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Pc 49

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Optimal Control of Greenhouse Climate

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Head of Process Engineering Division: Prof. W. Day

ENGINEERING for Life

1992

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Project Coordinator: J.Overvoorde

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Key Words: greenhouses, heating, tomato, energy savings

INDEX

1. Relevance to Growers

1.1 Application

The objectives of the project were:

(1) To demonstrate the feasibility of implementing a novel form of control of greenhouse heating, and

(2) To examine the practical implications to the grower of variable greenhouse temperatures.

The key results were:

(1) A computer program has been implemented on a commercial nursery to minimise heat consumption.

(2) The computer program runs on a PC which communicates with a commercial greenhouse computer system.

(3) The PC receives Meteorological Office's weather forecasts remotely via a modem.

(4) The computer program varies the temperature set point on an hourly basis.

(5) The calculated temperature set point was shown to vary inversely with wind speed.

(6) After initial hesitation, the grower gained confidence in this novel form of control.

1.2 Summary

The reason why essentially constant day and night set point temperatures are used to control greenhouse heating is simple - this was way the only way in which the first thermostats could be used, and this practice continued. However, in nature plants do not experience constant temperatures, so there is no fundamental reason why the greenhouse temperature should be held constant. Thus a variable heating temperature could be considered, especially if doing so gave some specific benefit. A novel form of heating control has been tested on a commercial nursery. The heating temperature was varied from hour to hour throughout the day in a way designed to reduce heat consumption. The primary of the experiment, however, was not to minimise heating but rather to determine the grower's reaction to this form of varying temperature control.

The heat loss from a greenhouse depends on external weather conditions. It increases as the wind speed increases, the temperature of the external air decreases and, to a lesser extent, as the cloud cover decreases. Heat input can be reduced by lowering the heating temperature under conditions when the heat loss would be high, and raising it during a period when the outside conditions are not so adverse, in order to obtain the same average temperature as would have been obtained using conventional fixed set points. Earlier research, funded by MAFF, had shown that doing this reduces heat consumption by 10-15%, depending on the type of greenhouse and its exposure to wind. Evidence from numerous horticultural trials in USA, Germany and the UK, has shown for many species of plants, including tomatoes, cucumbers, lettuce and chrysanthemums, that growth rate depends primarily on the average temperature at which plants are grown, and that limited variations in temperature above and below the average value have no detectable effects.

The control policy was based on (i) a mathematical model which predicted the heat loss from the greenhouse when given values for wind speed, solar radiation, cloud cover and internal and external air temperatures and (ii) a mathematical method for minimisation. The mathematical model and the mathematical method for minimisation were programmed into a personal computer linked to the existing greenhouse commercial environmental controller, so that the heating set point temperature, calculated for each hour, could be passed to the controller which then adjusted the greenhouse temperature as required.

To use this to minimise heat input, required information on how the wind speed, solar radiation, cloud cover, external and internal air temperature were expected to change over the following 24 hours. This was obtained using the forecasting service of the Meteorological Office. Every day forecasts of wind speed, solar radiation and air temperatures were faxed to Silsoe and then sent via a telephone link (modem) between a computer as Silsoe and the PC at the nursery.

The experiment was carried out on a commercial greenhouse (Carnation Nursery, Newport, near Saffron Waldon) growing tomatoes. To safeguard the crop, the calculated temperature was constrained to remain between upper and lower limits and at the grower's request, a differential between the day and night temperatures was introduced.

Technically the project was successful, the calculated heating set points decreased as wind speed increased and the required average temperatures were obtained over successive periods of day plus night. While this form of varying set point control has application in reducing heat consumption, it is potentially of much greater significance. Current research at Silsoe and HRI is aimed at developing a method for controlling CO_2 enrichment based on a comparison of the cost of supplying the CO_2 and the extra value it gives through increased productivity. This form of control will determine the concentration at which the cost margin between the increased value of the crop and the cost of providing the CO_2 is maximised; thus the optimal CO_2 concentration will vary with solar radiation and ventilation rate. A similar form of control is also possible over greenhouse humidity. Consequently this test of variable set point temperature control has demonstrated the acceptability of this form of control, which is aimed directly at increasing growers profit margins.

2. Science Section

2.1 Summary

1. A real-time optimal control algorithm for greenhouse heating has been implemented and tested on a commercial nursery with a tomato crop.

2. The algorithm is based on a model of the greenhouse energy requirements and on a numerical method for optimisation, and uses weather forecasts supplied by the Meteorological Office.

3. The algorithm resides on a PC which communicates with a commercial greenhouse computer system and which receives weather forecasts remotely via a MODEM.

4. The algorithm calculates the optimal values of hourly temperature setpoints which minimize energy consumption over a 24 hour period whilst maintaining the setpoints between lower and upper bounds and achieving a pre-defined 24 hour average setpoint value.

5. Despite initial uncertainty, the grower rapidly gained confidence that the control strategy was sensible.

6. Simulations have shown that energy savings increase with the temperature integration period; however, weather forecasts tend to become worse as the integration period increases.

7. Simulations have also shown that the energy savings increase significantly if the pre-defined 24 average temperature setpoint value is relaxed to vary between narrow bounds rather than set at a fixed level; however, the longer term average value of the temperature setpoints (i.e. over few days) needs to be maintained to achieve the required crop response to temperature.

2.2 Introduction

At present, climate control systems in greenhouses have fixed setpoints for temperature. Recent studies[1,2] have indicated that it is sufficient to maintain an average temperature in a greenhouse over a selected period. Crop growth and development are not compromised by short term fluctuations in temperature as long as the average value over the same period is maintained. Based on these studies, a different type of control strategy has been suggested[3].

A real-time optimal control strategy has been developed and implemented on a commercial greenhouse. This strategy changes the temperature setpoint frequently (limited by the thermal response time and heating capacity of the greenhouse) in order to minimize heating costs whilst simultaneously achieving the required temperature integral and maintaining the temperature between bounds. This HDC funded project has implemented the strategy in order to demonstrate the potential benefits and highlight the possible obstacles to its use by industry.

The objectives of the experiment were three-fold:
(i) to demonstrate the feasibility of implementing an optimal control algorithm on a commercial nursery,
(ii) to examine the practical implications to the grower of variable greenhouse temperatures, and
(iii) to carry out preliminary evaluations of energy savings.

2.3 Materials and Methods

2.3.1 Heating Control Strategy

The optimal control strategy is based on a mathematical model for calculating greenhouse energy requirements and on a mathematical method for minimizing total energy requirements. The model[4] calculates the rate of heat input required to maintain a temperature setpoint. Integrating this rate over the selected period gives the total energy consumption. The model is driven by external weather forecasts: air temperature, sky temperature, wind speed and solar radiation. It is parameterised by a set of coefficients which characterise the thermal coupling properties of the greenhouse. The optimisation method[5] uses the energy model to calculate the optimal temperature setpoints within the required constraints. The optimisation method starts with an initial estimate of the optimal setpoints and then adjusts their values iteratively until it converges to the optimal setpoints.

The initial optimisation strategy is based on a rolling 24 hour period for temperature integration. Provided the required average temperature is achieved over a 24 hour period, it is assumed that the plant response will not be influenced by short term and limited temperature variations. In this experiment, the temperature setpoint is changed on an hourly basis which means that there are

24 temperature setpoints over the period of integration. The constraints are defined in terms of fixed settings for the lower and upper bounds on daytime and nighttime setpoints and for the average daytime/nighttime differential.

2.3.2 Weather Forecasts

Forecasts of wind speed, air temperature and solar radiation over 24 hour periods are used in the control algorithm. The forecasts are obtained from the Meteorological Office. The sky temperature is calculated from the values of air temperature and a mean value for cloud cover.

2.3.3 Implementation

The PC containing the optimal control algorithm was linked to a nursery greenhouse control system. Each zone of the nursery was controlled by an ENVIROCON 3 greenhouse climate controller. The nursery has a local weather station and an office PC connected to the ENVIROCON network. The optimal control PC uses weather forecasts supplied by the Meteorological Office. These forecasts are received by the PC over a MODEM link and the calculated optimal setpoints are then broadcast over the ENVIROCON network every hour. Figure 1 shows a schematic diagram of the overall system.

The meteorological weather forecasts for the forthcoming 24 hour period (day i) are updated on the optimal control PC - sometime during the previous day (day i-1) - for the period between 6.00 GMT on the forthcoming day (day i) and 5.00 GMT on the following day (day i+1).

The optimal control algorithm can be divided into the following steps which are repeated on a daily cycle:

(1) At 6.00 GMT, update the weather forecasts for the 24 hour period between 6.00 GMT on day i and 5.00 GMT on day i+1;

(2) Run the optimisation module to determine the optimal 24 temperature setpoints for the period between 6.00 GMT on day i and 5.00 GMT on day i+1;

(3) Update the temperature setpoint on the ENVIROCON at every hour and on the hour between 6.00 GMT on day i and 5.00 GMT on day i+1 according to the values obtained in step 2.

The constraints on the optimal control algorithm are the lower and upper bounds of the temperature setpoints, their 24 hour average value and the average daytime/nighttime differential. The constraints are saved as setpoints in the ENVIROCON. They can be changed either from the EVIROCON 3 climate controller or from the ENVIROCON PC. When changed, the new constraints would become active at 6.00 GMT the next day.

2.3.4 Experiment

The trial of this novel control strategy was carried out at Carnation Nursery, Newport, Essex, on a tomato crop. It was implemented on the nursery's ENVIROCON system. Minimal changes were made to the existing configuration except to add the optimal control PC and re-define some of the setpoints on the ENVIROCON.

The experiment was conducted between January and March 1994. The weather forecasts were sent daily to the optimal control PC via a MODEM link from a communication PC at Silsoe. For monitoring purposes and analysis, daily experimental data on the optimal control PC were sent back to Silsoe's communication PC via the same MODEM link.

2.4 Results

2.4.1 Operation

Although the concept of optimising greenhouse heating is not novel[6], the implementation of such a strategy in practice is new. The rationale behind the working of this new control algorithm is that it should easily be integrated with existing, commercial greenhouse computer systems. It has been proved that implementing this algorithm on a commercial greenhouse computer system is technically feasible as long as the system can communicate with an additional PC to send setpoints and receive environmental data to and from the greenhouse climate controller. Incorporating weather forecasts is critical to the working of the algorithm. This was also proved to be technically feasible by sending the Meteorological Office weather forecasts remotely.

2.4.2 Grower's response

After initial hesitation, the grower became confident with the new system. Because the system is fully automatic, the grower had only to input the constraint settings for the temperature setpoints. He could vary these settings on a daily basis. The weather forecasts were sent automatically from Silsoe Research Institute and did not require his intervention. The displays on the optimal control PC were informative. He could look at the predicted hourly values of the optimal temperature setpoints and override any setpoint at the specified time if he wished to do so. He could also easily inactivate the algorithm at anytime and hand over the control to the standard system.

The grower has identified several problems with the system. These problems were mainly presentational. There were occasions on which he could not understand the choice of setpoints. There may be a need to incorporate an "intelligent" module to explain the reasoning behind some of the decisions.

2.4.3 Weather forecasts

The weather forecasts that were used in this experiment were provided by the Meteorological Office. The forecasts were for a grid cell centred on Stansted Airport which is the nearest weather station to the nursery. The temperature setpoints that are calculated by the algorithm are optimal if the weather forecasts are perfect. A statistical evaluation was carried out to find the appropriateness of the Meteorological Office weather forecasts for a particular location to predict weather conditions at a site near that location. Comparisons were made between the Meteorological Office forecasts of wind speed, temperature and solar radiation at Cardington and the recorded weather variables at Silsoe. The evaluation was carried out for the greenhouse at Silsoe rather than for that at Newport because the local, greenhouse weather station at Silsoe is more accurate than that at Newport.

The weather forecasts were provided on a daily basis (in the morning) for the following 72 hours starting from midnight and were given at three hourly intervals. Linear interpolation was carried out to determine hourly values. Figure 2 shows the histogram of the daily mean absolute deviation between the recorded and the 24 hour ahead forecasts of wind speed for February. Figures 3-4 are respectively the counterpart results for the 48 and 72 hour ahead forecasts. Although a detailed analysis is required to determine the sensitivity of the optimal values of heating setpoints to errors in weather forecasts, it is clear from these figures that up to 24 hour ahead forecasts are adequate for the purposes of this algorithm. The forecasts tend to become substantially worse for more than 24 hours ahead. This may have implications on the integration time interval.

2.4.4 Optimal temperature setpoints

Figure 5 shows a recorded trajectory of the optimal temperature setpoint over 72 hours. The temperature setpoint is changed every hour. The optimisation was carried out with the following constraints on the temperature inside the greenhouse: a daytime average of 19°C, a nighttime average of 17°C, a daytime maximum of 24°C, a daytime minimum of 14°C, a nighttime maximum of 20°C and a nighttime minimum of 14°C. Although in theory the heating setpoint could be changed more frequently than once per hour, in practice this is limited by the thermal response of the greenhouse. Moreover, there may be a need to put an upper bound on the deviation between successive values of heating setpoints.

Simulations were carried out on historical weather data to show the value is relaxed. However, because the average temperature is different in each 24 hours, it is important that the longer term average (e.g. over 5 days) is maintained in order to achieve the required crop response to temperature.

2.6 Conclusions

It has been demonstrated that an optimal control algorithm for greenhouse heating can be implemented on a commercial greenhouse computer system. The algorithm resides on a PC which communicates with a greenhouse computer system and which receives weather forecasts remotely via a MODEM link. The new control algorithm has been implemented and tested on a commercial nursery. The algorithm has been shown to work in practice. Although the energy savings were not as high as expected because of the strict constraints that the grower considered it necessary to impose, calculations suggest that small relaxations of these constraints can allow savings to approximately 15%. The grower's response to the new control system has been favourable.

Acknowledgements

We are very grateful to Pepe Vidal of Carnation Nursery for allowing us to use his greenhouse and for the time and effort he put in during the experiment. We would like to thank our colleagues Tony Lockwood, Lynn Short and Nick Teer for their assistance throughout this study.

References

1. Langhans,R.W.; Wolfe,M. & Albright,L.D. (1981) Use of average night temperatures for plant growth for potential energy savings. Acta Horticulturae 115, 31-37.

2. Hurd,R.G. & Graves,C.J. (1984) The influence of different temperature patterns having the same integral on the earliness and yield of tomatoes. Acta Horticulturae 148, 547-554.

3. Bailey,B.J. (1985) Wind dependent control of greenhouse temperature. Acta Horticulturae 174, 381-386.

4. Jolliet,O.; Danloy,L; Gay,J.B.; Munday,G.L. & Reist,A. (1991) HORTICERN: an improved static model for predicting the energy consumption of a greenhouse. Agricultural and Forest Meteorology 55, 265-294.

5. Bartholomew-Biggs,M.C. (1987) Recursive quadratic programming methods based on the augmented Lagrangian. Mathematical Programming Study 31, 21-41.

6. Seginer,I; Shina,G; Albright,L.D. & Marsh,L.S. (1991) Optimal temperature setpoints for greenhouse lettuce. J. Agric. Engng Res. 49, 209-226.

7. Aikman,D.P. & Picken,A.J.F. (1989) Wind-related temperature setting in glasshouses. Journal of Horticultural Science 64, 649-654.

8. Huang,Z. & Chalabi,Z.S. (1994) Use of time-series analysis to model and forecast wind speed. J. Wind Engineering & Industrial Aerodynamics. (in press)

Legends to Figures

Figure 1. A schematic diagram of the overall greenhouse computer system.

Figure 2. The daily mean absolute deviation between recorded values and 24 hour ahead forecast values of wind speed for February 1994 at Silsoe.

Figure 3. The daily mean absolute deviation between recorded values and 48 hour ahead forecast values of wind speed for February 1994 at Silsoe.

Figure 4. The daily mean absolute deviation between recorded values and 72 hour ahead forecast values of wind speed for February 1994 at Silsoe.

Figure 5. The trajectory of the standard heating setpoint (continuous line) alongside two optimised trajectories under different constraints (dotted and dashed lines).

Figure 6. Reduction in energy consumption over 24 hours due to using the optimised heating setpoint trajectory instead of a constant heating setpoint. The histogram is based on daily values between January and March of year 1.

Figure 7. Reduction in energy consumption over 24 hours due to using the optimised heating setpoint trajectory instead of a constant heating setpoint. The histogram is based on daily values between January and March of year 2.

Figure 8. Reduction in energy consumption over 24 hours due to using the optimised heating setpoint trajectory instead of a constant heating setpoint. The histogram is based on daily values between January and March of year 3.

Figure 9. Reduction in energy consumption over 24 hours due to using the optimised heating setpoint trajectory instead of a constant heating setpoint. The histogram is based on daily values between January and March of year 4.

Figure 10. Reduction in energy consumption over 48 hours due to using the optimised heating setpoint trajectory instead of a constant heating setpoint. The histogram is based on daily values between January and March of year 1.

Figure 11. Reduction in energy consumption over 72 hours due to using the optimised heating setpoint trajectory instead of a constant heating setpoint. The histogram is based on daily values between January and March of year 1.

Figure 12. The variation of optimised heating setpoint against wind speed for 15 February 1994.

Figure 13. Reduction in energy consumption over 24 hours due to optimisation with relaxed constraints. The histogram is based on daily values between January and March of year 1.

Figure 14. Reduction in energy consumption over 24 hours due to optimisation with relaxed constraints. The histogram is based on daily values between January and March of year 2.

Figure 15. Reduction in energy consumption over 24 hours due to optimisation with relaxed constraints. The histogram is based on daily values between January and March of year 3.

Figure 16. Reduction in energy consumption over 24 hours due to optimisation with relaxed constraints. The histogram is based on daily values between January and March of year 4.

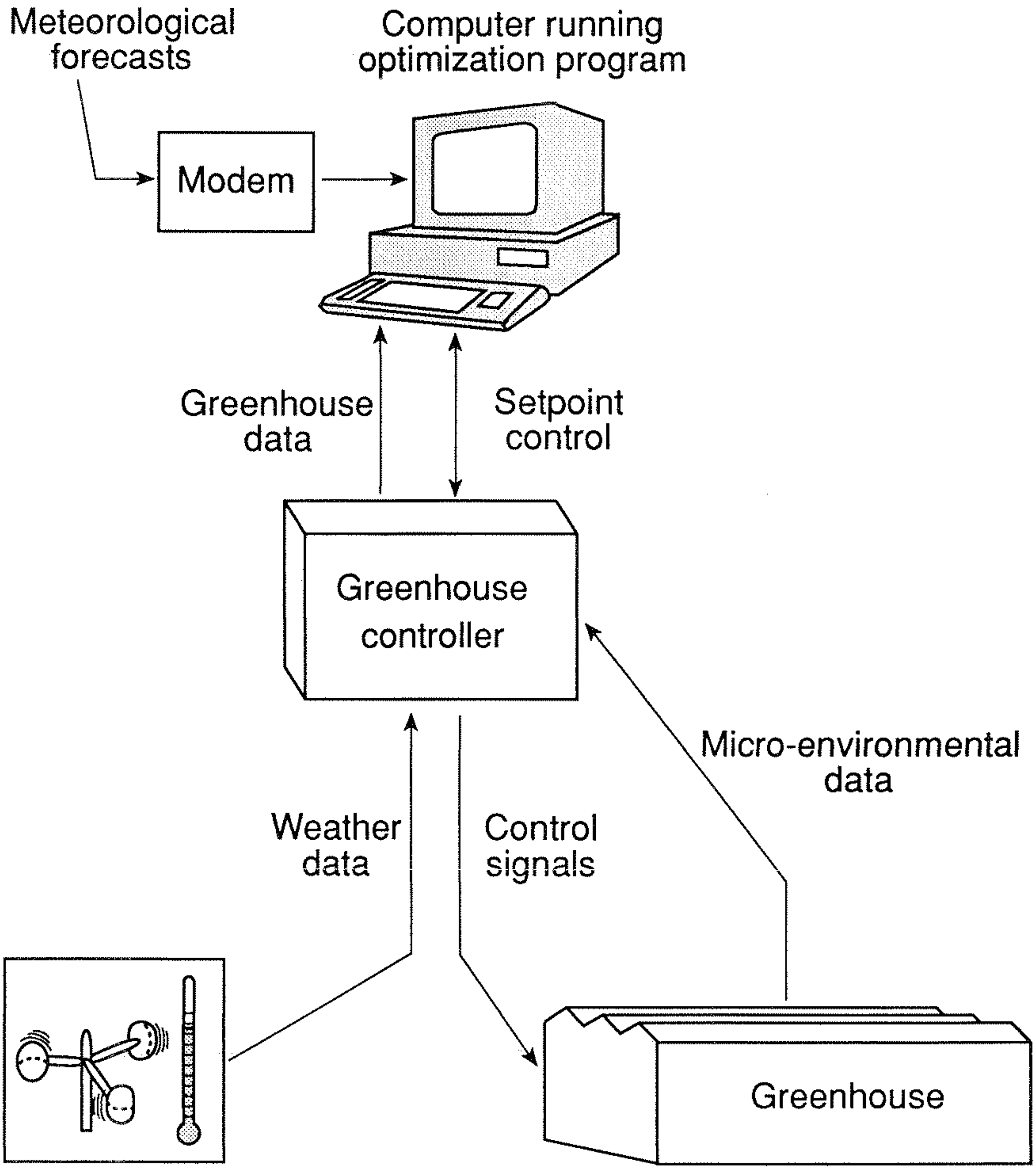

Meteorological forecasts
Computer running optimization program
Modem
Greenhouse data
Setpoint control
Greenhouse controller
Micro-environmental data
Weather data
Control signals
Greenhouse

Figure 1

Figure 2

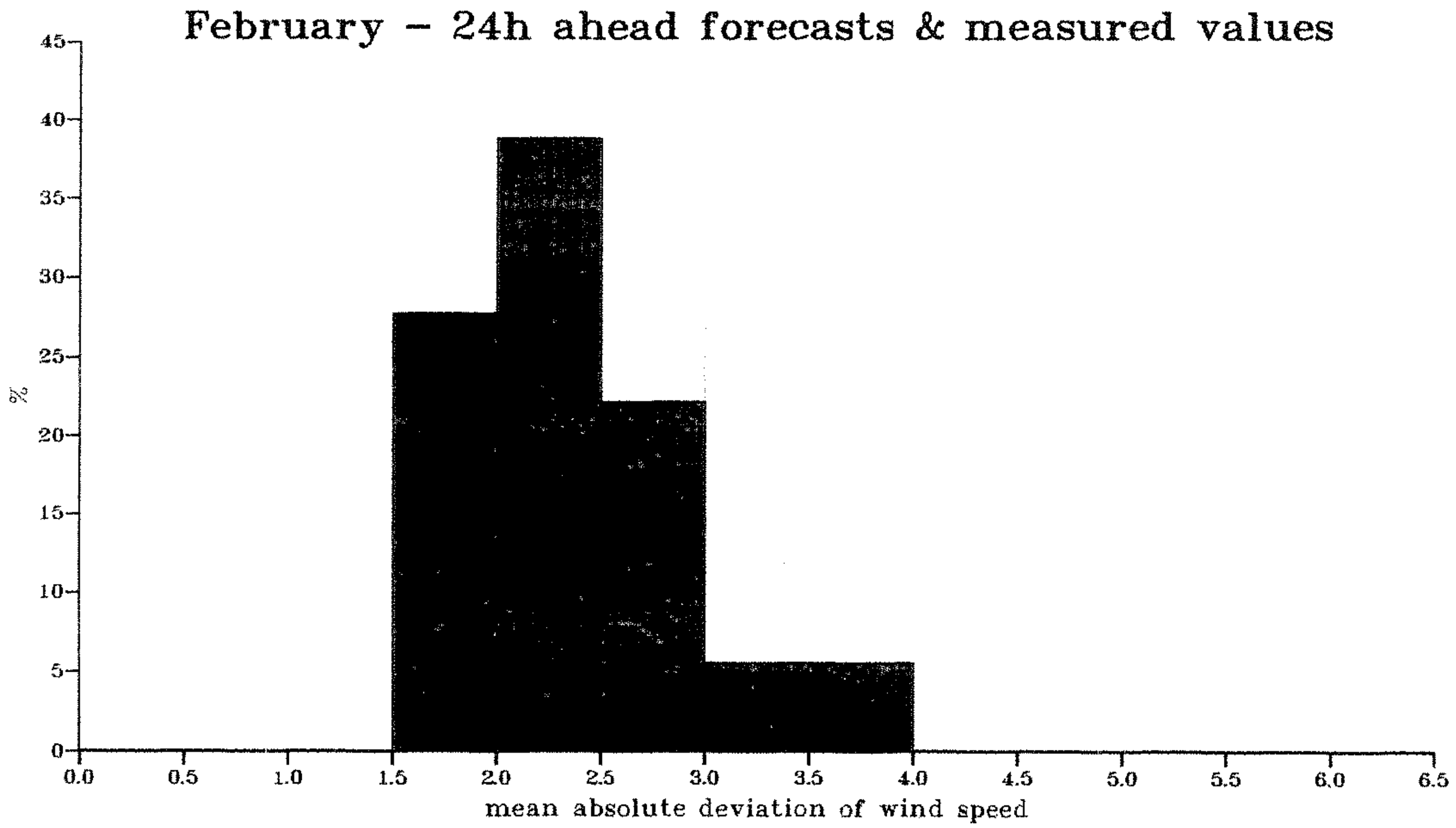
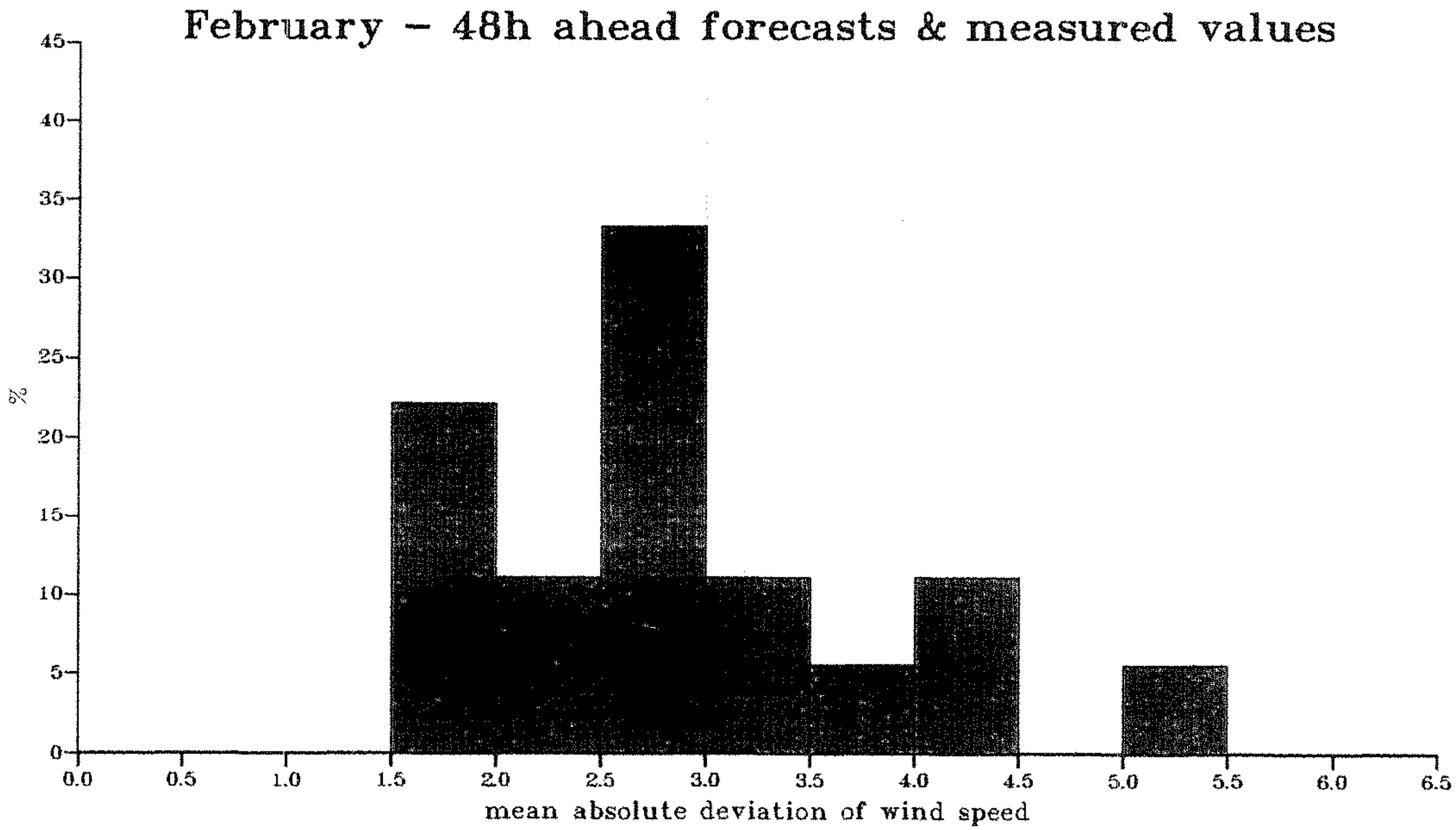

February - 24h ahead forecasts & measured values
%
45
40
35
30
25
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
mean absolute deviation of wind speed

Figure 3


February – 48h ahead forecasts & measured values
%
45
40
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3.5
4.0
4.5
5.0
5.5
6.0
6.5
mean absolute deviation of wind speed

potential of energy savings over 24, 48 and 72 hours. The hourly setpoints were allowed to vary between 15°C and 25°C with their daily average value set to 20°C. The simulations were carried out over 4 years. Figures 6-9 display the histogram of energy savings over 24 hours for the four years respectively. Simulations over 48 and 72 hours have shown that the energy savings increase with the temperature integration period. Figures 10-11 display the histograms of energy savings corresponding to 48 and 72 hours respectively for one of the years. This finding support other studies[3,7] which indicate energy savings of 15% for a 5 days temperature integration period. However, the weather forecasts become poorer as the integration period increases.

It is expected that, over the integration period, the optimised heating setpoint will decrease with increasing wind speed because heat loss increases with wind speed. A sample, 24 hour period was selected which gave the largest variation in wind speed. Figure 12 displays the optimised heating setpoint against wind speed and confirms the inverse relationship between optimised heating setpoint and wind speed.

2.5 Discussion

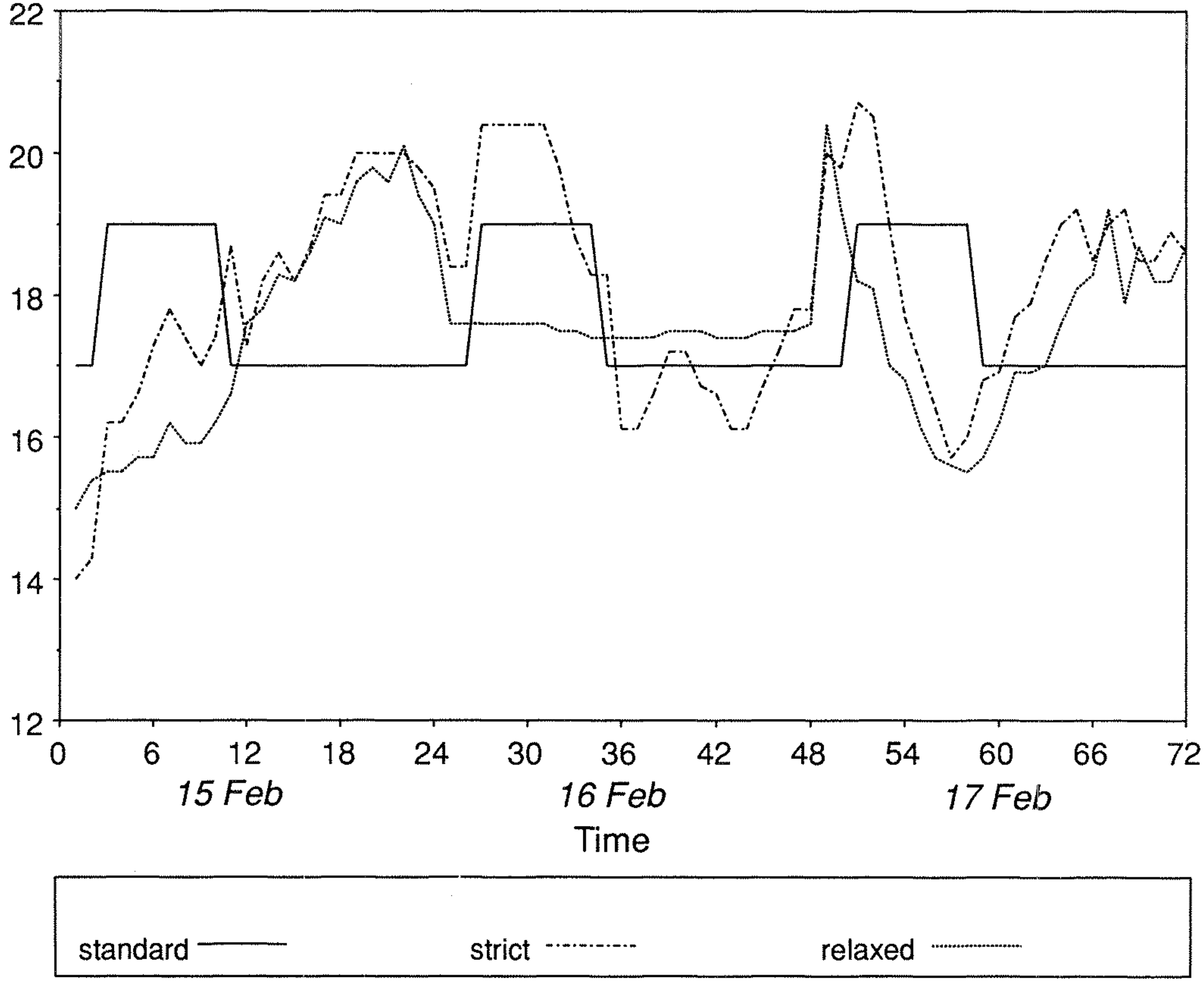
There are three main issues which require careful consideration as a result of this experiment. The first issue relates to the accuracy of the weather forecasts, the second relates to the constraints imposed on the temperature setpoints, and the third relates to the potential energy savings. In a way, these issues are related to each other.

Although no sensitivity analysis has been carried out, it has been demonstrated that weather forecasts are adequate (for the purposes of this study) for 24 hour ahead predictions. There is scope to improve the accuracy of the local weather predictions by augmenting the Meteorological Office's forecasts (which are good in predicting fronts and mean levels) with on-line and short-term statistically based forecasting methods[8].

The algorithm has been developed and implemented in a way to accommodate any bound-type constraints imposed on the temperature setpoints. These constraints could be imposed by the grower through his knowledge of crop responses to temperature, or imposed by him to limit greenhouse humidity or rapid changes in temperature setpoints.

The potential in energy savings obtained through optimisation increases as the constraints on the temperature setpoints are relaxed. Figures 13-16 show the simulation runs carried out under the same conditions as those of figures 6-9 but with the daily average temperature setpoint bounded between 19°C and 21°C instead of being set exactly to 20°C. It is clear that the energy savings increase significantly as the constraint on the 24 hour average

Figure 5


22
20
18
16
14
12
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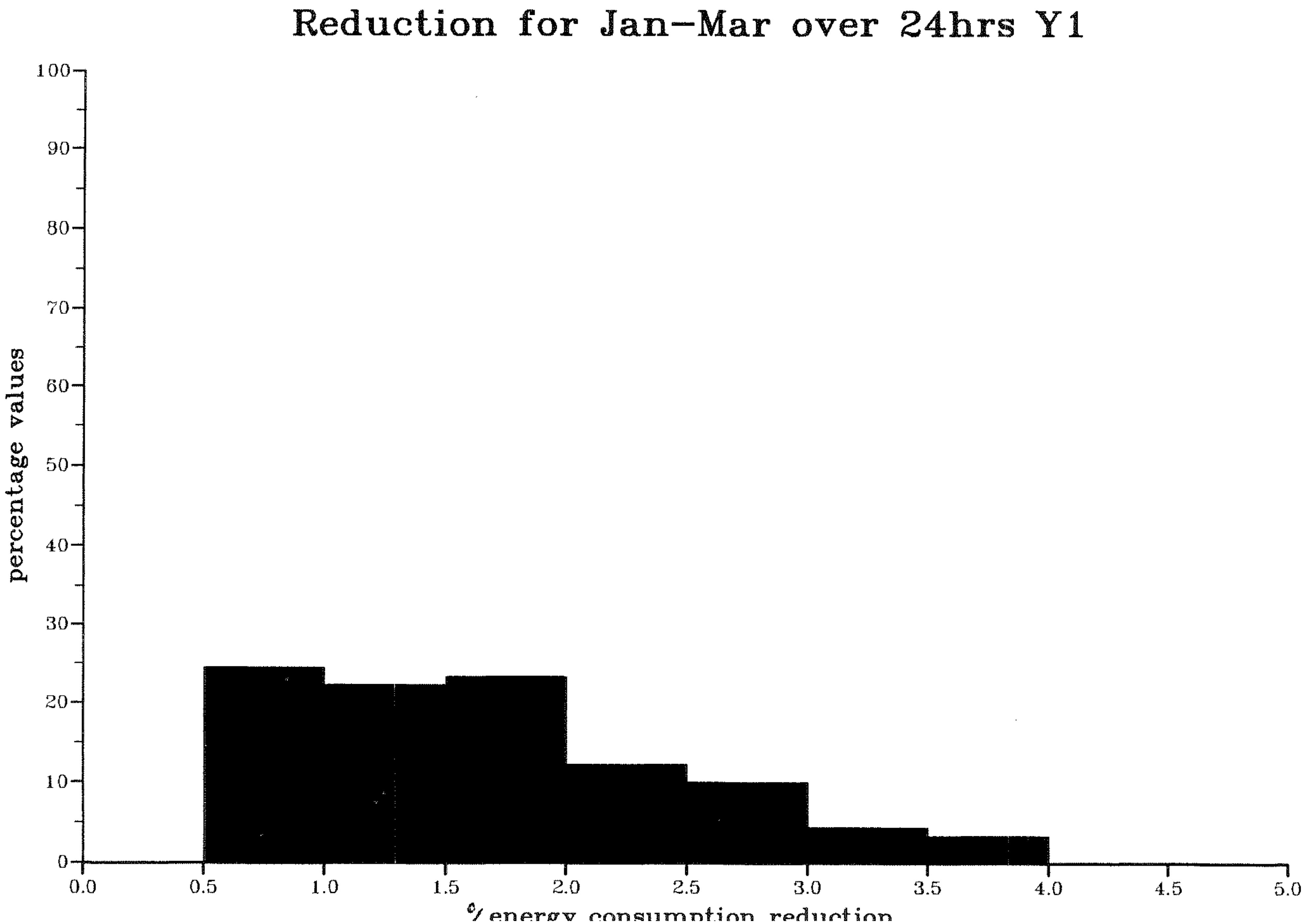
42
48
54
60
66
72
15 Feb
16 Feb
17 Feb
Time
standard
strict
relaxed

Figure 6


Reduction for Jan–Mar over 24hrs Y1
percentage values
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
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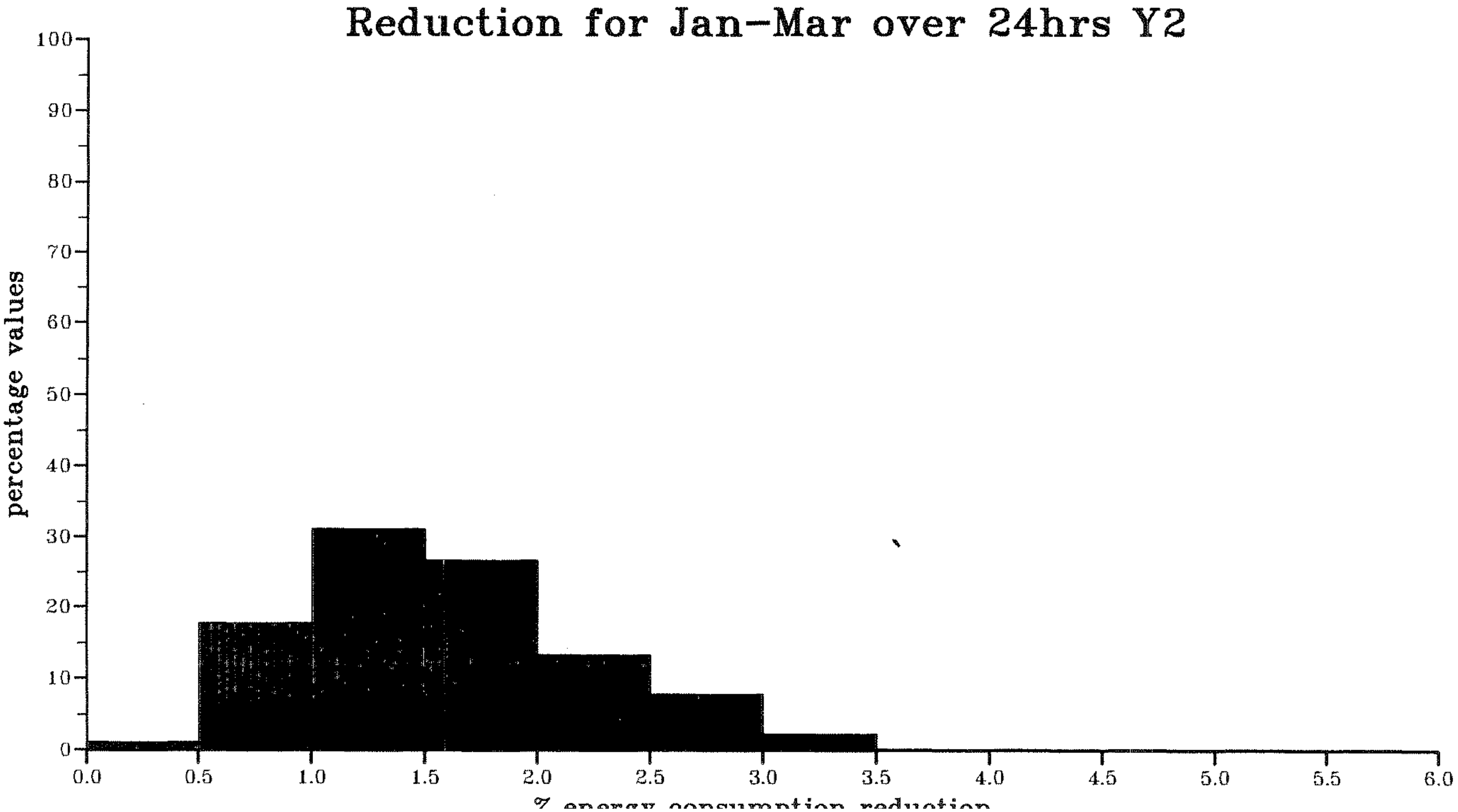
% energy consumption reduction

Figure 7


Reduction for Jan-Mar over 24hrs Y2
percentage values
100
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80
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0.5
1.0
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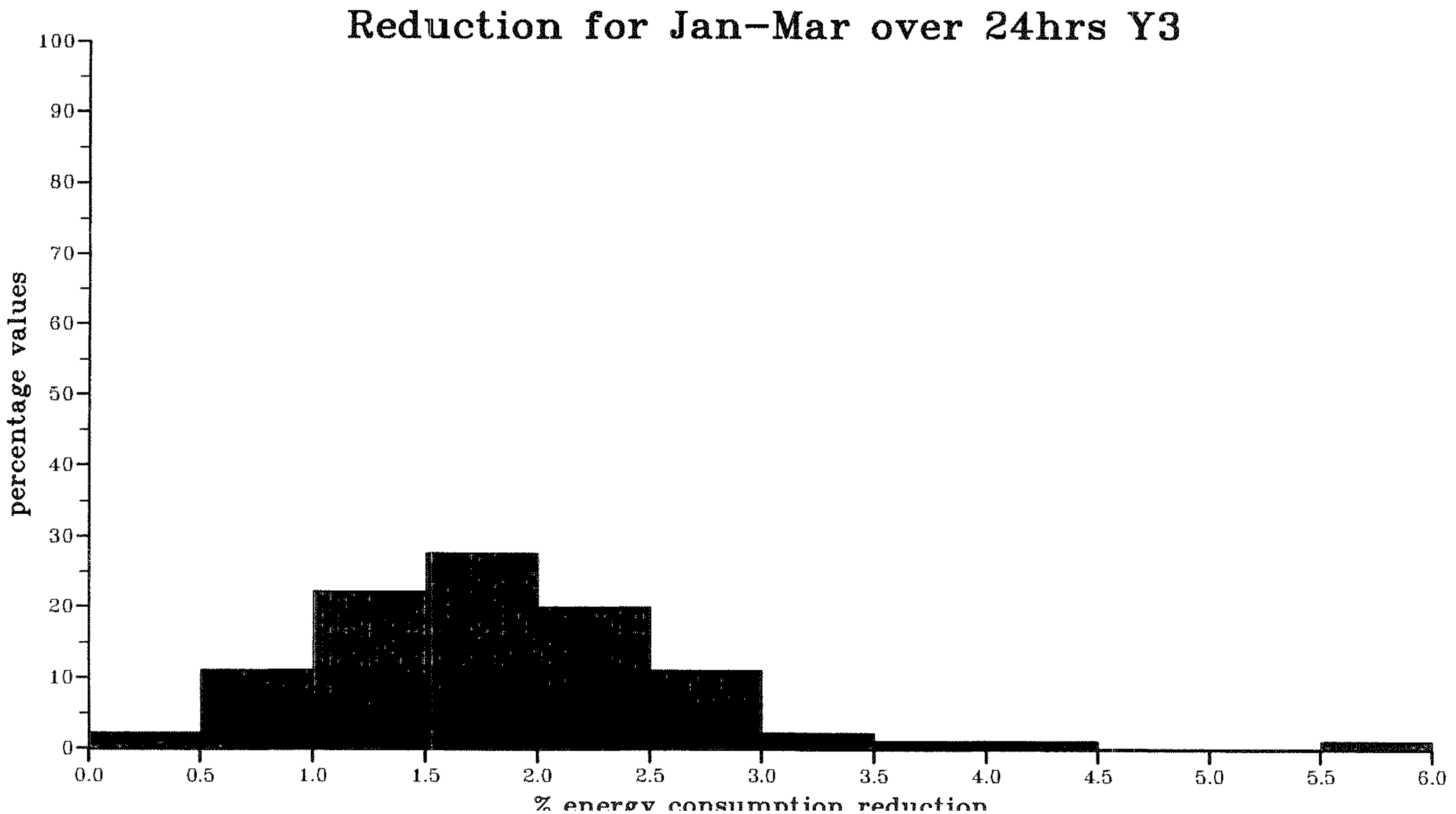
6.0
% energy consumption reduction

Figure 8


Reduction for Jan–Mar over 24hrs Y3
percentage values
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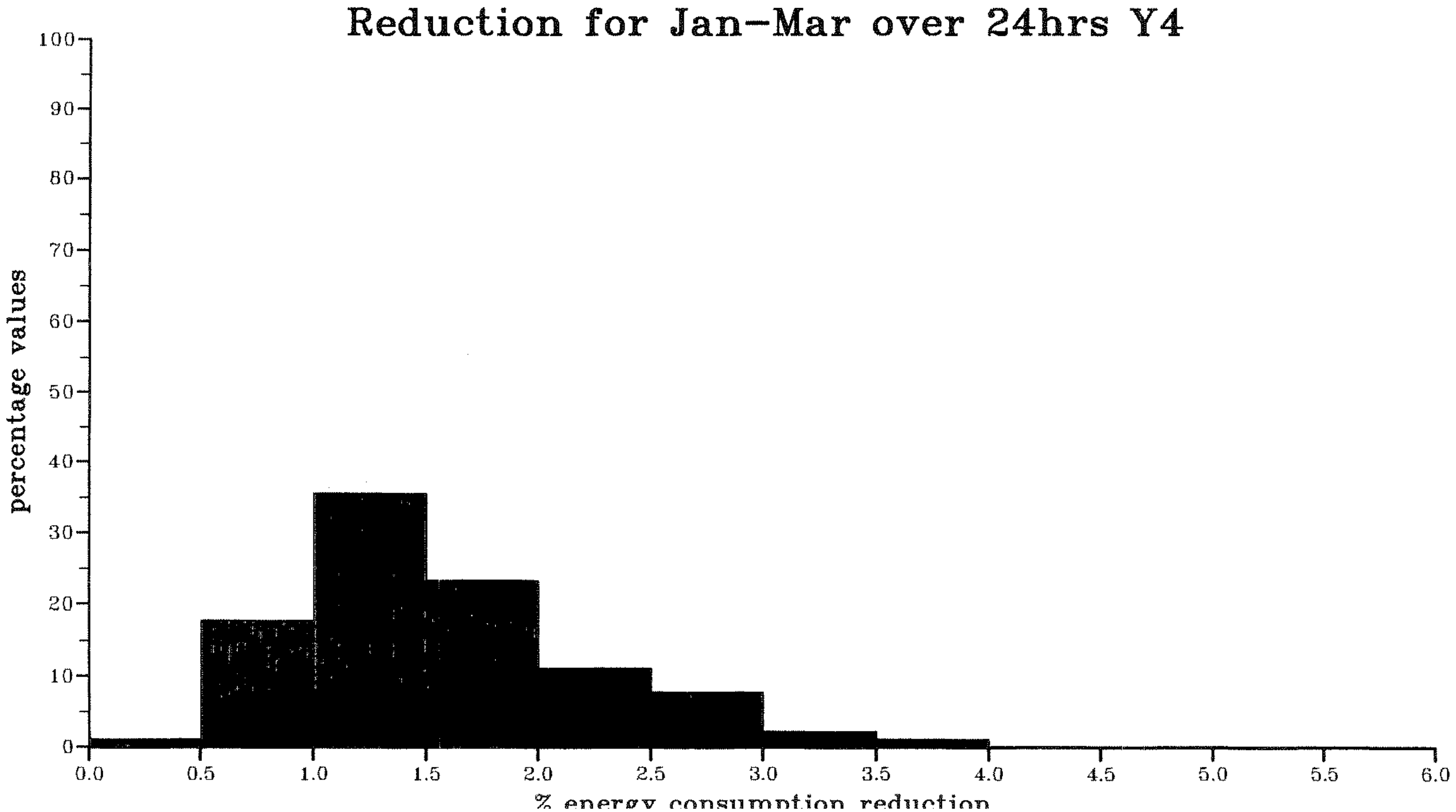
4.0
4.5
5.0
5.5
6.0
% energy consumption reduction

Figure 9


Reduction for Jan–Mar over 24hrs Y4
percentage values
100
90
80
70
60
50
40
30
20
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0
0.0
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1.0
1.5
2.0
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3.5
4.0
4.5
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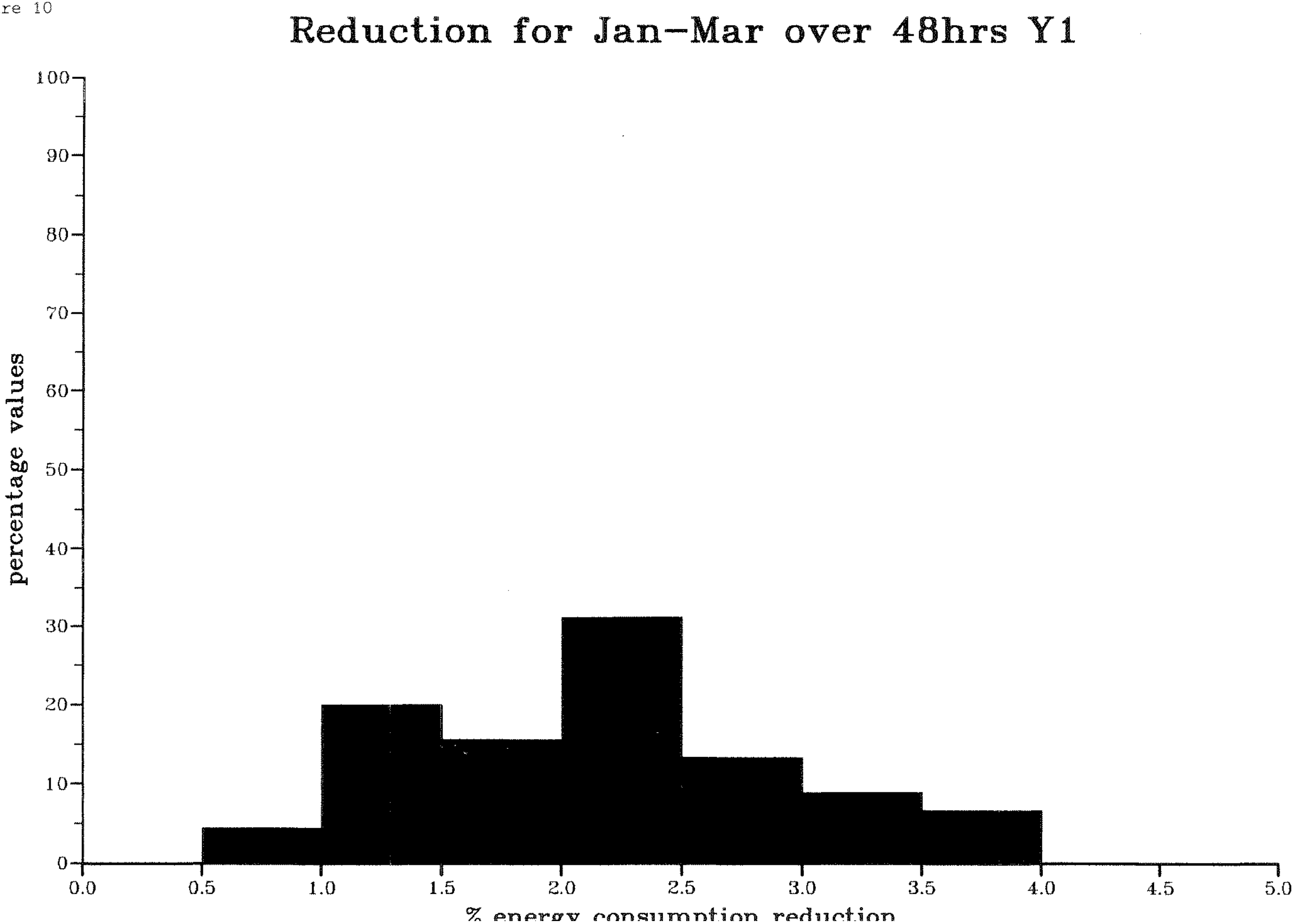
5.5
6.0
% energy consumption reduction

Figure 10


Reduction for Jan-Mar over 48hrs Y1
percentage values
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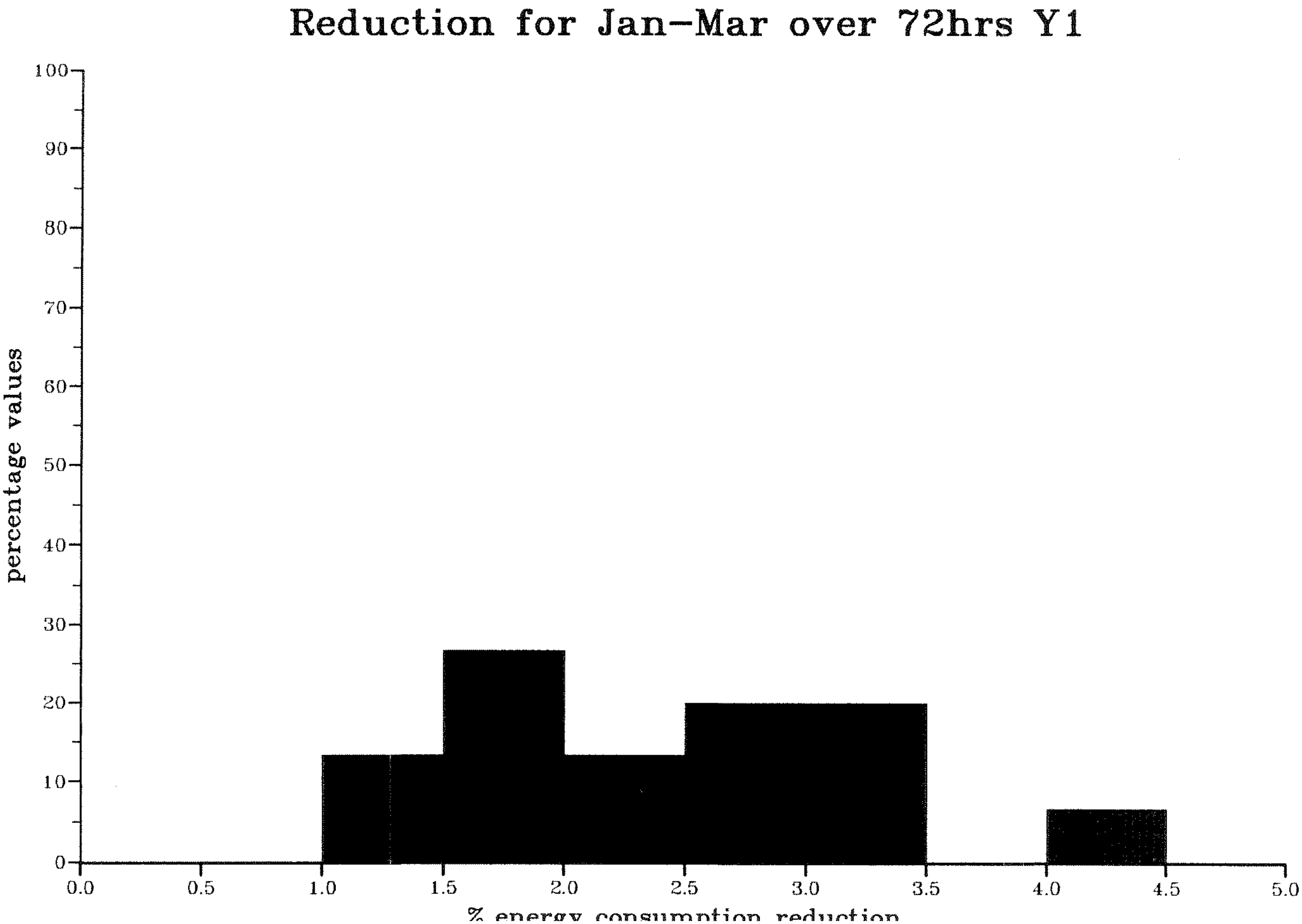
4.5
5.0
% energy consumption reduction

Figure 11


Reduction for Jan–Mar over 72hrs Y1
percentage values
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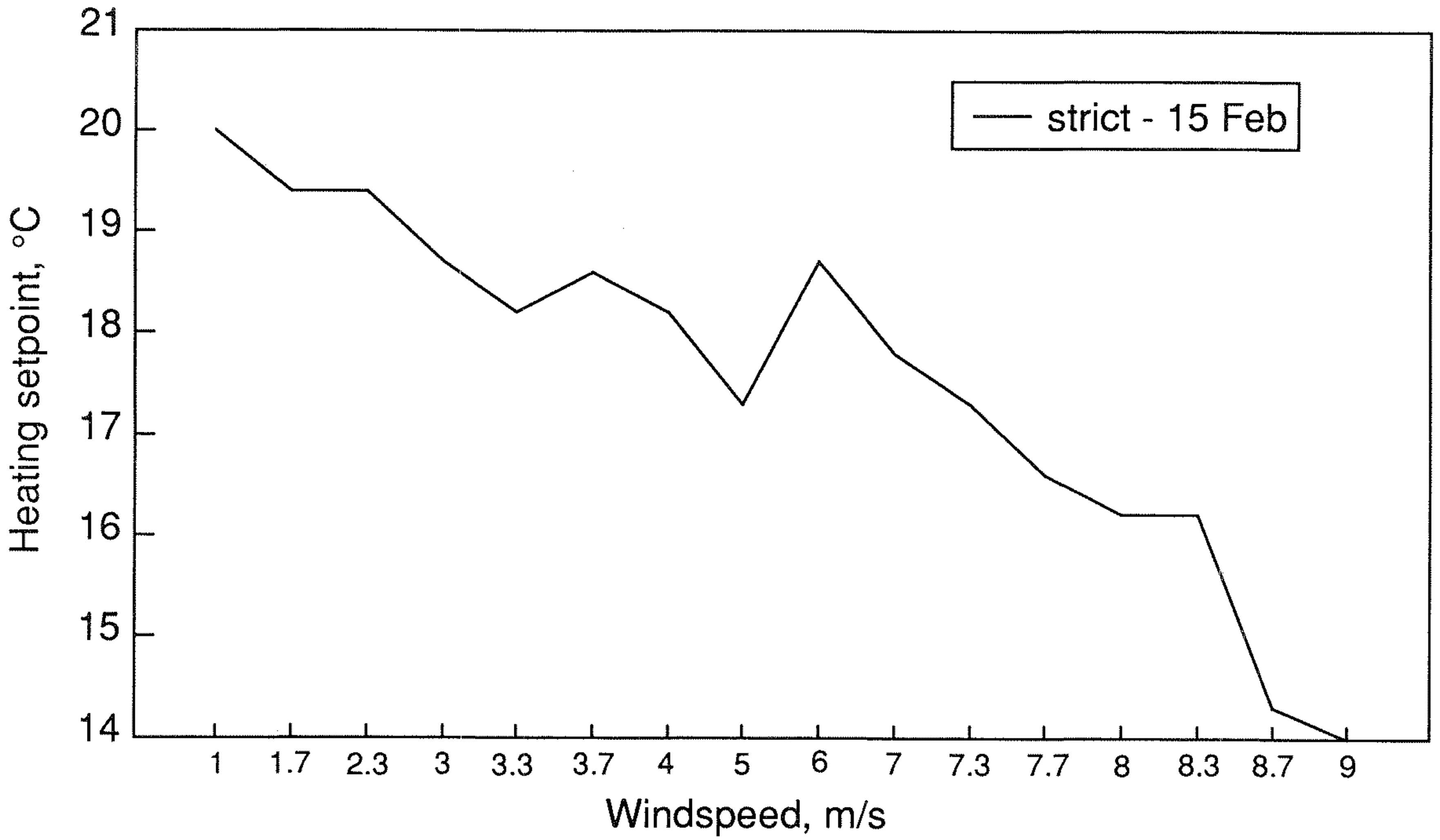
% energy consumption reduction

Figure 12


strict - 15 Feb
Heating setpoint, °C
21
20
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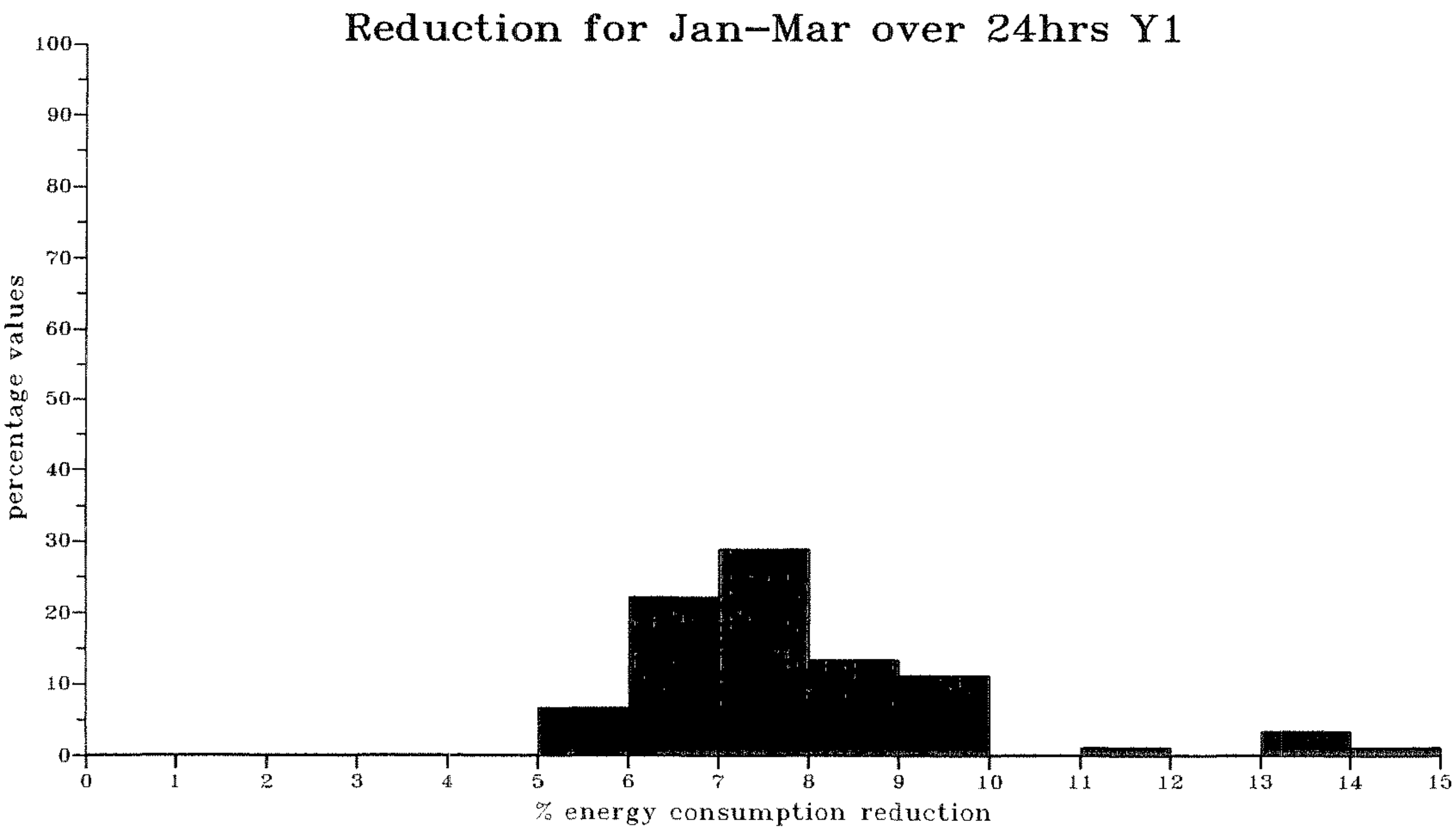
8
8.3
8.7
9
Windspeed, m/s

Figure 13


Reduction for Jan–Mar over 24hrs Y1
percentage values
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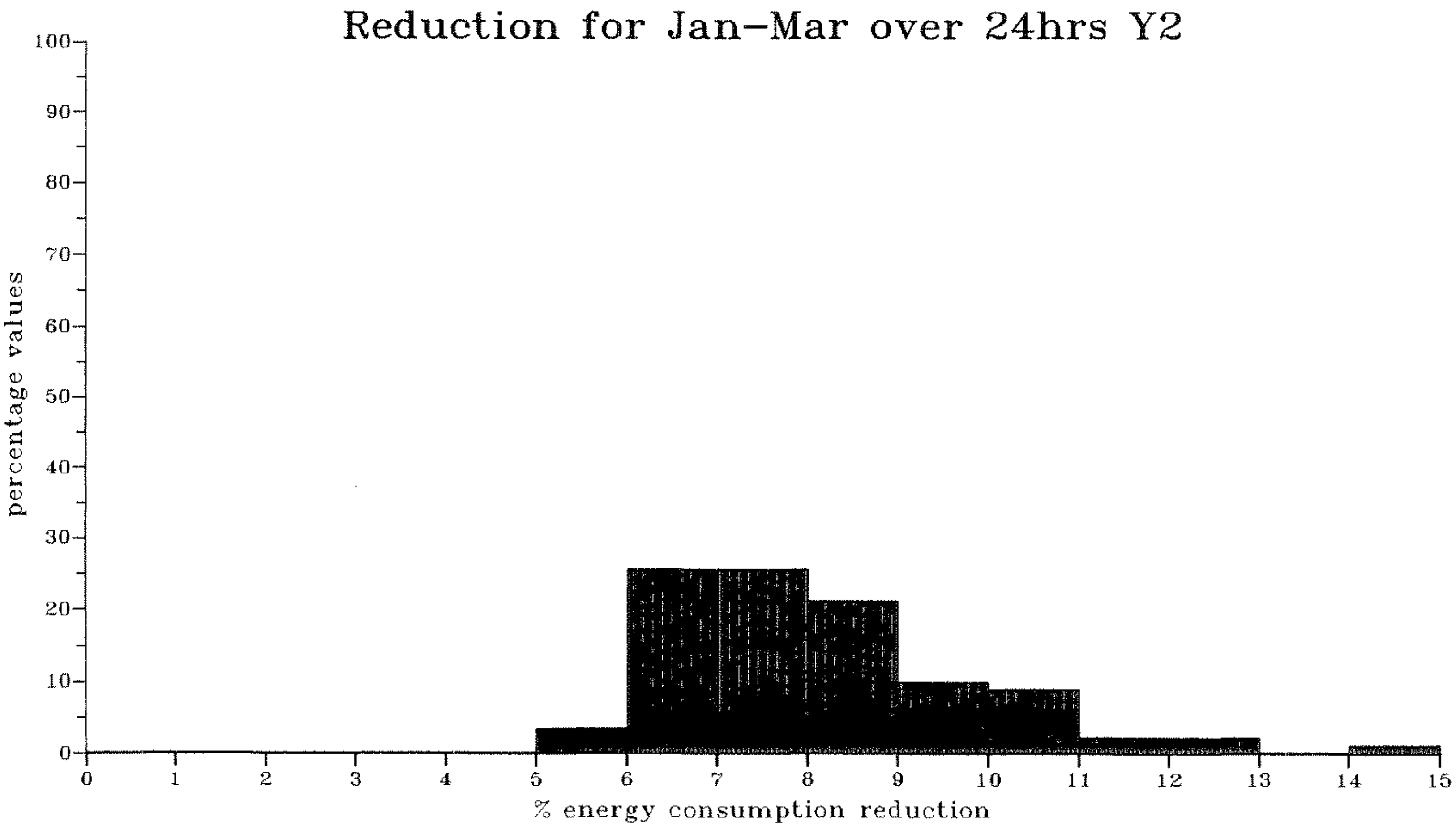
12
13
14
15
% energy consumption reduction

Figure 14


Reduction for Jan–Mar over 24hrs Y2
percentage values
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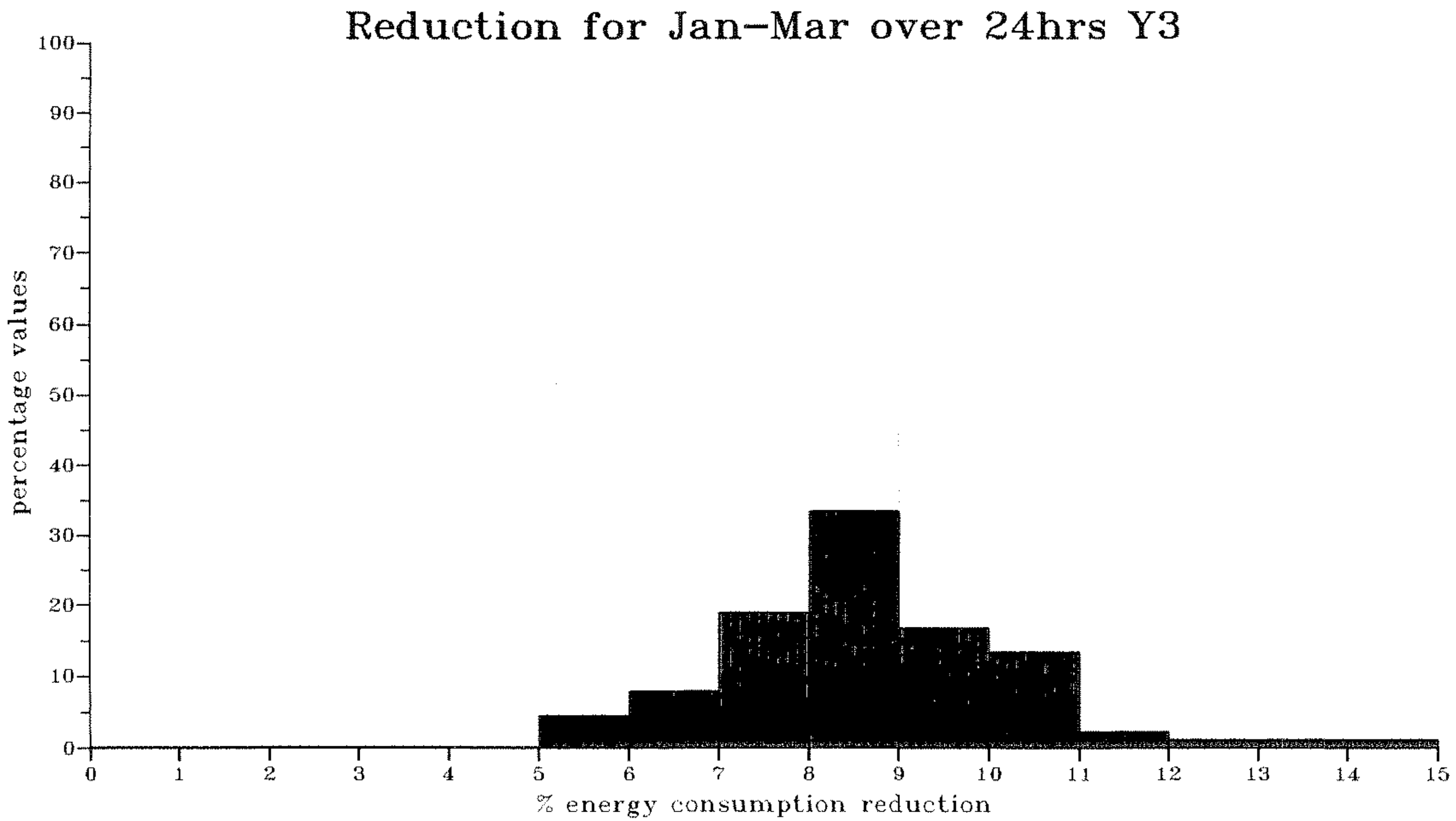
7
8
9
10
11
12
13
14
15
% energy consumption reduction

Figure 15



Reduction for Jan–Mar over 24hrs Y3

Figure 16

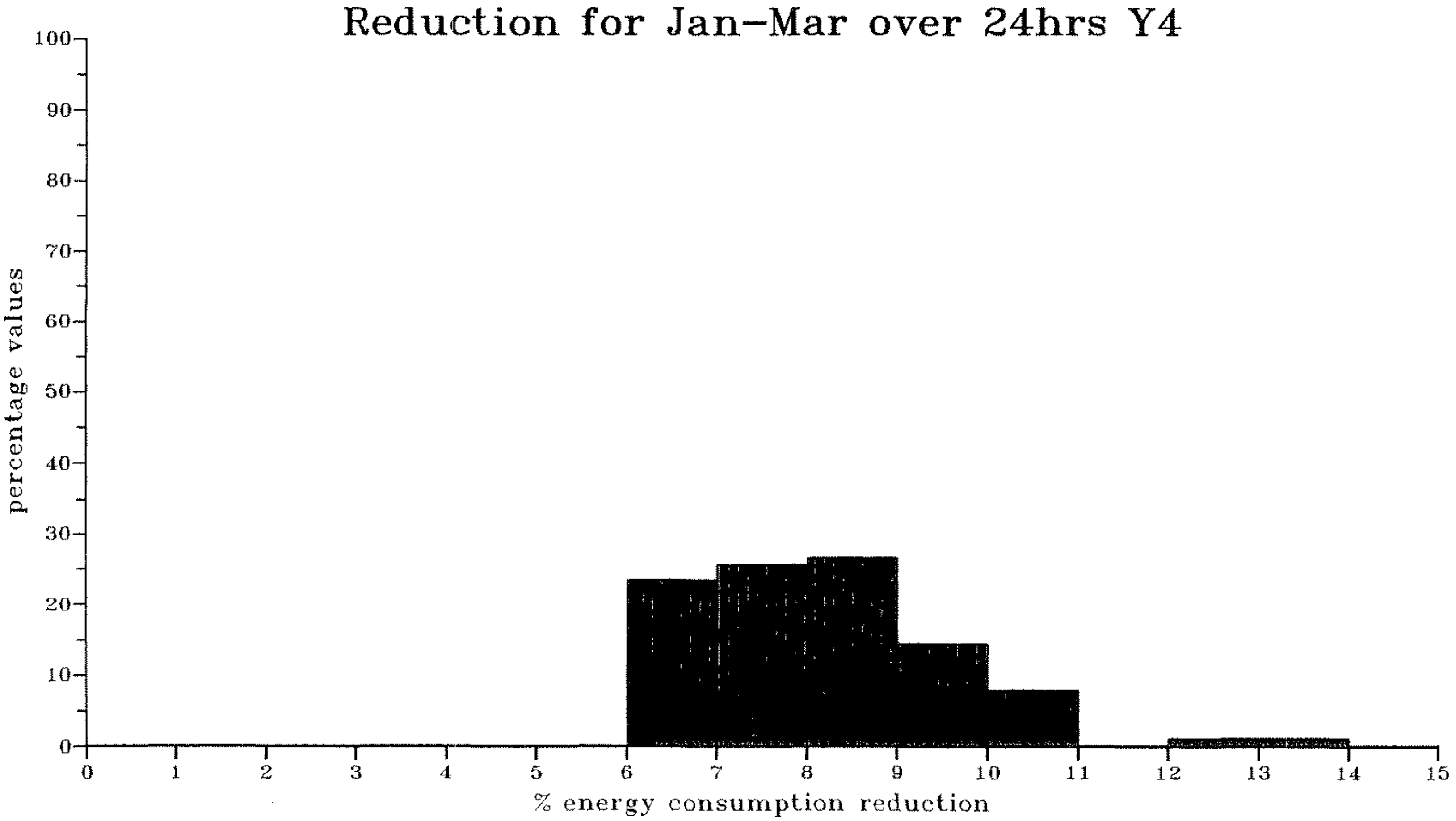
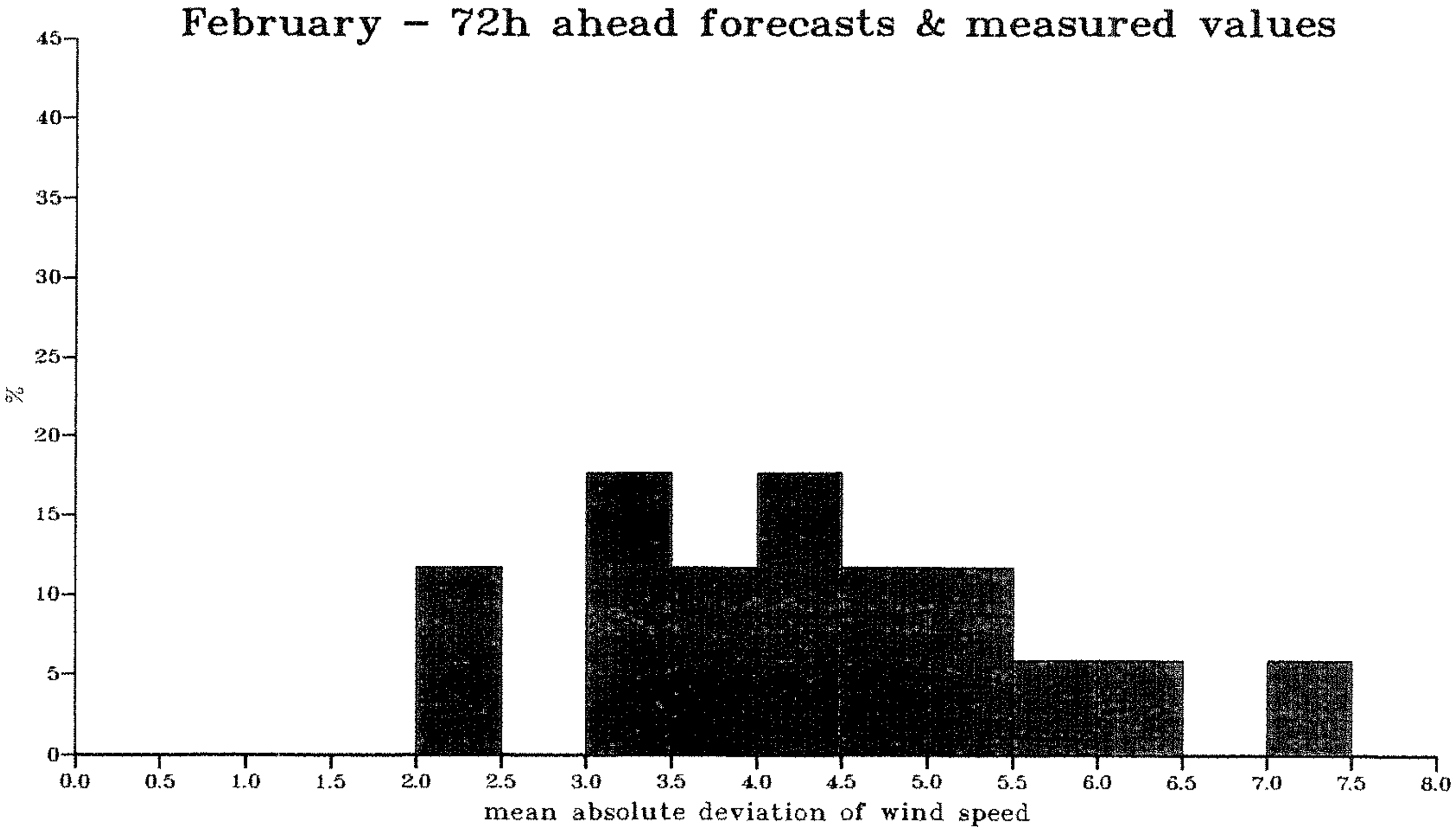

Reduction for Jan–Mar over 24hrs Y4

Figure 4


February – 72h ahead forecasts & measured values
%
45
40
35
30
25
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
mean absolute deviation of wind speed