Environmentally Responsive School Buildings in the UK

MEITAL BEN DAYAN[1]

[1]Environment and Energy Studies Programme, Architectural Association School of Architecture, London, UK

ABSTRACT: In recent years a large stock of new school buildings was built in the UK as part of large government investment programmes. A particular emphasis was given to sustainability and innovation, creating a large number of experimental built precedents that could be learned from. This paper summarises a research of selected recent school buildings, of which two are presented in more detail with observations obtained during the course of fieldwork. Successful elements as well as challenges of ventilation control, adequate daylight and energy consumption are identified. Following from the fieldwork findings, analytic studies were undertaken with the specification of a generic learning space as the basis for the model. The analytic work, using dynamic thermal simulations, focused on the position and size of openings for daylighting and ventilation, assessing space heating demands as well as indoor temperatures under free-running conditions. These studies showed that space heating energy use can be reduced significantly, compared to current practice. However, the study has also shown how different operational parameters can influence space heating demand, leading to higher energy use. The findings have been synthesised into design guidelines for primary school learning spaces, looking at improvement potential in terms of environmental design.
Keywords: School Buildings, Case Studies, Performance, Design guidelines

INTRODUCTION

The physical learning environment plays an important role in the health and well-being of its occupants, thereby affecting learning outcomes. Several researches have shown that poor acoustics, air quality, daylight and thermal conditions have an adverse effect on pupils' health and performance, while enhancing the quality of the learning environment improves pupils' achievements [1][2]. In addition, school buildings have a significant environmental impact: they amount to 15% of the UK public sector and 2% of the overall UK carbon emissions [3]. They can also act as an educational tool, teaching about environmental responsibility and impact.

Between 2004 and 2011 a large investment in school buildings in the UK took place. Key goals of the programme were sustainability and innovation. As a result, there are a large number of experimental school buildings that could be analysed. The aim of this research is to learn from the recently built stock of schools and the research that accompanied them and explore those architectural and environmental conditions that contribute to a quality learning environment, in order to derive lessons for the design of future primary schools.

Methodology

The initial investigation included literature review to identify the challenges of school buildings' environmental design and formulate benchmarks for assessment. Four built precedents, which had available literature on their performance and operation, were analysed and formed a reality base for the research.

Field work was then carried out in four additional recently built schools across the UK. The aim was to gain an understanding of how the learning space is being used and to identify successful elements as well as challenges of ventilation control, adequate daylight and energy consumption. The field work included two visits to each school, during which spot measurements of light level, sound, CO_2 and dry bulb temperature were taken and interviews were conducted. Dataloggers were used to measure dry bulb temperature over an extended period of one to three weeks.

Based on the investigation of the field work, simulation models in Ecotect [4], Radiance [5], TAS [6] and Ambiance [7], were developed. The models were used to evaluate the effect of different parameters on the performance of learning spaces. The conclusions from the research were synthesised into design guidelines which are presented through a learning space proposal.

Assessment criteria

There is limited research on comfort levels of children, therefore for the purpose of this research the thermal comfort assessment is based on the equations presented in European Standard 15251 [8], with a ±3°C range for normal expectation in new buildings. This model was chosen as it takes into account the influence of adaptive measures and because it is based on a running mean temperature, giving higher weight to the external temperature experienced within the previous few days. This is particularly suitable to the UK climate, which can have large differences in temperature within the same week.

Daylight level assessment is based on the required level of 300 lux for schools in the UK. Daylight availability studies show that in overcast conditions, 5% DF would give 300 lux for 80% of the year during the school hours of 9.00-16.00 [9]. Uniformity level of 0.3-0.4 is used as a benchmark, based on UK guidance for schools [10].

The air quality assessment is based on UK performance standards requirements of a maximum average CO_2 level of 1500 ppm and a recommendation for a maximum level of 1000 ppm [11]. Above this level cognitive functions such as concentration were shown to be affected [12]. These levels correspond to the required average ventilation rate of 5 l/s per person, a minimum rate of 3 l/s and the possibility of achieving a ventilation rate of 8 l/s per person at any time.

FIELD STUDIES

The schools chosen for the field work were completed between 2009 and 2010. Environmental design was a principal target of their design and they were acknowledged for architectural and environmental achievements in publications and awards. Two school studies are described here in detail.

A common denominator for all schools was an intermittent occupancy pattern and use of space. In the course of a typical day spaces were empty for a large percentage of the day, while at other times they are fully occupied with high internal gains and fresh air requirements. The flexibility and constant movement between spaces require diverse environmental conditions to be provided within a short amount of time, while internal gains are changing.

Case Study A

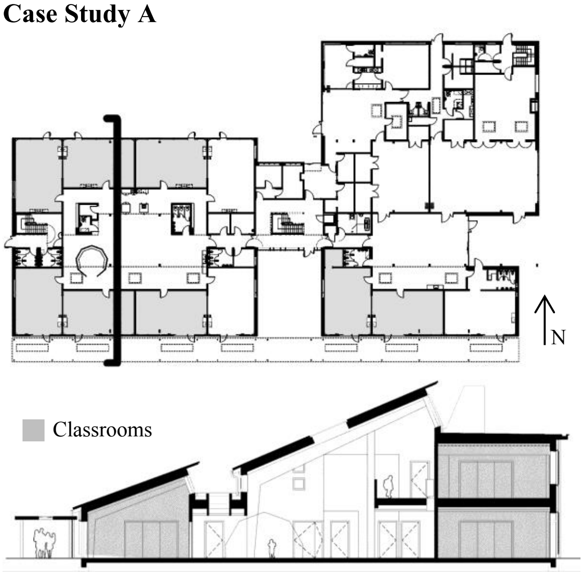

Figure 1: School A, ground floor plan and cross section.

School A is located in a low-density residential area in the West Midlands. It is a deep plan, one to two-storey building with classrooms, facing North and South, arranged around a communal multi-activity space (Fig.1).

Daylight and Solar Control

On a day with overcast conditions in May, good daylight levels of 300-700 lux were measured across the learning spaces in the school. These represented 2%-5% of the external light level. The best daylight conditions of 5% DF were measured in spaces that had 30% window-to-floor ratio, daylight provision from two directions, high level windows and high reflectivity of internal surfaces.

In sunny conditions glare caused disturbance in the south-facing classrooms. Although an external canopy protected the south façade from direct sun, glare was caused by reflection from external surfaces. It especially affected the visibility of the white boards, which are central to learning and fixed in position. As a result, there are plans to install internal blinds.

Ventilation and thermal comfort

Dataloggers measurements taken over 13 days showed that internal temperatures were kept within the comfort range and close or below the external temperatures. The internal temperature ranged between 18^{o}C and 25^{o}C and the external temperature reached 25^{o}C. An analysis of the dataloggers' output showed that this was achieved due to a combination of early morning purging and effective cross-ventilation during the day. At 5am, when the cleaners and the caretaker arrive, a clear drop in temperature occurs. At this time the building management system, which is not operating at night, starts to work and opens the high-level windows. The low external temperatures at this time bring the internal temperature to a low level before the start of the school day. This case demonstrates the effectiveness of out-of-hours purging. It also highlights an option of purging during low occupancy hours, with the possibility of operating the windows manually at these times.

CO_2 measurements were taken in a fully occupied classroom during a period of an hour at the end of the school day. Windows were partly open; the internal temperature reached 23^{o}C while the external temperature was 14^{o}C. The measurements showed that the CO_2 level was above the recommended maximum of 1000ppm for most of the time, reaching a level of 1450ppm. This demonstrated how easily this level of CO_2 could be reached in a full classroom.

Energy consumption

The school received a C rating in the performance energy certificate, with electricity consumption of 55kWh/m^2/y and gas consumption of 74kWh/m^2/y. When compared to existing schools' benchmarks [13], the gas consumption was lower than the good practice schools (113 kWh/m^2), but it was higher than predicted.

The electricity consumption was higher than the poor practice existing schools (45 kWh/m^2). The reasons, as identified in a POE of the school, which was carried out by the architect, are higher-than-predicted ICT (Information and Communication Technologies) usage, long hours of operation of external lights, longer occupancy hours and higher heating settings and duration. The energy consumption levels and the reasons for higher-than-predicted consumption are typical for the new schools that were investigated in the literature review.

Case Study B

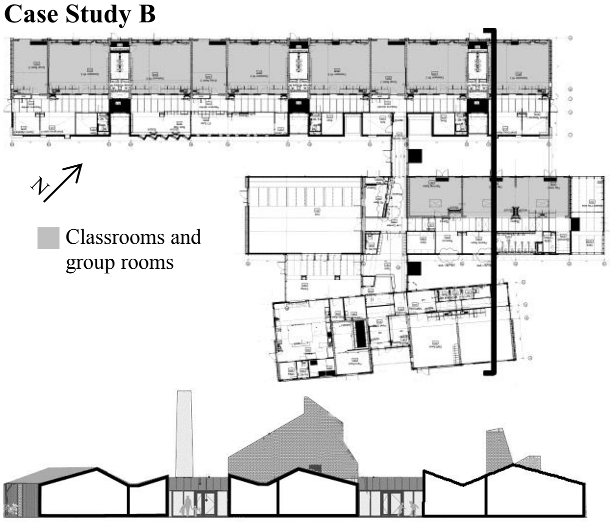

Figure 2: School B ground floor plan and cross section.

School B is located in a large open site in a residential neighbourhood in Yorkshire and the Humber. It is a single-storey, narrow-plan building with the classrooms facing north and the multi-activity spaces and other shared facilities, such as library and ICT room, facing south (Fig 2).

Daylight and Solar Control

Measurements taken on a sunny day in May showed insufficient daylight levels of 150 lux in the middle of the classrooms. Daylight was provided there through rooflights and staggered 2.2m-high windows on the north façade. The poor daylight level could be attributed to a combination of low window-to-floor ratio of 22%, a low surface reflectivity and lack of high level windows. Electric lights were constantly on in these spaces during the visits.

The corridors and multi-activity spaces had large rooflights and staggered windows to the south, with no solar protection. High daylight levels of 700-1000 lux were measured there. The impression during the site visit was that the direct sun and high contrast did not cause disturbance, but rather acted as an amenity, as most of the space was used for circulation or more flexible activities such as play and active classes.

The lack of solar control clearly caused overheating. The spot measurements showed high temperatures of 27^{o}C to 28^{o}C when the external temperature was 25^{o}C and while occupancy and internal gains were very low. The dataloggers output also demonstrated this. When unoccupied, partly cloudy and cloudy days with the same external temperature are compared, a difference of 1^{o}C to 2^{o}C is evident in the south-facing spaces.

Ventilation and thermal comfort

The corridor and multi-activity spaces have cross-ventilation through windows to the south and rooflights controlled by BMS. High temperatures of 28ºC were measured during the field studies, with an external temperature of 25^{o}C and with low internal gains. The dataloggers also showed overheating, even when the external temperatures were at a lower level of 19ºC. Factors contributing to overheating, apart from solar gains, were detected to be insufficient manual opening of windows due to obstructions of internal blinds, and due to the intermittent nature of occupancy.

During the field studies the CO_2 levels measured in an occupied classroom were below 1000ppm. The classrooms were equipped with CO_2 detectors which clearly indicated with a red light when a high level is detected. A press on the light opens the rooflight windows. The measurements indicate good air quality in summer and a good operation of the system.

ANALYTIC WORK

A generic learning space model was created, combining the successful elements that were identified in the literature review and during field studies. The layout includes three types of internal spaces and a covered external area with flexible connections between them that can accommodate a variety of learning activities, from individual work to group work and lectures (Fig 3). The narrow plan can accommodate daylight from two directions for all spaces, as well as effective cross-ventilation.

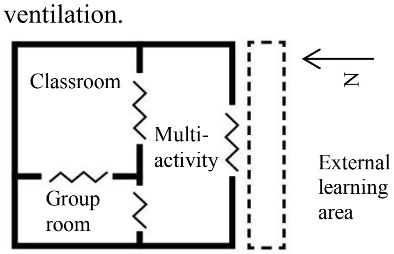

Figure 3: Analytic model layout

Daylight and Solar Control

The field studies and literature review indicated parameters that contribute to good daylight conditions. These include daylight sources from two directions, high-level windows or rooflight, high reflection of surfaces and avoidance of direct sun and glare in formal learning spaces, particularly where white boards are used. In addition, a good daylight level was measured when the window-to-floor ratio was 30% and in 3.5-5m height spaces. Effective solar control was found to be important in order to prevent overheating in summer.

In order to investigate further the influence of these parameters, two sectional variations of the model were checked; a model containing rooflights and a model with clerestory windows in the classroom and group room spaces. Solar control to the south facing windows of the clerestory model was provided with overhangs (Fig 4).

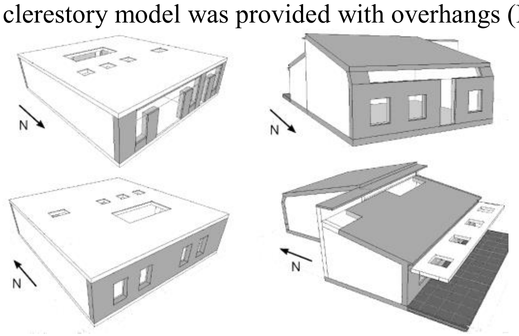

Figure 4: Rooflight and clerestory models..

The rooflight model showed the impact of the W/F (window-to-floor) ratio. When W/F ratios of 25% and 17% were simulated in the group room, DF of 4.2% and 3.3% were achieved respectively. The model also indicated that a W/F ratio in the range of 25% to 30% can achieve 5% DF. A W/F ratio of 29% in the classroom achieved 5.6% DF.

Based on these results, for the clerestory model a fixed W/F ratio of 27.5% was used in order to assess the other parameters of windows configuration. Reflectivity levels were also kept constant with 0.7 for walls and 0.5 for floors.

It was found that clerestory windows positioned higher than 2.5m from the floor reduce the amount of daylight brought in, when compared to lower ones (4.8% DF versus 4.0% DF) (Fig. 5). When the north clerestory window was tilted towards the sky, the light levels increased significantly (from 4.0 % DF to 4.8% DF). Increasing the height of clerestory above 0.6m does not contribute significantly to the daylight level; however, reducing its area by staggering windows reduces the daylight level (from 4.8% to 4.2%). W/F of 30% achieved an average DF level of 5% in this configuration.

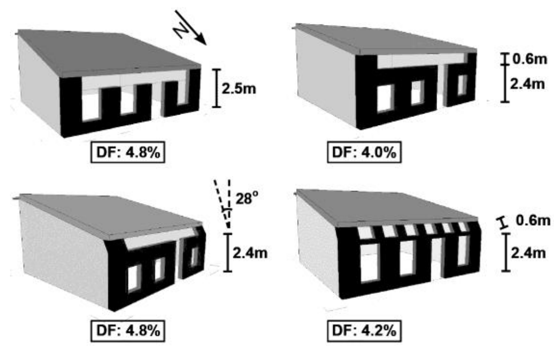

Figure 5: Clerestory model daylight simulation results.

Thermal and ventilation

The literature review showed that with high densities of $2m^2$ per-person, air quality is one of the main challenges in schools and ventilation is the largest component of heating loads. Review of case studies showed in addition, a challenge of overheating in summer and a recurring gap between predicted energy consumption and actual use.

Dynamic thermal model was used to assess the different parameters' influence on the thermal comfort and energy consumption. In order to test the model's reliability, it was simulated with heating and ventilation settings that were observed during the field studies. The inputs of the model included an occupancy pattern of a typical day and heating thermostat set to 21^oC between the hours of 5.00 and 18.00 (the overall occupied times). The ventilation followed the occupancy with levels of 5-8l/s and also considered windows left open at times. The result was $52.7kWh/m^2$. When considering boiler efficiency of 75% - 90%, the energy consumption for heating will be 58-78 kWh/m^2, which is in the range of the available energy consumption data. As a comparison, an ideal scenario containing minimum ventilation of 3l/s provided accurately during occupied times in spaces at full capacity was run. The result was a low heating demand of $5kWh/m^2/y$. This exercise demonstrates the weight of occupancy pattern, appliances gains, ventilation and heating settings on the energy consumption and confirms the Post-Occupancy-Evaluations that were reviewed and showed a gap between prediction and consumption.

In order to understand the influence of the operation settings, the factors of ventilation, heating settings and internal gains were checked separately. Figure 6 shows the effect of ventilation and heating settings on the heating loads. The dominance of the ventilation parameter is shown when the difference between a 5l/s provision which accurately follows the intermittent occupancy and a scenario of 8l/s provision according the spaces full capacity is 20.5kWh/m2, reaching $40.7kWh/m^2$ (50% higher). The heating settings are also dominant when a thermostat of 18°C operating 8.00-16.00 incurs a lower heating demand of 9.2kWh/m^2 in comparison to 20.2kWh/m2 with a 20°C thermostat operating 5.00-18.00.

The occupancy gain of 65W is almost equal to the heat loss incurred by 5l/s ventilation. Therefore it did not have a significant influence when ventilation settings were according to the occupancy. Appliances internal gains made a difference of 5kWh/m^2, when a scenario using a laptop per pupil and a white board at every class was compared to a low scenario of partial use of laptops during one hour and white board use during 3 hours.

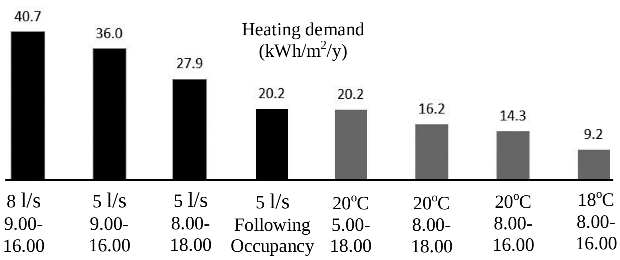

Figure 6: Heating demand of ventilation and heating scenarios.

Investigation of the influence of windows configurations and height of the space showed that larger rooflights and south-facing windows contribute to reducing the heating demand, while north-facing windows and higher space increase it. However, the influence of design changes of this scale in this layout were small (2-3%), in comparison to ventilation settings, An examination of the influence of the height of the space showed a higher consumption of 17kWh/m^2 in a 4.5m model in relation to a 3m model, with 113kWh/m^2.

Simulations of the model during a summer week in June showed that with windows set to start open when the temperature reaches 21°C and be 30% open at 23°C, the internal temperatures were within the comfort zone. Ambience model with air intake of 1.2m/s (for 15ach) and 0.02m/s (for 8l/s) showed that displacement of air is taking place at a comfortable velocity up to 0.1 m/s.

APPLICABILITY

The model of a learning space positioned in London (Fig. 7), synthesises the findings of the research.

Daylight and Solar Control

The more formal learning spaces of the classroom and group room where laptops and white boards or screens are frequently used and which have higher internal gains are facing north, getting diffused light and minimal solar gain. The window-to-floor ratio is 30%. Clerestory windows and view level windows are provided to the north. The north clerestory window is tilted, increasing the daylight level. The south clerestory window is protected from high-altitude sun by an overhang. This configuration achieves an average of 5% DF in overcast sky conditions and 0.4 uniformity.

The circulation and multi-activity spaces with flexibility of position in space and less internal gains are able to accommodate a wider range of conditions. Daylight is provided through a rooflight and façade windows which are protected from high-altitude sun by an overhang. In overcast conditions 5 % DF is achieved, with 0.5 uniformity. In sunny conditions low winter sun is provided as an amenity and for useful solar gain through the south windows.

The rooflight's position does not allow direct sun onto the working surfaces. However, contrast and glare are generated when direct sun hits the wall. This contrast can increase the use of electric lighting in the multi-activity space and also affects the perception of daylight level in the classroom.

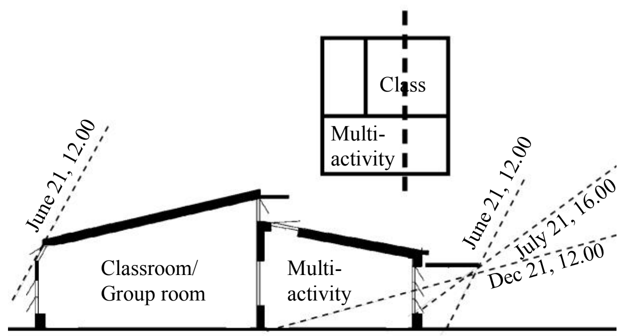

Figure 7: Proposed learning space model.

Ventilation and thermal comfort

Cross-ventilation is provided to all spaces. Both the north and south façades contain two rows of easy-reach, manually operable windows and a row of high-level windows manually operable by switch. In addition the clerestory windows and the rooflight contain switch operable windows.

The high-level windows are used in the winter to give a minimal required amount of fresh air without causing draughts. This was demonstrated through Ambience simulations with 5l/s provision.

In summer simulations in the analytic work showed that 30% of opening of the windows during occupied times is sufficient to keep the internal temperature within the comfort zone. This gives a flexibility of opening windows to a larger extent or for longer hours, including during early morning hours if required, in warmer conditions or higher internal gains. Case studies review showed that even with good manual operation a CO_2 detector is likely to be needed in order to maintain good air quality.

Usability

All windows are manually operated. A large proportion of windows are situated within easy reach. In particular, the height of the lower-level windows is adjusted to the height of the children, thus providing children both with a view out while seated and with the opportunity to open windows independently.

The winter ventilation setting used is a fixed opening of windows according to an average required amount of fresh air of 5l/s. Based on the field studies, it is assumed that a routine can be formalised whereby the windows are opened to this extent every morning and closed at the end of the day by the caretaker. Any additional required opening of windows can be done by the occupants during the day.

Energy

The simulation model showed that with 5l/s ventilation in winter, provided according to occupancy and heating between 8.00-18.00, with Thermostat 20^{o}C, 15.5 kWh/m^2/y was reached. However, the studies also showed that much higher consumption can be reached when the ventilation and heating settings are higher.

CONCLUSION

The research showed that it is possible to achieve a quality learning environment with good daylight, good thermal conditions and low energy consumption. It demonstrated that a low heating demand of 15.5 kWh/m^2/y could be reached with intermittent occupancy scenarios and with simple ventilation settings that can be operated manually.

This result was achieved by adopting a design that is attuned to the conditions generated by the different orientations and in relation to the required internal conditions. In this way, the challenge of providing flexibility of space use, while maintaining energy efficiency is addressed. The occupancy and operation patterns were based on the field studies that were conducted, in order to take into account a realistic operation.

The simulations also showed the sensitivity of heating demand to operation settings and, in particular, to ventilation. Together with heating settings they could incur high heating demand, highlighting the importance of controlled ventilation during the cold months. Trickle ventilation from high-level windows was shown to be a good strategy that did not cause draughts. Design parameters that reduce heating demand were found to be exposed south-facing windows and rooflights. North-facing windows and higher spaces were found to increase the heating demand.

During the warm period, daytime cross-ventilation combined with solar control was shown to be effective in keeping the internal temperature within the comfort level. Additional out of hours purging was shown to be effective in case studies and it can be used in warmer conditions or higher internal gains giving future flexibility.

The core school hours of 9.00-16.00 correspond with daylight hours for most of the year, thus demonstrating potential for school buildings' lighting to be mostly natural. It was found that a combination of 30% window-to-floor ratio and daylight provision from two directions can achieve good daylight conditions and no requirement of electric light for 80% of the year during school hours. Continuous high-level windows not higher than 2.5m enhance light level and uniformity. Tilting north-facing, high-level windows towards the sky further increases the daylight level.

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REFERENCES

1. Earthman, G. I. (2002), 'School Facility Conditions and Student Academic Achievement', [online], Available: http://escholarship.org /uc [July 2012]
2. Murphy, C, A. Thorne. (2010). *Health and productivity benefits of sustainable schools*, BRE Press.
3. Global Action Plan (2006). *'UK Schools Carbon Footprint Scoping Study'*, Sustainable Development Commission, Stockholm Environment Institute, Eco-Logica Ltd. [Online], http:// www.sd-commission.org.uk [July 2012]
4. Autodesk Ecotect Analysis 2011, Autodesk
5. Radiance 2000, Berkeley Lab
6. EDSL TAS (v.9.2.1.1) 2011
7. EDSL AMBIENS (v.9.2.1.1) 2011
8. CEN (2007) Standard EN15251 Indoor environmental parameters for design and assessment of energy performance of buildings. CEN, Brussels
9. British Standard 8206-2
10. Department for Education and Skills. (1999). Building Bulletin 90: Lighting design for schools, TSO.
11. Department for Education and Skills. (2006). Building Bulletin 101: Ventilation of School Buildings, TSO.
12. Coley, A. D and R. Greeves (2004), 'The Effect of Low Ventilation Rates on the Cognitive Function of a Primary School Class', Centre for Energy and the Environment, University of Exter.
13. Action Energy (2003), *Saving Energy- A Whole School Approach: Good Practice Guide 343*, Action Energy.