Performance indicators for energy efficient supermarket buildings

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Abstract

Performance indicators are needed to transform available measurement data into knowledge on the energy efficiency of a supermarket building. Such indicators are e.g. the supermarket size, the opening hours, the outdoor climate and applied energy saving options. When the energy use is related to the supermarket size, opening hours, and other performance indicators, it should be possible to appreciate the energy use of the supermarket: is it relatively high, normal, or relatively efficient. IEA HPT Annex 44 "performance indicators for energy efficient supermarket buildings" searches for performance indicators that will allow to evaluate energy efficiency of existing single supermarkets to similar supermarkets within one chain, supermarkets across different chains and even supermarkets in different regions or countries. Based on data from the Netherlands, this paper investigates the relation between sales area, opening hours and yearly energy consumption. The first conclusion drawn is that the common technical performance indicators alone can only partly explain the observed data. This paper continues to discuss other aspects that are needed to understand the observed data on supermarket energy consumption.

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Keywords: energy; refrigeration; supermarket; building; performance

1. Introduction

For managers who have the responsibility over the energy consumption of a chain of supermarket stores, it is important to make investments in energy efficiency that offer the best value for money. One way to do this, is to start with the store having the lowest energy efficiency, the weakest link in the chain. Therefore it is necessary to identify which store is, energetically speaking, the weakest link in the chain. This may not be obvious at first sight, and it is desirable to have an easy to use method to interpret available data.

Global energy consumption data for individual stores of supermarket chains is often available, through own measurements or from the utility bills. But this data only becomes meaningful when put in the right context of sales area, outdoor temperatures, etc. Only then can the actual energetic performance of individual shops be assessed. To develop a method to do this is the objective of Annex 44 "Performance indicators for energy efficient supermarket buildings" of the Technology Collaboration Programme for Heat Pumping Technologies of the International Energy Agency (IEA HPT).

The current work in Annex 44 has been preceded by work in IEA HPT Annex 31, that was presented at the 1st IIR International Conference on the Cold Chain and Sustainability [1]. In Annex 31, supermarket (and hypermarket) energy consumption data was collected from Sweden, the USA and Canada. The system boundary in both Annex 31 and Annex 44 is the whole supermarket, which includes all energy systems (HVAC, refrigeration, lighting and other uses).

The most widely used performance indicator is the size of the supermarket or hypermarket, in m^2. In Annex 31, the total supermarket area has been used, and not just the sales area. As a first step, the total yearly energy consumption per m^2 has been related to the supermarket size, as shown in figure 1. From the regression lines drawn in this figure it is clear that there are systematic differences between the groups of data collected from Sweden, the USA and Canada.

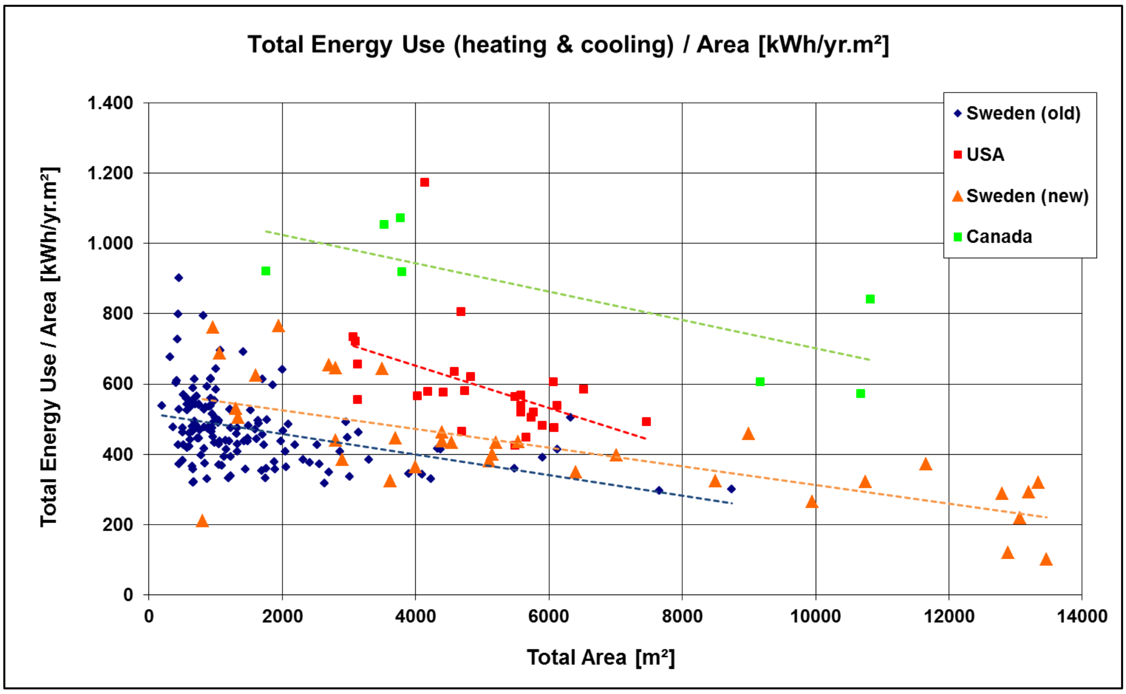

Fig. 1. Total energy use for heating and cooling per year and per m2 of total area for supermarkets from Sweden, USA and Canada, with respective linear regression lines. Data collected in IEA HPT Annex 31.

In the earlier work in Annex 31 the systematic differences in the yearly total energy consumption data for supermarkets from Sweden, the USA and Canada have been explained by the differences in opening hours. In Annex 44 a more general approach is chosen for explaining differences in measured data, based not only on the "opening hours" Performance Indicator, but on a larger number of Performance Indicators.

The scope of the work in IEA HPT Annex 44 is limited to supermarkets. In the International Standard Industrial Classification of all Economic Activities (ISIC Rev. 4, United Nations Statistics Division, August 11, 2008) supermarkets are placed under section G, division 47, group 471, class 4711and defined as "retail sale in non-specialized stores, with food, beverages or tobacco predominating. This definition excludes specialized grocery stores and superstores / hypermarkets where food and beverages are not predominating.

2. Initial analysis of 2013 yearly data for Dutch supermarkets

An initial analysis of 2013 yearly data for Dutch supermarkets has been presented at an earlier conference on refrigeration [2], but the headlines are repeated here for easy of reference. As part of the work for IEA HPT Annex 44, yearly energy consumption data has been collected for 150 supermarkets in the Netherlands, all of which are part of a single supermarket chain. This data concerns electrical energy use for all electrical subsystems combined, and gas consumption for heating. One third of the data points has been set aside for validation purposes; the other 2/3 of the data (concerning 100 supermarkets) is used for analysis.

The first questions that arise in the analysis are related to the introduction. Should we consider the total yearly energy consumption as one value (as was done in Annex 31), or separate quantities for electrical energy consumption and other forms of energy consumption (e.g. natural gas for space heating). And should we use the total supermarket area (as was done in Annex 31) or the sales area, also a common indicator, as a basis for the further analysis? Or is there an even better option, such as using the amount of refrigeration equipment as a basis, instead of floor areas – which is to a certain extent logical since it is estimated that 50 % of the total electrical energy consumption in supermarkets is related to the refrigerating system.

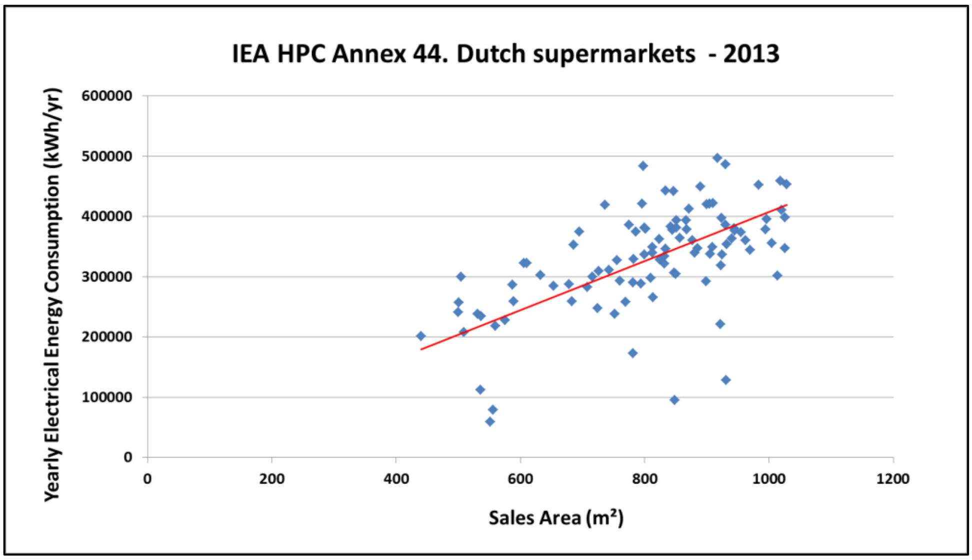

Fig. 2. Data points for analysis of the yearly energy consumption of 100 supermarkets from the Netherlands – 2013, with the yearly electrical energy consumption plotted against the sales area. Regression with R^2 = 0,63.

When the yearly electrical energy consumption of the supermarkets in the analysis is plotted against the sales area, a simple regression without offset can be made, illustrated by the red line in figure 2. The resulting regression coefficient (407,45 kWh/yr.m^2) can be used as a first estimate for the yearly electrical energy consumption of a supermarket, based on its sales area:

$$E(\text{el.estimate S.A.}) = 407{,}45 * \text{S.A.} \quad (1)$$

Where:

E(el.estimate S.A.) = Estimated yearly electrical energy consumption based on sales area (kWh / yr).
S.A. = Sales Area (m^2).

It is clear from figure 2 that the deviation of any single supermarket's measured yearly electrical energy consumption from E(el.estimate S.A.) is large; the average absolute deviation (|di|) is 15,9 %. Which brings us back to the questions posed at the beginning of this paragraph, if maybe the total energy consumption could better be considered, or (an)other parameter(s) instead of the sales area should be chosen. Table 1 shows a number of alternative regressions made with the same data.

Table 1. Results of regression analysis of Dutch supermarket data for yearly electrical energy consumption E(el.estimate) and yearly total energy consumption E(total.estimate). parameters used were the sales area S.A. and the total floor area T.A. (both in m^2) as well as the volumes (in m^3) of Refrigerated Display Cabinets (RDC) for both cooling (Vol.cool) and freezing (Vol.frozen) RDC's.

Regression parameter(s)	Relation	Average |di| *(%)*
$E_{(el,estimate\ S.A.)}$; S.A.	$E_{(el.estimate\ S.A.)}$ = 407,45 * S.A.	15,9
$E_{(el,estimate\ T.A.)}$; T.A.	$E_{(el.estimate\ T.A.)}$ = 284,78 * T.A.	16,6
$E_{(el,estimate\ RDC)}$; RDC volumes	$E_{(el.estimate\ RDC)}$ = 187,6 + 2,71 * Vol.cool + 4,83 * Vol.frozen	17,7
$E_{(total,estimate\ S.A.)}$; S.A.	$E_{(total,estimate\ T.A.)}$ = 575,5 * S.A.	28,8

It is clear from table 1 that the relation between yearly electrical energy consumption and sales area provides the estimates with the smallest deviations. Alongside the estimate based on RDC volumes, we have also made a second estimate which did not only consider the RDC volumes but also the volumes of the storage cells in the supermarket – and found an average absolute deviation ($|di|$) of 17,2 % in this case. It may alternatively be argued that for RDC's it would be better to use the Total Display Areas (TDA's) instead of volumes, but this could not be tested as the Dutch data only shows volumes, not TDA's.

The regression coefficient of yearly electrical energy consumption on sales area (S.A.) leads to a value which is called the electrical energy intensity (yearly electrical energy consumption per m^2 of sales area). The electrical energy intensity is 407,45 kWh/yr.m^2 for the 2013 Dutch data set. Coincidentally, the regression of total energy consumption (electrical + heat sources) against total area (T.A.) would lead to a very similar value for the Dutch data set. The reason is that the average total energy consumption for these Dutch supermarkets is 143 % of the electrical energy consumption, and the average total area for these Dutch supermarkets is 143 % of the sales area. The value can thus also be compared with the international data shown in figure 1.

3. Performance indicators

The project team of Annex 44 wishes to define Performance Indicators for the energy efficiency of supermarket buildings. Generally the efficiency of a single instance from a group of similar energy using objects is evaluated by comparing the measured energy consumption with the average energy consumption of the group at the same functionality. In its simplest form, we can take the functionality to be the sales area of the supermarket. For the analysed set of Dutch supermarkets, we can then calculate the average yearly electrical energy consumption $E_{(el.average)}$ with formula (1), and compare it to the measured value $E_{(el,measured)}$. This is illustrated in table 2 for three instances of the Dutch data set.

Table 2. Comparison of measured and calculated yearly electrical energy consumption for three supermarkets from the IEA HPT Annex 44 Dutch data set..

ID	Sales Area *(m^2)*	$E_{(el.measured)}$ *(kWh/yr)*	$E_{(el.average)}$ *(kWh/yr)*	Comparison	Efficiency
81	1020	416.000	411.103	- 2 %	Average
30	736	300.000	418.925	+ 40 %	Low
53	922	376.000	221.612	- 41 %	High

The comparisons in Table 2 give a first impression of the energy efficiency of the selected supermarkets, based only on one functionality: the sales area. The value of $E_{(el,measured)}$. / $E_{(el.average)}$ can in this case be interpreted as a "first order" performance indicator. When we have more information on other functionalities, such as the weekly opening hours, the total volume of RDC's in the supermarket, special equipment (e.g. bake-off ovens) present or applied energy saving options, we can give a more refined estimate of the expected energy consumption. When we express the other functionalities in terms of deviations from the average value for that functionality, we can write:

$$E_{(el.estimate\ N.)} = 407{,}45 * S.A. + c2 * f(2) * S.A + c3 * f(3) * S.A + \ldots.. + cN * f(N) * S.A. \qquad (2)$$

Where:

$E_{(el.estimate\ N.)}$ = Estimated yearly electrical energy consumption based on N functionalities (kWh / yr).
S.A. = Sales Area (m^2).
f(2)…f(N) = functionalities, expressed relative to the average value of that functionality (-)
(the functionalities f(2)… f(N) are based around 0).
c1,c2,….cN = coefficients for the respective functionalities (kWh/m^2.yr.)

As an example we take one additional functionality, being the wattage of special equipment (such as bake-off ovens). The average wattage of extra equipment related to the sales area for the set of Dutch supermarkets is 0,021 kW/m2. For a specific supermarket with an extra wattage of 0,030 kW/m2, the functionality f(2) expressed relative to the average then becomes + 0,43 (43% higher). The value of coefficient c2 in this case, determined in a multi variable regression, is 16,7 kWh/yr. At a sales area of 500 m^2 we then find:

$E_{(el.estimate\ S.A.)}$ = 407,45 * S.A. = 203.725 kWh/yr.
$E_{(el.estimate\ 2.)}$ = 407,45 * S.A. + c2 * f(2) = 203.725 + 16,7 * 0,43 * 500 = 207.316 kWh/yr.

Now if we can justify the fact that this specific supermarket has a higher wattage of extra equipment, we can judge its performance by using the value of $E_{(el,measured)}$. / $E_{(el.estimate\ 2)}$ as a second order Performance indicator based on sales area and extra equipment.

In table 3 a number of functionalities and the corresponding coefficients are presented, that were found by multiple regression of the IEA HPT Annex 44 Dutch data set. This is not yet the complete listing, since an additional 50 parameters (all of them technical energy saving options) were analysed in the multiple regression.

Table 3. Functionalities and coefficients are given that correspond to the IEA HPT annex 44 Dutch data set used for analysis. The coefficient values have been found by multiple variable regression analysis.

Parameter	Functionality f(i)	Coefficient ci
T.A. = Total Area (m^2)	T.A. / S.A. – 1,43	172,4
OH = Opening hours per week	(OH – 72,66) / 72,66	- 43,9
Vol.cool = RDC cooling Volume (m^3)	(Vol.cool / S.A. – 0,044) / 0,044	31,1
Vol.frozen = RDC frozen Volume (m^3)	(Vol.frozen/S.A. – 0,012) / 0,012	46,4
Cell.cool = Cold Storage Volume (m^3)	(Cell.cool / S.A. – 0,072) / 0,072	15,7
Cell.frozen = Frozen Storage Volume (m^3)	(Cell.frozen / S.A. – 0,028) /0,028	- 31,2
Extra = Extra equipment (kW)	(Extra / S.A. - 0,021) / 0,021	16,7
High efficiency cooling compressor	+1 if available, -1 if N.A.	- 5,18
High efficiency freezing compressor	+1 if available, -1 if N.A.	0
Electronic expansion valves	+1 if available, -1 if N.A.	- 37,9
Variable speed control on compressors	+1 if available, -1 if N.A.	6,0
Energy efficient RDC’s	+1 if available, -1 if N.A.	15,3
Night covers on RDC’s	+1 if available, -1 if N.A.	-8,5
Automatically closing storage cell doors	+1 if available, -1 if N.A.	- 73,6
Heat recovery	+1 if available, -1 if N.A.	0
High efficiency space heater (gas)	+1 if available, -1 if N.A.	- 14,0
Weather dependent control space heating	+1 if available, -1 if N.A.	- 24,4
Optimization control space heating	+1 if available, -1 if N.A.	- 11,2
Pump control for space heating	+1 if available, -1 if N.A.	- 10,3
High efficient lighting fixtures	+1 if available, -1 if N.A.	13,0
HF ballast for fluorescent lighting	+1 if available, -1 if N.A.	1,4

It must be noted that the resulting (multiple) regression coefficients are not always in line with expected behaviour. As can be expected, the (multiple) regression coefficient for a high efficiency cooling compressor has a negative value – leading to a lower average energy consumption when high efficiency cooling compressors are used. But for energy efficient RDC’s the (multiple) regression coefficient is positive, which leads to a non-expected higher energy consumption where these RDC’s are present. This unexpected behaviour may be due to the interdependencies with the other regression coefficients, but may also be due to a flaw in the determination of the presence of high efficiency RDC’s.

With the functionalities and coefficients of all 71 parameters, we have made a yearly electrical energy consumption estimate as given by equation (2) with N=71 for all supermarkets in the Dutch data sets that were analysed. The result of this exercise is shown in figure 3.

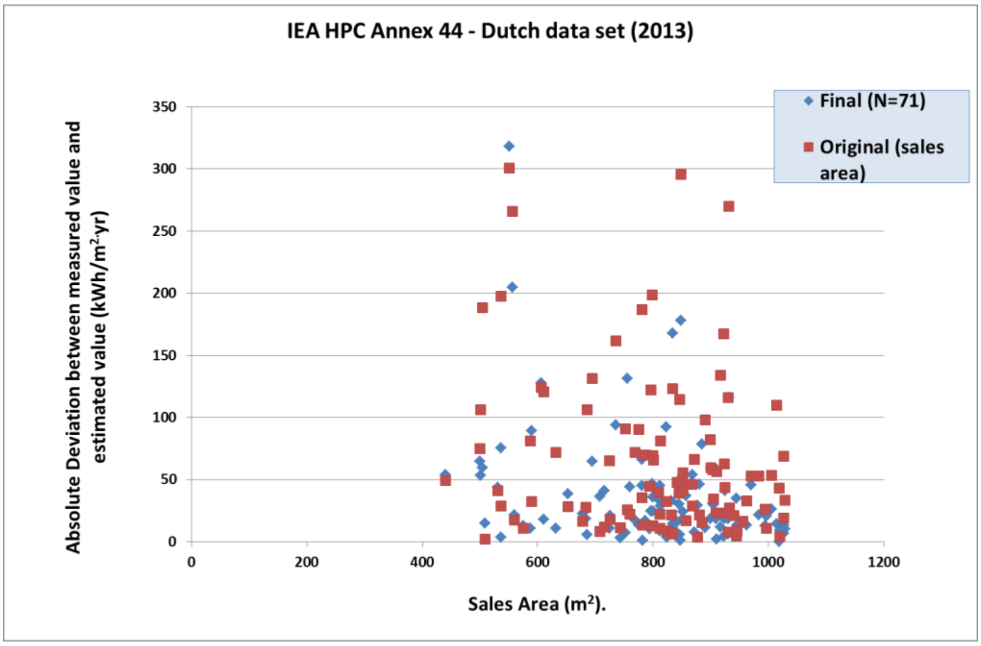

Fig. 3. Absolute deviation between estimated value and measured value of electrical energy intensity (kWh/m2.yr) in the original formula (with only sales area as parameter) and the final estimate (with 71 parameters).

With the original estimate of the electrical energy intensity (kWh/yr.m^2) based on sales area only, the average absolute deviation between measured value and estimate was 15,9 %. With the final estimate of the electrical energy intensity (kWh/yr.m^2) based on 71 parameters, the average absolute deviation between measured value and estimate is 9,4 %.

However, even when the average deviation has been reduced by the more elaborate estimate, the deviation for individual supermarkets is still large. We must conclude that even with an estimate based on quite many technical parameters (mostly energy saving options), we do not yet have a good prediction of the yearly electrical energy consumption of a supermarket.

4. Alternative non-conventional performance indicators.

From the findings so far we can conclude that conventional technical parameters alone cannot sufficiently explain the practical yearly energy consumption of a supermarket. “Non-conventional” technical parameters such as system dynamics and indoor humidity, and non-technical parameters such as management focus, maintenance, sales volume or customer density probably play an important role in the overall energy consumption.

An additional data set on the same Dutch supermarkets that were used in the analysis above has been obtained for the year 2014, which is one year later. The 2014 data set for Dutch supermarkets provides, when compared to the 2013 data set, an example of the influence of management focus. The electrical energy intensity for both supermarket data sets (2013 and 2014) as a function of sales area is shown in figure 4.

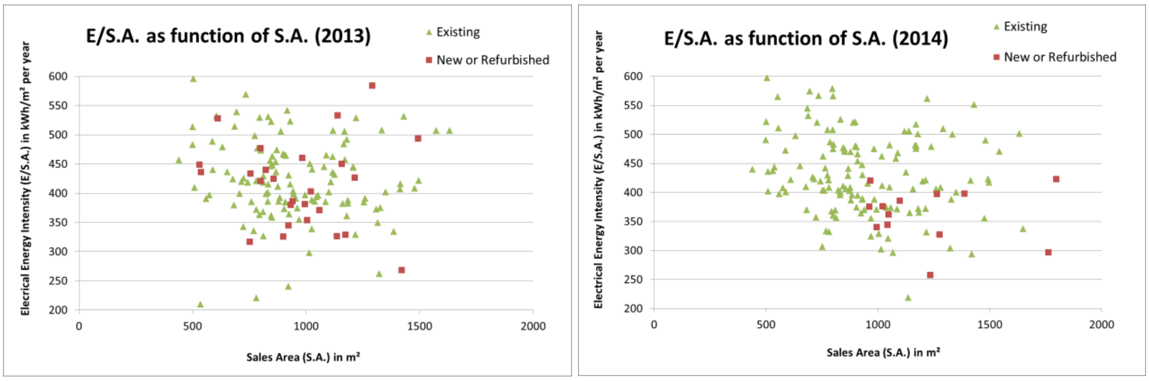

Fig. 4. Electrical energy intensities for the 2013 supermarket data set (left) and the 2014 supermarket data set (right). Markets that have been refurbished or constructed in the applicable year, are indicated in red whereas the other markets are indicated in green.

Comparing the energy intensity versus sales area plots for both years, highlighting the new and refurbished supermarkets against the existing ones (figure 4), we see a shift in management focus. In 2013 there was no specific focus for building new (or refurbishing) supermarkets; it was done for all sizes and with an energy intensity for the new markets comparable to existing ones. In 2014 however, the attention in building and refurbishing supermarkets was directed only at larger supermarkets, and accomplishing low energy intensities.

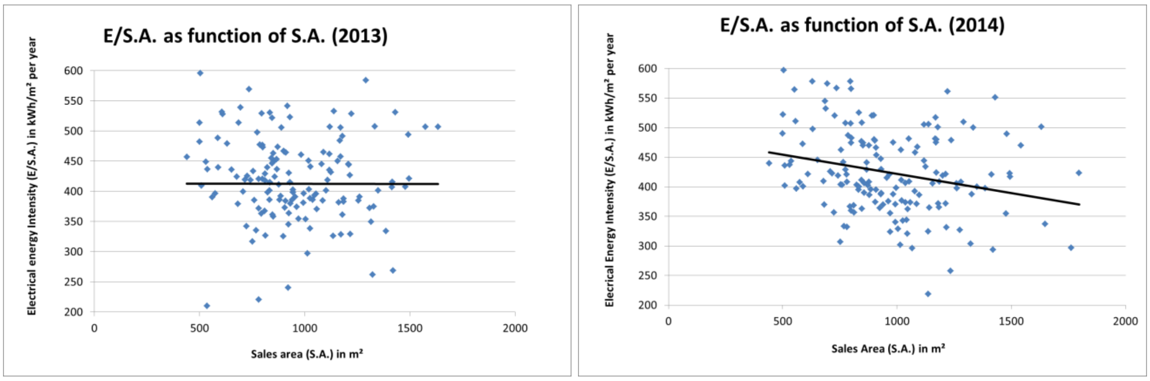

Fig. 5. Electrical energy intensities for the 2013 supermarket data set (left) and the 2014 supermarket data set (right), with linear regression lines shown. Weak dependencies with $R^2 = 0$ (2013) and $R^2 = 0{,}06$ (2014). Data covers all markets: existing, new and refurbished.

The effect of this change in management focus becomes very apparent when we plot the regression lines for the complete data set, as in the figures directly above. In 2013, the regression did not show the "common trend" of decreasing energy intensity for increasing sales area (as shown by the regression lines in figure 1). But the regression for the 2014 data set does show this trend, which is familiar from existing international studies. In the international studies this trend is associated with an increasing "non-food" share for larger supermarkets (and thus a relative lower need for refrigeration). For the supermarkets in our data set the trend is associated with management focus, there is no particular increase of the "non-food" share.

Even though the influence of management focus may be very apparent from figure 5, it remains yet unaccomplished to associate a quantifiable performance indicator. It seems obvious that due to the shift in management focus the energy efficiency must have improved, since all new and refurbished supermarkets have a low energy intensity (figure 4, right side). Still, the average energy intensity of all supermarkets in the data sets has not changed from 2013 to 2014 – indicating that for existing supermarkets the energy intensity has in the meantime increased.

5. Conclusion

The main performance indicator for the electrical energy consumption of supermarket buildings is the electrical energy intensity (yearly electrical energy consumption in kWh per m^2 of sales area). The sales are is preferred as basis above total area or volumes of refrigerating equipment. It is also preferable to treat the electrical energy consumption and energy consumption for heating separately.

Even with detailed knowledge about a large amount of conventional technical parameters, the yearly energy consumption of a supermarket building can still not be adequately determined. This brings us to conclude that we must include parameters of a different kind. Most notably, we are thinking of the maintenance and dynamics of the systems, sales volume or customer density, the indoor temperature & humidity, cleaning and loading procedures, and the training of personnel. Further investigations will be performed in the ongoing IEA HPT Annex 44 “Performance indicators for energy efficient supermarket buildings”

References

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