night cooling techniques can lead to substantial energy savings of the cooling load (Loiso & Springer, 2000) (Davis Energy Group, 2004). Use of predictions on the outdoor climate to control the night cooling strategy could lead to additional savings of 10-15 % (Kummert, 2001).

ANALYSES OF WEATHER FORECASTS

Two parallel surveys were conducted in the project. A retrospective survey on the accuracy of local weather forecasts from a meteorological office. And analyses of the theoretical energy saving potential due to intelligent night cooling control strategies, based on weather forecasts.

There is a difference in how predictable the weather is in different locations. For this survey an inland and a coastal near station was selected (figure 1). The forecasts were then compared to readings from these stations.

Figure 1. Location of Skrydstrup and Holbæk meteorological stations used in the retrospective survey.

Weather forecasts

The first condition for being able to control the night cooling in a building in a more intelligent way requires knowledge of the weather the next day with a reasonable accuracy.

An often used perception of tomorrow's weather is that if you don't know better, the weather tomorrow will be the same as today. This simple forecast however showed up to be a rather rough estimate and too rough to be used as a qualified guess for controlling night cooling of a building. In only 45 % of the cases this guess will lead to an error of less than ± 2 K on the predicted outdoor temperature 12 hours later. More accurate predictions do thus require more sophisticated algorithms in the energy monitoring and control system of the building. This is assumed to be more difficult than obtaining forecasts from a meteorological office.

The meteorological office conducted a retrospective survey of their weather forecasts from Skrydstrup (inland station) and Holbæk (coastal near station). Both stations are located in Denmark, having a cool or moderate climate, dominated by Westerly winds from the sea. The goal of the survey was to see how accurate the outdoor dry bulb air temperature and the global solar irradiation had been forecasted 12 and 24 hours before the readings. All forecasts were issued at 0 UTC (Universal Time Coordinate), which is 1 AM wintertime, respectively 2 AM at summertime.

From this survey it was shown that the ambient temperature could be predicted 24 hours in advance with an accuracy of ± 2 K in 97 % of the case and with ± 1 K in 70 % of the cases (figure 2).

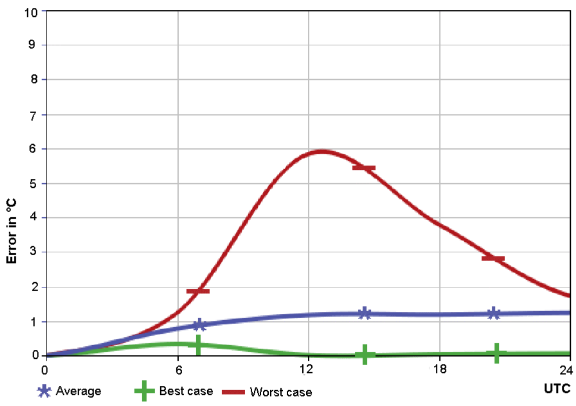

Figure 2. Error in predicted outdoor temperature for 0 to 24 hours ahead during July and August 2004 for the meteorological station at Skrydstrup (inland). The curves show the error for the average forecast, the best forecast and, the worst forecast.

Solar irradiation, the predominant factor for determining the cooling load in many buildings, is more difficult to predict. Locally occurring clouds have a strong impact on the energy content of the solar irradiation at a given location. These local variations are difficult to predict as they strongly depend on the wind direction and thermal heating over land.

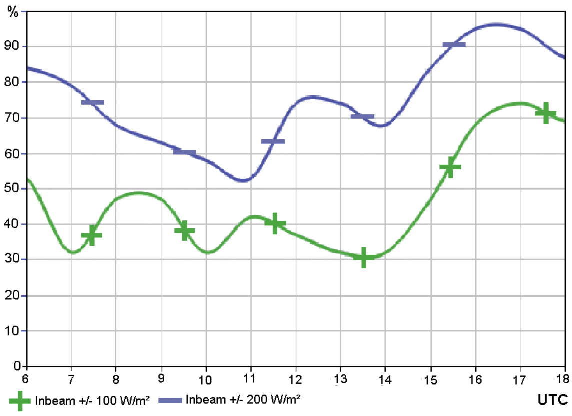

Figure 3. Predictability (±100 W/m², ±200 W/m² respectively) for solar irradiation forecasts 6 - 18 hours ahead as average during July and August of 2004 for the meteorological station at Holbæk (coastal near).

In general the survey proved it possible to predict solar irradiation within a margin of ± 100 W/m² for the coming day in less that 50 % of the cases. Solar irradiation with a margin of ± 200 W/m² could be predicted in approximately 70 % of the cases (figure 3). The largest absolute errors are found around 11 UTC (1 PM local summertime), which normally is the hour with the highest absolute value of solar irradiation.

A numerical large error in predicted solar irradiation around noon is not necessarily critical for the prediction of the cooling load in a building. At this time of the day the solar altitude is high solar gain can thus easily be reduced by and horizontal, fixed shading.

From this retrospective survey, it seems that using forecasts from a meteorological office can give reasonable input for a predictive night cooling strategy. The analyses of the night cooling strategy in office buildings have thus been conducted under the assumption that it is possible to get reasonable accurate forecasts that makes it possible to establish a optimal night cooling strategy.

NIGHT COOLING ANALYSES

The second part of the research project focused on determining the potential energy saving by using an optimised 24 hour weather forecast to control the night cooling level of an office building.

In this work the acceptable comfort level have been judged from the simulated operative (average of air- and mean radiant temperature) temperature of the room. This is not a precise evaluation of the comfort level, but the simulation model does not provide information about the comfort level (PMV or PPD, Fanger (1972)). The operative indoor temperature, which is assumed to give an acceptable comfort level, has been fixed to 21 °C in this study.

Forecast model

The goal of the intelligent night cooling strategy is to eliminate or minimising the heating and cooling load of the next day by using passive cooling of the constructions to the right temperature. The right temperature is determined by a simulation of the next day's cooling and heating loads when using the weather forecast as input for the simulations.

To investigate the energy saving potential, a computer model was set up. The model uses knowledge of the climate data file to make a 100 % accurate prediction of the weather for the next 24 hours.

Such a prediction is the most extreme one can imagine and represents thus the maximum energy saving by optimising the control of a passive night cooling system. This forecast model was used as a first attempt to determine the energy saving potential when using advanced night cooling control strategies. Real energy savings due to less accurate predictions are thus less.

The "prediction" method was implemented in the hygro-thermal simulation tool BSim (Wittchen et. al, 2000-2005) (Rode & Grau, 2003). Results from simulations of the intelligent night cooling control were compared to results from simulations with a standard night cooling strategy and more traditional ventilation strategies.

Model implementation

In the model two parameters can be adjusted when trying to find the optimum night cooling of the constructions in a building to meet the free gains. One is evidently the temperature that the constructions should reach during the night. The other parameter is the volume of the airflow to cool the constructions. The airflow volume together with the actual temperature difference determines the passive cooling capacity of the night air. Increase of the airflow will increase the cooling if the set-point temperature can not be reached during the time-span of the night.

The 100 % accurate forecast of the next 24 hours of climate was implemented in the BSim program package as:

1. The program is interrupted at the time of the beginning of a night cooling period. Optimisation iterations are then carried out.
2. Simulation, using the night cooling set point from the previous simulation until the end of the next day, is performed.
3. Results are compared to upper and lower acceptable limits (heating and cooling set points) of the operative indoor temperature. If the indoor temperature is within the limits, the program will try to minimise energy consumption for cooling and heating.

4. If the indoor temperature is *not* within the limits, a new night cooling set point and airflow is calculated in order to be inside the limits of the indoor operative temperature and minimising the energy consumption, and the simulation loops back to 2.
5. When the results are within the limits of the indoor operative temperature, or the cooling and heating load is minimised, results are added to the result log and normal simulation resumes.

A night cooling technique – with or without an advanced control strategy – should only be used if there is sufficient cooling potential in the night air. The advanced night cooling is thus subject to the general night cooling start conditions. The night cooling set point must be some degrees below the indoor operative temperature and the outdoor temperature must be some degrees below the night cooling set point – at least if the cool night air is to be moved by a mechanical ventilation system. This conditions ensures that the ventilation system do not run unless there is a reasonable cooling potential in the night air, and that this potential is higher than the energy consumption used by the fans to move the air.

RESULT ANALYSIS

A simple building model was set up to investigate the potential of the forecasting technique to control night cooling. The rooms were equipped with standard office equipment and profiles of use. The investigated model (figure 4) has constructions with a relatively high thermal mass. The inner leaf of the walls is made of 50 mm concrete and the floor 150 mm concrete under a wooden floor. The ceiling is a lightweight construction with wood on insulation facing the room.

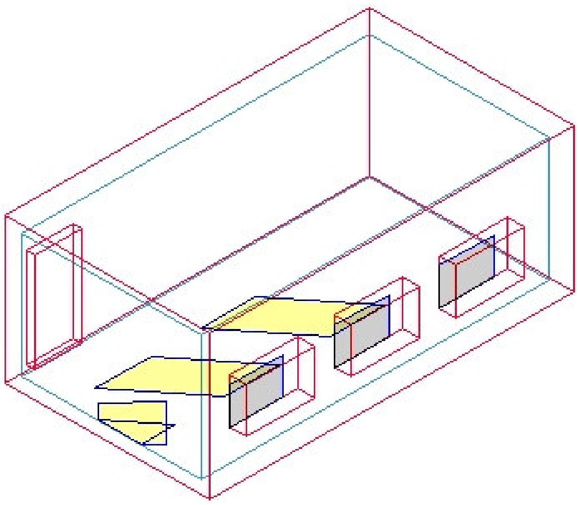

Figure 4. Wire frame diagram of thermally heavy model with indication of solar gains through windows in the facade.

In the simple building model the air is fully mixed – meaning there is only one air node. This situation is an advantage for the night cooling approach as no obstacles hinder the air from getting in contact with the constructions. In a real building, the constructions closest to the air inlets will first be influenced by the stream of cool night air. Furniture and other obstacles will in some other places hinder the air-movement over the constructions and thus reduce the storage effect of that part of the thermal mass. On the other hand, furniture does add to the surface and the thermal mass of a room. At least in thermally light rooms, furniture increases the thermal mass significantly. It is thus assumed acceptable to neglect the influence from full mixing of the air as the different parameters points in opposite directions.

Reference case

The reference model is the same model as used for passive night cooling, just with the ventilation system running on normal control outside working hours. The cooling coil of the ventilation system must thus cope with the free gains during working hours and keep the indoor temperature at the same level as in the other models.

The goal of the simulation exercise was to keep indoor conditions at the same level. This means that the maximum indoor operative temperature and the number of hours - during working hours - with indoor temperatures below 20 °C, should be the same.

Standard night cooling strategy

The case with standard night cooling strategy aims at reaching a fixed indoor temperature during the night by ventilating the building. The temperature set-point will normally be slightly lower than the desired temperature during the working hours.

The standard night cooling strategy is used as a supplement to the traditional cooling strategy during working hours.

In this case the standard night cooling set point is 18 °C. Night cooling will only be started if the operative temperature of the sensor zone is 3 °C (21 °C) above the night cooling set point and if the ambient temperature is 3 °C below the night cooling set point temperature (15 °C). These limitations will ensure that the cooling potential of the night air is sufficient to meet the energy consumption to the fans if the cool night air is moved via a mechanical ventilation system.

The standard night cooling strategy leads to 59 % savings of the energy requirement for cooling compared to the annual cooling load in the reference case. At the same time the energy consumption for the heating coil increases with 43 %. In total the energy saving due to utilisation of night cooling is 38 %.

Table 1. Annual energy consumption (kWh) for heating and cooling coil in the ventilation system for reference and standard night cooling case.

	REF.CASE	STD.NC
Heating coil	130	186
Cooling coil	494	203
Total	624	389

As a side effect to the energy savings, the indoor climate during summer time has been improved. The annual number of hours with indoor temperatures above 23 °C is almost cut to half. If one only look at the working hours, the number of hours with indoor temperatures above 23 °C have decreased due to the night cooling from 66 % of the hours to 52 % of the hours. At no time the indoor temperature rises above 24 °C in any of the models (see figure 5).

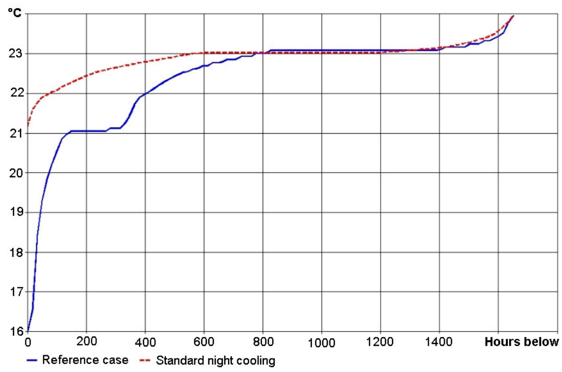

Figure 5. Working hours with indoor operative temperature below different levels in the reference case (+), and with normal night cooling.

In figure 6, heating and cooling consumption for a normal ventilation system (reference case) and a system with standard night cooling is shown during a hot summer week. Morning hot boosts are required when running night cooling, but the cooling load of the next day is decreased.

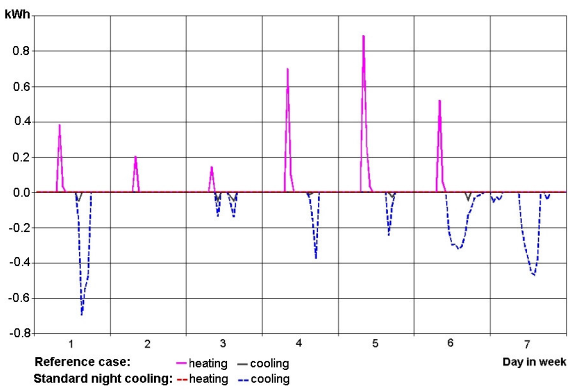

Figure 6. Cooling and heating requirement during a hot summer week in the reference case vs. a traditional night cooling strategy. Cooling energy shown as negative values.

The general indoor temperature level of the room have decreased significantly when using the night cooling compared to a normal mechanical ventilation system (figure 7). It is however necessary to heat the room air before work hours to avoid complains about the building being too cold. The reason for the discrepancy between the temperatures at the beginning of the week is due to lack of free gains from office equipment and persons during weekends and low outdoor temperatures during the weekend.

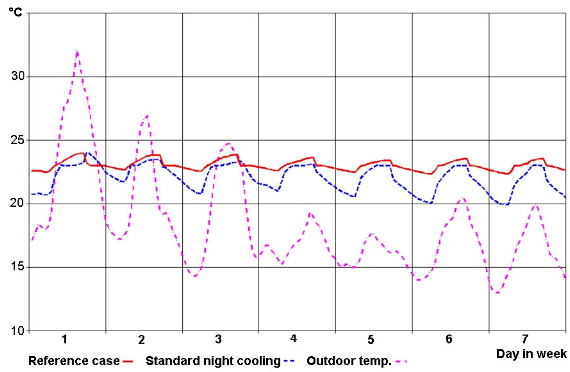

Figure 7. Indoor operative temperature during a hot summer week in the reference case and with standard night cooling.

Forecasted night cooling strategy

The advanced night cooling strategy utilising weather forecasts aims at minimising energy consumption for conditioning the room over the next day and at the same time maintaining the level of indoor thermal comfort. The indoor thermal climate can not be kept at exactly the same level, but the number of hours between the heating and the cooling set points should not differ significantly.

Table 2. Annual energy consumption (kWh) for heating coil and cooling coil in ventilation system for standard night cooling case, and forecast night cooling case.

	STD.NC	FC.NC
Heating coil	186	240
Cooling coil	203	129
Total	389	369

The annual energy consumption for heating has increased by 28 % while the energy consumption for cooling has decreased by 36 % (table 2). The total energy consumption for conditioning the room has thus been decreased by 5 %.

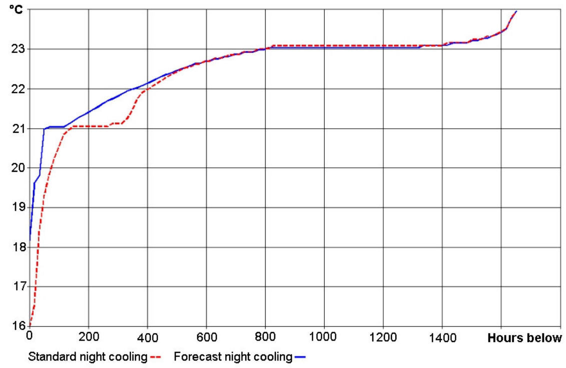

Figure 8. Working hours with indoor temperature below different levels in the standard night cooling case and with forecasted night cooling strategy.

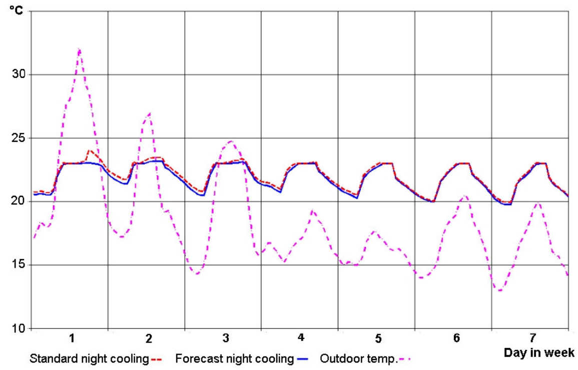

Figure 10. Indoor operative temperature during a hot summer week with standard night cooling strategy and with a forecasted night cooling strategy.

At the same time the indoor climate has been improved. The cold morning temperatures (below 21 °C) have decreased. The number of hours with high indoor temperatures has not increased due to the use of forecasting night cooling strategy (figure 8).

Figure 9 show, as an example of the heating and cooling loads during a hot summer week in a system with normal night cooling strategy and with forecasted night cooling. The hot morning boost has increased using the forecast strategy while the cooling consumption has decreased.

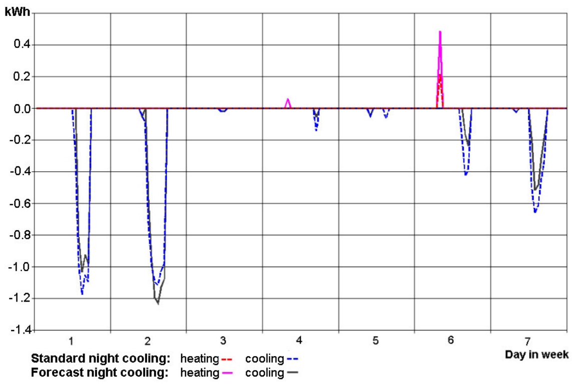

Figure 9. Heating and cooling requirement during a hot summer week with traditional night cooling strategy (red and blue), and a forecasted night cooling strategy. Cooling energy shown as negative values.

In figure 10, a graphical representation of the indoor operative temperature in the normal night cooling case and the intelligent night cooling case is shown. The forecasted night cooling control cools the building slightly more during the night. The installed cooling power and airflow is the same in the systems of the two models.

DISCUSSION

The weather forecast of the coming 24 hours used in the simulation model is – contrary to real weather forecasts - 100 % accurate. This means that the energy savings identified by using this forecast method for controlling the passive night cooling is overestimated. In the real world, control according to a forecast issued by a meteorological office, will sometimes lead to too much night cooling and sometimes to too little night cooling. Real savings must thus be expected to be lower, but on the other hand, the investigation have shown that this control method have an energy saving potential. The potential might not necessarily lead to large energy savings, but it can definitely lead to improvements of the thermal indoor climate, especially in the morning.

The retrospective analyses of weather forecasts have been made for two Danish meteorological stations, and the uncertainties might thus not be valid for any geographical location and any meteorological office.

The forecast method is implemented as a control strategy of a mechanical ventilation system. The consumption of energy is thus connected to running the fans during night-time. A more energy efficient system configuration would be to operate the night cooling system as a natural ventilation system – i.e. by operating windows or shutters to allow cool night air to move into the building by natural buoyancy. The energy consumption for running the fans has thus been neglected in this study.

As the method has only been tested on a few theoretical models, it is not evident that the method will work for any arbitrary building configuration. The number of possible combinations in terms of internal free gains, climate conditions, glazing types, solar shading, air conditioning systems, building geometry, orientation, and thermal mass, etc. is unlimited.

For the time being the method have only been tested on theoretical basis. To prove its validity further development and tests have to be made. When reaching a more final state, the method must be tested in real buildings and implemented in energy monitoring and control systems. At the end, the method must be implemented in a generally available thermal building simulation tool in order to allow consultants to simulate the control strategy for their specific, actual building projects.

Future research and development of the method is necessary in order to refine the method and optimise the control laws. As a result of the current research project, an application for funding of a second phase will be submitted. In this second phase, forecasts from the meteorological office will be fed into an energy monitoring and control system in a demonstration building. The system will be equipped with an algorithm to calculate the optimal night cooling set point, given the knowledge of next day's climate and the other free gains in the building.

Some factors drag in the direction in advantage of utilisation of the thermal mass. On the other hand, all models are subject to the same conditions. The results and conclusions are thus assumed to be valid.

CONCLUSION

The use of local weather forecasts to control the passive night cooling in a building, aiming at reducing the energy consumption for cooling and morning boost heating, seems to be a promising methodology. The energy savings might not be the most important outcome from using such a method, but there are indications of improvements to the thermal indoor climate, without additional energy consumption.

If the airflow for night ventilation is driven by a mechanical ventilation system – utilising free cooling – it will lead to increase in the energy consumption for running the fans. This increase may well be of the same magnitude as the energy saving obtained by reducing of the cooling load due to efficient night cooling.

The method needs further development and testing before it can be implemented in real buildings for full-scale test and commercialisation.

ACKNOWLEDGEMENTS

The project (Project no. 335-006, *Optimising of night cooling in buildings using local weather forecasts*) has been supported financially by ELFOR's (Association of Danish Power Producers) PSO (Public Service Obligations) R&D programme 2003.

Without the corporation of the project partners from Birch & Krogboe A/S, Consultants and Planners and Vejr2 meteorological office this work would never have been made.

REFERENCES

Braun J.E., 1990. Reducing energy cost and peak electrical demand through optimal control of building thermal storage. ASHRAE Transactions, Vol. 96, No. 2.

Davis Energy Group, 2004. Alternatives to Compressor Cooling, Phase V: Integrated Ventilation Cooling. California Energy Commission. Public Interest Energy Research Program. P500-04-009.

Fanger P.O., 1972. Thermal comfort analysis and application in environmental design. Mac Graw Hill.

Givoni B., 1998. Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Energy and Buildings, vol. 28 (1998) pp 25-32.

Kummert M., 2001. Contribution to the Application of Modern Control Techniques to Solar Buildings. Simulation-Based Approach and Experimental Validation. Fondation Universitaire Luxembourgeoise, Luxembourg.

Loisos G. & Springer D., 2000. Alternatives to Compressor Cooling. California Energy Commission. Public Interest Energy Research Program. 500-97-013.

Oestreicher Y., Bauer M. & Scartezzini J.-L., 1996. Accounting free gains in a non residential building by means of an optimal stochastic controller. Energy and Buildings, Vol. 24, No. 3. pp 213-221.

Rode C. & Grau K., 2003. Whole-building Hygrothermal Simulation Model. ASHRAE, American Society of Heating, Refrigeration and Air-conditioning Engineers. Recent Advances in Energy Simulation: Building Loads, Symposium CH-03-09 - Chicago.

Wittchen K.B. Johnsen K. & Grau K., 2000-2005. BSim User's Guide. Danish Building Research Institute, Hørsholm, Denmark (www.bsim.dk).