Technology Collaboration Programme on
Heat Pumping Technologies (HPT TCP)

Annex 44

Performance indicators for energy efficient supermarket buildings

Final Report

Operating Agent: The Netherlands

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Preface
This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) which is an Implementing agreement within the International Energy Agency, IEA.

The IEA
The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of over 40 Implementing Agreements.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)
The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the Heat Pumping Technologies Programme. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP collaborative tasks or “Annexes” in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex. The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

The Heat Pump Centre
A central role within the HPT TCP is played by the Heat Pump Centre (HPC). Consistent with the overall objective of the HPT TCP the HPC seeks to advance and disseminate knowledge about heat pumps, and promote their use wherever appropriate. Activities of the HPC include the production of a quarterly newsletter and the webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
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IEA HPT TCP Annex 44: Performance indicators for energy efficient supermarket buildings

Final Report

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Contents

Summary

The work in IEA HPT Annex 44 “Performance Indicators for energy efficient supermarket buildings” has been focused on finding average values for the energy consumption of supermarket buildings, using easily available performance indicators. This information can be used by policy makers and researchers to set a reference for average supermarket energy consumption. It can also be used by supermarket owners to compare the energy consumption of a specific supermarket to the average consumption, and thus determine whether the specific supermarket is energy efficient or not.

- A supermarket is energy efficient when its total energy consumption is below 400 kWh/m^2.year compared to supermarkets from Denmark, Sweden and The Netherlands. The area (m^2) referred to is the total supermarket area.
- 400 kWh/m^2.year is the average energy intensity found for supermarkets in Denmark, Sweden and The Netherlands, with an average total area of 1360 m^2 and 73 opening hours per week. Corrections are presented for differences in size and opening hours.
- Based on the available measured data no relation could be found between the total energy consumption (heat & electricity) and the geographic region of the supermarkets; additional computer modelling in this case also did not provide such a relation.
- Developments, especially in refrigeration systems and lighting, lead to an increase of energy efficiency in new or refurbished supermarkets ranging from 1 - 10 % per year. Refurbishment therefore is an effective management decision to increase energy efficiency.

Supermarkets are defined as “retail sale in non-specialized stores, with food, beverages or tobacco predominating” which excludes small specialized stores and hypermarkets. The most common performance indicators for supermarkets are size (total area or sales area), opening hours, refrigeration system type, installed refrigerating capacity and climate or geographical location. More uncommon performance indicators are sales volume, year of construction (or refurbishment), management attitude and system control and dynamics. The sales volume does not influence the energy intensity.

The supermarket energy consumption comprises the consumption of all subsystems: lighting, electric equipment, heating and ventilation, air conditioning and refrigeration. Since the introduction of heat recovery from the refrigerating system, energy consumptions for heating and for cooling must no longer be treated separately.

Data from the countries participating in the annex (Denmark, Sweden and The Netherlands) shows a good similarity concerning average Energy Intensity, the average total yearly energy consumption per m^2 of supermarket area, of around 400 kWh/m^2.year (± 10%).

Data set.	Energy Intensity (kWh / m² per year)	
	Base: total energy / total area	Base: electrical energy / sales area
Sweden	396	
The Netherlands 2013	397	422
The Netherlands 2014	369	413
Denmark (2015)		390

The energy intensity decreases with increasing supermarket area, on a basis of approximately 1% for each 100 m² of additional total supermarket area.

The energy intensity increases when opening hours are extended, on a basis of approximately 0,5% for each additional (weekly) opening hour.

Data sets from the USA, Canada and UK show energy intensity values well above 400 kWh/m².year, partly relating to a higher number of opening hours per week.

Statistical analyses confirm that the simple approach of relating total energy consumption to supermarket area provides better results than other performance indicators based on the summed volumes or lengths of refrigerated display cabinets, or installed refrigeration capacity. For electrical energy consumption instead of total consumption, installed capacity is a good performance indicator.

Currently systems are introduced that can evaluate the refrigeration system's Coefficient of Performance (COP) and the efficiency in relation to an ideal refrigeration cycle (Carnot efficiency or system efficiency index, SEI). These values may provide good performance indicators in the future, but currently not enough measured data is available yet.

Two data sets from The Netherlands were available containing information on the presence or absence of 65 different energy saving options. It was attempted to extract relations between energy intensity and energy saving options from these data sets, but no statistically relevant relations could be extracted – neither by means of a t-test nor by means of a multi variable regression method.

The objective of the work in this Annex was to provide an estimate for the energy consumption of a supermarket, based on a variable number of performance indicators. With only one performance indicator used, the energy consumption will be a first estimate, but with more performance indicators used the estimated energy consumption will be more precise. Based on the work in this Annex, we suggest to use the yearly total energy consumption per sales area unit as the performance indicator to best provide a first estimate of energy consumption. However, the formulation of additional performance indicators for precision of the first estimate has not succeeded based on the available data.

One of the basic premises for the project was to use data from meters and sensors already available in the Building Management System and the subsystems for refrigeration systems controls etc. as stated in the legal text for Annex 44. This has not led to the desired result of an estimate more precise than the first estimate based on supermarket area. To reach that objective, we recommend to use methods based on a combination of measured data and computer modelling of supermarkets.

Supermarket energy consumption remains a field where improvements in energy efficiency can be made, as long as there are supermarkets with an energy intensity of 55 % above the average value and at the same time supermarkets that can do with only 60 % of the average energy consumption.

It is becoming a good practice to use heat recovery on supermarket refrigeration systems, but it is still uncommon to see these systems as heat pumps. The HPT can play a role in bringing the heat pump and refrigeration sectors closer together, to the mutual benefit of both sectors.

1. Introduction

In our “information society” there is an abundance of data, but this data remains meaningless when it is not transformed into knowledge. Someone may have collected fuel station bills for years and years, but as long as he doesn’t know the car’s mileage there is no knowledge on the car’s fuel efficiency. And even then, only the driver would know if this efficiency mostly reflected city drives or the long distance fuel efficiency.

The same is true in the supermarket environment. There is a clear trend that more and more monitoring systems are installed in supermarkets measuring e.g. temperatures (typically to secure and validate food quality) and other relevant data. Measurements are taken and stored, and overall energy consumption data is available, but still in many cases there is no knowledge about the supermarket’s energy efficiency compared to other supermarkets in the same chain, or to competing supermarkets.

There are supermarket chains that are collecting overall energy consumption data (quite commonly from the energy providers) for their individual supermarket sites, and that are relating these data to basic performance indicators such as the sales area and the year of the most recent technical overhaul. Obvious anomalies in the data are related to special features of some of these sites, such as an on-site bake-off facility (providing freshly baked bread in the supermarket) or the presence of glass doors on refrigerated cabinet rows. In this way, a supermarket chain can successfully create an internal benchmark, and selectively increase energy efficiency at sites with low efficiency.

These existing internal benchmarks are internal to the specific supermarket chain that uses them. They provide no information concerning a chain’s position regarding energy efficiency to other chains. Also, they cannot reveal information on systems that are not yet deployed at the specific supermarket chain, such as innovative refrigeration systems, or refrigeration systems with alternative refrigerants. Therefore, also for supermarket chains that already employ an internal benchmark, there is a strong interest to extend the comparison to other (competing) supermarket chains and to include innovative technologies in the benchmarks.

The objective of Annex 44 has been to study and expand performance indicators for evaluating the energy efficiency of supermarket buildings, based on readily available measured data on supermarket energy consumption from different countries. Detailed computer modelling of supermarket buildings would also be a possible method to arrive at this goal, but supermarkets cannot generally spare the time needed for gathering the large amounts of data needed by such models.

Performance indicators are needed to transform available necessary 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 etc. When the energy use is related in the correct way to the supermarket size, it’s opening hours, and other performance indicators, it should become possible to appreciate the energy use of the supermarket: is it relatively high, normal, or relatively efficient.

It would allow to evaluate energy efficiency of existing single supermarkets, supermarkets within one chain, supermarkets across different chains and even supermarkets in different regions or countries.

The work of Annex 44 is primarily aimed at supermarket (chain) owners and their energy advisors, and can be interesting for policy makers and researchers.

Supermarket (chain) owners

For the owner of a chain of supermarkets, what is the way to invest in energy efficiency with the best value for money? That is to start with the store having the lowest energy efficiency, the weakest link in the chain. Therefore he needs to identify which store is –energetically- the weakest link in the chain. This may not be obvious at first sight, a good projection helps to identify the weakest link – just as the image shows. This "projection" is what is the intended result of Annex 44. The results of this Annex provide the average yearly (total) energy consumption value for a supermarket based on its sales area, with which to compare "your" supermarket.

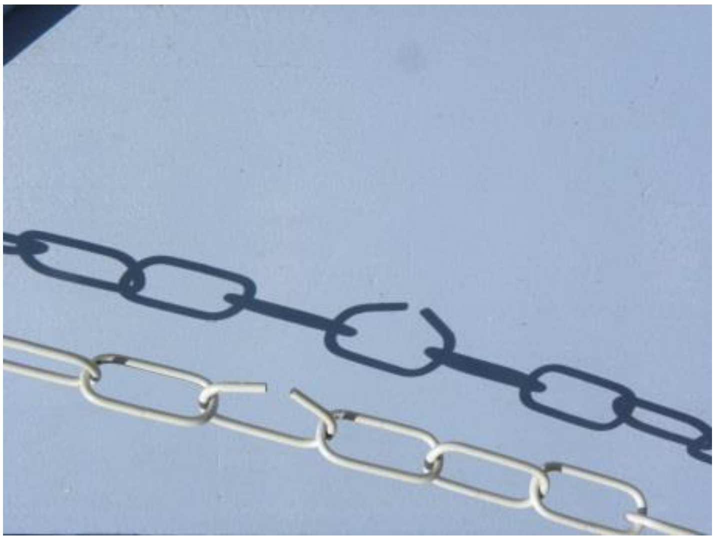


Figure 1: It can be easier to identify the weakest link in the chain from its shadow (the "projection") than from looking at the chain itself.

Policy makers

Useful energy consumption data for supermarkets can also be used by policy makers at a national level to map energy use and benchmark best practices for supermarket buildings. With the results of Annex 44 it is possible to map current supermarket energy use, and the expected development over time. Best practices are mentioned, but quantitative conclusions could not be reached from the results from this annex.

Researchers

For researchers it is often useful to know the "reference" value for the energy use of a supermarket, in order to make a comparison of suggested improvements to the reference or base case situation. Such reference values are provided in this report.

Furthermore, the work in this Annex 44 can be seen as a follow-up to the work carried out earlier in Annex 31. The earlier work in Annex 31 was presented at the 1st IIR International Conference on the Cold Chain and Sustainability (Arias et al, 2010). 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 (heating, ventilation, air-conditioning, refrigeration, lighting and other uses).

The objectives of the work in this annex 44 have been:

- to create key performance indicators for energy efficient supermarket buildings, so that measurements and monitored data can be converted into knowledge concerning the energy performance of supermarket buildings.

- to create knowledge concerning the energy efficiency of supermarket buildings from measurements and monitored data, that is useful for decision making, benchmarking and development of energy efficiency strategies for supermarket buildings.

- to provide an estimate for the energy consumption of a supermarket, based on a variable number of performance indicators. With only one performance indicator used, the energy consumption will be a first estimate, but with more performance indicators used the estimated energy consumption will be more precise.

Based on the work in this Annex, we suggest to use the yearly total energy consumption per sales area unit as the performance indicator to best provide a first estimate of energy consumption. However, the formulation of additional performance indicators for precision of the first estimate has not succeeded based on the available data.

The work in this Annex has been performed by teams from Denmark, Sweden and The Netherlands:

- The Netherlands: Saint Trofee (S.M. van der Sluis), Coolsultancy (R. Jans)

- Sweden: RISE (U. Lindberg, A.-L. Lane), KTH (J. Arias, S. Sawalha).

- Denmark: DTI (C. Heerup, R. Borup), Danfoss (L. Larsen, S. Piscopiello), IPU (J. Wronski, M. Winter), AK-Centralen (T.Gøttsch)

The work has been carried out in the period July 2013 - June 2017.

2. Scope

Supermarkets and the supermarket sector are the main targets for the work carried out for this Annex. However, the methodology created this Annex may - when modified accordingly - also be applied to other food retail establishments (e.g. hypermarkets) where an important part of the total energy use is for refrigeration for display and storage of foodstuffs.

International

The international definition of supermarkets can be found through 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 (retail trade, except of motor vehicles and motor cycles), and more specifically under group 471, class 4711 “retail sale in non-specialized stores, with food, beverages or tobacco predominating”.

In this international classification, specialized food stores (such as bakeries, butcheries etc.) are excluded, as these are considered specialized. In the ISIC classification, they reside in class 4721. Also, stores at fuel stations are excluded. These stores, classified as “retail sale of fuel in combination with food, beverages etc., with fuel sales dominating (class 4730).

The Netherlands

The Dutch classification system deployed by the chambers of commerce (Standard classification of economic activities, SBI 2008) is similar to the ISIC classification. Supermarkets are found here under code 4711. It is further clarified in the Dutch classification that shops selling deep-freeze products only, are not considered within this code, but rather as specialized food stores. Also, retail trade not in shops (on markets, and via internet) is not considered within this code.

In 2016, according to CBL (the Dutch bureau of food retailers) there were 4.300 supermarkets in The Netherlands (SBI class 4711). The average shopping surface of the Dutch supermarkets (exclusive the mini supermarkets) was 882 m^2 (2012). A distribution by area is given in the table below.

Table 1: Distribution of supermarket sizes in The Netherlands (2012).

Shopping surface	Percentage (2012)
> 2.400 m^2	1,6 %
2.000 - 2.400 m^2	1,3 %
1.600 - 2.000 m^2	3,9 %
1.200 - 1.600 m^2	14,1 %
1.000 - 1.200 m^2	13,7 %
800 - 1.000 m^2	19,7 %
600 - 800 m^2	17,9 %
400 - 600 m^2	11,2 %
200 - 400 m^2	11,4 %
< 200 m^2	5,4 %

Sweden

The Swedish classification system by SCN (Statistics in Sweden) is similar to the Dutch classification. Supermarkets are found here under code 4711.

Code 4711 - **Retail sale in non-specialized stores with food, beverages and tobacco**
This code covers the retailing of a wide range of goods which, however, with food, beverages or tobacco has at least 35 percent of sales. In addition to its main sales of food, beverages or tobacco, marketed also several other types of goods such as clothing, furniture, appliances, hardware, cosmetics and related products

Code 47111 – **Department stores and supermarkets with food, beverages and tobacco**
Department store trade, meaning the retail space with at least 1 500 m2 of sales area and wide range supermarket trade, meaning the retail premises with a minimum of 2 500 m2 of sales area and external mode and wide range or specialized in frozen food

In 2011, statistic from the market sector itself shows 6.200 supermarkets, where 4.760 are from the 10 largest chains. In 2011, statistic from SCB (Statistics Sweden) shows 5.199 supermarkets (code 47.11), classified by the number of employees.

Table 2: Data from SCB (Statistics Sweden) on Swedish food retail stores by number of employees.

47.11 Non-specialized stores with food, beverages or tobacco predominating (e.g. supermarkets)	2010	2011	2012
0 employees	1 794	1 945	1 857
1-4 employees	1 343	1 354	1 387
5-9 employees	596	613	610
10-19 employees	660	649	654
20-49 employees	423	429	419
50-99 employees	131	138	133
100-199 employees	54	54	58
200-499 employees	5	4	5
500+ employees	13	13	13
Total stores	**5 019**	**5 199**	**5 136**

Table 3: Number of supermarkets in Sweden per supermarket chain, data from supermarket sector (2011).

Chain	Number (2011)
ICA	1331
Axfood	1016
COOP	705
Reitan Convenience	506
OKQ8	380
Statoil	303
Menigo Foodservice	243
Total 7 largest supermarket chains	**4484**
Other Stores (estimate)	1700

Total Supermarkets Sweden (estimate)	**6200**

The distribution between different supermarket formulas in the largest supermarket chain of Sweden is presented in Table 4.

Table 4 Number of supermarkets in different sizes within ICA, 2017 (Source ICA)

Type of supermarket	Number of supermarkets	Total area, m^2	Sales area, m^2
Near	670	947	600
Supermarket	431	1717	1238
Kvantum	123	3083	2271
Maxi	81	6497	3918
Total stores	**1305**		

3. Supermarket energy systems

3.1 System Boundaries

For sustainable buildings, including supermarkets, one needs to consider energy efficiency at a system level. For the refrigeration system, each product and combination of product must be well designed in order to contribute to the efficiency of the refrigeration system.

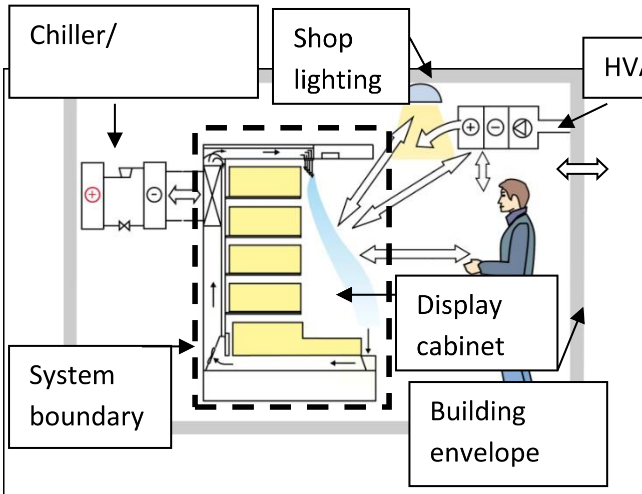
A supermarket is a complex system where many energy systems such as the HVAC system (Heating, Ventilation and Air Conditioning), the refrigeration system, lighting and other energy using subsystems (which also constitute a heat source) interact. Supermarkets have a wide range of heating and cooling demands depending on the outdoor condition and indoor climate requirements.

In order to achieve the goal of energy efficient supermarkets, it is important to have an understanding of the functional requirements and of the refrigeration system scenarios, i.e., the overall chiller-distribution-display cabinet system. In addition relevant performance indicators are needed in order to make comparisons between different supermarkets including the refrigeration system.

The calculated energy efficiency of a supermarket depends on where the system boundary is drawn. It is necessary to clearly define the system, its function/s, and the system boundaries. Regardless of the system boundary, the efficiency should be based on a whole year (to take account of both summer and winter situations regarding heating, ventilation, air conditioning and refrigeration).

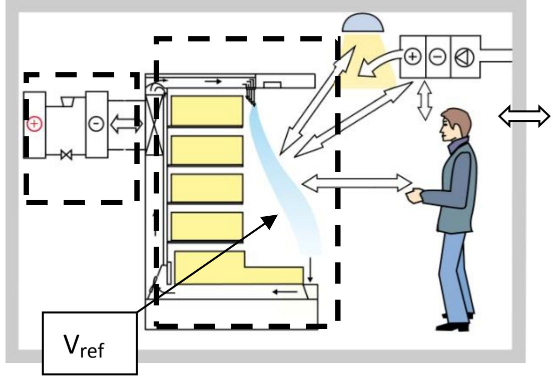
A consistent choice of energy-efficient products, and knowledge of optimal storage conditions for the food, will help to provide safer and better quality products, and at the same time save energy. In Europe, as well as in the U.S.A. and Australia, there are policies targeted especially at supermarket refrigerated display cabinets and condensing units (refrigeration systems), which “steer” towards the selection of energy efficient (refrigerating) equipment. When the system boundary for supermarket energy efficiency would be drawn around the refrigerated display cabinets only, such policies (and their measurement basis) would provide a good basis to determine energy efficiency. But although the refrigerating system has an important role in the overall energy use of the supermarket, it is not the sole distinguishing aspect in supermarket energy consumption. Therefore, other system boundaries must be considered as well.

Four different system boundary options are illustrated in the figures below. These options are related to the inclusion or exclusion of the refrigerating system(s), where the refrigeration system is divided into one or more condensing unit(s) and a varying number of display cabinets (in the figure represented by one condensing unit and one display cabinet).



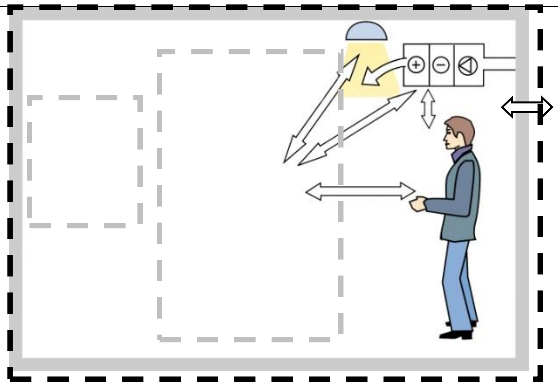
(a) System 1
The boundary is set around the display cabinet.(e.g. EcoDesign). Does not include the refrigerating system, nor practical values (opening hours, indoor environment) of the specific supermarket

Proposed goodness factors: kWh/(m3,year)



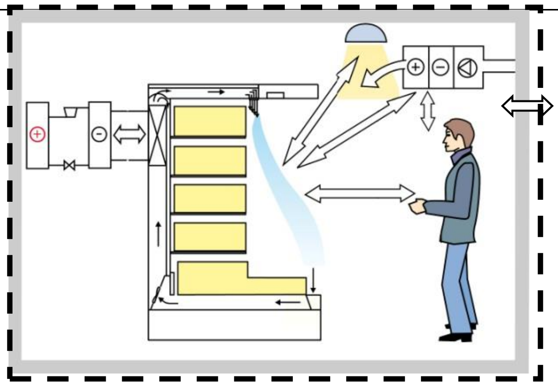
(b) System 2
The boundaries are set around the chiller/condenser unit (refrigerating system) and around the display cabinet.

Proposed goodness factors: kWh/(m3,year)
Note! Independent of size of supermarket.



(c) System 3
The boarder is set around and outside the building envelope, but excludes the refrigerating system and refrigerated display cabinets (e.g. EPBD).

Proposed goodness factors: kWh/(m2,year)



(d) System 4
The boarder is set outside the building. All energy systems are included, including the refrigeration system.
Proposed in Annex 44

Proposed goodness factor: kWh/(m²·year)
- Total Energy Consumption (*)
- Sales Area.

(*) Electricity and Heat/Gas/Oil

Figure 2. Illustrating four different options for system boundaries in a supermarket. (from Lindberg, Axell and Rolfsman 2011, ICR2011 ID 869). Figures (a)-(d) illustrate different system boundaries.

The system boundary in Annex 44 is the whole supermarket (system 4 in Figure 2), which includes all energy systems (HVAC, refrigeration, lighting and other uses).

3.2 Energy subsystems and energy consumption

In this Annex report much attention will be given to the supermarket refrigeration subsystem. It is not surprising when considering that most of the authors are refrigeration specialists, but it is also justifiable since the refrigeration subsystem is the largest energy user of all energy subsystems. In terms of electrical energy consumption (without energy consumption for heating), the refrigeration system accounts for roughly half the total supermarket electrical energy consumption (Figure 3).

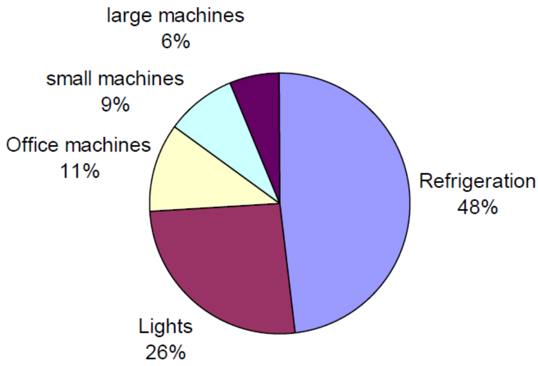


Figure 3: average distribution of electrical energy consumption in German supermarkets (Kauffeld, 2007).

This percentage agrees well with recent measurements (2015) in 49 Danish supermarkets (of smaller size), where the refrigeration energy consumption on average was 49,4 % of the total (electrical) yearly energy consumption.

Nevertheless, the percentages are indicative, since it is not always clear whether self-contained refrigeration units (”plug-in” units) are included under “refrigeration” or under “large machines”, and whether lighting of refrigerated display cases is included under “lighting” or under “refrigeration”. Similarly, it is not always clear whether electricity using components of the heating and ventilation systems (pumps and fans) are included as electricity consumption or as energy consumption for heating (and ventilation).

3.3 The Refrigeration System

The basic purpose of refrigeration systems in supermarkets is to provide cooling for refrigerated display cabinets (for the display of perishable food) and for chilled or frozen storage rooms. There are two principal refrigeration temperature levels in supermarkets: medium temperature (MT) for preservation of chilled food and low temperature (LT) for frozen products. Chilled food is maintained between 1°C and 14°C, while frozen food is kept at -12°C to -18°C (or -21°C for ice cream), depending on the regulations prevailing in a specific country.

A cold space (refrigerated display cabinet or storage room) would stay cold forever, if it was perfectly isolated so that no heat could leak in. In practice of course that is not the case, and heat leaks in. The function of the refrigeration system is to remove the heat that is leaking into the cold space, and thus keeping the temperature of the cold space at the desired (low) level. To collect the heat from the cold space, the refrigeration system has an evaporator. The evaporator is a heat exchanger and is kept at a temperature (the evaporation temperature) that is below the temperature of the cold space. The heat collected by the refrigeration system is discharged, usually to the outdoor air (ambient). To discharge heat to the outdoor air, the refrigeration system has a condenser. The condenser is a heat exchanger and is kept at a temperature (the condensing temperature) above the ambient temperature. These steps are depicted in Figure 4.

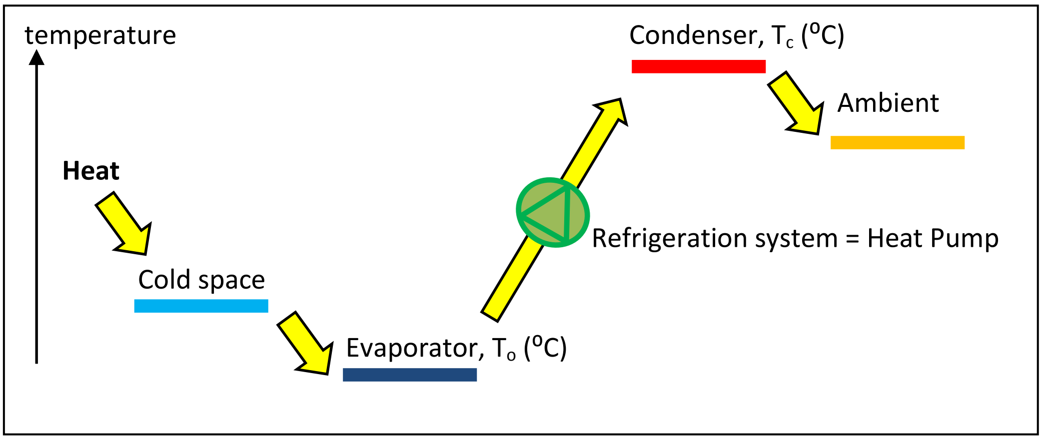


Figure 4: heat leaks into the cold space, is absorbed by the evaporator and pumped to a higher temperature by the refrigeration system. From the condenser the heat flows to ambient.

Heat flows freely from a higher temperature level to a lower temperature level. But in the opposite direction, such as from the evaporation temperature T_o to the condensation temperature T_c in Figure 4, it must be "pumped". Energy is needed for this pumping action, and the amount of energy needed per unit of heat pumped depends on the temperature difference, Tc – To. For an ideal heat pump (refrigeration system) the pumping energy can be formulated exactly:

Pumping energy per unit of heat (ideal) = $\frac{Tc-To}{To}$ (with *Tc* and *To* in Kelvin instead of ^oC)

For a chiller at T_o = +6 ^oC and an ambient at +20 ^oC, the pumping energy per unit of heat is 0,05 (ideally). But for a freezer at T_o = -18 ^oC and the same ambient temperature the pumping energy per unit of heat is three times as high at 0,15 (ideally) .

The inverse of the 'pumping energy per unit of heat' is the 'heat moved per unit of energy' and is referred to as the COP (Coefficient of Performance) of the refrigeration system. The COP is often interpreted as a kind of "energetic performance" of a heat pump or refrigeration system, but be aware that the COP depends most of all on the temperature levels. For the chiller at +6 ^oC the ideal COP is 20, whereas for the freezer at -18 ^oC, with the same ideal refrigeration system, the COP is 7 (both again at an ambient of +20 ^oC).

The very basis for energy saving in refrigeration can be learned from the above formula. It consists firstly of reducing the amount of heat to be pumped, and secondly of reducing the temperature difference over which the heat has to be pumped. Of course there is much more to say about energy saving in refrigeration, but these two are the most important points. For more details on refrigeration systems, refer to Appendix A.

3.4 Heating systems in supermarkets

Heating systems in supermarket cover space and tap water heating demand. Space heating is required in the sales area, offices and back rooms for customer and personnel thermal comfort. Tap water heating is required for early morning preparation of prepared meals and late night cleaning of the supermarket before closing. In cold climates, another usage of heating is to melt the snow and protect the soil/ground from freezing in the entrance zone or car parking area.

Generally, and where needed, the sales area is heated by warm air provided by a centralized air handling unit (AHU). This is mainly the case for medium-large size supermarkets. Stand-alone or distributed smaller heating systems are used in smaller supermarkets. There are few examples of Nordic supermarkets using floor heating, but there it is not installed in the refrigerated zone of the supermarket. In other European countries, floor heating is more common. The offices and back rooms can be heated by air or hydronic systems including radiators.

The heating can be provided by oil or gas boiler/condensing boiler, electric heater or district heating. But the most energy-efficient, cost effective and environmentally friendly method, known as heat recovery, is to use the waste heat rejected by the refrigeration system through the condenser and/or de-superheater (if available). The amount of heat pumped by the refrigeration system can cover a great share of the heating demand, sometimes even more than the supermarket needs. An example of proper heat recovery is the "open district heating" project running in Stockholm where a number of supermarkets and data centres recover and sell their excess heat to the city district heating network.

Heat recovery

Many supermarkets utilize heat recovery (or heat reclaim) from condensers as an effective way to increase the overall energy efficiency of the system. The "waste" heat from the condenser of the refrigeration system is then used for space heating purposes. One drawback of heat recovery is that the condensation temperature must be kept at a level where heat can be transferred to the heating system of the supermarket. The typical required temperature level for the condenser coolant is 38°C after the condenser. This leads to a reduction of energy consumption for the heating system, but at the same time it increases energy consumption from compressors at low outdoor temperatures (working at a higher condensing temperature than necessary).

Systems without heat recovery can use "floating condensing temperature" where the condensing temperature is always kept at a few degrees above the outdoor temperature (except at very low outdoor temperatures, where the condensing temperature is kept at a fixed minimum level). The use of floating condensing temperature improves the coefficient of performance and decreases the energy consumption of the compressors at lower outdoor temperature.

An option is to utilize both heat recovery and floating condensing pressure depending on the heat requirements of the premises.

There are several technical designs available to recover "waste" heat from the refrigeration system, depending on the system design and the refrigerant. Some examples are given in Appendix A.

3.5 Ventilation

A ventilation system distributes and provides outdoor air to the customers and personnel of the supermarket. It is also essential for maintaining the quality of the products. Furthermore, it provides the required air change rate to limit the concentration of pollutants, smell, mould, fog and bacteria.

Supermarkets have a unique mix of several different thermal zones under one roof. Each of the zones have unique thermal and air flow demands. Simultaneously, most of the thermal zones are not isolated and interact and affect each other. This makes the design of the ventilation system a complex task. The supply of the required air with a proper temperature level and flow rate is not the only complex part of the design. The zones which are supplied more with the outdoor fresh air, such as the sales area, should be pressurized to force the air to migrate to the zones which produce exhaust gases, such as the supermarket kitchen or bakery.

High volume flow rate of outdoor air intake means both high fan power consumption and more need for pre-treatment of the outdoor air, such as higher need for heating the air in winter time. This is the reason why it is recommended to minimize the air intake. A minimum air intake flow rate ranges between 0.3-1 cfm/ft^2 [1.5-5 $lit./s{\cdot}m^2$] (Clark, 2015).

The conventional ventilation systems are constant volume air distribution systems, which have generally high energy consumption. There are some options to make ventilation systems more energy-efficient and, consequently, eco-friendly.

3.6 Air conditioning

Air Conditioning (AC) cools and controls the temperature level in supermarkets. The size and type of this system is dependent on the supermarket size; it ranges from small units, for example moveable plug-in ones, to large stationary central AC systems. Two major categories of AC systems in the supermarkets are “packaged systems” where all components are built into a single casing and “split systems” where essential components are built into several casings. Split systems can be ducted or non-ducted. Some AC systems are reversible; this means they have the possibility to reverse the cycle flow direction and can hence be converted into a heat pump during cold months (Gschrey and Zeiger, 2015).

Stationary air conditioners are also large consumers of HFC refrigerants in Europe and they will be affected by the EU F-gas Regulation. R134a, R410A and R407C still are the dominant refrigerants used in European AC systems. A recent trend is to use R32 as a refrigerant with a lower GWP value.

In addition to the traditional HFC-based AC solutions, natural refrigerant based systems are also available in the market. Many good case studies and examples of NH_3 or hydrocarbon chillers can be found in http://www.hydrocarbons21.com/ and http://www.ammonia21.com/. Furthermore, there are a few studies of CO_2 air conditioners (reversible heat pump) (Girotto, 2016), (Minetto et al., 2016).

Another interesting AC system solution introduced to the market a few years ago is integration of AC into the CO_2 booster refrigeration system. This is a very recent technology, and there are research works ongoing to investigate whether the AC function of this integrated solution is more efficient than an isolated HFC-based AC system or not. Karampour and Sawalha (2015) have found that the COP of air conditioning in an integrated CO_2 system is higher than in an isolated HFC-based AC system for ambient temperatures lower than 25 °C. Examples and performance analysis of commercial systems using this CO_2 integrated solution for AC have been presented in different studies such as (Karampour and Sawalha, 2016).

3.7 Dehumidification

High humidity in supermarkets has several disadvantages such as more frost formation on the (refrigerated display cabinet's) evaporator coils and subsequently more energy consumption for defrosting, higher anti-sweat heating demand and possible fogging of cold glass surfaces.

However, despite all these mentioned disadvantages, the majority of supermarkets is not supplied with a dehumidification system of any kind. The humidity control is usually done by introducing excess dry outdoor air. Open refrigerated display cabinets and freezers also play a role in the dehumidification of the indoor air. Neither of these methods however can be considered as energy-efficient solutions.

Many research works have tried to quantify the effect of reduced space humidity on refrigeration energy use. Kosar and Dumitrescu (2005) have summarized some of these research works, providing measured ranges of 3–21 % reduction in compressor energy use with a 20 % relative humidity (RH) reduction in the space, a 4–6 % reduction in defrost energy, and a 15-25 % reduction in anti-sweat heater energy.

To dehumidify the air, two primary solutions are available. The first one is to cool the humid air below its dew point. This leads to condensation of a part of the water content. For cooling the air, a branch of cold refrigerant/brine stream from the refrigeration system or a separate refrigeration system can be used. Dehumidification by condensation can be integrated with the ventilation or refrigeration system.

The second method is to use water absorbing materials like silica gel. The most well-known equipment which uses this technique is called a desiccant wheel. A desiccant wheel is the major component in a desiccant dehumidification system. It is a slow rotating wheel containing some absorbent chemicals, normally silica gel. When moist air passes one portion of the wheel, the moisture is absorbed. While it is rotating, in the other portion of the wheel a hot drying air is blown across the wet absorbent to dry and "regenerate" it. In this system, the desiccant wheel plays the role of a "moisture transporter"; extracts the moisture out from the supply air and transports it to the exhaust air.

The hot drying air can be produced by different heating systems but the most eco-friendly solution is to use refrigeration heat recovery, for example by CO_2 systems which can provide the high temperature demand for the regeneration. Such a system with CO_2 heat recovery for regeneration has been studied through computer modelling by Sharma et al. (2014). Desiccant dehumidification systems can be integrated with an air handling unit (AHU) of the ventilation system.

3.8 Lighting

Lighting in supermarkets accounts for about 20-25% of total electricity used in supermarkets. Cost savings between 25-50% of the electricity consumed for lighting are possible by using LED lamps, better control system and maximising the use of daylight.
The UK Carbon Trust provides directions for energy savings on lighting in retail (Carbon trust, 2012), the first om these being a higher level of attention in management by means of instructions to the (super)market personnel concerning switching off lighting where possible, and replacing inefficient older lighting systems with newer efficient versions. This is an example of the possible influence of supermarket management on energy efficiency, which is discussed in chapter 8.3 of this report.

A further recommendation is the use of occupancy sensors and daylight sensors in supermarket areas for personnel, outdoor areas (such as parkings) and sales areas outside opening hours.

Whereas only a few years ago recommendations were provided to replace tungsten light bulbs with fluorescent lamps, these are now obsolete in the EU. Today's recommendation would rather be to replace fluorescent lamps with LED lighting where possible (e.g. in cabinet lighting). The costs of LED lighting are rapidly decreasing over time, and an additional advantage of LED lighting is that almost no heat is dissipated (which in turn eases the load on refrigeration systems, and thus saves energy). A publication by the EU JRC shows a number of examples where 50% of lighting energy was saved by retrofitting lighting systems in supermarkets with LED lighting systems (Schönberger et al., 2013).
The report on supermarket refurbishing of the EU Supersmart project provides a number of options for refurbishing lighting systems with LED lighting (Mainar Toledeo, D., and Garcia Peraire, M., 2016).

The use of daylight has been avoided for many years in supermarkets, but the US energy star building manual (chapter 11 on supermarkets and grocery stores) mentions that the use of diffuse daylight avoids the negative effects of direct daylight (glare and heat load) and furthermore has a positive effect on customer perception and consequently on sales (Energy star, 2008). Needless to say, the use of daylight is a major (lighting) energy saver. Daylight must be combined with artificial lighting and a suitable control system (e.g. dimmable artificial lighting to produce a constant lighting level).

4. Monitoring systems in supermarkets

4.1 Energy monitoring

Energy-meters are used as basis for payment of energy between energy suppliers and their customers. Energy bought by the supermarket is therefore the easiest energy to get measure on. Bought energy is electricity. District heating, gas Oil, pellet and other combustible fuels could be bought for heating and district cooling could be bought for air conditioning and in some cases to take care of heat waste from the refrigeration system.

In Sweden the supplier of electricity has to offer values for used energy for every hour. Many electricity companies offer this service on their web-site.

A supermarket could be a tenant in a building with other shops and operations. Some of the energy used by the supermarket could be included in the rent and not always measured. It is quite common by landlords to spread energy costs proportional to rented area among tenants in a building. This situation makes it hard to get a measure of all energy used by the supermarket, which makes it hard to compare energy usage with others.

Other monitoring systems used in supermarkets are connected to installations and the primary aim of these systems is control and regulation. Common installations are heating, ventilation, comfort cooling (HVAC) and for refrigeration of food. The HVAC systems often have internal systems for control and regulation, which also the refrigeration system has. There is also a possibility to install a superior system for control and regulation in the building. These systems are often related to the systems for HVAC but not for refrigeration systems for food. There are other superior systems used for the refrigeration, mostly in larger supermarkets. Energy meters can be mounted and connected to this superior system, both building and refrigeration related control systems. There are also separate systems, just for energy measures, that can be installed. In 4.5 an investigation done in Sweden of three different systems for energy measurement in supermarkets is described. One of the systems is just for energy measurements and the others are integrated with the systems for control of the refrigeration system.

One of the important lessons learned during the work of this Annex is that, apart from the main meters for billing purposes for electricity and heat, all other data sourced from auxiliary meters and sensors on subsystems cannot be trusted unless there is a set-up in the company equivalent to energy management. Without the proper documentation, it cannot be evaluated if the measured values are comparable especially not from one supermarket building to another. This is also true for other parameters such as refrigerated display area etc.

4.2 Monitoring of temperatures & humidity

To keep the quality for frozen and refrigerated food there are legal requirements for temperature measurements. For this purpose temperatures are measured and logged in display cabinets and storages. Monitoring systems are often used in bigger supermarkets which give an easy overview of the installed cooling equipment on a computer screen.

Temperatures in the building and outdoor are often measured in the HVAC-system for control and regulation of the indoor environment. These temperatures are mostly momentary measurements.

Humidity could be measured but is not common.

4.3 Monitoring the overall refrigeration system

The refrigeration system plays an important role in the overall energy consumption of the supermarket. It is estimated that refrigeration accounts for roughly half of the supermarket total energy consumption (electricity + heating). It is therefore very worthwhile to monitor the performance of the overall refrigeration system.

The overall refrigeration system consists of the end-users of “cold” (refrigerated display cabinets and chilled and frozen storage cells), the production of “cold” (the compressor racks and condensers) and the distribution system. Refrigeration systems are equipped with many sensors that are used for controlling their functioning. It is quite common nowadays that the readings from these sensors are dispatched by internet to the refrigeration service company. The service company then monitors these readings (usually automatically), and an alarm is raised when a measured value deviates from its normal set point for a longer period of time. In such cases, the service company will interpret the alarm and will usually take an appropriate action.

This form of monitoring is appropriate for tracking malfunctions of the refrigeration system; it is not intended for an overall evaluation of the energy efficiency of the system. The information retrieved from such a monitoring system relates only to the specific installation on which it is installed, and it is not generally intended to be compared to information from monitoring systems at other sites.

For monitoring and management of more than one site, a management system is needed. Supermarket chains have a need for an efficient handling of their alarm monitoring, data structure, HACCP[1] procedures, HACCP policies, refrigeration energy consumption, service calls and refrigeration maintenance management. The scale of these chains thus requires management services that can handle massive setups of stores, plants, controllers, service partners, store personnel, chain management, documentation and more. Service companies undertaking these services for the supermarket chains have emerged in the market over the last decades.

The Danish company AK-Centralen A/S has for the last 15 years provided supermarket chains with these services and has built a high-end management system that takes care of these complex tasks

[1] Hazard analysis and critical control point here specifically related to safe handling of food

taking responsibility on behalf of the supermarkets and in accordance with chain management policies.

“Turning of the lights in the children’s room is common sense. Turning off the lights in every room in every house is facility management.”

AK-Centralen’s method of taking responsibility is to use the equipment already installed and unleashing the full potential of the options available. New sites go through a data structure process where master data is collected and structured on behalf of a master plan that has been developed together with the supermarket. All sites are then aligned to the new scheme and tested before going online, activating the 24/7 monitoring and continuous optimization. The value of having an aligned policy and data structure combined with expertise and management tools is essential when the portfolio of refrigeration systems reach the scale of modern supermarket chains. Through the acquisition of large data sets better informed decisions can be made on both the chain and the supermarket level. The primary quality parameter is the air temperature of the refrigerated display cabinets. The supermarket decides the quality level of their refrigeration setup and the resulting temperature set points are then used as targets for optimising. A common optimization strategy for a chain needs to contain both minimum optimisation levels and individual set point optimisation down to the evaporator level in order to gain the maximum value regarding quality, energy and maintenance.

In this project AK-Centralen A/S has supplied data from the Danish supermarkets analysed in the following sections.

4.4 Inline COP evaluation method

Contrary to the overall refrigeration system monitoring, which is intended to control the system and to detect temporary malfunctions, it would be desirable to have a refrigeration plant monitoring system that evaluates the regular performance of the system over longer periods of time. The performance of the refrigeration system is in essence described by its “Coefficient of Performance” (COP). Danfoss has recognized this need, and developed a COP calculation algorithm that can be used as COP monitoring system.

Apart from a well-designed system, the first step toward effective energy consumption in a refrigeration system is related to the monitoring of the efficiency of the system. The key for energy saving is the possibility to find an answer to these questions: how good is the plant running and what is possible to do to improve it. The general ideal of the COP calculation algorithm is to produce a group of key performance indicators (KPIs) able to quantify the performance of a refrigeration system in order to answer to such questions.

The Danfoss COP monitoring system makes use of the measurement data that is already regularly measured by the overall monitoring system as described in the previous paragraph. In addition to this already available data, two extra (temperature) measurement points must be installed on the refrigeration system. The COP monitoring system does not require the installation of a (refrigerant) mass flow meter, but rather calculates the mass flow rate from the running capacity of the compressor pack. This does however require that the compressor volumetric efficiency is given.

The main monitored performance parameters are:

- Real Coefficient of performance (COP) and Compressor electric power consumption.

- Plant Efficiency (relation between the real COP and COP of the same cycle with ideal parameters)

- Carnot Efficiency (relation between the real COP and the ideal COP at the same temperature lift)

The current algorithm version (June 2017) supports refrigeration systems with the following marked features:

Plant Type:
☒ One MT Pack
☒ One LT Pack
☐ One MT Pack + HP valve
☐ One LT Pack + HP valve
☐ Booster System
☐ Booster System + IT
☐ Booster System + Ejectors

Refrigerants:
☒ None and low glide refrigerants (< 1K);
☐ High Glide Refrigerants (> 1K);
☐ CO2 (transcritical phase);

Heat Recovery:
☐ 1 Heat reclaim (Space Heating)
☐ 2 Heat Reclaim (Tap water + Space Heating)

Heat Rejection:
☒ Cooling Tower (w. intermediate warm brine loop)
☐ Dry-cooler (w/o. intermediate warm brine loop)
☐ Dry-cooler (w. intermediate warm brine loop)

Other:
☐ Internal Heat exchanger;
☐ External Subcooler;

The algorithm start with the data logging of all values needed to make the calculations for 3 refrigeration cycles: the “Real cycle”, the “Ideal Cycle” and the “Carnot cycle”. The “Real cycle” contains the thermodynamics properties only based on the inputs measurements of the system, it is the straightforward refrigeration cycle as available in the system as it is built, with “real life” components and characteristics.

The “Ideal cycle” contains an idealized version of the same real cycle where some real measurements are substituted with ideal parameters. In this ideal cycle, “State of the Art” values are substituted for major components such as heat exchangers (ΔT = 5K is used as state of the art) and compressor (volumetric efficiency ηvol=0.9, =0.65 (the "best of class" isentropic efficiency) and εHL=15% (expected heat loss factor in the compressor). A standard superheat of 5K at compressor inlet is used. The concept of “Ideal Cycle” makes it possible to see how much the actual system deviates from a similar “State of the Art” system.

The “Carnot cycle” represents the best cycle from a purely thermodynamic point of view. This is a theoretical value, that cannot be reached with “real life” components, even when the best of the best of components were being selected. It is therefore a theoretical optimum.

Based on the logged values, calculation is performed of the three corresponding Coefficient of Performances: COP, $COPideal$ and $COPcarnot$. These COP values are then used to evaluate

$PE\ = COP\ /\ COPideal$

$DPI = COP/COPcarnot$.

In addition to COP, the algorithm evaluates isentropic efficiency of the compressor (ηis) and the specific capacities $q0$, qc, w. These specific values need to be scaled up to power capacities using an estimation of the refrigerant mass flow $\dot{m}$. The algorithm does perform this by using the logged input running capacity of the compressors, swept volume and volumetric efficiency. The outputs of the algorithm are furthermore used to evaluate "Economics KPIs" and the "Deviation KPIs".

Another set of (measured) inputs and parameters are used to evaluate the cooling tower KPI. To check the validity of the calculation some of the outputs are subjected to a validation test which leads to flag all the calculations performed as valid or invalid. Only if the validation test is passed successfully, all the outputs calculated (instant values) are included in (time) averaging calculations. Two types of average are calculated: hourly (a new values every hour) and daily (new value every day). Compressor power is used as weighting factor for all the other outputs.

A list of all output parameters of the algorithm is as follows:

ηis [-]	Isentropic Compressor efficiency;
εct [-]	Cooling tower efficiency;
COP [-]	COP cooling- Coefficient of Performance for cooling;
DPI [-]	Danfoss Performance Indicator;
$DevActSH$ [°C]	Actual deviation of superheat
$DevActT0$ [°C]	Actual deviation for evaporation temperature
$DevActTc$ [°C]	Actual deviation for condensation temperature
$DevSH$ [-]	COP Deviation using ideal superheat
$DevP0$ [-]	COP Deviation using ideal P0 (evaporation pressure)
$DevPc$ [-]	COP Deviation using SH ideal Pc (condensation pressure)
$DevComp$ [-]	COP Deviation using SH ideal η_{is}
EUR_{ct} [€/h]	Total cost of the water in the cooling tower.
EUR_{kWh} [$€/kWh$]	Specific cost for the cooling;
$EURm_2$ [$€h\,m_2$]	Specific cost for refrigerated area;
EUR_{total} [€/h]	Total cost for the cooling;
$\dot{m}_{water}$ [kg/h]	Water consumption cooling tower;
PE [-]	Plant Efficiency;
PotentialSaving [€/h]	Potential Saving in the plant
kWh_{m2} [kW/m_2]	Specific power consumption per refrigerated area;
Q_0 [kWh]	Cooling Capacity;
Qc [kWh]	Condenser Capacity;
W [kWh]	Compressor Capacity;

The most important monitoring parameter in relation to the work of annex 44 is the real COP value, which can be compared to real COP values measured at other supermarkets. It takes into account all aspects of the refrigeration system, including the choice of evaporating and condensing pressures. The Carnot efficiency is a more objective comparison parameter, but it does not include whether the condensing and evaporating temperatures are chosen in a "wise" (energy efficient) manner.

The COP calculation algorithm has been validated in terms of calculated compressor power consumption versus measured consumption, and currently agrees within 20% on two systems that were validated. It is our expectation that variations in COP in real life supermarkets are much larger than 20%. So when an experience base of measured COP values is created over time, it will be possible to evaluate the real COP values for cooling and for freezing of a specific supermarket with the average COP for cooling and COP for freezing – and take appropriate actions according to the result of this comparison.

A COP monitoring system will be a very useful tool in assessing the energy performance of a supermarket refrigeration system. Of course, we must not forget that it will still be necessary to minimise the cooling load by choosing energy efficient refrigerated display cabinets.

4.5 Monitoring periods

If a monitoring system is installed including energy meters, there is a possibility to present data for different periods like hour, day, week, month and year.

One characteristic of key performance indicators is that they are based on energy use over a whole year. With real-time measurements, there is a possibility to look at values for shorter intervals, in which case the comparisons do not apply. One possibility that can work in some cases is to multiply the value by an appropriate quantity to bring it up to the corresponding value for one year. It has to be considered when the energy usage relates to outdoor climate and other variable parameters.

In the diagram a comparison between three supermarkets is done in this way and related to sales area for food. The values can be compared with reference values for a whole year related to the same area, kept in mind that there is some variation in energy usage related to the outdoor temperature. In the other diagram the energy usage without conversion is shown.

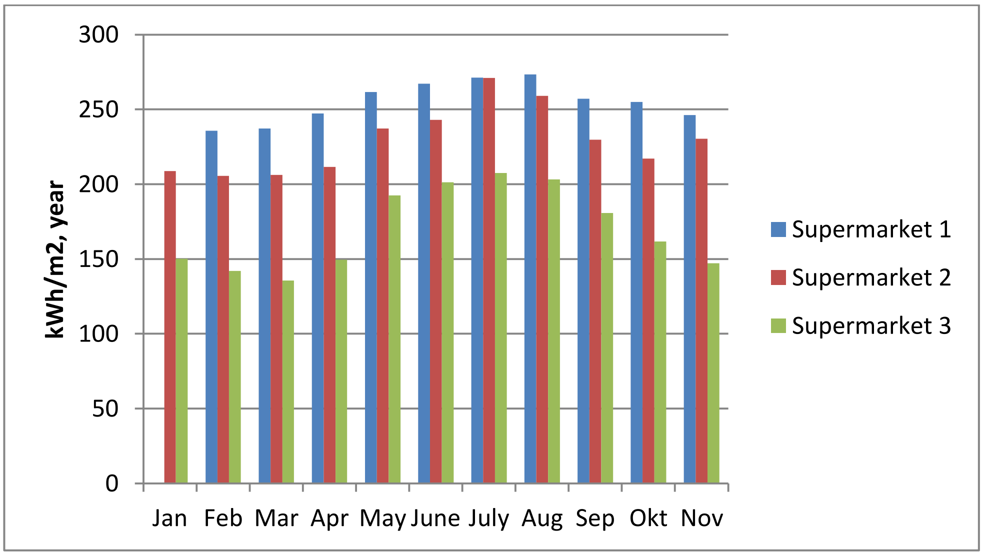


Figure 5: Energy used for refrigeration from January to November (2013), with monthly values converted to annual use and related to sales area for foodstuffs

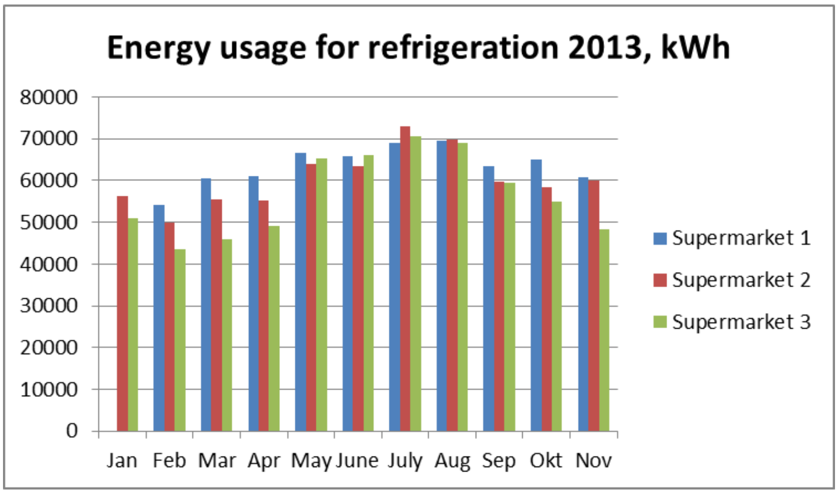


Figure 6: Energy used for refrigeration from January to November (2013), without conversions.

Energy usage per hour is useful to find unnecessary energy usage when the supermarket is closed. Examples are shown in the diagrams below

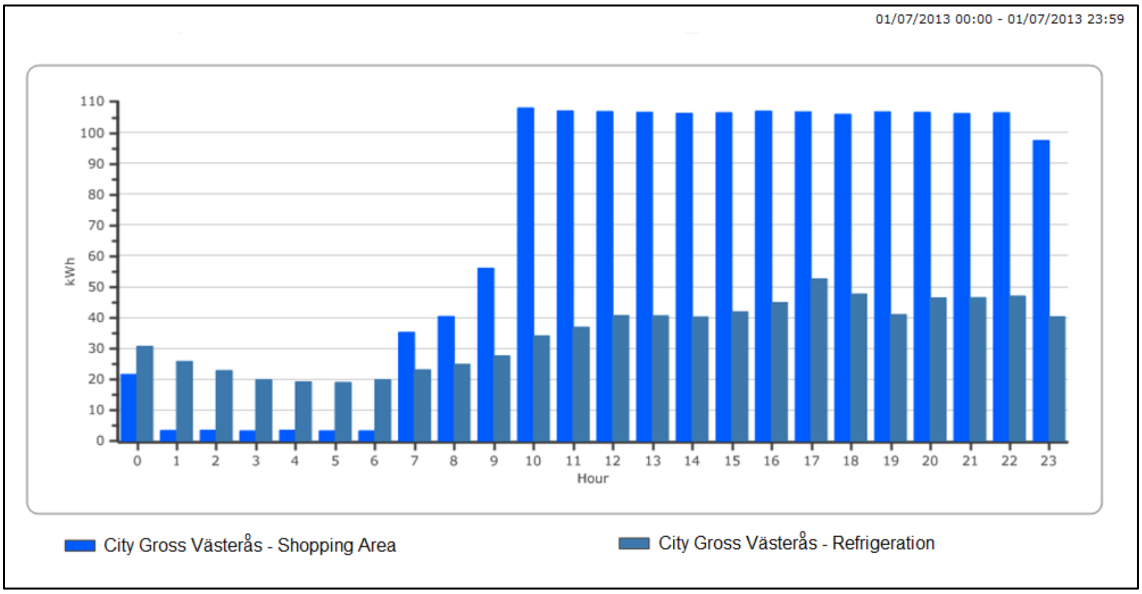


Figure 7: Energy usage in sales area and energy use for refrigeration. Energy use during night hours is strongly reduced in the shopping area, and slightly reduced for the refrigeration system (compared to daytime use). There are doors on the cabinets in the supermarket.

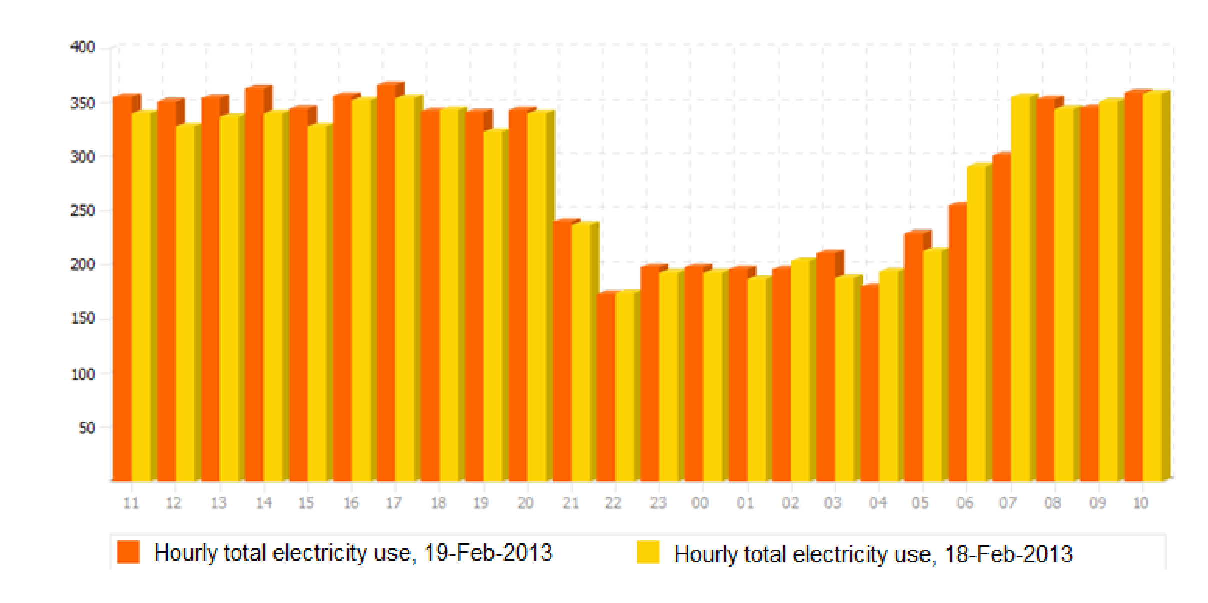


Figure 8: Example of diagram in monitoring system comparing total electricity usage per hour for the days 18th and 19th of February for a supermarket.

In Sweden a demonstration project was done in 2013 where three different monitoring systems where installed in one equal supermarket each. Energy meters were installed for different functions in the supermarkets. Before installation areas for energy measurement were discussed in a group including representatives for the supermarket chain. An introduction in the systems was held with some of the persons in the management.

Results:

- According to existing electrical cabling it was hard to get exactly the same division in function and areas for the energy meters. More than one energy meter was necessary to cover a measurement area in some cases.
- All systems had a lot of possibilities to data for different periods and in different combinations but many "clicks" where needed to get the information.
- Reliable documentation on electrical installations is needed to make the installation easy and trustable.
- Measurement systems are not a quick fix for energy efficiency, but are a useful and important tool in combination with knowledge and priority in the organisation for energy efficiency

Table 5: comparison of monitoring systems in 3 supermarkets

	Supermarket 1	Supermarket 2	Supermarket 3
Total Area	5535 m^2	9955 m^2	9698 m^2
Sales area other goods	835 m^2	2750 m^2	2325 m^2
Sales area food	3000 m^2	3170 m^2	Ca 4000 m^2
Opening hours	4745 h/y	4524 h/y	5110 h/y
Tested system	Megacon	IWMAC	Huurre Hot

Steps to compare total electricity use between current month and preceding month	8	8	8
Steps to compare product refrigeration/ total refrigeration with total month-by-Pulse-type month electricity use	6	9	9
Diagram type	Column/line/pie (selectable)	Column	Line
Refrigeration system	R404A, R507	R404A, brine CO2	CO2 in cascade
Cabinets	Open cabinets , Covers on Freezers	Open cabinets, covers on freezers	Doors on all
Heat recovery from refrigeration	Prepared for, but not in use	Yes, to ventilation	Yes, to ventilation

5 Methodology

5.5 Yearly energy consumption estimate

The intention is to make a formula with a flexible number of terms, where the accuracy increases with the number of terms used. Each term will be related to one Performance Indicator. In this way, the method can be used both in cases where only one or a few performance indicators are known, but also in cases where many performance indicators are known. Of course, when more performance indicators are known, the result of using the method will be more precise than in the case where only one or a few performance indicators are known.

Which performance indicators are known in a certain supermarket case may differ from supermarket to supermarket, and the intention is to create a method that is applicable in all these cases. Or in other words, to create a formula where each known performance indicator can be inserted, and which still remains valid when each unknown performance indicator is left out.

This requires that we create 'terms" in such a formula for every possible performance indicator. There are numerous performance indicators possible, and we will start out with the most commonly available and used performance indicators, which are:

- Size (m^2)
- Sales and/or number of employees and/or number of visitors
- Opening hours
- Outdoor temperature
- Indoor temperature
- Humidity (indoor)
- Type and amount of refrigerated display cabinets (m length or m^2 display or m^3 volume)
- use of night covers and/or day covers (glass doors), and other energy saving options
- Product temperatures
- Refrigeration system (DX or Indirect) and refrigerant

The most suitable form a formula that meets the requirements, is to start with an initial value and add corrective terms to this initial value for each performance indicator. The corrective term must then be "zero" in case the particular performance indicator is unavailable or unknown. In that case, we must assume that this particular (unknown) performance indicator has a value identical to the average value for the population of supermarkets as a whole.

For the initial value, we will make use of the most commonly known performance indicator available, which is the sales area (S.A. in m^2) of the supermarket. The relation between sales area and yearly energy consumption is generally referred to as the "Energy Intensity" of the supermarket, which is the amount of energy (in MJ or more commonly kWh) used per square meter per year.

Initial value of yearly energy consumption = sales area (m^2) x energy intensity (kWh/year.m^2):

E (initial value) = S.A. x E.I. (1)

With S.A. the sales area (in m^2) and E.I. the Energy Intensity (in MJ/m^2.year or kWh/m^2.year). The energy intensity (E.I.) is a given value (provided in this report), that relates to the average of all supermarkets.
Because the Energy Intensity (E.I.) is a value that relates to the average of all supermarkets, it also relates to the average of energy saving options used in practice. For example, when in 3,5 % of all supermarkets heat recovery is used as an energy saving option, the energy intensity would relate to a supermarket with 3,5 % heat recovery and 96,5 % without heat recovery. This is of course not a realistic situation for a supermarket, but it is a realistic estimate in case we do not know whether a specific supermarket has heat recovery or not; it assumes a 3,5 % probability that heat recovery is present.

In the same heat recovery example, when we know that heat recovery is present in the supermarket under consideration, we can refine the initial estimate of yearly energy consumption (based only on sales area as performance indicator) with a second term based on heat recovery as performance indicator. This term describes the difference from average for that Performance Indicator ($P.I._{difference}$), and the resulting effect ($P.I._{effect}$). The $P.I._{effect}$ term is the total effect of the performance indicator on the energy consumption (what is often called “the energy saving”).

$$E\,(\text{new value}) = E(\text{initial value}) * (1 + P.I._{difference} * P.I._{effect}) \qquad (2)$$

Example: Heat Recovery
Effect of heat recovery on total energy consumption = -0,07 (savings on total energy cons. 7 %)
Average presence of Heat Recovery = 0,05 (13 out of 238)
E(initial value) = 550 kWh/m^2.yr
Then:
P.I. = 1 (Heat recovery available): E(new value) = 550 * (1 + 0,95 * - 0,07) = 513 kWh/m^2.yr
P.I .= 0 (No Heat Recovery): E(new value) = 550 * (1 – 0,05 * - 0,07) = 552 kWh/m^2.yr

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 an ever 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:

$$E(\text{estimate } N) = E\,(\text{estimate } N\text{-}1) * (1 + P.I._{difference}(N) * P.I._{effect}(N)) \qquad (3)$$

E(estimate N.) = Estimated yearly energy consumption based on N functionalities (MJ / yr).
E(estimate N-1) = Estimated yearly energy consumption based on N-1 functionalities (MJ / yr).
P.I. = Performance Indicator
$P.I._{difference}(N)$ = Difference of the actual P.I. (N) value from the average for P.I.(N)
$P.I._{effect}(N)$ = Relative effect on overall supermarket energy consumption of P. I.(N)

For any Performance Indicator which is described by “presence” (value = 1) or “non-presence” (value = 0) of a certain feature, the average value of the P.I. is between 0 and 1 (the relative presence) and the value of $P.I._{difference}$ is between -1 and +1.

However there are also Performance Indicators that have a “real” value, such as the number of opening hours per week. In such cases the P.I. value, average P.I. value and $P.I._{difference}$ are real values and the relative effect $P.I._{effect}$ is given in terms of relative effect per unit (e.g. effect per extra hour).

As an example, we take a specific supermarket with 80 opening hours per week and we know that the average number of opening hours for all supermarkets equals 73,3 hours. Then the $P.I._{difference}$ in this cases equals + 6,7. If furthermore we know that there is a 0,47 % increase in overall supermarket energy consumption for each additional opening hour[2], The $P.I._{effect}$ equals + 0,0047 per hour and using formula (3) we find E(new estimate) = E(former estimate) * 1,0315.

In fact the $P.I._{effect}$ values are identical to energy saving percentages found for energy saving options in literature. We must just take account of the fact that in our case there is already a certain average presence of that energy saving option in the existing stock of supermarkets. Thus we cannot use the “savings percentage” (or as we call it, $P.I._{effect}$) as such, but we must use $P.I._{difference}$ * $P.I._{effect}$.

In some cases the terms “performance indicator” and “energy saving option” may seem interchangeable. However the term performance indicator is broader, as it does not only relate to energy saving options but can also relate to other parameters such as opening hours, average outdoor temperature, staff training and many more.

> So far we have considered the yearly energy consumption of a supermarket as a single value, expressed in MJ/year (Mega Joules per year). However, it is quite customary to split the total energy consumption in an electrical energy consumption (in kWh/year) and an energy consumption for heating, expressed in MJ/year or alternatively in m^3/year - when natural gas is used for heating. Be aware that in literature quite often only the electrical energy consumption is referred to as the Energy Intensity - which would then better be called Electrical Energy Intensity E.E.I. or $E.I._{electrical}$ (kWh/m^2.year).

We now have a basic methodology, by which we can determine E(initial value), an “Estimated yearly energy consumption” for a specific supermarket based on its sales area (m^2). And, when additional information is available we can make an even better “Estimated yearly energy consumption” E(new value) or E(estimate N) based on one or more performance indicators.

With this methodology we can also determine the energy efficiency of a specific supermarket, when we know the actual yearly energy consumption for that supermarket:

Index = Actual yearly energy consumption / Estimated yearly energy consumption (4)

A high value of this Index means the supermarket used more energy than average and thus needs attention. A low value of this Index indicates that the supermarket is energy efficient.

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2 As deducted in chapter 7.2

5.6 Datasets

In order to obtain values for the energy intensity (E.I. in kJ/m^2.year), the electrical Energy Intensity E.I.$_{electrical}$ (kWh/m^2.year) and the Energy Intensity for heating E.I.$_{heating}$ (m^3/m^2.year), as well as for the average of performance indicators and their effects, we need a data set on yearly energy consumption covering all supermarkets and including extended information on performance indicators. Such a data set is not available. What is available, to some extent, are National data sets for certain countries.

National data sets do not usually cover all supermarkets, but may still be a good representation of the average supermarkets in the specific country. Furthermore, the information contained in these national data sets may cover many performance indicators or just a one or a few performance indicators. Some performance indicators, such as the average annual outdoor temperature, may not be available in the (national) data sets themselves, but may be resolved through other sources or from literature.

Data set Sweden (Annex 31 + new additions).

The data set from Sweden covers a total of 146 + 36 (new) supermarkets. For all of these, the total area (m^2) – not the sales area - and total yearly energy consumption (kWh/year) are given (total energy = electrical + heating).

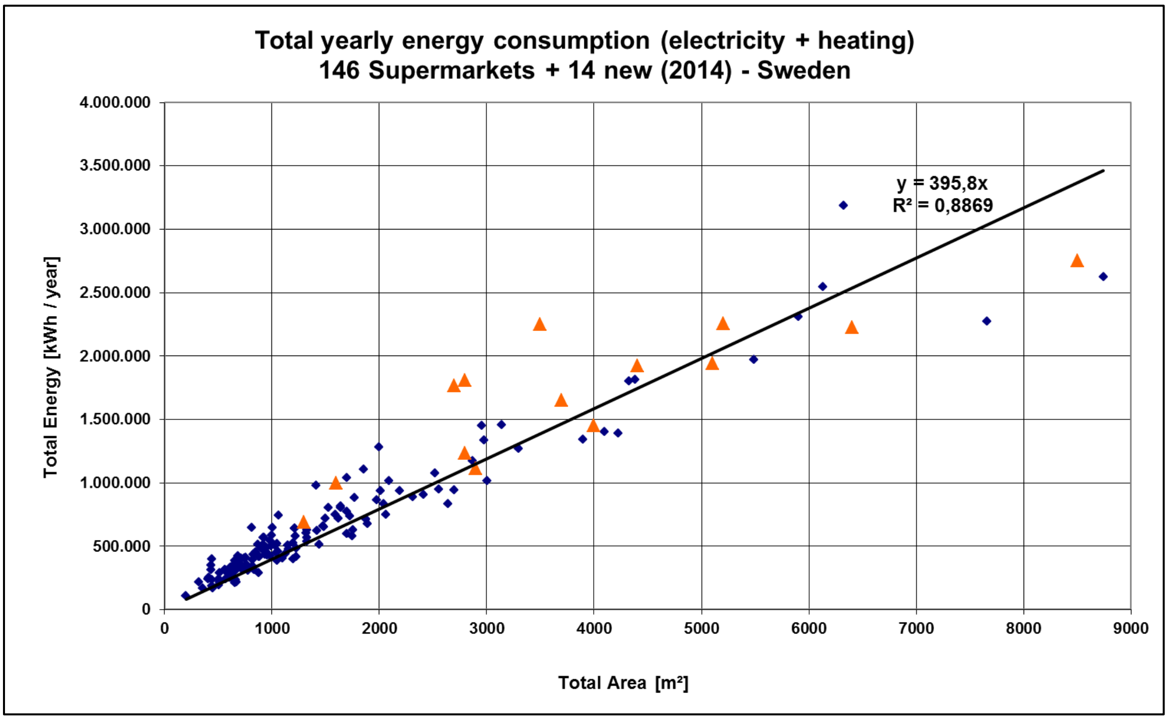


Figure 9: Representation of the Swedish data set

The Swedish data set furthermore contains information on opening hours and installed refrigerating capacity (kW). Of the “new” data, a smaller data set (14 markets) distinguishes electrical and heating consumptions.

Data set U.S.A. (Annex 31).

The U.S.A. data set covers a total of 27 supermarkets, spread out over various states of the U.S.A. For all of these, the total area (m^2) – not the sales area - and total yearly energy consumptions of electricity (in kWh/year) and for heating (in kWh/year) are given separately.

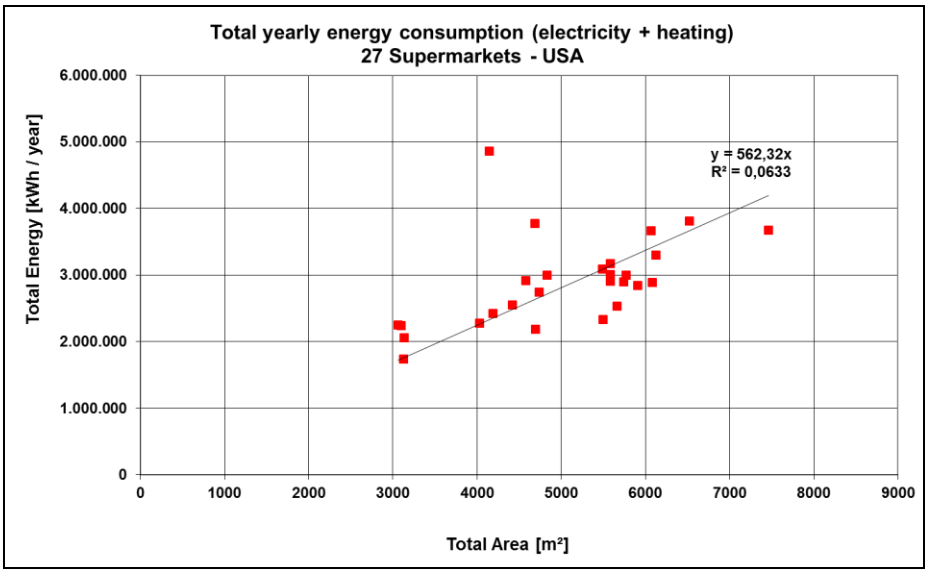


Figure 10: representation of the USA data set (Annex 31)

The U.S.A. data set shows “24/7” opening hours for all contained supermarkets. The data set furthermore contains information on installed refrigerating capacity (kW) for 21 of the 27 supermarkets contained in the data set.

Data set Canada (Annex 31).

The data set from Canada covers a total of 7 supermarkets. For all of these, the total area (m^2) – not the sales area - and total yearly energy consumptions (in kWh/year) for electricity and heating combined are given.

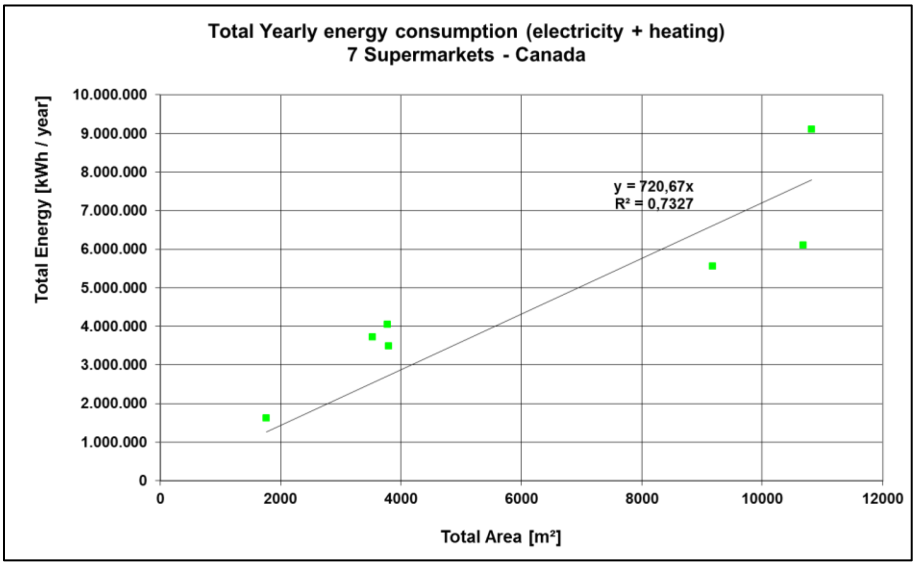


Figure 11: representation of the Canadian data set (Annex 31).

The Canadian data set does not show opening hours, but it does contain information on installed refrigerating capacity (kW). Opening hours nevertheless may be assumed to be "24/7".

Data set The Netherlands 2013 & 2014.

The data sets for the Netherlands (2013 & 2014) were especially collected for the work in Annex 44, and cover a total of 150 supermarkets (2013) and 162 supermarkets (2014) from one Dutch supermarket chain. The supermarkets from this chain are a good representation of the "average" Dutch supermarkets. For all supermarkets contained in the database, the total area (m^2) and the sales area (m^2) are given, as well as the total yearly electrical energy consumptions (in kWh/year) and the total yearly energy consumption for heating by means of natural gas (in m^3/year). 5 % of the 2013 data has been discarded as outliers leaving a data set of 143 supermarkets. For the 2014 data set the gas consumption was not yet available for many markets, leaving a full data set of 95 supermarkets. The sets for 2013 and 2014 cover the same supermarkets, but for two separate years.

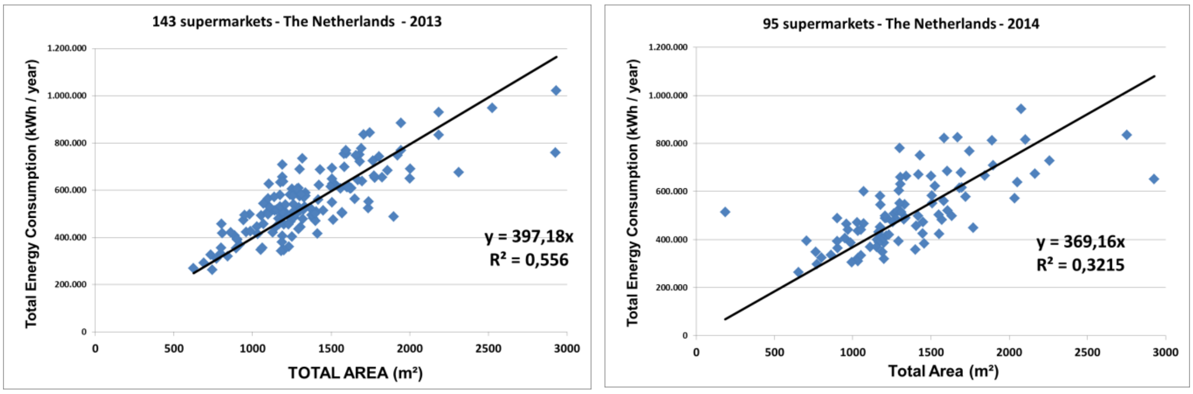


Figure 12: representation of the Dutch data sets for 2013 and 2014

The Dutch data sets contain (detailed) information on opening hours, but do ***not*** contain any information on the installed refrigerating capacity (nor the heating capacity).

The Dutch data sets contain a number of performance indicators related to the size of the supermarket: total area, sales area, the volume (m3) of refrigerated display cabinets, display cabinets for frozen food, chilled storage cells and frozen storage cells. Also, the capacity (in kW) of special energy intensive machinery (such as bakery ovens) is included. Furthermore, the presence or absence of 65 different energy saving options is contained in the database for each supermarket.

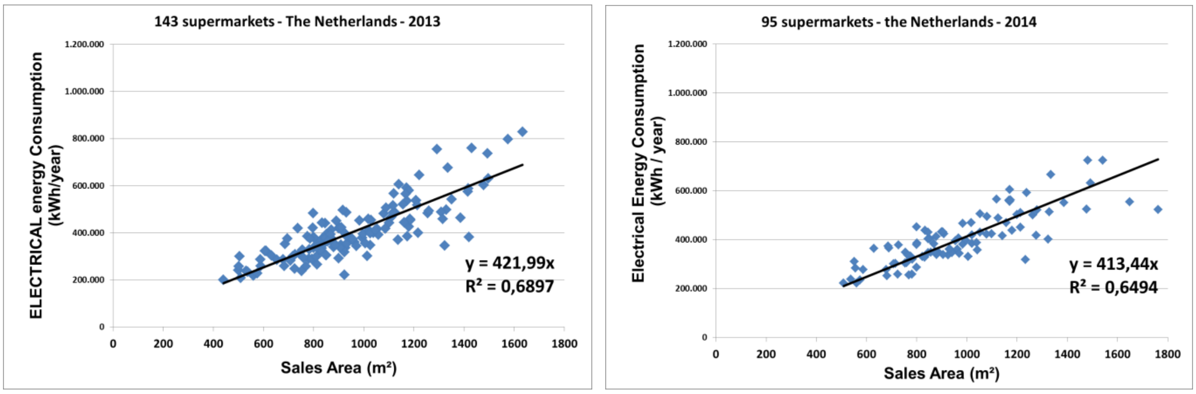


Figure 13: representation of the Dutch data sets: electrical energy consumption versus Sales Area (2013 and 2014).

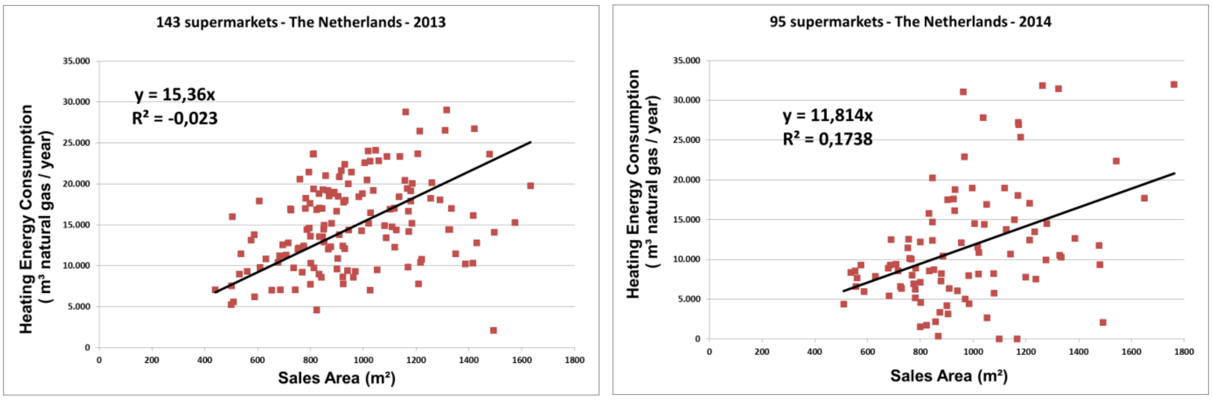


Figure 14: representation of the Dutch data sets: heating energy consumption versus Sales area (2013 and 2014).

From Figure 13 and Figure 14 it can be seen that the yearly electrical energy consumption shows a clear dependency on the sales area (R^2 of the regressions 0,69 and 0,65) whereas the dependence of the energy consumption for heating is much less correlated to the sales area (R^2 of the regressions 0,02 and 0,17). The influence of the energy consumption for heating makes the regression of total energy consumption on the total area less correlated (R^2 of these regression according to Figure 12 are 0,56 and 0,32).

Data set Denmark (2015)

The Annex 44 data set for Denmark (2015) was recorded by the Danish company AK-Centralen A/S.

The data recorded by AK-Centralen is deemed very reliable because the company knows which energy users are wired to the different electrical panels in the supermarkets and thus what exactly is logged on the power meters. This makes the data transparent and enables one to compare/benchmark across the different supermarkets.

The data set from Denmark covers a total of 49 supermarkets. After deletion of 5% outliers in the data set, 47 supermarkets remain. For all of these, the sales area (m^2) and the total area (m^2) are given, as well as the yearly energy consumption for the refrigeration system and the (overall) total yearly electrical energy consumption (kWh/year) – but not the energy consumption for heating. The supermarkets are from one supermarket chain, and have a relatively small size.

The electricity use is made available in two groups: for refrigeration, and for the rest of the supermarket, accounting for 46.8% and 53.2% of the total electricity use respectively, which is in line with earlier estimates.

The Danish data set is special compared to the other databases, as it contains detailed information on the totalled refrigeration load of refrigerated display cabinets (kW), and on installed cooling and freezing capacities (kW). It also contains information on the type of refrigeration system (R404A or CO_2, direct or indirect). Furthermore, the data contains information on the number of customers (receipts).

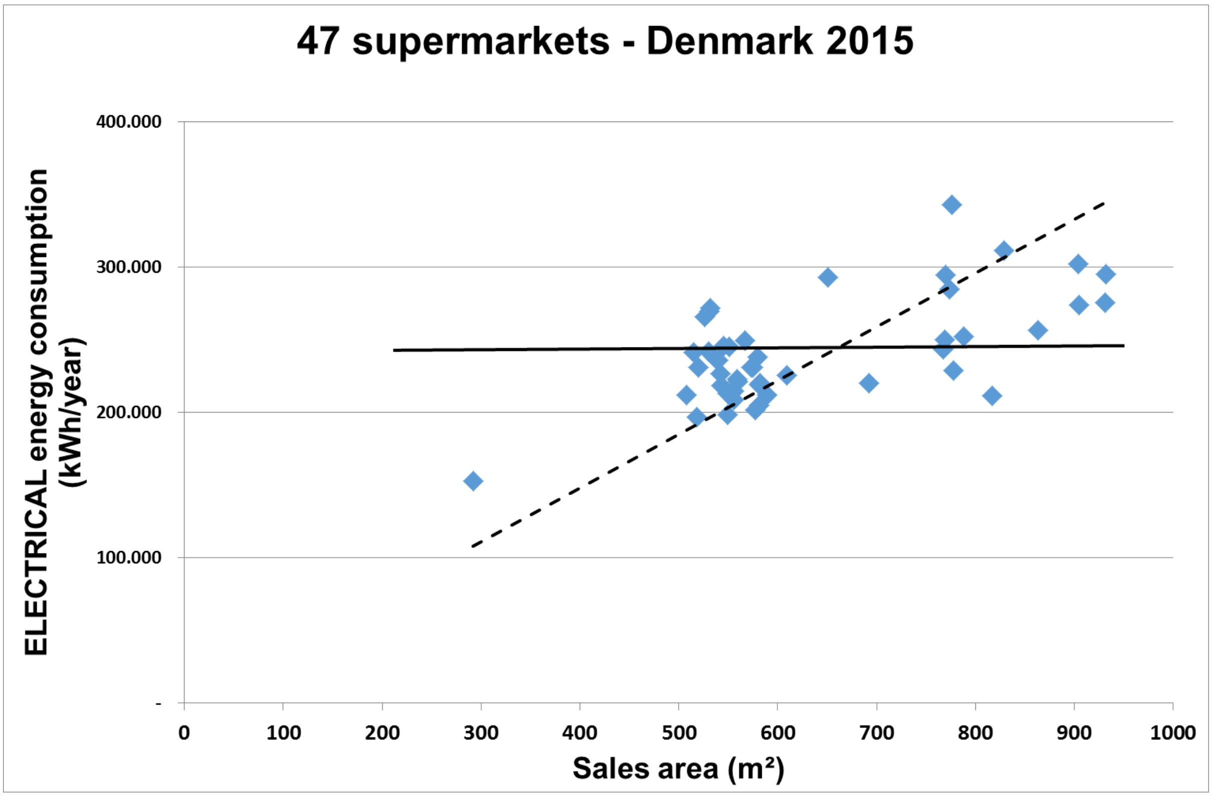


Figure 15: representation of the Danish data set, total yearly electrical energy consumption vs. sales area. The trend line is not shown (only dashed), since a constant value explains the data better than the trend line through the origin (negative R^2 value).

The average electrical energy intensity EEI for the Danish data set is 390 kWh/m^2.yearwith the trend line through origin used in Figure 15. The trend line however has a negative R^2 which means not enough of the variance is explained with a linear trend line through the origin.

Comparison of Swedish and Dutch data sets.

It is quite remarkable that the total energy intensity (total energy consumption / total area) is very similar for the Swedish (396 kWh/m^2) and Dutch (397 kWh/m^2 for 2013 and 369 kWh/m^2 for 2014) data sets. Nevertheless, this must be seen as a coincidence. There are differences concerning the refrigerating technology used; in Sweden there are many indirect refrigerating systems, whereas in The Netherlands all systems are with direct expansion. Generally speaking, direct expansion systems use less energy than indirect systems. There are differences in outdoor temperatures, even with a mild climate the average outdoor temperature in Sweden is lower than in The Netherlands which would lead to less energy consumption for supermarkets (as refrigeration is a more important component in the overall energy consumption than heating). There may also be differences in the use of energy saving options in both countries. The average opening hours on the other hand are almost identical: 73,6 (Sweden) vs. 73,7 (NL 2013) and 74,7 (NL 2014)hours per week.

There are some aspects that would indicate a higher energy consumption in Sweden than in The Netherlands, but also some aspects that would indicate a lower energy consumption, as well as aspects that are equal. Overall, the total energy intensity for supermarkets is the same in both countries, but the underlying performance indicators are in many cases different.

Comparison of European and North American data sets.

The total energy intensity (total energy consumption / total area) is considerably higher for the U.S.A. data set (562 kWh/m^2) and Canadian data set (721 kWh/m^2) than for the Swedish and Dutch data sets (around 400 kWh/m^2). In the previous work of Annex 31 an effort has been made to explain these differences, and the difference in opening hours has been identified as an important source (for the North American supermarkets opening hours are "24/7" or 168 hours per week, which is more than twice the opening hours in Sweden and The Netherlands, 74 hours per week).

But apart from the opening hours, there are many other technological differences in the use of energy saving options, climatization and refrigeration. Especially refrigeration technology (which takes up an important part of the total energy consumption) has long developed along different paths in North America and Europe. Only in recent years these paths are coming somewhat closer together.

Comparison of Dutch and Danish data sets

Both the data sets from the Netherlands and from Denmark contain data on electrical energy consumption and sales area (and total area). The values for the Electrical Energy Intensity EEI (total yearly electrical consumption / sales area) are not far apart, and do seem to show a trend in accordance with the year of evaluation: 422 kWh/m^2.year (NL, 2013), 413 kWh/m^2.year (NL, 2014) and 390 kWh/m^2.year (Denmark, 2015).

Even though many supermarkets in the Dutch data set are larger than those in the Danish data set, the ratio of total area / sales area is quite the same in both data sets (NL: 1,42 and Denmark: 1,40).

6 Supermarket size as primary performance indicator

6.5 Energy Intensity

Size is the most important performance indicator for supermarket energy consumption, we might call it the primary performance indicator. Without information on the size of a supermarket, there is no way to make a worthwhile estimate of its yearly energy consumption.

It would be futile to compare the energy consumption of supermarkets of totally different sizes, and therefore the energy consumption is often compared on the basis of energy consumption per unit size. This is referred to as the "Energy Intensity" and is the energy consumption (in kWh) divided by surface area (in m^2).

There are several ways to express the Energy Intensity. The energy consumption can be the total energy consumption (in kWh/year) or only the electrical energy consumption (in kWh/year) – the third possibility, only the energy consumption for heating, is not often used. On the other hand, the size may be defined as the overall supermarket size (in m^2) or as the sales area size (in m^2). In literature, often the latter – sales area size – is used. Therefore we have 4 common definitions of Energy intensity:

E.I. (#1)= yearly electrical energy consumption / sales area (kWh/year.m^2)

E.I. (#2) = yearly overall energy consumption / total area (kWh/year.m^2) or (MJ/year.m^2)

E.I. (#3) = yearly electrical energy consumption / total area (kWh/year.m^2)

E.I. (#4) = yearly overall energy consumption / sales area (kWh/year.m^2) or (MJ/year.m^2)

Needless to say, it is important to realize which one of the above definitions is used when interpreting Energy intensity data referred to in literature or given in databases.

In the Dutch databases, sufficient information is available to evaluate all 4 Energy Intensity definitions, and these are given in Table 6.

Table 6: Evaluation of Energy Intensity (E.I.) by four definitions – as provided in the text above- for the Dutch data set. The values are evaluated by means of regression analysis; R^2 values for the regression indicate the spread in data.

Energy Intensity definition	The Netherlands 2013		The Netherlands 2014	
	Value (kWh/m²)	R^2 value ()	Value (kWh/m²)	R^2 value ()
E.I. #1 (E electrical / sales area)	422	0,69	413	0,65
E.I. #2 (E total / total area)	397	0,56	367	0,41
E.I. #3 (E electrical / total area)	294	0,66	287	0,42
E.I. #4 (E total / sales area)	572	0,67	529	0,65

From Table 6 it is apparent that the best correlation (highest R^2 values) is presented by the first Energy Intensity definition (Electrical energy consumption / sales area). This definition is often found in literature. However, other considerations must also be taken into account. Taking these into account, our choice will fall upon the Total Energy Consumption / Sales Area as preferred energy intensity definition.

6.6 Electrical energy consumption versus total energy consumption

Although it would appear from Table 6 that the best Energy Intensity definition would be the one relating electrical energy consumption to sales area – and this is a definition often encountered in literature – it is not an "up to date" choice.

In the past, the supermarket electrical energy system and the supermarket heating system were often not directly related. The interactions between these energy systems were mainly unintended, due to the mixing of spilled cold air from refrigerated display cabinets with the air as provided by the indoor climate system.

These interactions are now more and more diminished due to the introduction of glass doors and glass lids on refrigerated display cabinets. But at the same time, there has been a significant development towards heat recovery, the use of waste heat from the refrigeration system for climatization purposes. Heat recovery can increase the electrical energy consumption for refrigeration, but will reduce overall energy consumption. This means that in an "up to date" treatment of supermarket energy use, it is no longer correct to treat the electrical energy system and the heating system separately – and we must focus on overall energy consumption. This means we must select a definition of Energy intensity based on overall energy consumption.

6.7 Sales area versus total supermarket area

1. Sales area

The sales area, expressed in m^2, is related to where the customers can get in touch with the range of products within the supermarket.

2. Storage area

The storage area expressed in m^2 is where (refrigerated or unconditioned) storage of products take place, and includes further areas that are accessible only or primarily to supermarket employees (such as offices).

3. Total area

Total area of the supermarket: the sum of sales area and storage area.

The energy intensity can be expressed in terms of sales area or total supermarket area. In the data sets from The Netherlands there is a good correlation (R^2 = 0,84 … 0,86) between the sales area and the total supermarket area. Nevertheless, the spread in sales area / total area creates a lower correlation for an Energy intensity based on total area (R^2 = 0,56 for 2013 data and 0,41 for 2014 data) than for an energy Intensity based on sales area (R^2 = 0,67 for 2013 data and 0,65 for 2014 data). Therefore, the sales area is the optimum choice as size parameter. The sales area is often used in literature as size parameter.

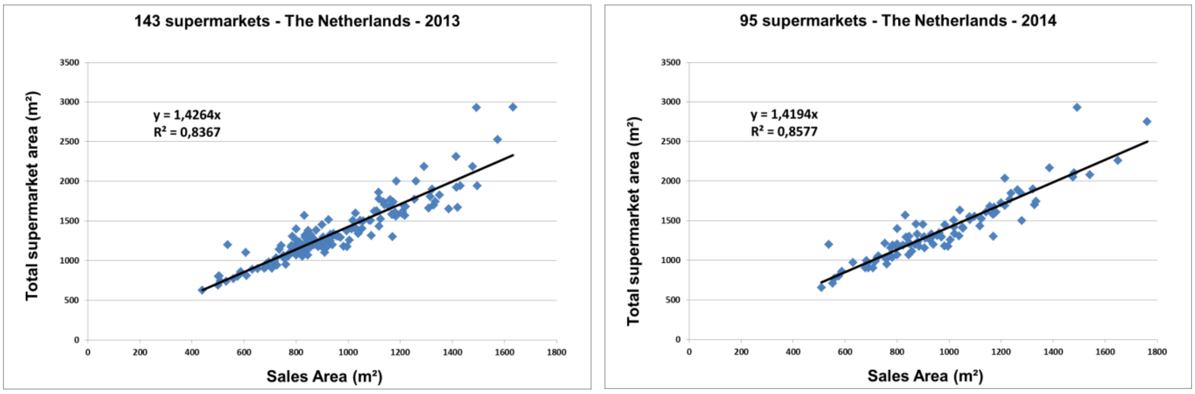


Figure 16: relation between sales area and total supermarket area in the Dutch data sets (2013 and 2014).

6.8 Quantity of refrigerating equipment

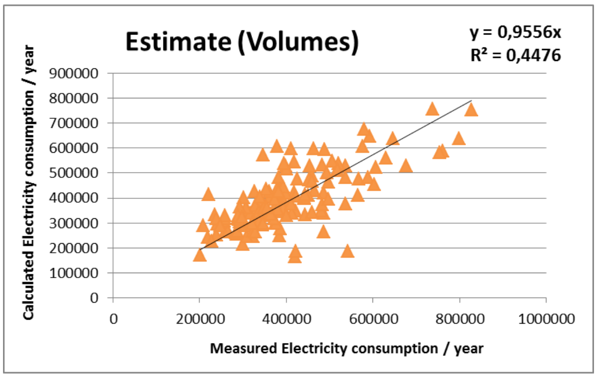
It is sometimes argued that instead of the area of the supermarket (sales area or total area), the amount of refrigeration equipment would be a better indicator for the yearly (electrical) energy consumption – taking into account that refrigeration plays a very important role in the electrical energy consumption.

In the Dutch data set, information on the amount of refrigerated equipment is available in terms of the volumes (in m^3) of refrigerated display cabinets (V_{RDC-MT}), refrigerated display cabinets for frozen products (V_{RDC-LT}), chilled storage cells ($V_{CELL-MT}$) and frozen storage cells ($V_{CELL-LT}$). There is a shortcoming in this data in the sense that the volumes of refrigerated display cabinets are not distinguished between “closed volumes” (such as in cabinets with glass doors or covers) and “open volumes”. In terms of (refrigeration) energy consumption, there is an important difference between closed and open cabinets (van der Sluis, 2007, Lindberg et al., 2008).

By means of regression analysis with multiple variables on the data set for The Netherlands 2013, the coefficients were found for calculating the yearly electrical energy consumption as a function of the volumes of RDC’s and storage cells:

$$\text{Electrical Energy / year} = 4300 * V_{RDC-MT} + 14039 * V_{RDC-LT} + 804 * V_{CELL-MT} + 594 * V_{CELL-LT}$$

A similar formula can be found for the total yearly energy consumption. It is quite intensive to make an inventory of the volumes of all RD’s and storage cells in a supermarket. But if the resulting yearly energy consumption estimate is better than other estimates, it is worth the trouble. However, this is not the case. It turns out that an estimate of the yearly electrical energy consumption based on sales area only, provides a better estimate than one which is based on volumes of RDC’s and storage cells when there is no distinction between closed and open cabinet volumes. This is illustrated in the figures below.



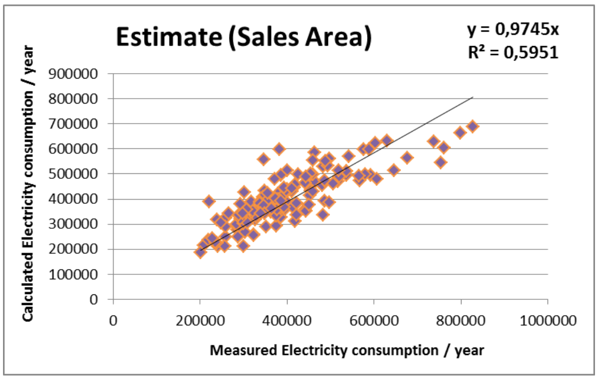


Figure 17: Estimate of yearly electrical energy consumption based on volumes of RDC's and storage cells (left) and based on sales Area (right)

Where the yearly electrical energy consumption can be better calculated based on sales area than on volumes of RDC's (without closed/open distinction) and storage cells, this is even more true for the calculation of the total yearly energy consumption.

Based upon this analysis, the sales area is a better "size parameter" than the volume of refrigerated display cabinets and refrigerated storage cells, when there is no distinction between closed and open refrigerated display cabinet volumes.

The currently available data sets do not make it possible to check whether a size parameter based on volumes and including the closed/open distinction, would make a better size parameter. However, there is a similar methodology which also uses the inventory of refrigerated display cabinets (and storage cells) as a basis. This methodology uses the length of the individual cabinets and the cabinet type. For each cabinet type a specified refrigeration load per meter (Watt/m) is used[3], and in this way a total refrigeration load CL is calculated and can be used as size parameter. S. Acha (2016) shows that CL is a better indicator than sales area for *refrigeration* (electrical) energy consumption for a sample of 25 UK supermarkets with CO2 refrigeration systems (Figure 18).

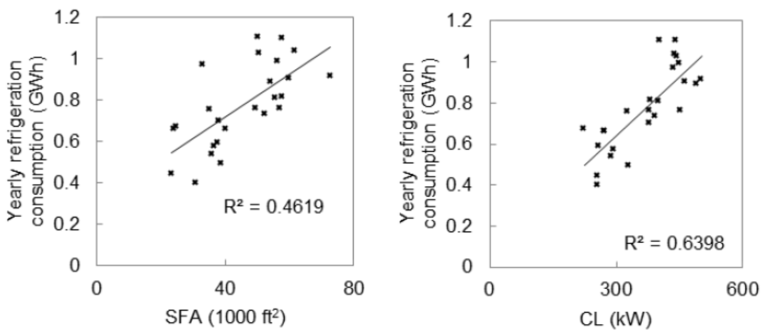


Figure 18: Correlations of refrigeration energy consumption with Sales Area (SFA) and refrigeration load (CL) taken with permission from the article by S. Acha (2016). Sample of 25 UK supermarkets (CO2 refrigeration systems only), cabinet loads evaluated at test conditions (25°C, 60% RH).

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[3] Such tables are often used by refrigeration installers to determine the total capacity for sizing the refrigeration system. An example of such a table is given in paragraph **Fel! Hittar inte referenskälla.**

An identical approach to the total refrigeration load CL (being the calculated refrigeration demand) is available in the Annex 44 Danish data set (2015). In this data set the demanded refrigeration capacity is given. This capacity refers to the cooling that the remote refrigerated display cabinets in the shop need to keep the temperature in the cabinet at the right level both for low and medium temperature expressed in kW. The different refrigeration systems are planned and installed by the Danish refrigeration company Super Køl A/S. The approach used by Super Køl to dimension the size of the refrigeration plant is to use average refrigeration capacity per meter length values for different types of cabinets. The different cabinet types used to sum up the demanded cooling capacity can be seen in Figure 19.

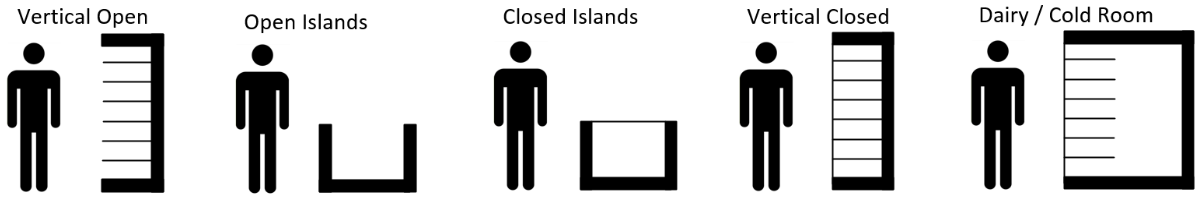


Figure 19. Display cabinet types

The key values regarding capacity demand of the different cabinets used by Super Køl and AK-Centralen originates from EN441 (now replaced by EN23953), and are mean values for the various types representing cabinets manufactured and documented by the display cabinet manufacturer. These key values can be seen in Table 7. The colour of the row defines the temperature in the cabinet. Dark blue is lowest temperature.

Table 7: Key values provided by a specific display cabinet manufacturer regarding heat load (capacity) for different types of cabinets inside a supermarket (not equally valid for other manufacturer's brands).

Type of display cabinet	Temperature	Evaporation temperature	Capacity
Vertical Open	0°C – 2°C	-10°C	1470 w/meter [length]
Vertical Open	2°C – 4°C	-10°C	1310 w/meter [length]
Vertical Closed	0°C – 2°C	-10°C	725 w/meter [length]
Vertical Closed	2°C – 4°C	-10°C	650 w/meter [length]
Closed Islands	-18°C	-31°C	420 w/meter [length]
Closed Islands	2°C – 4°C	-10°C	315 w/meter [length]
Open Islands	2°C – 4°C	-10°C	441 w/meter [length]
Closed End Islands	-18°C	-31°C	532 w/unit
Closed End Islands	2°C - 4°C	-10°C	400 w/unit
Diary/ Cold room	2°C – 4°C	-10°C	160 w/m^2
Glass doors for room	2°C – 4°C	-10°C	280 w/glass door
Frozen Storage	-18°C	-31°C	180 w/ m^2

In the Danish data set (2015), the yearly refrigeration electricity consumption is available, together with information about which refrigeration system type is used in a specific supermarket. Here it is interesting to note the correlation between refrigeration system type and refrigeration electricity consumption (Figure 20).

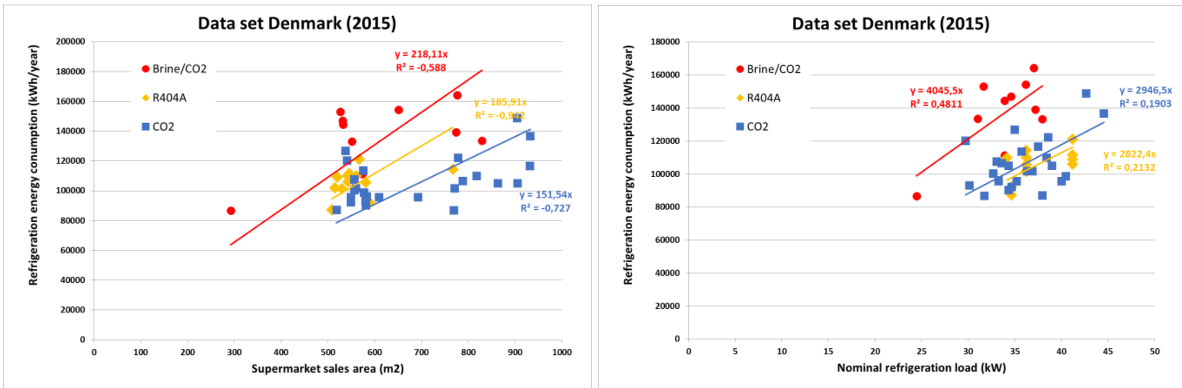


Figure 20: Correlations of refrigeration energy consumption with Sales Area and nominal refrigeration load for the Annex 44 Danish data set (2015) – with separate correlations for different refrigerating system types.

6.9 Other overall performance indicators

In the preceding paragraph, the summation of all refrigerated display cabinet loads (CL) was used; which is used by refrigeration installers to size the refrigeration system capacity. This latter value, the refrigeration capacity, is available in the Annex 44 data sets from Sweden, USA, Canada and Denmark. The installed refrigerating capacity (in kW) of the supermarket refrigerating system could be used as an overall "size" indicator (assuming the other supermarket energy subsystems correlate in size with the refrigeration system). The cooling capacity correlates well with the total yearly energy consumption, as shown in Figure 21, Figure 22**Fel! Hittar inte referenskälla.** and Table 8.

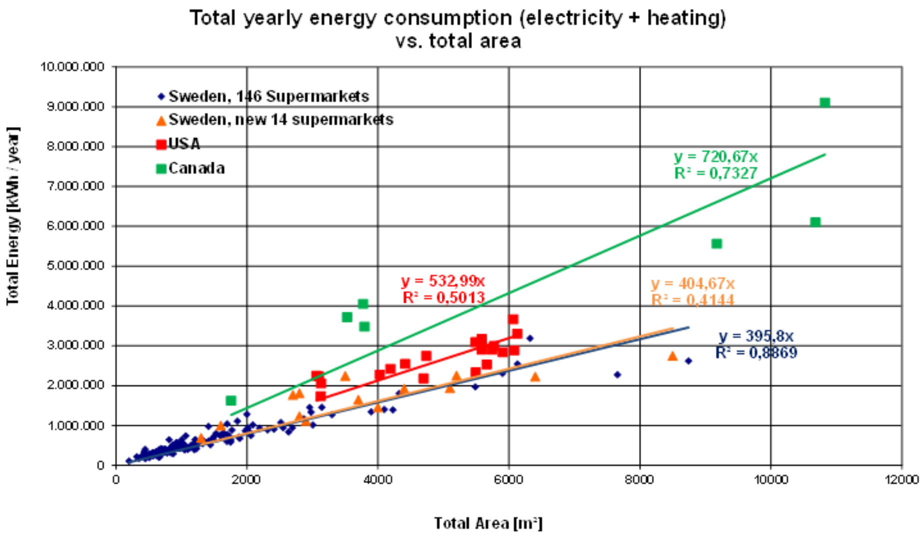


Figure 21: Regressions of total yearly energy consumption with supermarket area for the data set of Swedish, USA and Canadian supermarkets (Annex 31).

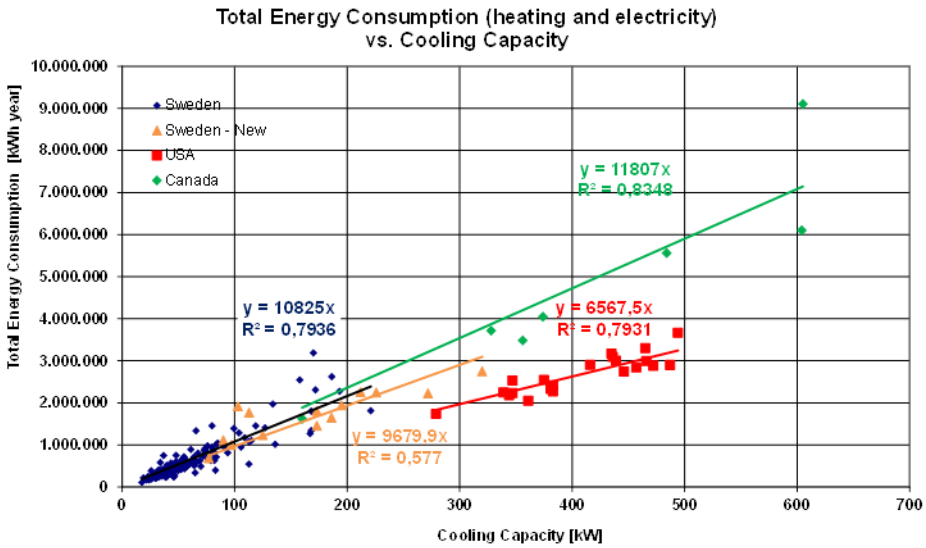


Figure 22: Regressions of total yearly energy consumption with installed cooling capacity for the data set of Swedish, USA and Canadian supermarkets (Annex 31).

Table 8: R^2 values for the correlations of total energy consumption with total supermarket area and with total refrigeration capacity for the Annex 31 data sets (Sweden, USA and Canada).

Data Set	R^2 value total area correlation	R^2 value capacity correlation
Sweden 146 supermarkets	0,89	0,79
Sweden 14 new supermarkets	0,41	0,58
USA	0,50	0,79
Canada	0,73	0,83

It can be argued that the simple addition of cooling capacity and freezing capacity is not the best way to proceed, and that instead the capacities should be weighted according to their Coefficient of Performance (COP). This could then be done according to:

Total refrigeration capacity (weighted) = capacity MT/COP(MT) + capacity LT/COP(LT)

Where MT is medium temperature (cooling) and LT is low temperature (freezing). COP(MT)/COP(LT) would then have a value somewhere between 1,5 and 2,0 depending on condensing conditions. Indeed the R^2 values of the regressions can be slightly improved by this method (0,7% - 2,5%) but at different values for COP(MT)/COP(LT) for each of the data sets. Therefore this refinement is usually not considered.

What is remarkable in Figure 22 is the agreement between Swedish and Canadian data when refrigeration capacity is taken as size parameter; which is far better than the (dis)agreement based on total area (Figure 21) – which gives rise to the suspicion that area definitions differ between the data sets. The USA data set shows that larger cooling capacities are installed in the US for similar total yearly energy consumption values.

The sales area is a better “size parameter” than the installed refrigeration capacity only for the original data set of 146 Swedish supermarkets, which happen to be of predominantly small size (average total area 1500 m²). For the other Annex 31 data sets – with predominantly larger supermarkets or even hypermarkets - the refrigeration capacity is a better “size parameter” in estimating the total energy consumption.

The Annex 44 data set for Denmark (2015) does not contain the energy consumption for heating, but only the total electrical energy consumption. The trend line of total electrical energy consumption related to sales area and to installed refrigerating capacity both have a correlation ($R^2 > 0,1$), but they also both have a high intercept relative to the average total electricity use in the data set (Figure 23). A multi-variable regression analysis performed in **Fel! Hittar inte referenskälla.** will shed more light on the interplay of these and other parameters, and the resulting intercept value.

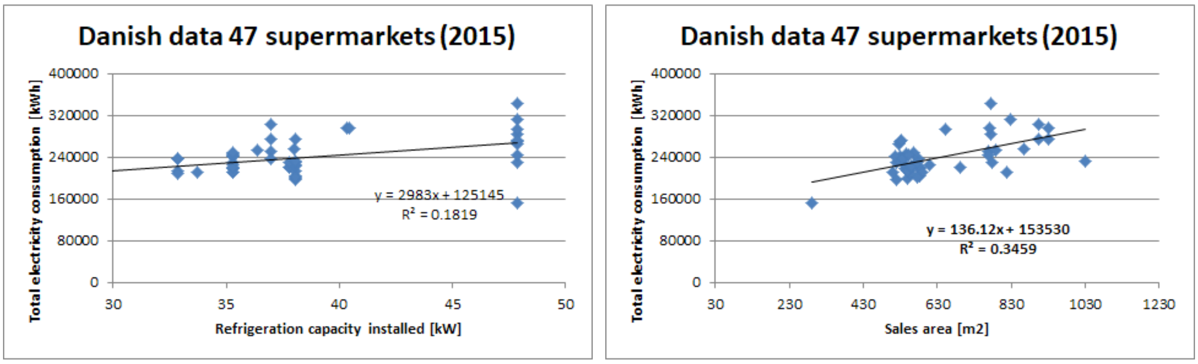


Figure 23: trend lines of total electrical energy consumption based on installed capacity (left) and sales area (right) for the Annex 44 Danish data set (trend lines not through origin but with intercept).

The System efficiency Index (SEI) has been suggested as one performance indicator for refrigeration systems by SP (Sweden), IoR (UK) and VDMA (Germany). It essentially compares the real performance (COP) of the refrigeration system to the performance of an ideal refrigeration system at the same conditions. This indicator considers only the refrigeration subsystem. Measurement data for the actual cooling demand and refrigeration energy consumption and the associated temperature are needed. Generally this is not available but measurement equipment can be installed for short or long time measurements.. However, when the SEI can be established for a supermarket refrigeration system, it can be used as performance indicator as discussed in chapter 7.

7 Conventional Performance Indicators

7.1 Supermarket size

In the preceding chapters we have been using the supermarket total area as an estimator for the total yearly energy consumption. For smaller supermarkets (200 ~ 3000 m² total area) this is a relatively good estimator (the sales area is better), whereas for larger supermarkets the best estimator is the total refrigerating capacity. We have, so far, used a single value (in kWh/m².year) to represent supermarkets of all sizes within a certain data set – these values are presented in Table 9.

Table 9: Single values for total energy consumption / total supermarket area in the different data sets.

Dataset	Data points #	kWh/m².year (trend-line)	Average total area m²
Sweden, Annex 31	146	396	1.500
Sweden, new (14 values)	14	405	3.900
Sweden, new (36 values)	36	293	6.000
USA	27	533	5.000
Canada	7	721	6.200
The Netherlands 2013	145	397	1.400
The Netherlands 2014	95	367	1.400

There are several reasons why a single value for energy intensity (kWh/m².year) does not suffice for a large range of total supermarket areas. The general size effect where energy intensity becomes lower for larger areas (e.g. energy for heating per m² decreases), and also the effect that at larger areas the predominance of "food" becomes less as the ratio of general merchandise increases.

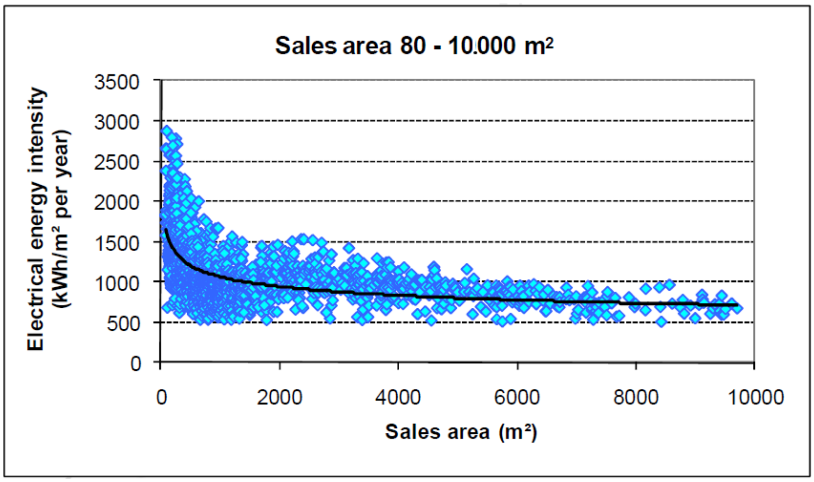


Figure 24: illustration of the decrease in energy intensity as the supermarket size increases (with permission, from Tassou, 2010).

This effect is shown in Figure 24 for an inventory of UK stores (from Tassou, 2010), where the range of area ranges from small convenience stores to hypermarkets. It is therefore worthwhile to investigate whether a similar trend can be found in the Annex 44 (and annex 31) databases. The results of this investigation are shown in Figure 25, Figure 26 and summarized in Table 10.

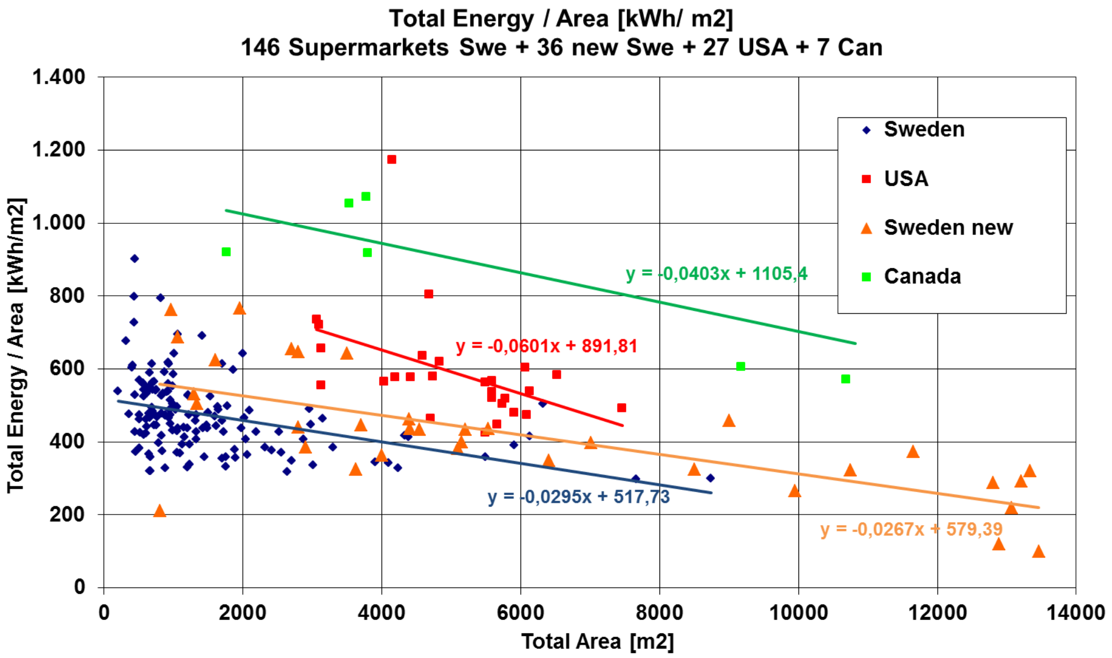


Figure 25: variation of energy intensity (total energy consumption / total area) for Annex 31 data sets.

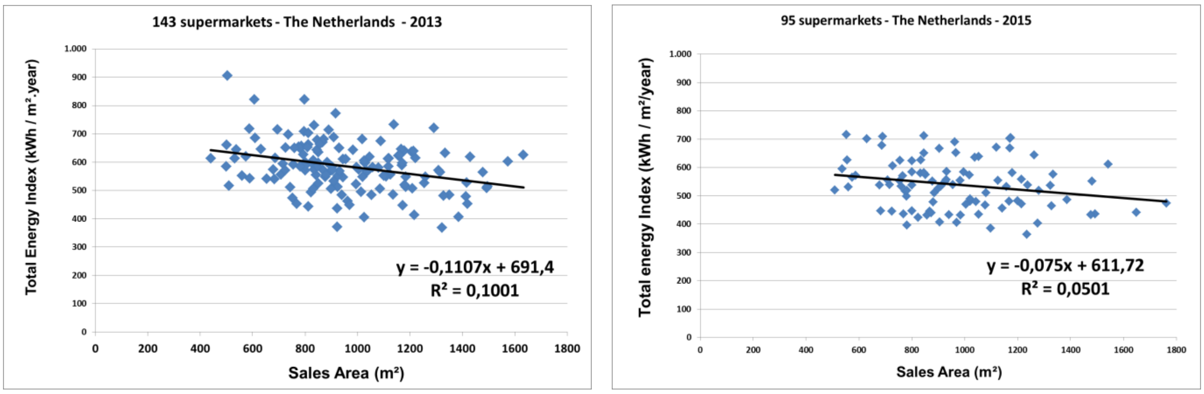


Figure 26: variation of energy intensity (total energy consumption / sales area) for Annex 44 data The Netherlands.

Table 10: trends for the change in energy intensity as a function of change in the supermarket area for the data sets used in Annex 44.

Data set	Energy Intensity trend (% change / 100 m² area increase) (Referenced to the average area in the data set)	
	Total area base	Sales area base
Sweden	-0,6 % / 100 m² (@ 2000 m²)	
Sweden, new	-0,7 % / 100 m² (@ 7000 m²)	
USA	-1,0 % / 100 m² (@ 5000 m²)	
Canada	-0,5 % / 100 m² (@ 6000 m²)	
The Netherlands 2013	-1,6 % / 100 m² (@ 1400 m²)	-1,9 % / 100 m² (@ 1000 m²)
The Netherlands 2014	-1,8 % / 100 m² (@ 1400 m²)	-1,4 % / 100 m² (@ 1000 m²)

The correlations do not have high R^2 values, they are weak but nevertheless present. Considering the average results for the different databases we can say that around the mean total area value, there is a change in energy intensity of -1 % for 100 m² of additional total area. On a sales area base, around the mean sales area value the energy intensity change would be -2 % for 100 m² of additional sales area.

Keeping in mind the methodology introduced in chapter 5.5 we can now use the total area or the sales area as a performance indicator, and we have:

$$E(\text{estimate } N) = E(\text{estimate } N\text{-}1) * (1 + P.I._{difference}(N) * P.I._{effect}(N)) \quad (3)$$

E(estimate N.)	=	Estimated yearly energy consumption based on N functionalities (MJ / yr).
E(estimate N-1)	=	Estimated yearly energy consumption based on N-1 functionalities (MJ / yr).
P.I.	=	Performance Indicator
$P.I._{difference}(N)$	=	Difference of the actual P.I. (N) value from the average for P.I.(N)
$P.I._{effect}(N)$	=	Relative effect on overall supermarket energy consumption of P. I.(N)

When we have the area A_{total} (m²) or A_{sales} (m²) for a specific supermarket, and an estimated energy intensity based on a data set of supermarkets with a known mean area value $A_{total,mean}$ (m²) or $A_{sales,mean}$ (m²) we can then write:

Total area base: $E(\text{estimate } N) = E(\text{estimate } N\text{-}1) * (1 + (A_{total} – A_{total,mean})/100 * 0{,}01)$

Or

Sales area base: $E(\text{estimate } N) = E(\text{estimate } N\text{-}1) * (1 + (A_{sales} – A_{sales,mean})/100 * 0{,}02)$

For the data sets used in Annex 44 and Annex 31, the value $A_{total,mean}$ (m²) or $A_{sales,mean}$ (m²) values are given in Table 10.

The performance indicator as given in the formulas above can (of course) be used to calculate a new estimate E(estimate N.) when the original estimate E(estimate N-1) is based on average energy intensity (W/m².year). But it can just as well be used when the original estimate is based on a correlation with cooling capacity or refrigerated display cabinet volumes, as discussed in chapters 6.8 and 6.9.

7.2 Opening hours

The opening hours of a supermarket have an influence on all of the energy systems employed in the supermarket. Outside of the opening hours, the lighting level is usually diminished or completely turned off; the settings for the indoor temperature may be released and the load on the refrigeration system is usually lower (both due to lower indoor temperatures and less disturbances of the display cabinets).

Statistical analysis

An attempt was made to evaluate the relationship between opening hours and Energy Intensity EI (total yearly energy consumption per m²) from the different data sets available. This was done by first finding the average number of opening hours and average Energy intensity, and then plotting for each supermarket the difference in opening hours from average (ΔOH) and the corresponding difference in Energy Intensity from average (ΔEI). Ideally, this would provide a straight line with a positive slope that corresponds to the increase of energy intensity per additional opening hour.

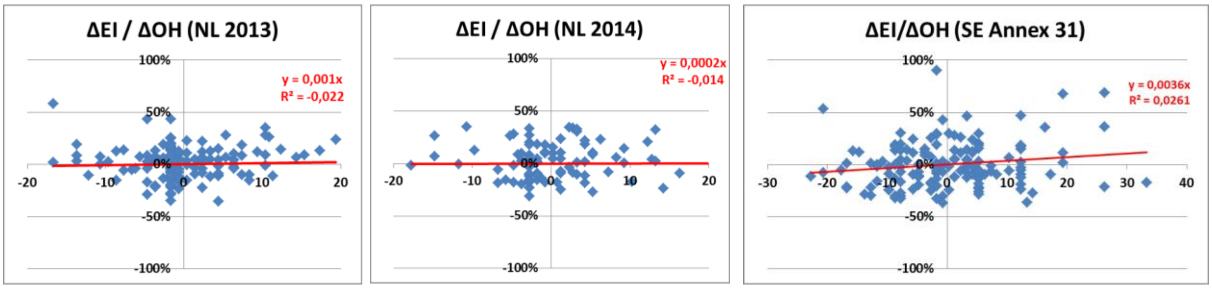


Figure 27: relation between energy intensity changes (in %) and opening hour changes (in hours), with trend-lines (in red) for three different databases (The Netherlands 2013, The Netherlands 2014 and Sweden Annex 31).

The result of this attempt is shown in Figure 27. The (trend-) line slopes are respectively 0,10 %/hr, 0,02 %/hr and 0,36 %/hr – but in all cases the correlation is extremely weak and therefore no conclusions can be drawn from these data regarding the effect of opening hours on energy consumption.

Theoretical analysis

In IEA HPT Annex 33 different performance indicators were presented but only some of them were fully evaluated due to the limited amount of data collected (Lundqvist, 2012). One performance indicator evaluated was annual total energy demand per opening hours versus total area. This was done after the initial analysis of yearly energy consumption versus area showed supermarkets from the USA had a distinctly higher yearly energy consumption than those in Sweden (Figure 28, first graph). However, the supermarkets from USA were opened 24 hours a day while the supermarkets in Sweden have in average about 14 opening hours a day. Therefore, when using the total yearly energy consumption divided by the total opening hours per year as a new performance indicator, a plot of supermarkets against this new performance indicator (Figure 28, second graph) showed USA supermarkets performing better than Swedish supermarkets.

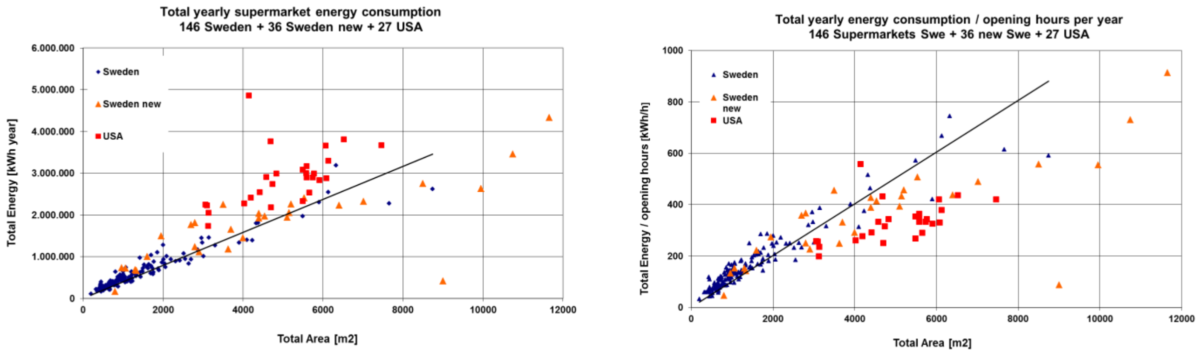


Figure 28 Total yearly energy consumption versus area (left graph) and total yearly energy consumption / (yearly) opening hour versus total area (right graph) for Sweden and USA (Annex 31, 2011).

Figure 28 gives an indication that a correction for opening hours must be made to energy consumption data, but not as straightforward as assigning the total yearly energy consumption to open hours only. Supermarkets do use energy (but less) outside the opening hours. Different studies have shown that the total energy usage decreases between open hours and closed hours in a single supermarket. This is mainly caused by lighting and heating, but also by the refrigeration system (which keeps functioning outside opening hours, but uses less energy due to lower indoor and outdoor temperatures) Some comparisons of total refrigeration system for chilled and frozen food show a decrease in refrigeration energy usage for closed supermarkets with as much as 55 %.

For this reason, a correction factor for opening hours was evaluated. The correction factor takes into account the reduction of energy utilization from lighting, equipment and the refrigeration system when the supermarket is closed. The factor was developed assuming the energy utilization for the refrigeration system is 50% of the total energy usage of the supermarket and the other 50 % is from the other subsystems.

The Correction factor (CF) was calculated as a function of the amount of hours the supermarket is opened during a week (OPW). according with the following equation

$$CF = \left(65 * \frac{OPW}{168} + 35\right) / 100$$

And a new performance indicator PI was evaluated, which is equal to the “total energy consumption per opening hour” shown in Figure 28 (right graph), multiplied with CF.

$$PI = \frac{Total\ Annual\ Energy\ Consumption}{(yearly) Opening\ Hours} * CF$$

Comparison of supermarkets from Sweden and USA on the basis of this (corrected) Performance Indicator shows a perfect agreement between Swedish and USA supermarkets (the trend lines in Figure 29 differ by less than 1%)..

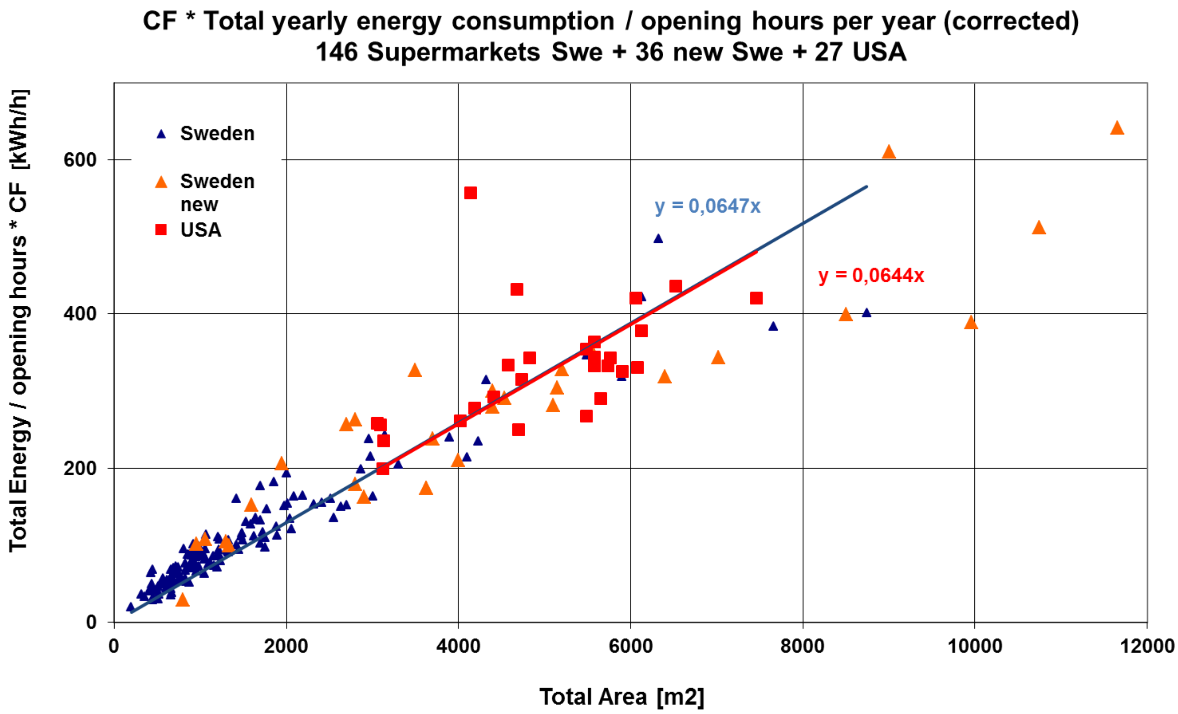


Figure 29: Total energy demand / opening hours with correction factor versus total area for supermarkets in Sweden and USA. Trend lines for 146 Supermarkets SWE (blue line) and 27 USA supermarkets (red line) with coefficients shown.

The data sets for supermarkets from The Netherlands, both for 2013 and 2014, was evaluated with the same correction factor and results are presented in Figure 30. The trend line of the data set for the Netherlands 2013 agrees very well in this representation with the trend lines for Swedish and USA data (within 2%). The coefficient of the trend line for the Netherlands 2014 data set is slightly lower (6%).

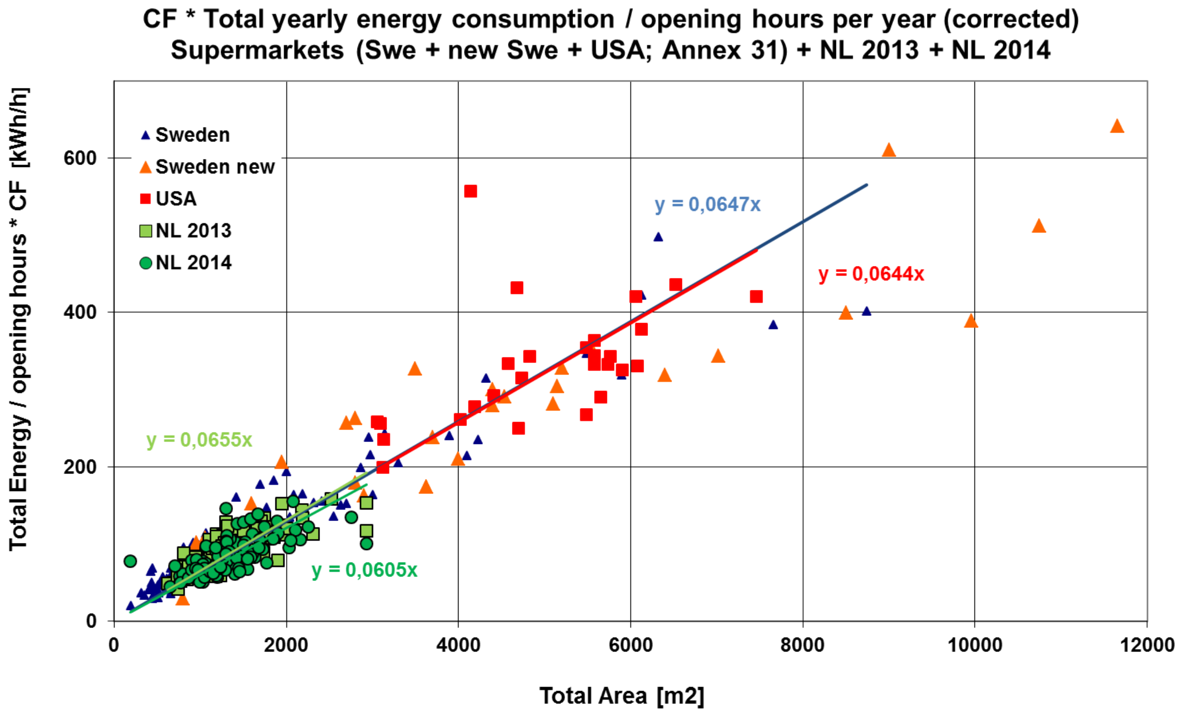


Figure 30: Total energy demand / opening hours with correction factor versus total area from supermarkets in Sweden USA and Netherlands. Trend lines for 146 Supermarkets SWE (blue line) and 27 USA supermarkets (red line) with coefficients shown. Additional trend lines and coefficients are shown for NL 2013 (light green) and NL 2014 (dark green).

Based on the correction factor CF it is possible to calculate for a specific supermarket, what the relative increase in total energy consumption (E/E’) would be for an given increase in opening hours (from OPW to OPW’), assuming that the PI (Total energy/opening hours * CF) stays constant:

E’/E = (65 * OPW/168 +35) / (65 * OPW’/168 + 35) * (OPW’ * 52) / (OPW * 52)

For an increase of OPW from 71,7 (as in the Swedish data) to 168 (as in the USA data) we then find an increase in energy consumption of 47%. At first glance that would be an average of 3,4% per opening hour, but the formula is more complicated and gives a percentage change which is higher at low OPW values and lower at high OPW values, as shown in Figure 31.

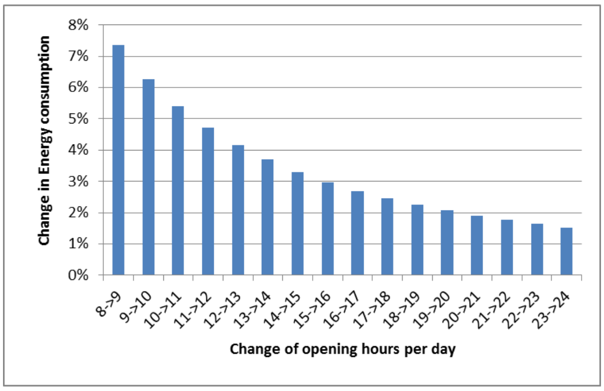


Figure 31: relative energy consumption change per additional opening hour, as evaluated from the new PI based on CF

The percentages in Figure 31 appear to be quite high at OHW values typical for Swedish and Dutch supermarkets. The proposed correction factor CF and new performance indicator PI do provide a better agreement between European and USA data (Figure 30). But of course the difference in USA and European data may have other origins besides opening hours, such as climate differences and a difference in the predominance of air-conditioning in the USA and Europe. The agreement between Swedish and Dutch data existed even before the new PI based on CF was applied.

A decisive argument in favour of the CF and new PI methodology could be found when it appears that the spread in Energy Intensity in the existing data set (with variations in OPW) would be reduced if all energy consumption figures were normalized to the same OHW value (i.e. eliminating the spread in OHW values from the data set). The result of this exercise (based on the formula for E'/E above) is shown in Figure 32 for the Swedish data set of Annex 31, with an original spread in OHW from 49 to 105 hours per week (average 71,7 hours per week). Unfortunately there is no obviously reduced spread in Energy intensity (the R^2 value of the trend-line does not decrease). Therefore the proposed methodology based on CF and the new PI is not finally decisive, and alternative methods or formulations must still be considered.

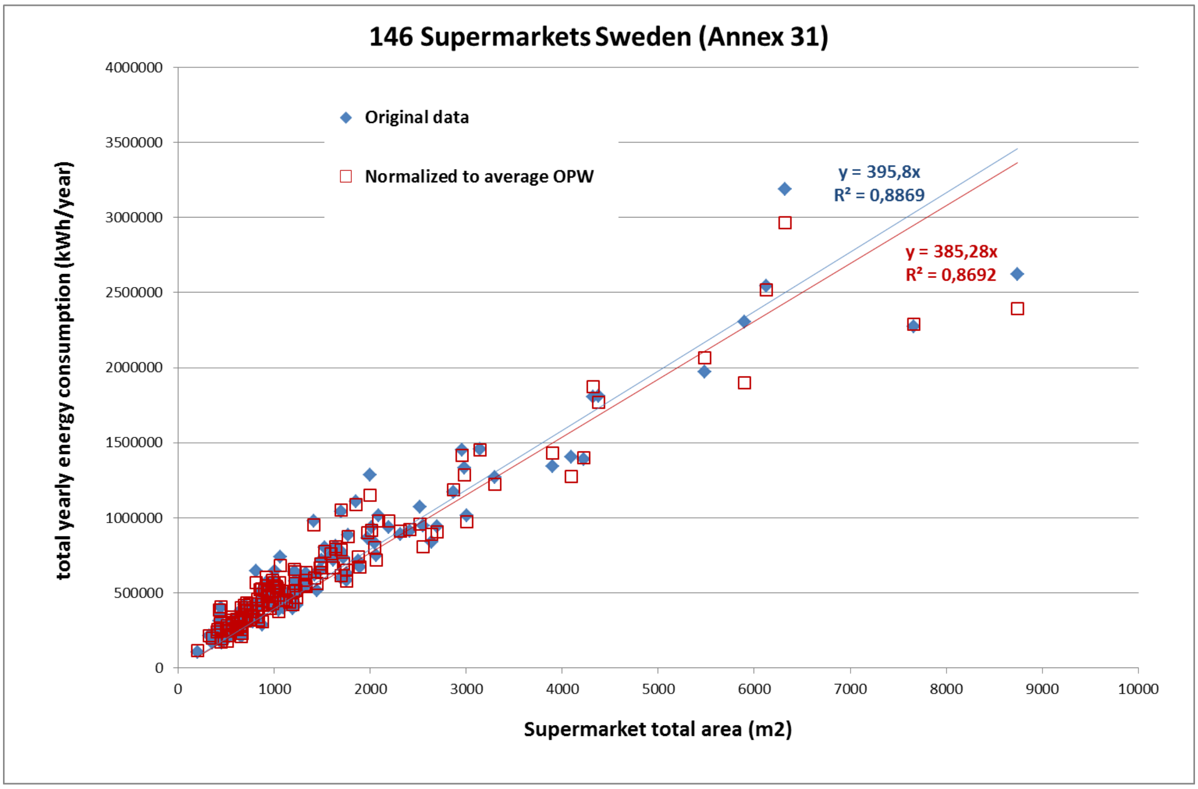


Figure 32: Original data and OHW normalized data for the Swedish Annex 31 data set.

The Single supermarket approach to opening hours

In a study on performance indicators for supermarket refrigeration systems (excluding the other supermarket energy systems), S. Acha (2016) found an increase of energy use for the refrigeration system of 0,94 % per additional opening hour at a single (UK) supermarket with a sales area of 3300 m². This was done by comparing the average (refrigeration) energy consumption of days with 14 open hours to the energy consumption on (sun)days with 6 open hours. The study did not include other energy systems, so the effect of opening hours on total energy consumption is not given.

For the Annex 44 work, we have a data set available for a single Danish supermarket, with energy measurements on the energy subsystems taken each hour for a period of slightly over 2 years. Based on this data set and opening hours (08:00-20:00 on weekdays, 08:00 – 18:00 Saturday and Sunday) we can perform a similar analysis. We then find the hourly energy use for refrigeration as a function of the weekday (Figure 33), and can calculate an increase of energy use for the refrigeration system of 1,2 % per additional opening hour (which agrees reasonably with the value 0,94 % found by Acha). There is a variation in refrigeration hourly energy consumption also during days with the same number of opening hours, but a statistical analysis (t-test) has shown the difference in weekdays and weekends to be statistically relevant (with 95% confidence).

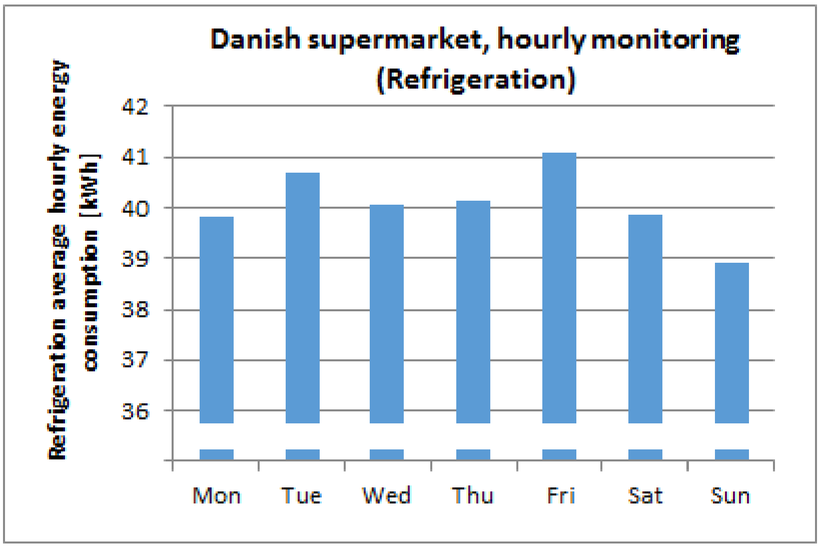


Figure 33: Refrigeration energy use per hour as a function of weekday for a Danish supermarket.

The Danish data set also makes it possible to evaluate the increase in total energy consumption (electricity and heating) for an additional opening hour, in the same manner. The result is shown in Figure 34 and gives a change of 3,2 % in total energy consumption per additional opening hour. This change is observed in the range of 10 – 12 open hours. The result has been satisfactorily checked for statistical relevance (t-test, 95%).

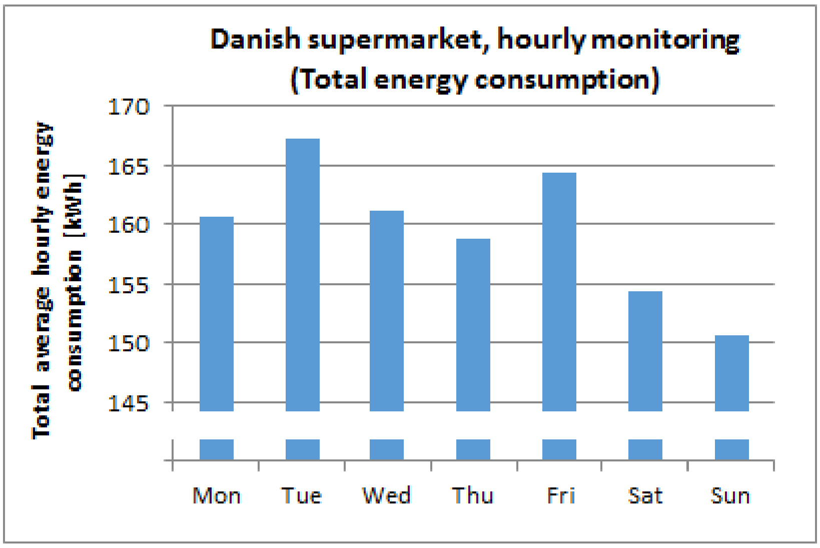


Figure 34: Total energy consumption (electricity and heating) per hour as a function of weekday for a Danish supermarket.

The correction factor (3,4 % total energy consumption increase per daily opening hour increase) was applied to the original Swedish data set (normalizing all entries to average OHW), but no reduction in the spread of data resulted.

Opening hours in the Annex 44 methodology

From the theoretical analysis we found a value of 3,4 % total energy consumption increase per additional (daily) opening hour fitting well to align the Swedish and USA data sets, at opening hour variations from 10 to 24 hours. The theoretical analysis gives higher percentages at small opening hour variations (e.g. from 10 to 12 hours), but no supporting proof in this region. From the single supermarket approach we found a value of 3,2 % total energy consumption increase per additional opening hour at opening hour variations from 10 to 12 open hours. We therefore propose to use a value of 3,3 % total energy consumption increase per additional (daily) opening hour – or 0,47 % per additional OHW – over the entire opening hour range.

Keeping in mind the methodology introduced in chapter 5.5 we have:

$$E(\text{estimate N}) = E(\text{estimate N-1}) * (1 + P.I._{difference}(N) * P.I._{effect}(N)) \quad (3)$$

E(estimate N.)	=	Estimated yearly energy consumption based on N functionalities (MJ / yr).
E(estimate N-1)	=	Estimated yearly energy consumption based on N-1 functionalities (MJ / yr).
P.I.	=	Performance Indicator
$P.I._{difference}(N)$	=	Difference of the actual P.I. (N) value from the average for P.I.(N)
$P.I._{effect}(N)$	=	Relative effect on overall supermarket energy consumption of P. I.(N)

For the Swedish data set we have an average OHW = 71,7 and for the data sets from the Netherlands we have average OHW = 73,6 (2013 data) and average OHW = 74,7 (2014 data). Using an overall average OHW = 73,3, and the $P.I._{effect}$ of 0,47 % per additional OHW we can then write:

$$E(\text{estimate N}) = E(\text{estimate N-1}) * (1 + (OHW – 73,3) * 0,0047)$$

Where OHW is the number of opening hours per week.

7.3 Geographical location / outdoor temperature

The outdoor temperature has a distinct effect on the energy consumption of refrigeration systems, as the condensation temperature depends on the outdoor temperature, and the COP depends on the difference between the condensation and (fixed) evaporation temperatures. A higher outdoor temperature leads to a lower COP and a higher energy consumption for the refrigeration system. Since refrigeration is a predominant subsystem in a supermarket, it can therefore be expected that the overall energy use will increase with higher outdoor temperatures.

In the datasets available in the Annex 44 work, the outdoor temperature is not available as a parameter, so it is not possible to make correlations based on measured data.

Therefore an alternative approach has been attempted, in the form of modelling the yearly energy consumption of a number of supermarkets (14) in different geographical locations: Stockholm, Paris and Madrid.

The expectation that the same supermarket will have the lowest yearly energy consumption in Stockholm and the highest yearly energy consumption in Madrid, is **not** confirmed by the modelling. This is in line with the fact that average energy intensities for Swedish and Dutch supermarkets are quite similar, despite the difference in climate. This can partly be explained by the fact that in a hotter climate the refrigeration energy consumption will increase, but the energy consumption for space heating will decrease.

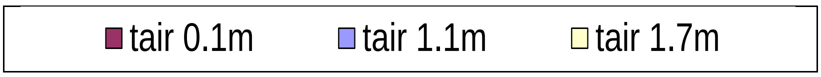
At this stage the modelling has not yet been double-checked, and as indicated there is no precise field-data available, so we cannot yet draw conclusions concerning the effect of outdoor conditions on yearly supermarket energy consumption in general.

7.4 Supermarket indoor environment

In a supermarket there are three different categories to be considered for designing and maintaining an appropriate indoor environment; food, personnel and customers. They have sometimes incompatible requirements. The value of good indoor environment and energy efficiency is not always the target for all the categories, especially not if the chilled food is displayed in refrigerated cabinets that are open and not equipped with doors. It must therefore be understood that display cabinets are selling machines and the visibility for the chilled goods and accessibility is of high importance to be considered for the manager. Energy efficiency should not adversely affect food, personnel and customers.

Several parameters influence the quality of the indoor environment. Temperature is one of them. Other parameters can be odours, noise, light, indoor air quality and thermal environment. The parameters influence the human perception of the indoor environment (Lindberg, 2009).

The indoor temperature, and in front of the refrigerated cabinet, will vary during a year which is illustrated in below Figure 35 with measured values from three different supermarkets (A, B and C) in front of two different designs of cabinets for dairy and meat (1,2). For supermarket B, the B1 measurements are performed in a walk-in cold room (where customers can pass through). A more efficient cabinet can keep the cold air inside the cabinet . Other systems such as HVAC and also customer interaction can disturb the cabinets.



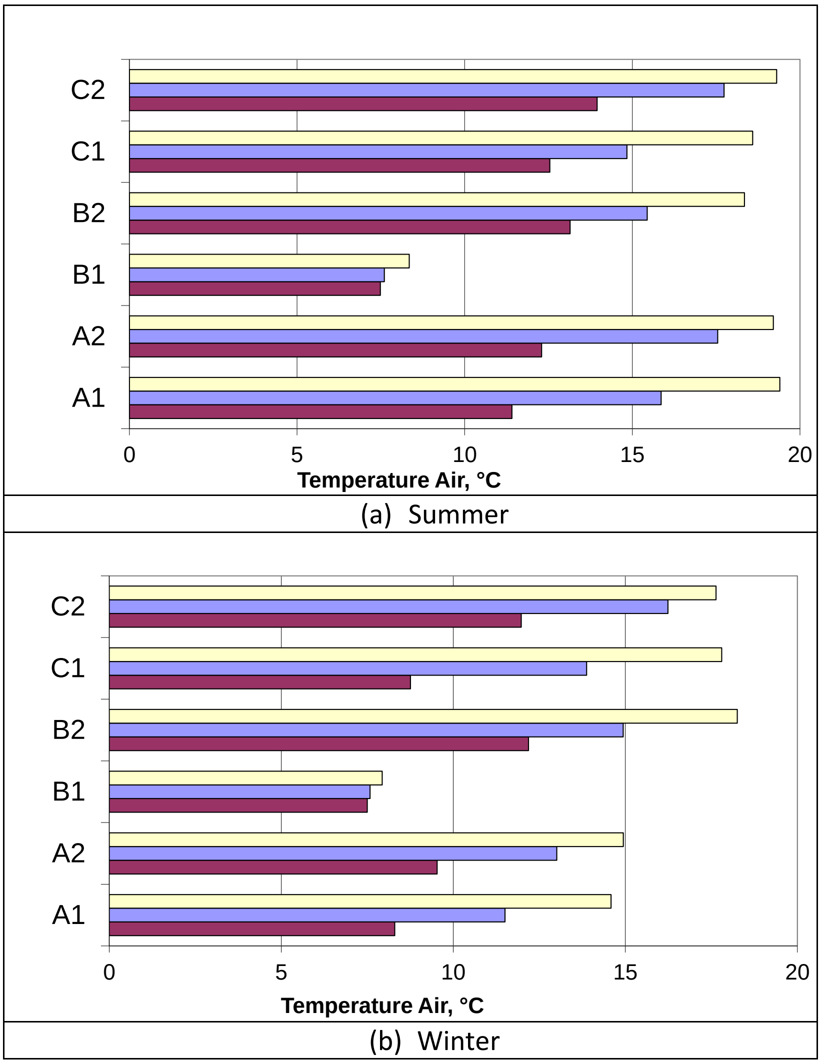


Figure 35: Measured average air temperatures, tair, at three different heights above the floor and 0.5 m in front of refrigerated display cabinets during summer and winter conditions (data from Lindberg, 2009).

The outdoor conditions (temperature and relative humidity) strongly affect the indoor thermal environment and the indoor environment will therefore vary depending on seasonal variations. During summer the enthalpy is higher and in the surroundings of the cabinets higher temperatures and enthalpy will result in a weaker air curtain influencing the performance of refrigerated display cabinets and not only the energy use but also the thermal environment for people and the storage temperature for the food.

Perishable foodstuffs are usually displayed in refrigerated cabinets for maintaining quality and safety. The vertical cabinets are popular due to the fact that they can store a big volume of food on a small floor area. However, in the area where the vertical cabinets are located it is common that the comfort is poor for the people due to the interaction between the cold interior in the display cabinet and the infiltration with the surroundings. The thermal comfort problem in supermarkets, particularly in front of display cabinets has been studied by several researchers by modelling and measurements both in laboratory and in-store (Foster, Foster and Quarini, Lindberg et al, Lindberg). Cold air from the cabinet falls out of the cabinet causing the customers´ feet to become cold. The cooling load of display cases is strongly dependent on the relative humidity in the store. Howell (1999) among other authors and researchers has shown the importance with moisture balance in supermarkets. They investigated the impact of temperature and humidity and interactions between display cases and the effect of ambient store relative humidity. They reported the three factors for the display that all were affected by humidity; the case refrigeration, anti-sweat heaters and finally the case defrost. Further Brolls (1986) collected data in order to show the relation between (open) refrigerated display cabinet cooling demand and relative humidity / dry bulb temperature resulting in Figure 36 below.

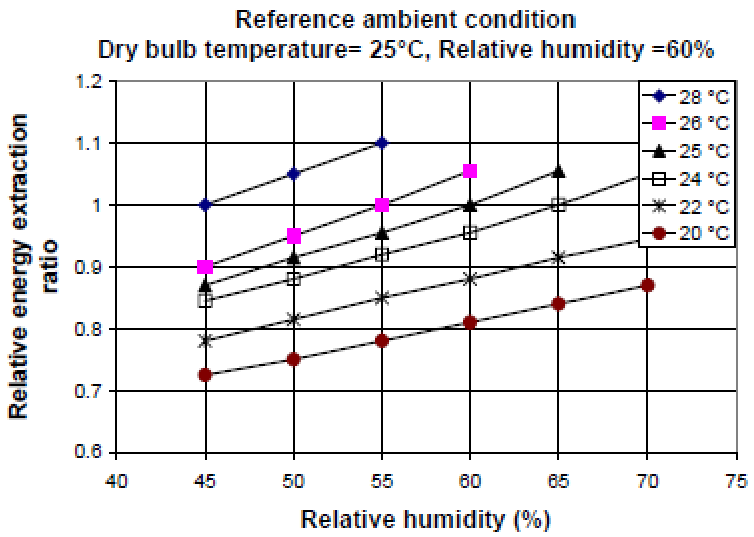


Figure 36. Relative heat extraction rate (cooling load) in a vertical open display cabinet as a function of ambient relative humidity (according to Brolls and diagram from Axell (2002).). For horizontal (island type) cabinets the influence is lower, as well as for cabinets covered by night curtains or glass doors.

The standard EN ISO 23953-2 (2005) defines M-package temperature classes (storage temperatures for the food), different climate classes for test performances of cabinets under controlled conditions, i.e. laboratory tests. However, it must be remembered that those conditions might not be representative for the real conditions in-store. In store not only the climatic conditions vary but also the load arrangement, number of products in the cabinet and of course there are customer interactions in the real supermarket.

Therefor it is suggested to use a representative indoor temperature which is common most of the year and a relative humidity representative to such store conditions. Moreover it helps if it is possible to refer to the standard climatic conditions as the cabinet have data measured from such conditions which can be used in order to follow up its performance. One suggestion is the 20 (50) condition which also is a representative condition in the supermarket environment for the Nordic country and many European countries.

Table 11: proposed reference indoor environment conditions and current standard (EU) testing condition. The water content is not a separate condition, but follows directly from the dry bulb temperature and relative humidity.

	Dry bulb temperature °C	Relative humidity %	Water content (g H_2O / kg dry air)
Proposed reference condition	**20**	**50**	**7,3**
ISO Standard test condition	**25**	**60**	**16,7**

Even when a reference condition can be defined, it is not easy to formulate a performance indicator to relate supermarket total energy consumption at indoor condition “X” to the energy consumption at the reference condition. A higher indoor temperature will increase the cooling demand of refrigerated display cabinets, and thus for the cooling system, and also for the heating system in a cold climate. But in a warm climate a higher indoor temperature will decrease the energy consumption for the air conditioning system.

7.5 Compiled performance indicators

A student project carried out at the Department of Energy technology at the Royal Institute of Technology in Stockholm Sweden evaluated some performance indicators for supermarkets. The following criteria were applied to evaluate different indicators.

- Criterion 1: The performance indicator allows fair comparison of supermarkets of different (size) categories (small markets / supermarkets / hypermarkets).
- Criterion 2: The performance indicator allows fair comparison of supermarkets across different countries and cultures
- Criterion 3: The performance indicator can be calculated from the available supermarket data (data sets from annex 31)
- Criterion 4: The performance indicator minimizes the influence of other factors that are unaccounted.

Data from supermarkets in Sweden and USA was used to evaluated two performance indicators:

1. Total energy consumption / (Cooling Capacity * Store Area)
2. Total energy consumption / (Cooling Capacity * Opening Hours)

A graphical evaluation of the first proposed performance indicator is given in Figure 37. This performance indicator is the total energy consumption / (refrigeration capacity * total area). The resulting trend lines do show very good correlations (high R^2 values), but they are exponential – which makes them somewhat less easy to use. The exponents are in the same range (0,8 – 1,1) for the data sets, but the multipliers have largely differing values (2.200 – 17.000). Another drawback of this performance indicator is that there is no obvious physical interpretation of the resulting metric (which is expressed in $kWh/(m^2.kW_{refrigeration})$, or ($h/m^2$).

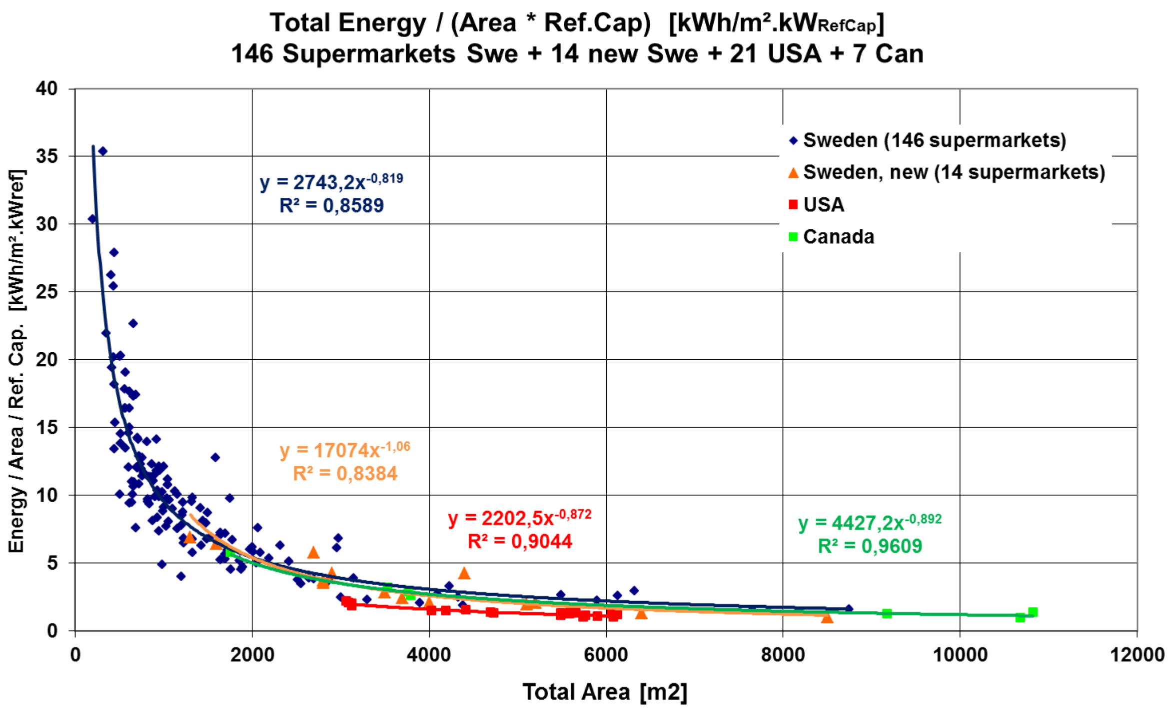


Figure 37: graphical evaluation for the proposed performance indicator "Total energy consumption / (total area * installed refrigeration capacity), based on data sets from Annex 31.

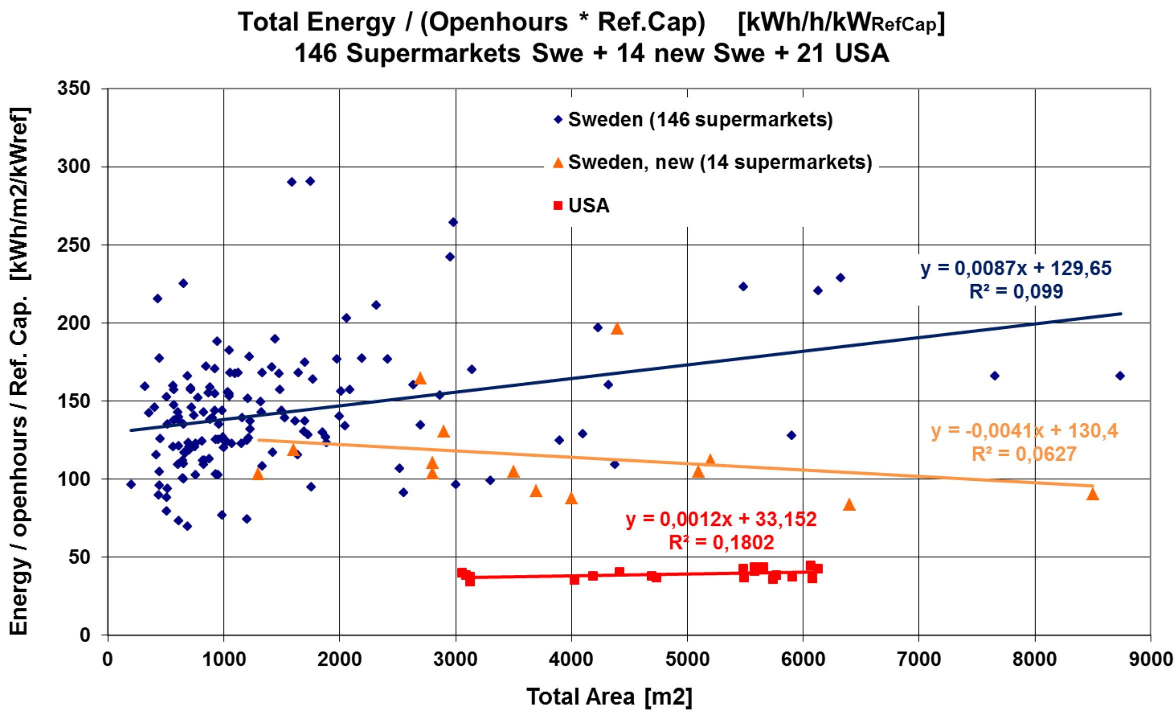


Figure 38: graphical evaluation for the proposed performance indicator "Total energy consumption / (opening hours * installed refrigeration capacity), based on data sets from Annex 31

A graphical evaluation of the second proposed performance indicator is given in Figure 38. This performance indicator is the total energy consumption / (refrigeration capacity * opening hours). The resulting trend lines do not show much correlation (low R^2 values). The interesting feature of this performance indicator is that it is dimensionless. The values for different data sets however are greatly different. USA values are lower than Swedish because USA opening hours are 24/7 (versus an average 72 and 94 for the Swedish data sets). Furthermore, the installed refrigeration capacity in the USA is higher than in Sweden at similar yearly energy consumption values. (according to Figure 22).

Data from simulations using the software CyberMart was used to evaluate four additional performance indicators. Simulation permits to identify data that should be collected in the supermarkets to evaluate and compare energy utilization. 14 supermarkets were simulated and the indicators evaluated were:

- CyberMart Indicator 1: Total energy/ (Compressor energy x Sales Area)
- CyberMart Indicator 2: Total energy/ (Compressor energy x Sales Area * Opening Hours)
- CyberMart Indicator 3: Compressor energy/ (Cooling capacity * Sales Area)
- CyberMart Indicator 4: Compressor energy/ (Cooling capacity * Sales Area * Opening Hours)

The performance of the four CyberMart indicators are compared to the two original ones on the basis of the four criteria developed for assessing indicators, as can be seen in Table 12.

A stepwise methodology has been used to separate data into smaller subsets (both in area categories and in geographical sense), normalize the data in each subset and finally to compare the normalized data of the different subsets. Due to these normalizations much of the physical meaning of the comparisons is lost, and the comparisons relate mainly to the statistical properties of the subsets.

As expected, all four CyberMart indicators do not perform well in Criterion 3, which requires being able to derive them from currently data available. Two CyberMart indicators perform as well as the real ones in other criteria. On the other hand, while Cybermart Indicators 1 and 2 are not currently possible from available data, they perform excellently in Criterion 4 - Minimizing the influence of other factors.

Table 12: Comparison between indicators

Indicator Criteria	Indicator 1	Indicator 2	CyberMart Indicator 1	CyberMart Indicator 2	CyberMart Indicator 3	CyberMart Indicator 4
Criterion 1	Ok	Ok	Ok	Ok	Ok	Ok
Criterion 2	Ok	Ok	Ok	Ok	Ok	Ok
Criterion 3	Ok	Ok	X	X	X	X
Criterion 4	Ok	Ok	Ok	Ok	Ok	Ok

CyberMart indicators 1 and 2 include the value of total energy consumption / compressor energy consumption, for which the inverse value approximates the percentage of refrigeration energy consumption in the total supermarket energy consumption (~ 50 %).

Cybermert indicators 3 and 4 include the value of compressor energy consumption / cooling capacity, which value approximates the number of yearly running hours of the refrigeration system divided by the average COP. For a continuously running system, its value is 8760 / $COP_{average}$.

7.6 System Efficiency Index (SEI)

The System Efficiency Index is a concept which can be used to evaluate and compare efficiency for installed refrigeration systems using short term measurements. It is a measure useful for momentary measurements, not for accumulated energy usage over time. When SEI is used for over time measures the purpose is the analyse variations in the performance of the refrigeration system.

The SEI is created by defining the COP of a 100% efficient refrigeration process between the desired temperature levels and comparing the actual COP with this loss free process. The ideal or Carnot COP provides the ultimate reference, consistent with the laws of thermodynamics, for a process of transferring heat energy to a higher temperature level. The COP achieved through design or through field measurements is divided by the ideal COP:

$SEI\ (cooling) = Actual\ COPCarnot\ COP$ = $Cooling\ capacityPower\ Input\ /Tref,cTref,h-Tref,c$
(1)

$SEI\ (heating) = Actual\ COPCarnot\ COP$ = $Heating\ capacityPower\ Input/Tref,hTref,h-Tref,c$
(2)

Where Tref,h and Tref,c are the secondary fluid temperatures at the reference conditions. Figure 39 illustrates the general concept of system boundaries and reference temperatures where SEI1 refers to the refrigeration cycle itself, SEI2 accounts for power input to fans and pumps required to operate the cycle and SEI3 and 4 include addition of heat (in the case of heat pump supplementary heaters) and power required to circulate fluid around the building.

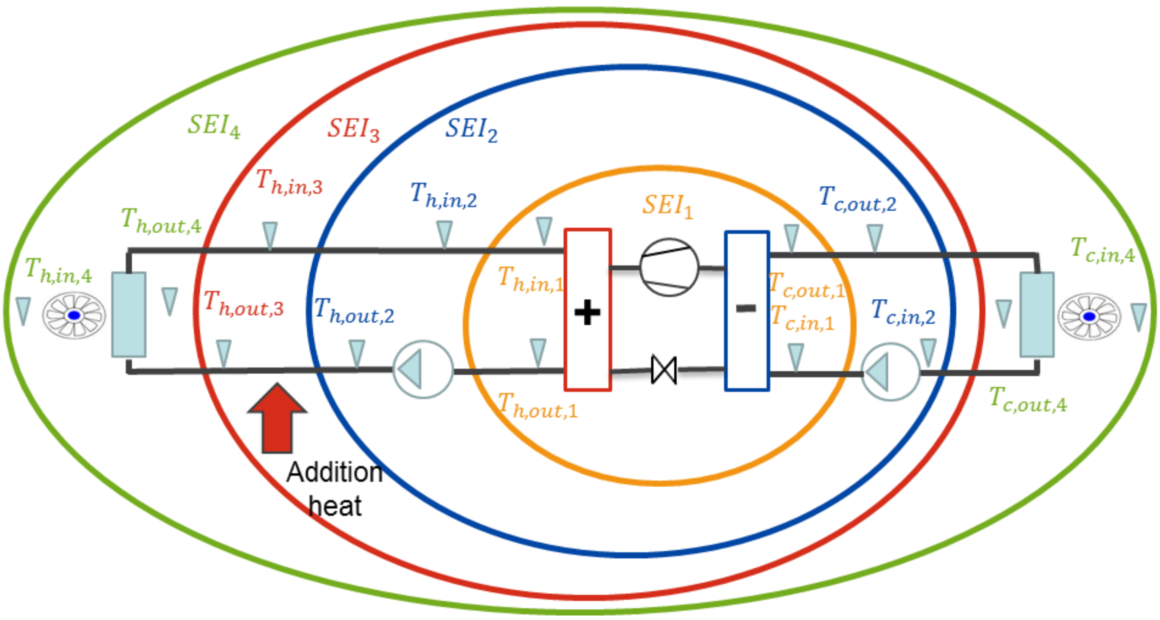


Figure 39 System boundaries used to define SEI1,2,3,4 and reference temperatures Tref,x,n

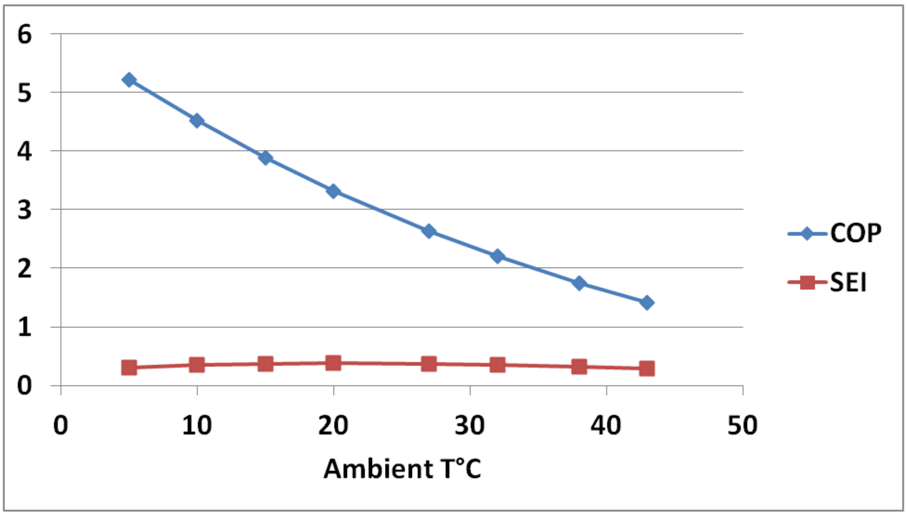


Figure 40: Theoretical values of COP and SEI based on manufacturer's data, using R404A, with fixed evaporation at -10 °C, and 20 °C suction gas temperature.

In Figure 40 the difference in appearance between COP and SEI is illustrated. COP variate according to temperature levels, but SEI is constant. Variation in SEI indicates variations in performance.

SEI answers the question how efficient the process is in the same point. The measured value can be compared with values for other conditions. In this way SEI is a general indicator. The difference tells about the performance at the measured point according to ideal performance, other measured points or dimensioning data. It shows the potential for optimization and the quality of COP.

For a cooling process that works well in all operating modes the difference of COP and SEI can be described like this. The characteristic of COP is increasing with decreasing temperature lift. The characteristic of SEI is relatively constant in the operating range, however an optimum can be found. Near the limit of operating range the SEI typically drops. This means that a variation in the operation mode is easier to notify with SEI than with COP. But still the COP tells about the energy performance in the specific operating point.

The System Efficiency Index (SEI) is the ratio between the measured COP and the COP for an ideal refrigeration process, known as the Carnot efficiency operating between the same temperature levels (A-L Lane et al, 2014). In collaboration between SP Technical Research Institute of Sweden, IOR, VDMA and Climacheck the method has been further developed. Analysis can be done for example with equipment from ClimaCheck for a short interval or with a permanent installation with connection to the internet, so it is possible to follow the variation in performance. The Clima Check system also provides other valuable information about the performance of the system. In the ClimaCheck system the refrigeration capacity is calculated based on internal measurement points of temperature and pressure in the refrigeration circuit.

The SEI can also be calculated based on external measurements for indirect refrigeration systems, where the cooling capacity is measured in the secondary system. In both methods power to the compressor and other electrical equipment within the used system border has to be measured.

The System Efficiency Index is a useful performance indicator for evaluation of the refrigeration system of a supermarket. It provides insight into the effectiveness of the refrigeration system in relation to an ideal refrigeration system (the Carnot refrigeration cycle). Aspects outside the chosen system boundary have to be evaluated and taken into account in other ways, as for example if the used temperature levels in the systems could be optimized.

The advantage of SEI is the short measurement time needed.

For the evaluation of the overall energy efficiency of a supermarket, the System Efficiency Index SEI does not suffice by itself. First of all, the SEI is independent of the refrigeration load. Even with a good SEI the overall refrigeration energy consumption may be high when the refrigeration loads (the refrigerated display cabinets) are not chosen to be energy efficient (e.g. with glass doors). Secondly, the SEI is designed to be independent of evaporation and condensing temperature levels – whereas the choice of energy optimized temperature levels is of high importance for the energy efficiency of a real life supermarket refrigeration system. And finally of course, the SEI relates only to the refrigeration system and not to the other energy systems of the supermarket.

Still, at fixed load and fixed temperature levels, the SEI provides a valuable key to the efficiency of the refrigeration system, and especially to its design and performance of its components. In engineering terms, a comparable value is known as the Carnot efficiency η_{Carnot} .

For the SEI to become a useful performance indicator, it is necessary to know the (yearly or seasonal) average value of the SEI in current supermarkets (SEI-average). Then it becomes clear whether a specific supermarket has a better SEI than average or not. Of course, the SEI is not a single value, in a supermarket there generally is a $SEI_{cooling}$ for the MT refrigeration system and a $SEI_{freezing}$ for the LT refrigeration (freezing) system. They could be combined to one SEI value by taking into account an estimated relative energy consumptions for MT and LT systems.

For the three Annex 31 databases where information on MT and LT refrigeration capacities is available (USA, Sweden and Canada) the capacity of the MT system is on average 3,3 times as high as the LT system capacity. The Coefficient of Performance (COP) for the MT system is typically 1,5 .. 2,0 times better than the COP for the LT system (depending on evaporating and condensing temperatures). When we take $COP_{MT}/COP_{LT} = 1{,}66$ ([4]) we then find that the energy consumption of the MT system is twice the energy consumption of the LT system. We can then evaluate the estimated average SEI as:

$$SEI = 2/3 * SEI_{cooling} + 1/3 * SEI_{freezing}$$

When a supermarket has SEI values 10 % above average (and the refrigeration loads and temperature levels are state of the art), we know that the refrigeration systems are 10 % more efficient than average. In terms of overall supermarket energy consumption, this would translate approximately to an overall energy saving of 3,3 % (as the heating system and other energy consuming systems, such as lighting, are not affected by the SEI values).

In the methodology proposed in the work of annex 44, we can write for SEI as a performance indicator:

$$E\ (\text{new value}) = E(\text{initial value}) * (1 + (SEI / SEI\text{-average} - 1) * (-0{,}33))$$

[4] At MT evaporating temperature -10 ºC, LT evaporating temperature = -33 ºC and condensing temperature 35 ºC. For the Annex 44 Danish data set (2015), the value a = 1,66 (in total capacity = cooling capacity + a x freezing capacity) provides the highest R^2 value (best fit) fort he trend line of refrigerating energy consumption related to total cooling capacity..

With

$SEI = 2/3 * SEI_{cooling} + 1/3 * SEI_{freezing}$ (measured or known SEI values in specific supermarket)
SEI-average = average SEI value for all supermarkets.

When the total energy intensity E(initial value) = 572,04 kWh/m^2.year (as in the 2013 database for The Netherlands) and we have an SEI value 10% above average, we would thus find a new value for the energy intensity E(new value) = 553 kWh/m^2.year. in this case, we already know that the refrigeration system is efficient. When the measured total energy intensity is above 553 kWh/m^2.year, we can conclude that there is an inefficiency in the other energy systems (or in the refrigeration load, the refrigerated display cabinets). On the other hand, when the measured energy intensity is below 553 kWh/m^2.year, we can conclude that the other energy systems (besides the refrigeration system) are also efficient.

In fact the formulas above do not apply only to the SEI, but also to other COP values (including the COP and DPI values provided by the Danfoss COP monitoring system mentioned in Chapter 4).

The Annex 44 data set for Denmark (2015) allows checking the influence of the COP, as seasonal COP values (SCOP) can be calculated for all data points from the nominal load and yearly refrigeration plant electricity consumption. These SCOP values – based on a simple addition of the calculated medium and low temperature refrigeration loads – are presented in Figure 41.

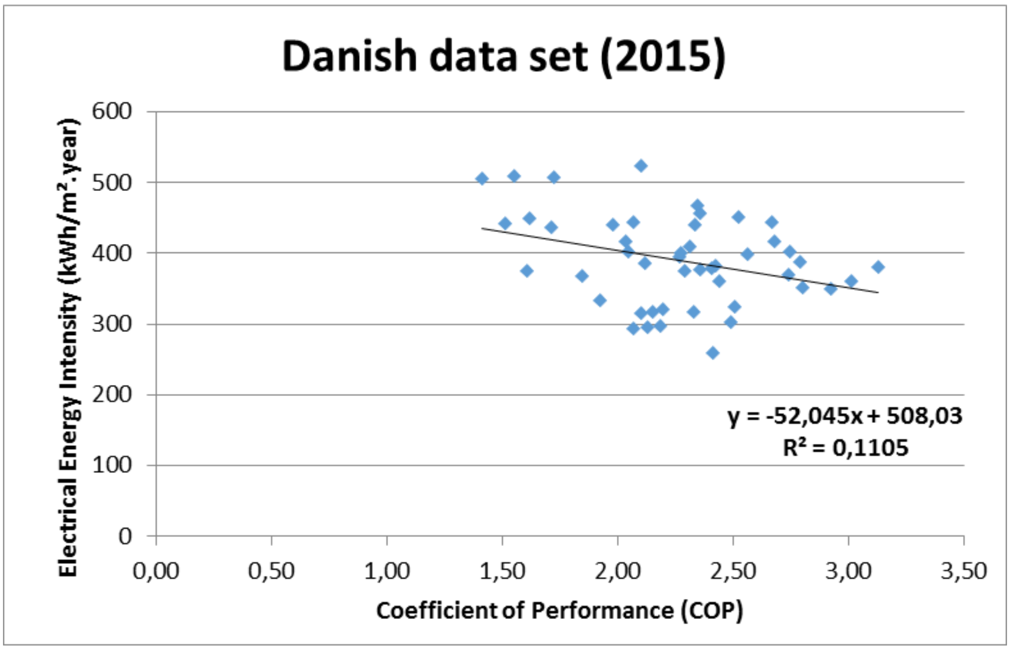


Figure 41: SCOP values calculated on the basis of calculated refrigeration demand and measured yearly energy consumption for refrigeration, for the Danish data set (2015).

Although the correlation of the trend line is weak ($R^2 = 0,11$), the trend line shows an influence of the SCOP on the (Electrical) Energy Intensity of -3 % for a 10 % increase in SCOP value.

However, the individual values of the SCOP are calculated from the electricity use in the data set, so using them to also *predict* the electricity use would not be correct. An option is to average the SCOP over a group of supermarkets with similar refrigeration systems, so that a representative SCOP value for each of those groups is created. This is of course only possible if there are enough similar refrigeration systems in the data set, and a user can only know how good their system runs in comparison to others, but not what the maximum obtainable efficiency is for their system. The grouped SCOP is shown in Figure 42.

The nominal refrigeration load in the Danish data set is influenced by the age of the display cabinets, as more efficient cabinets have been installed in more recent systems.

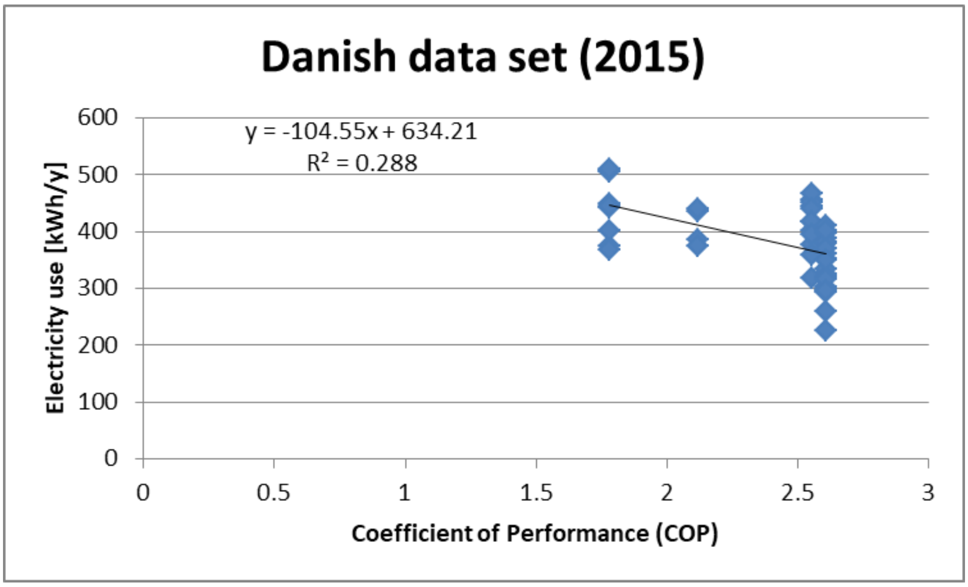


Figure 42: SCOP values calculated from nominal refrigeration demand and measured yearly energy consumption for refrigeration, for the Danish data set (2015), grouped per refrigeration system type

7.7 Statistical analysis of Dutch data

At the outset of the work of Annex 44, the collection of large amounts of supermarket energy consumption data in combination with information on applied energy saving options in these supermarkets was thought to be the main source for establishing performance indicators. For this purpose, the data sets from The Netherlands have been very useful. The earlier data sets from Annex 31 (Sweden, USA and Canada) were only partially useful, as no information on presence of energy saving options was included in these databases.

In the 2013 and 2014 data sets on energy consumption of supermarkets from the Netherlands, a set of 71 parameters is available for each entry (each supermarkets) describing the presence of energy saving options (yes/no) and some other indicators (opening hours, area and refrigerated volumes).

For each of these options, the supermarkets can be divided in two groups: one group with the saving option present, and one group without this saving option. Then, the energy intensity (kWh/m^2.year) can be compared between the two groups. Of course, there are also many other parameters that may change between these groups, and therefore it must be checked whether the difference in energy intensity found between the two groups (with and without the saving option) is statistically relevant. This check was done for each energy saving option by means of a t-test with 95% confidence interval.

The result has been utterly disappointing: for many energy saving options there appeared to be a result on the energy intensity in accordance with the expectation that an energy saving options reduces energy consumption (and thus energy intensity). However, only very few of these differences proved to be statistically relevant. The few energy saving options that proved to be statistically relevant in the 2013 database did not prove relevant in the 2014 database, and vice versa. The relevant options are listed in the table below.

Table 13: statistically relevant energy saving options in the Dutch databases 2013 and 2014

Option	2013 data savings %	2014 data savings %
Night Covers on RDC’s		6,4 %
10744K (Glass doors on Multidecks)	9,4 %	
Ima		6,8 %
Weather control on heating		6,4 %
RDC Settings (3 savings options)	-/- 5,7 %	
Lighting control (3 savings options)		6,5 %
Ventilation control		6,9 %
Insulation of heating pipework		5,7 %

The statistical relevance of the energy saving options was tested with respect to the savings on total energy consumption. Some of the options did show a statistical relevance with respect to either the electrical energy consumption or the energy consumption for heating (gas consumption), but not with respect to the total energy consumption. Most notable in this respect is the energy saving option “heat recovery” which showed a relevant saving on energy consumption for heating in both 2013 and 2014 data sets. As expected, the electricity consumption was higher with heat recovery (in both datasets). An overall reduction in total energy consumption was observed for heat recovery in both data sets – as expected - however these reductions were not statistically relevant.

Seeing that there is not any option for which the energy savings are statistically relevant in both data sets at the same time, there is not sufficient ground for distilling performance indicators from these data sets (which could in theory be easily done with the formula provided in paragraph 5.5.

But even so, it would be questionable to define performance indicators on the basis of the statistically relevant energy savings of the evaluated energy saving options. The reason is, that the individual options may not be uncorrelated. For example, the use of heat recovery would most probably correlate with the use of electronic expansion valves in the refrigerating system. We would then find a certain energy savings percentage at each of these options, which in fact would be the energy saving of the combination of these options.

Therefore, it is advisable to evaluate all energy saving options together by means of a multi variable regression analysis. This has been attempted, but has failed to provide meaningful results in case of the Dutch data sets.

7.8 Refrigerant

As discussed in chapter 3.2, the transition from traditional (HFC) refrigerants to natural refrigerants gives rise to the presence of refrigeration system with various refrigerants and various configurations in the market at present. The type of refrigeration system and refrigerant has an influence on the energy consumption for refrigeration, and thus on the overall supermarket energy consumption.

In many congress papers and articles over the past years, overviews can be found on the calculated or simulated influence of refrigerant and system type on the energy consumption for refrigeration. An example of such an overview, relating energy consumption for refrigeration, Global warming impact (TEWI) and investment costs is given in Table 14. The values for energy consumption provided in this table are not actually measured in practice, but based on theoretical compressor power input which is taken from compressor selection software or, in cases where data is not readily available, by using typical efficiency data. Real – measured – comparisons are rare. Cost data relates to 2010, and is subject to considerable changes over time.

Table 14: normalized relative values of three parameters - energy consumption, environmental impact (TEWI) and investment cost. All numbers are expressed as a percentage compared to the R404A scroll base case (Emerson climate technologies, 2010).

Case		1	2	3	4	5	6	7	8	9	10	11	12	13	14
System		Direct Expansion				Direct Expansion Distributed		Cascade				Secondary			Booster
Refrigerant Medium Temperature		R404A	R404A	R134a	R407A	R404A	R407A	R404A	R407A	R134a	R134a	R410A chiller	R290 chiller	HFO chiller	R744
Refrigerant Low Temperature		R404A	R404A	R404A	R407A	R404A	R407A	R744	R744	R744	R744	R744	R744	R744	R744
Compressor technology Medium & Low Temp.		Scroll	Recip.	Recip.	Scroll	Scroll	Scroll	Scroll	Scroll	Recip.	Scroll	Scroll	Scroll	Scroll	Scr/ Recip.
Normalised Score	Power	**Base**	12%	5%	**-3%**	0%	**-3%**	7%	4%	12%	9%	7%	9%	12%	12%
	TEWI	Base	6%	-18%	-24%	-24%	-36%	-2%	-23%	-27%	-28%	**-42%**	**-43%**	**-41%**	**-42%**
	Investment Cost	**Base**	3%	11%	0%	**-14%**	**-13%**	13%	13%	25%	21%	17%	18%	32%	48%

The annex 44 data set for Denmark (2015) offers a precious opportunity for evaluation of the influence of refrigeration system and refrigerant type on the measured energy consumption for refrigeration. The data set covers 49 supermarkets of one chain, where basically one of 4 types of refrigeration systems is present: a R404A direct expansion system, a partially indirect refrigeration system and two types of direct expansion CO_2 systems (Figure 43).

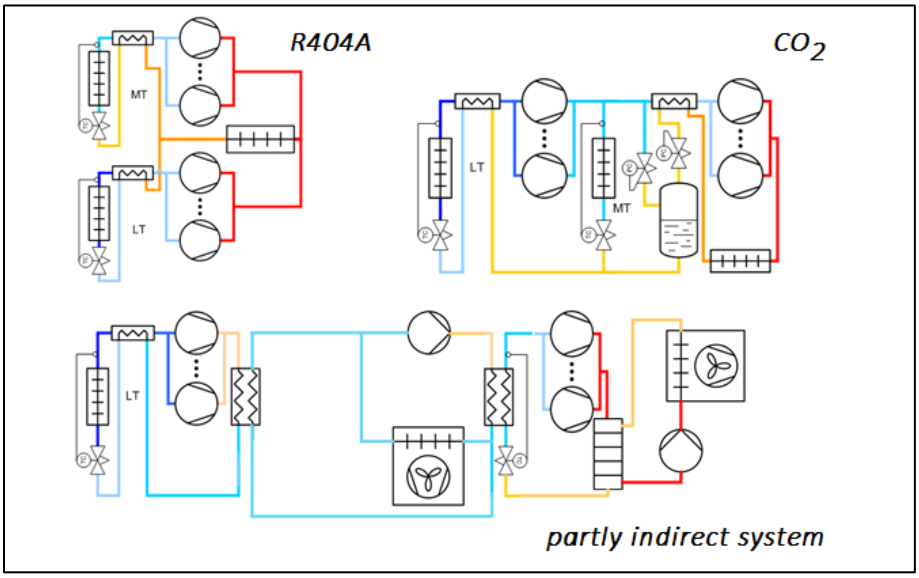


Figure 43: refrigeration system types covered in the Annex 44 Danish data set (2015)

When the total yearly electrical energy consumption values, split up according to the type of refrigeration system, are plotted against the supermarket sales area, the resulting trend lines show the different energy efficiencies between the systems (Figure 44).

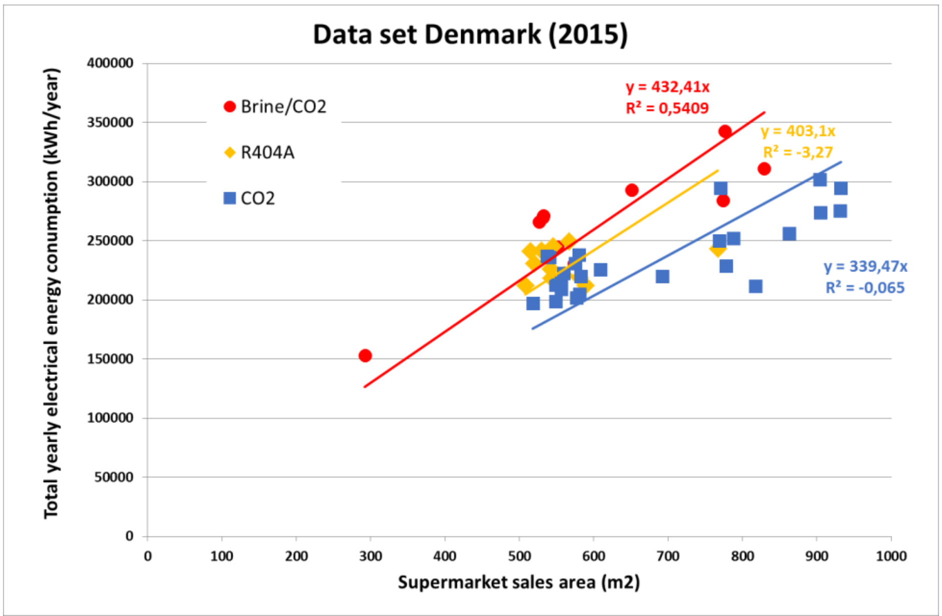


Figure 44: yearly electrical energy consumption against sales area for supermarkets in the Danish data set, split up according to the type of refrigeration system.

Not all of the trend lines in Figure 44 have convincing R^2 values, which is why an additional t-test was performed to show that the distinction in electrical energy intensity (kWh/m².year) between R404A systems and CO_2 systems is statistically relevant with 95% confidence. This is also true for the difference between the R404A systems and the partially indirect (brine/CO_2) systems, and the difference between the CO_2 systems and the partially indirect systems. From this analysis we find that the electrical energy intensity for supermarkets in this database with partially indirect systems is 9 % higher than for supermarkets with R404A systems. The electrical energy intensity for the supermarkets in this database with CO_2 systems is 16 % lower than for supermarkets with R404A systems. It must be noted that these values relate specifically to the supermarkets and systems in this database, and may not without danger be generalized to other supermarkets or refrigeration system types in general.

It is important to note here that the three types of refrigeration systems have to be seen in the context of the Danish legislation enforced in 2007 banning systems with more than 10 kg refrigerant charge per circuit. Prior to this year all refrigeration systems in this particular branch of supermarkets was R404A scroll packs except for a few experimental set ups and a few older systems of various kinds. From 2007 the systems installed had to comply with this requirement in charge restriction and the Brine/ CO_2 solution was the first introduced. Later the CO_2 only systems were introduced for various reasons where one important one was the unacceptable increase in energy consumption by introduction of the Brine/ CO_2 systems. Parallel with this development the display cabinets changed to types with lower load due to more efficient fans and the increasing share of closed cabinets and generally improved design. This is also true for other types of power consuming components in the supermarkets, so a part of the reason that the CO2 only systems appear more energy efficient is that they are part of newer supermarket installations. See also section 8.2 “Year of commissioning”.

In the methodology proposed in the work of annex 44 (chapter 5.5), we can create a performance indicator when we define an R404A direct expansion system as “base line”:

E (new value) = E(initial value) * (1 + (if R404A=0 | if other=1)) * ($P.I._{effect}$(REF))

With

E(estimate N.)	=	Estimated yearly energy consumption based on N functionalities (MJ / yr).
E(estimate N-1)	=	Estimated yearly energy consumption based on N-1 functionalities (MJ / yr).
$P.I._{effect}$(REF)	=	Relative effect (in relation to base line R404A DX) on overall supermarket energy consumption of refrigeration system and refrigerant type.

In the case of the Danish data set, the $P.I._{effect}$(REF) for the partially indirect system would be + 0,09 and the $P.I._{effect}$(REF) for the CO_2 system would be - 0,16.

7.9 Modelling SCOP values from the Danish data set

Besides the nominal load, in relation to the Annex 44 data set for Denmark (2015), information about the refrigeration system design such as plant type, refrigerant(s) and compressors used, and installed refrigeration capacity, were also collected. As these were not numeric values, they could not be directly used in a regression analysis, but it was found that there was a correlation by simple plotting (Figure 20).

In chapter **Fel! Hittar inte referenskälla.**, consideration has been given to the System Efficiency Index (SEI), and calculating a Seasonal Coefficient of Performance (SCOP) using the nominal load and refrigeration-related electricity use in the Danish data set. It was noted that the SEI has the downside that it is designed to be independent of evaporation and condensing temperature levels – whereas the choice of energy optimized temperature levels is of high importance for the energy efficiency of a real life supermarket refrigeration system. The calculated SCOP, which is dependent of the evaporation and condensing temperature levels, showed a correlation with an R^2 of 0.11 (Figure 41).

With the above in mind, and the knowledge about refrigerants from chapter 7.8, an effort was undertaken to model the SCOP for each of the four plant types in the Annex 44 data set for Denmark (2015), and to see whether such a modelled SCOP could perform better in regression analysis than the calculated SCOP.

Modelling approach

Each refrigeration system type in the data set was modelled using a tool called Pack Calculation Pro[5] under the same nominal load conditions of 20.9 kW cooling and 8.1 kW freezing load respectively, which is 75% of the installed capacity in the data set, which is close to the actual average nominal load of 21.1 and 9.1 kW respectively.

It was assumed that the load decreases 1% with each 1 K of ambient temperature reduction between the dimensioning temperature 32 ^{o}C to 20 ^{o}C for all plants, as outlined in Figure 45 showing the default values in Pack Calculation Pro.

[5] Pack Calculation Pro is a simulation tool for calculating and comparing the yearly energy consumption of refrigeration systems and heat pumps, using compressor performance polynomials and hourly weather data.

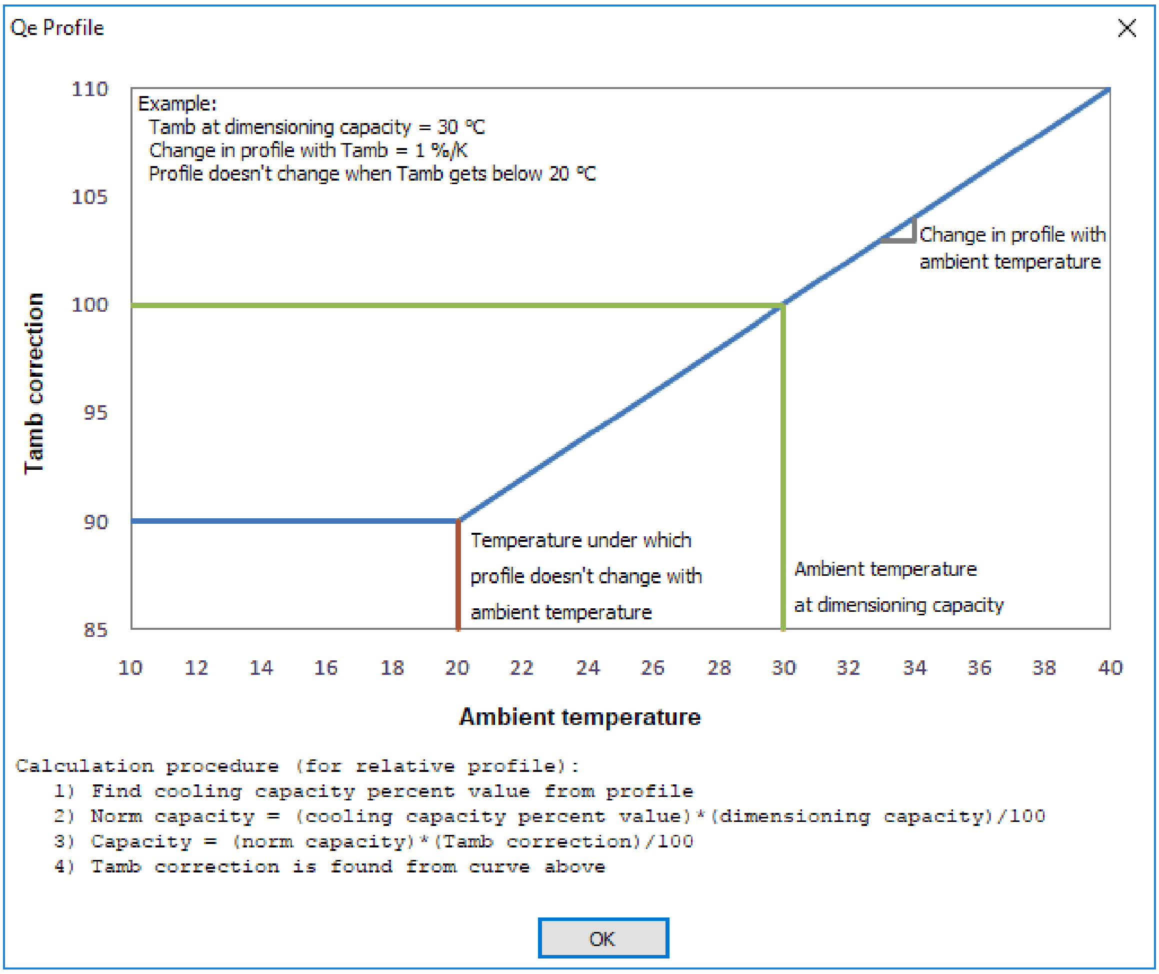


Figure 45: Cooling capacity change with change in ambient temperature. The ambient temperature at dimensioning capacity is 32 °C, the load change with ambient temperature is 1%, and the profile doesn't change further if ambient temperature is below 20 °C

Despite some geographic spread between plants in the data set, each plant was simulated with the same weather data, the Design Reference Year (DRY) for Copenhagen, Denmark (Kern-Hansen, 2013).

Pack Calculation Pro does not take dynamic behaviour into account, i.e. from mismatch between capacity and load. Furthermore, the modelling tool automatically disables compressors that are not needed in a certain hourly period. It is assumed that dynamic behaviour has a similar effect on performance on any refrigeration system type in the analysis, and that it therefore is acceptable to not consider dynamic behaviour when comparing the seasonal performance of different refrigeration systems.

Results and discussion

The modelling resulted in the SCOP values shown in Figure 46. Here, a much stronger correlation (R^2 = 0.40) was found for refrigeration-related electricity use than with the data set-derived SCOP in Figure 41.

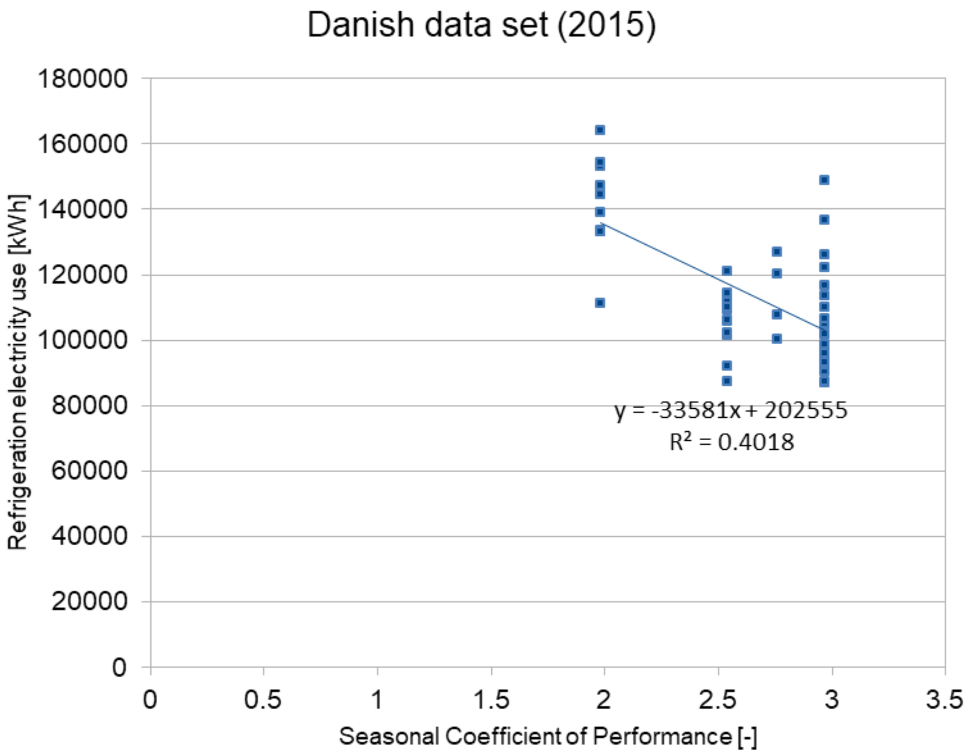


Figure 46: Seasonal COP values calculated with Pack Calculation Pro from refrigeration system specifications, for a reference nominal load of 9 kW at LT and 21 kW at MT, representative for the Annex 44 data set for Denmark (2015), for the four refrigeration system types in that data set.

The average SCOP values per refrigeration system type, from both the modelling-based and data-based approach, are summarized in Table 15. The four CO2 (2)-type plants seem to perform significantly worse in reality than expected from the model, while for other plant types the model matches better with measurements, which can also be seen in Figure 46.

The internal electricity use of refrigerated display cabinets for fans, lighting, defrost and rail heating are not included in the modelled SCOP, while it is included in the SCOP calculated directly from data. Depending on the cabinets and compressor pack used, this internal electricity use can amount to as much as 40-50% of the total refrigeration-related electricity. At the same time, the calculated SCOP is calculated with a fixed (nominal) load, which is much higher than actual load most of the year, while for the modelled SCOP the load varies with ambient temperature. The calculated and the modelled SCOP are thus not directly comparable.

It is assumed that the mismatch between nominal and actual load affects all refrigeration systems in the data set equally, as they are exposed to a similar climate – although air conditioning is not used in this chain other factors might influence the actual difference. The disregard of internal electricity use of the display cabinets in the modelling may have an equal effect on all supermarkets in the data set as well, though it wasn't possible to confirm whether the cabinets were similar enough within the data set, for supporting that assumption.

Within the scope of the Annex 44 project, it wasn't possible to develop more accurate models. It is recommended to further develop a Seasonal Performance Factor KPI, so it can be applied in a more reliable and user-friendly way. An option is to look into the Seasonal Energy Performance Ratio (SEPR), where climate influence could be included in the form of different rating climate conditions.

Table 15: Average data-based and modelling-based SCOP values for the four refrigeration system types in the Annex 44 data set for Denmark (2015). Too large difference between "measured" and modelled for CO2 (2) systems

System	$SCOP_{data}$ [-]	$SCOP_{model}$ [-]
R404A	2.55	2.65
CO2 (1)	2.61	2.94
CO2 (2)	2.12	2.91
Brine/CO2	1.78	2.00

8. New Performance Indicators

The conventional performance indicators described in the previous chapter do not fully cover all differences between supermarkets; therefore some additional (new) Performance Indicators are suggested in this chapter.

8.1 Sales volume

In a paper on performance indicators for supermarket refrigeration systems (excluding other supermarket energy systems) s. Acha (2016) concluded: “It can be seen […] that unlike what is commonly believed, pack consumption is not influenced by sales throughout the week. While trading intensity increases dramatically towards the end of a week, energy consumption fluctuates around 1500 kWh except for a drop on Sundays, which is attributed to shorter opening hours instead of changes in sales. Thus […] trading intensity is assumed to have no influence on refrigeration energy consumption”.

The Annex 44 data set for Denmark (2015) contains information on the sales volume per supermarket (number of receipts) as well as information on yearly electrical energy consumption and supermarket size (sales area).

For the year 2015 the total number of customer receipts is stated in the data file. This value can be used to understand the number of transactions and flow of customers in each supermarket. This value cannot be used to compare between different store formats as the typical or mean value of turnover per customer per visit as well as the relation between food and nonfood will be different. However, in this analysis it is convenient to check for variations between the supermarkets in the Danish data set as these are comparable in size and market the same product portfolio.

Analysis of this data confirms the conclusion that there is no relation between the sales volume (number of receipts) and the EEI (electrical energy intensity in kWh/m².year) for the supermarkets in the database. The conclusion is based on two approaches, firstly the EEI as a straightforward function of the number of receipts (normalized for reasons of confidentiality), and secondly the EEI as a function of the sales area weighted number of receipts (again, normalized). Both approaches show regressions with very low R^2 values, indicating that there is no relation between EEI and sales volume (Figure 47).

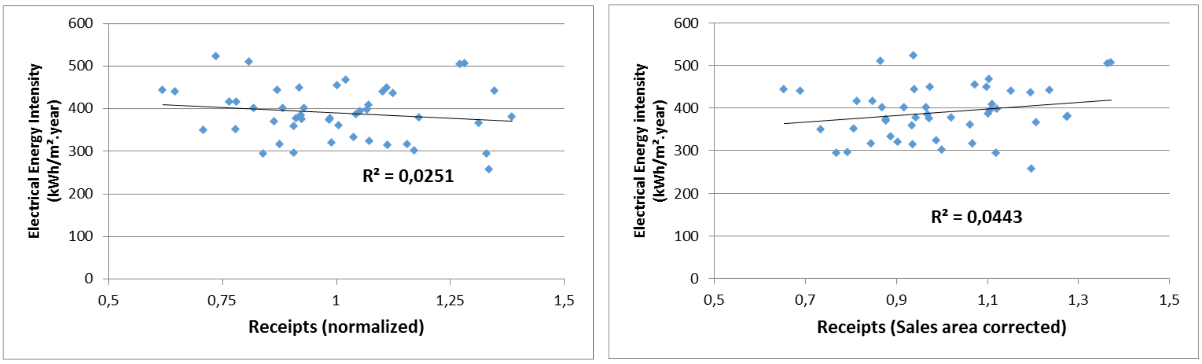


Figure 47: Electrical energy intensity as a function of (normalized) number of receipts and as a function of the (normalized) number of receipts corrected for supermarket size, for the Annex 44 Danish data set (2015).

8.2 Year of commissioning

In supermarkets as well as in society, there is a trend towards higher energy efficiency. The supermarket that is being built today, will therefore very likely be equipped with higher efficiency energy systems than existing supermarkets. Today's lighting systems will make more use of efficient LED lighting. Even though the general overhead lighting may remain conventional, lighting in special applications (like display cabinets) has often made the changeover to LED lighting.

Nowadays vertical refrigerated display cabinets are more commonly fitted with glass doors than older refrigerated display cabinets. These glass doors not only save energy on the refrigeration systems, but the fact that less cold air spills out of the cabinets into the shop also has a positive effect on the heating needs in winter. And even in summer, when it might seem helpful to have the cold air spilling from the cabinets to keep the supermarket cool, it is still more energy efficient to supply this need for cooling by means of an air conditioning system (due to a higher COP).

Heating and ventilation is also becoming more energy efficient, through the introduction of heat recovery. There is more common heat recovery of the ventilation air by means of an air to air heat exchanger, and there is also a growing application of heat recovery of the waste heat from the refrigeration system, both for water heating purposes and for space heating purposes.

Due to policy changes, especially in Europe, CO_2 refrigeration systems are now replacing conventional HFC refrigerant systems (Chapter 3.2). In the development of CO_2 refrigeration systems, energy efficiency has played an important role, and still does in the further development of these systems. This makes these newest CO_2 refrigeration systems more energy efficient nowadays than the conventional predecessors (as has been illustrated in chapter 7.8).

In energy consuming equipment in general, there is a trend towards higher energy efficiency (policy stimulated by minimum energy efficiency standards and energy labelling schemes). This can be illustrated by the development of the energy efficiency of refrigerated display cabinets over a number of years, which has shown a constantly improving trend of 2,5 % per year (Figure 48).

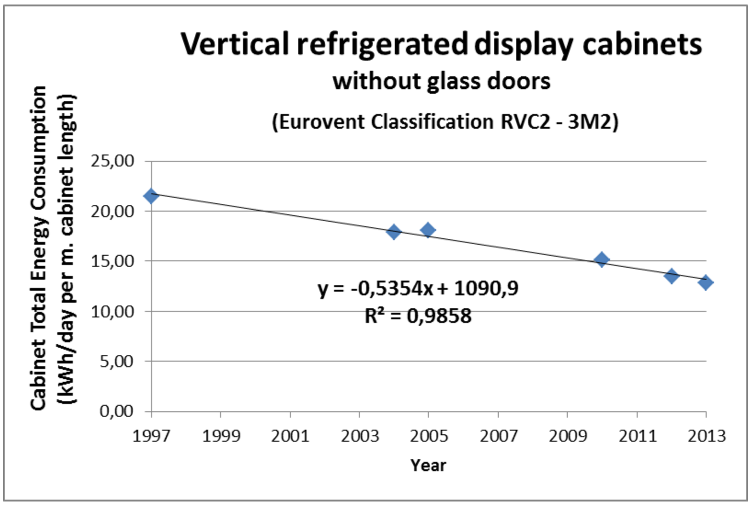


Figure 48: trend in energy use of vertical refrigerated display cabinets, based on the analysis of a large collection of cabinets offered on nthe market by different (EU) manufacturers (from H.Moons, 2014).

The data sets for the Netherlands 2013 and 2014 provide an opportunity to evaluate the combined effect of the energy efficiency trends in all supermarket energy subsystems. For this purpose, the data sets and their trend lines have been plotted together in Figure 49. Here we see (from the trend lines) a marked improvement in overall energy intensity (total yearly energy consumption per m² of sales area) from 572 kWh/m².year to 529 kWh/m².year. This is a 7,6 % improvement in just one year.

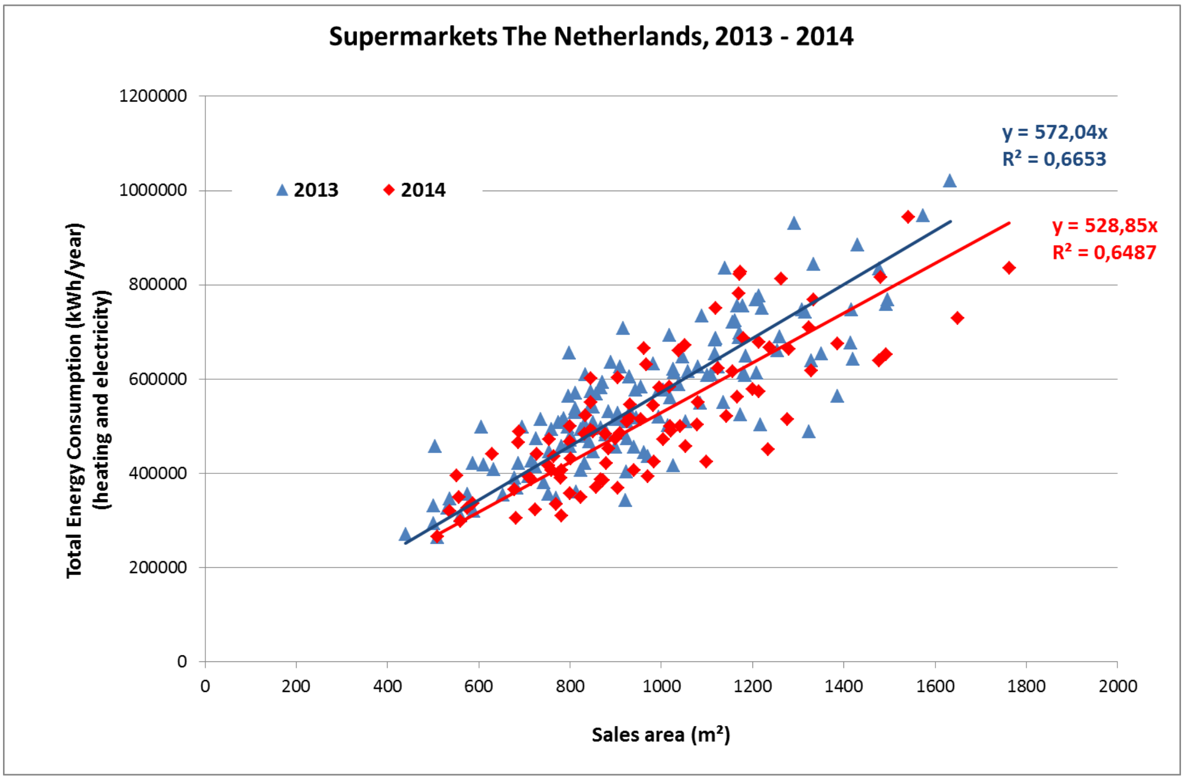


Figure 49: Total yearly energy consumption versus sales area for supermarkets in the Dutch databases 2013 and 2014.

It is not permissible to draw far-stretching conclusions from the comparison of two yearly data sets from just one country. But it is highly likely that, taking the efficiency developments in all energy sub systems into account, there is a strong dependency between the energy intensity of a supermarket and the year that it was commissioned. More data sets are needed to substantiate a yearly energy intensity improvement percentage, such as the 7,6 % shown for the Dutch data sets between 2013 and 2014. Danish data indicates an improvement of about 1 % per year over the period 1996 – 2015. It is likely that the percentage has changed (improved) over more recent years, as it seems the developments in energy efficiency of subsystems are nowadays faster than they were in the past.

The year of commissioning as performance indicator

When detailed information about energy subsystems is available, and corresponding performance indicators are applied (e.g. for the type of refrigerant, for the presence of glass doors etc.) there is no need to apply a performance indicator based on the year of commissioning – as this is already accounted for in the subsystems.

But when no information on subsystems is available, and only information on energy consumption, area and year of commissioning (YoC) is available, we could use the YoC as a performance indicator in the form:

$$E\text{ (new value)} = E\text{(initial value)} * (1 + (\text{YoC} - \text{reference year})) * (P.I._{effect}(\text{YoC}))$$

With

E(estimate N.)	=	Estimated yearly energy consumption based on N functionalities (MJ / yr).
E(estimate N-1)	=	Estimated yearly energy consumption based on N-1 functionalities (MJ / yr).
$P.I._{effect}$(YoC)	=	Relative change in overall supermarket energy efficiency per year.

Expected values for $P.I._{effect}$(YoC) are anywhere in the range -1 % to -10 % per year, but at this stage there is not sufficient data to propose a value. Moreover, it is very likely that $P.I._{effect}$(YoC) itself has changed over recent years.

8.3 Management Attitude

Supermarkets with good management often have less energy consumption compared to similar supermarkets. This is the story told by people who have worked with supermarket refrigeration systems and their energy consumption for many years. These people have a good sense of whether the refrigeration system use a large amount of energy or not by observing the state of the supermarket in terms of the cabinets are not over stacked with goods and how clean the floor is, if the floor washing machine, when not in use, is parked in the designated space and is well maintained and so on. It seems that these observations can reveal if the supermarket has a good management or not. The story goes that it is possible to follow a manager if he or she takes a new position in another supermarket in the same chain, as this will be mirrored by a change in the energy consumption. If the various tasks are well executed the supermarket are under good management and this is also somehow leading to a higher energy efficiency. However, it is very difficult to obtain measurable parameters for management efficiency, that can be documented and logged similarly to the logging of the electricity meter. The data of economic character that might reflect it, like turn over, but also information about sick leave and exchange rate of employees, is generally not available as they are considered confidential.

The energy consumed in a supermarket can be divided in two parts:

1) The base load of the energy to run the supermarket consumed by the light, cooling systems, ventilation etc. related to the outside weather conditions and temperature quality in the cabinets, storage rooms etc.

2) The energy related to the daily activities of the employees and customers in the supermarket related to the following:

- When the bake-off ovens are switched on in the morning, too early or right in time.
- Cleaning of condenser coils on plug-in units
- Number and duration of door openings in cold storages
- Number and duration of lid openings in the cabinets.
- Stacking of goods in cabinets.
- Use of other electrical equipment in the supermarket.
- Etc.

The important property of the energy influenced by the activities of the employees is that this consumption can be minimised by instruction and supervision from the management of the supermarket.

Management attitude towards supermarket renewals

One aspect of management attitude is the attitude towards supermarket renewals, meaning the complete refurbishment of existing shops as well as building new shops. In a supermarket nowadays, the shop is renewed from time to time, to keep its attractiveness for customers. Such a renewal is often not a mere "visual" renewal, but also includes updating or renewing the energy systems. And as newer energy system (such as LED lighting) generally have a better energy performance than older systems, the renewal has an effect on the supermarket energy efficiency.

The Annex 44 databases for The Netherlands 2013 and 2014 include information on whether a specific supermarket was renewed (or completely new) in the stated year. Therefore it is possible to split the databases in "old" and "renewed" supermarkets, and investigate the effect on energy performance. This exercise results, for the 2014 Dutch database, in Figure 50.

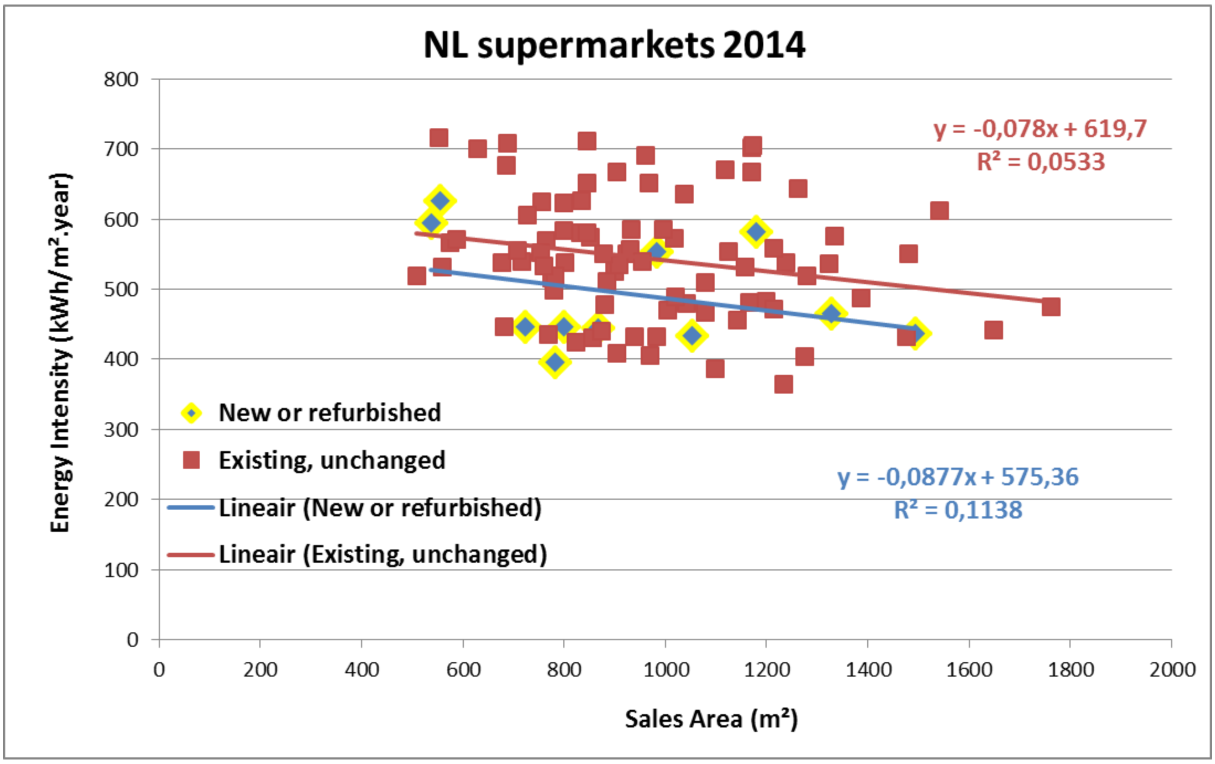


Figure 50: Energy Intensity for the Annex 44 database for The Netherlands (2014), split between unchanged supermarkets and new or refurbished supermarkets – with associated trend lines.

Even though the trend lines have a low R^2 values, a statistical analysis (t-test with 95% confidence) shows that there is a relevant difference on energy intensity between the “old” and new or refurbished supermarkets of -9,5 %.

Thus, the management attitude toward renewal has a direct effect on supermarket energy efficiency. When renewals are done often and include the renewal of energy systems, the energy efficiency will improve faster than in supermarkets where the management is not keen on investing in renewals.

8.4 System Control

The supermarket staff does not prioritize energy consumption. They care about satisfied customers and how to increase sales.

When not subject to the priorities by an energy management scheme, the settings used in the different controllers on the whole refrigeration plant including the refrigerated display cabinets are changed from time to time to solve local problems as they occur.

These problems could be related to high temperature alarms, dew on glass doors, ice blocking heat exchangers, etc. The solution to these local problems involves the associated refrigeration company who solve the problems. The refrigeration service technician will aim to avoid future temperature alarms and generally minimise service revisits and in the heat of problem solving the importance of changing set points related to energy consumption are largely ignored.

What the problems have in common is that the changed setting on the different controllers in the supermarket is overlooked because the local problem was solved. Consequently, the power consumption over time will drift to increase the operating cost.

The above-mentioned issue is hard to document. However, AK-Centralen A/S has done some investigations showing that the settings on the different controllers has some importance to the total energy consumption and should be controlled/balanced often. AK-Centralen create value for their costumers, the supermarkets, by monitoring the refrigeration plant including the refrigerated display cabinets on different parameters such as temperatures, electrical energy consumption, operating pressures etc. With access to this information and close cooperation with the supplier of the refrigeration plant AK-Centralen can help their costumer maintain and operate their cooling facilities in an cost effective way.

The investigations were carried out in two stages, one in 2009 and one in 2016/2017. The details are described in the two following chapters.

Parameter optimization in 2009

The project investigated the power saving potential in different adjustments/balancing on the refrigeration system and cabinets by documenting the power consumption before and after the performed adjustments. An overall saving of 26% was found.

By exploiting the features of the control system facilitating surveillance of temperatures and conditions of the systems AK-Centralen has found that up to a further 12% saving is achievable depending on the system. This will however require investments with a direct payback time ranging from 0.6 to 4 years based on energy savings, but not including the effects from reduced service cost and better temperature quality.

The adjustments where implemented on 7 Danish supermarkets in a period of 4 weeks. Details about each supermarket regarding chain and installed refrigeration system are shown in Table 16.

The power consumption related to the refrigeration system were acquired 5 weeks before the adjustments and 4 weeks during the adjustments to make comparison. Including: compressors, condensers and cabinets (light, fans, rail heat, defrost heaters) The project took place from the beginning of August to mid-October in 2009.

Table 16: System details regarding refrigeration system on the 7 supermarkets who participated in the investigation.

Supermarket (City)	Refrigeration system (Supplier)	Capacity, Medium temperature [kW]	Capacity, Low temperature [kW]
Hvidovre	Transcritical CO_2 (Advansor)	45.1	19.5

Holbæk	DX Boost R134a (Knudsen)	124.2	35.9
Valby	Transcritical CO_2 (Knudsen)	64.5	28.9
Kværndrup	Transcritical CO_2 (Knudsen)	33.6	9.5
Glostrup	DX Boost R404A (Knudsen)	85.9	25.3
Hellerup	DX Boost R404A (Knudsen)	57.0	15.5
Rødovre	DX Boost + Single comp. (Metasch)	55.3	16.8

Adjustments and test period

This paragraph will describe on which adjustments the energy savings were achieved. Table 17 shows when the adjustments were implemented during the test weeks. The different adjustments are explained in more detail below Table 17.

Table 17: table showing when each optimization was implemented on the supermarkets

Week	Adjustment
33	N/A
34	N/A
35	N/A
36	N/A
37	N/A
38	Rail heat modulation: 90/60% Temperature settings on refrigerated display cabinets adjusted Night lift
39	Rail heat modulation: 70/30% Fans in refrigerated display cabinets modulated when temperature reached.
40	Condensation- evaporation pressure optimization
41	

Modulation of rail heat

Most display cabinets are fitted with electrical rail heaters. The purpose of these heaters is to ensure no condensation takes place on the outside of the cabinet. In many supermarkets, these heaters are not controlled and consume large amounts of energy. By implementing pulse width modulation of the heaters energy can be saved. The first approach implemented was to modulate the heaters to be on 90% during the opening hours and 60% in the night time. This setting was further decreased later in the test period to 70/30%.

Cabinet fan control

Also, the fans in each cabinet was pulse width modulated, but only when the desired temperature was reached in the cabinet.

Night lift

During night when all cabinets and cold rooms are not subject to infiltration by door openings the evaporation pressure can be lifted 1-2K without lowering the temperature quality.

Temperature settings

The temperature settings on the refrigerated display cabinets in supermarkets are not always fixed on the right level. The main settings is +2°C (fresh meat preservation), +5°C (general perishable goods) and -18°C (frozen products) for the air temperature in the cabinets.

Condensation- and evaporation pressure optimization.

AK-Centralen did also optimize the condensation and evaporation pressure on the refrigeration systems. The set points are -10°C and -32°C respectively for the saturated temperature setting on the pack controller. For the condenser fans the minimum setting is 20°C and 15°C saturated condensing temperature for HFC and CO_2 systems respectively.

However, these settings were only a general guideline; wherever applicable depending on the type of system the settings were optimised to further reduce energy consumption, but without compromising the temperature quality in the display cabinets.

Results

The results of the change in settings for CO_2 respectively HFC based systems are shown graphically in Figure 51. The area between the vertical lines indicate the 2 weeks where the changes in settings were implemented. The curve for each supermarket shows a characteristic dip in consumption on the last day in each week. These are Sundays with reduced opening time. The overall tendency is a decline in consumption over the measuring period. The overall consumption is reduced by 26% comparing the weeks after with the weeks prior to the changes.

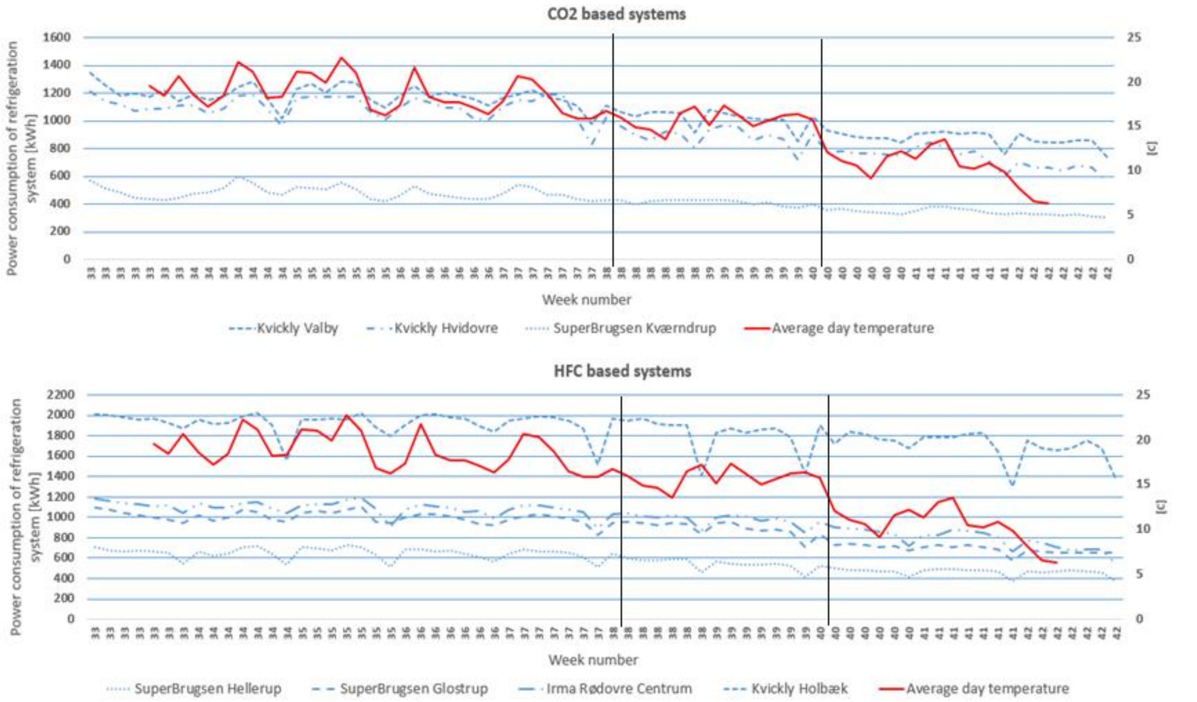


Figure 51: refrigeration energy consumption before, during and after the test period for CO2 based systems (above) and for HFC based systems (below).

The ambient temperature is shown in red as daily mean values for the general temperature in Denmark and thus does not reflect variations between the different geographical locations. Prior to the changes the mean temperature is 18.1 °C and after it is 13.2 °C, thus a reduction close to 5 °C.

Discussion

As the decline in consumption seems to correlate with the temperature the obvious question is whether this is coincidental or not.

AK-Centralen has the general observation at the time of the test that a drop in ambient temperature of 1K will decrease the total consumption by 0.5%. As approximately half of the consumption is compressor absorbed power this value seems quite low and would result in a correction by only 2.5% of the total consumption. This could be explained if the figure includes a significant percentage of refrigeration plants without floating head pressure control. And conversely that the reduction in absorbed power is realised by the reduced setting of the minimum head pressure control e.g. condenser fan minimum cut out saturated temperature. In other words, it means that without the changed setting the consumption would have been higher.

As rule of thumb assuming constant load, it is generally assumed that the compressor absorbed power would decrease by 3%/K for a drop in ambient temperature. Further there will be a drop in the refrigeration load due to changes in both the room temperature and humidity. From an earlier study a reduction of the load of app. 1% would be expected per 1°C drop of the ambient temperature. This is true for the interval 30 °C to 10 °C and with a mix of open and closed display cabinets (ESO2 ref to be added). Note that a prerequisite here is that there is generally no or limited use of fresh air cooling in Danish HVAC systems in supermarkets and prior to the heating season, as in this case, the indoor climate will reflect the changes in ambient conditions.

Thus the 5°C change would result in 5% lower load. This combined with the improved performance of the compressors gives an expected reduction in the total load of app. 0,5 + 0,5*0,95*0,85 = 0,10 or 10%. This is a substantively higher than the 2.5% stipulated by AK-Centralen and is believed to be a fair correction.

Parameter optimisation 2016/2017

AK-Centralen tested 4 supermarkets with trans-critical CO_2 systems and ran an optimisation period of 60 days. Parameters such as set points for evaporation pressure, night set back, display cabinet temperature, rail heating, condensation/ head pressure etc. were tuned to minimise energy consumption while still upholding the desired temperature quality target in the supermarket. When a quality level is set the correct optimization point is at that level, not lower, not higher. When the quality level deviated from the target the parameters were readjusted. The balancing and the tuning allowed the 4 stores to save 15-20% on average of the energy used by the refrigeration system. In this test, the balancing was done manually every day of the test period. AK-Centralen now has invested in the tools to go through this process on a large scale automatically requiring human interaction in the future only to revise algorithms and to make informed decisions to intervene in the right place at the right time.

Conclusion

In general refrigeration systems are installed to give the supermarket a certain temperature quality in all situations, that is never to exceed a certain temperature. Thus, a lot of systems are born with a certain safety margin that can be used to optimize for energy consumption. This test and as well as other tests performed by AK-Centralen confirm the conclusion: There are potential energy savings awaiting realisation.

By revising and trimming the control settings in 2009 of 7 supermarket refrigeration systems substantial savings were achieved. The total saving was 26% where 10% could be ascribed to the change in ambient temperature over the measuring period. The remaining 16% will result in all year savings. An important part of the 10% is related to a lower set point for the condenser fans which will achieve further savings in the cold season.

Further the subsequent test of 4 trans-critical CO_2 systems in 2016/ 2017 confirms the optimisation potential by identifying 15-20% energy savings.

All in all, these studies by AK-Centralen emphasises the importance of revising parameter settings on control systems on a regular basis as a best practise approach to achieve and maintain the lowest possible energy consumption.

Further benefits can be realised and maintained when the functionality of the control systems is used to its full potential with automated parameter optimisations.

Control parameter settings, example in a Belgian supermarket

In 2015, measurements were performed on a number of "plug-in" chest freezers in a Belgian supermarket, regarding internal air temperatures and energy consumption. The control parameter settings of these cabinets were "factory default", meaning they were used as delivered from the manufacturer without adjustments. These measurements on 5 identical cabinets showed significant differences in internal air temperatures (Table 18).

Table 18: internal air temperature measurements in 5 identical chest freezers in a Belgian supermarket (2015).

	Internal air temperatures		
	Minimum	Maximum	Average
Freezer 1	-20,8 °C	-18,0 °C	-19,6 °C
Freezer 2	-21,6 °C	-17,0 °C	-20,1 °C
Freezer 3	-25,7 °C	-20,6 °C	-23,6 °C
Freezer 4	-22,1 °C	-19,7 °C	-21,0 °C
Freezer 5	-23,8 °C	-18,9 °C	-21,6 °C
Average			***-21,2 °C***

On the same plug-in chest freezers, daily energy consumption measurements were performed at different temperature settings. From these measurements, it is possible to evaluate the trend line of energy consumption with the internal air temperature setting.

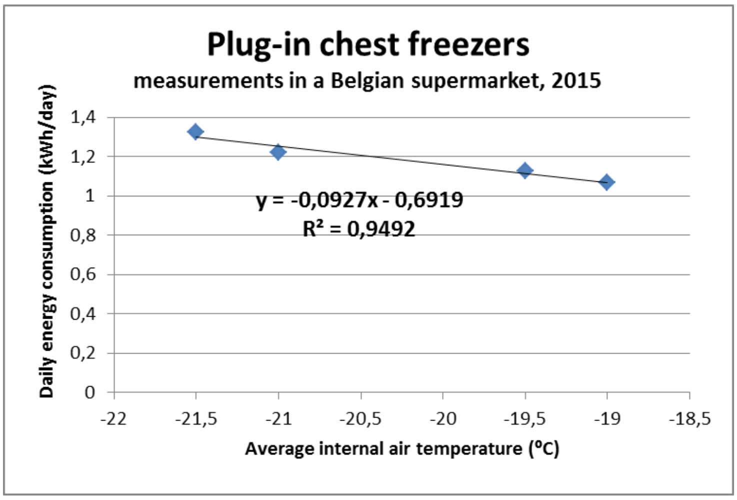


Figure 52: trend line of energy consumption with average internal air temperature for measurements on plug-in chest freezers in a Belgian supermarket (2015)

We can apply the energy consumption trend on the internal air temperature measurements in the chest freezers with original factory settings (Table 18). For the case with optimum performance (freezer 1) we then find an energy consumption of 1,125 kWh/day. But for the average of all freezers we find an energy consumption of 1,273 kWh/day. This is an additional energy consumption of 13 % which is completely unnecessary, and could be avoided when all freezers had optimum settings.

It must be noted that these plug-in chest freezers were equipped with mechanical thermostats. In newer models electronic thermostats are used, which probably have better factory settings than their mechanical predecessors.

8.5 System Dynamics

Closely related to the system control are the system dynamics. Where the control refers to the (correct) setting of system parameters, the dynamics refer to the (dynamic) reaction of the system to the parameter settings. Especially for refrigeration systems (but also in climate systems), the system dynamics can have an effect on the refrigeration system's energy consumption. This subject is not explored extensively in literature, but examples where the system dynamics have an effect on energy consumption can be shown for refrigerated display cabinet control and for compressor rack control.

Refrigerated display cabinet control

The cooling of a refrigerated display cabinet can be done by "on / off" switching of a fixed refrigeration capacity, or by means of a continuous refrigeration capacity adapted to the load. In other words, when 1,5 kW of refrigerating capacity is needed by the display cabinet, this could be done by supplying 3,0 kW for half an hour and then supplying no refrigeration for the next half hour, or it could be done by supplying 1,5 kW over the entire hour (Figure 53). Common household refrigerators operate in the "on / off" manner, which is often quite audible.

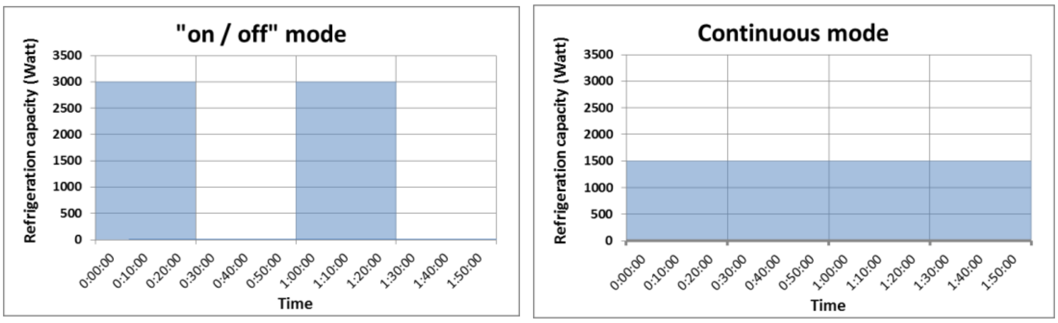


Figure 53: Refrigeration capacity demand as a function of time for a refrigerated display cabinet operated in "on off" mode (left) and in continuous mode (right).

When the heat exchangers of the refrigerated display cabinet remain the same, and at a fixed temperature inside the display cabinet, there is a difference in temperature levels of the refrigeration cycle between the 'on / off" mode and continuous mode. This is caused by the fact that the temperature difference over the heat exchanger is proportional to the heat load, and in the "on / off" mode the heat load is higher (3 kW in our example) than in the continuous mode (1,5 kW in our example). The differences in temperature levels have an effect on the energetic performance of the refrigeration cycle (the coefficient of Performance, COP). An example is shown in Table 19. In this example, the difference in refrigeration energy consumption is 24 % purely due to the difference in system dynamics.

Table 19: Comparison of temperature levels and energy consumption for a 1,5 kW refrigerated display cabinet operated in "on / off' mode and in continuous mode.

	"On / Off" mode	Continuous mode
Refrigerated display cabinet temperature	2 °C	2 °C
Ambient temperature	20 °C	20 °C
Refrigeration system low temp. level (evaporation)	- 12 °C	-6 °C
Refrigeration system high temp. level (condensation)	27,5 °C	23,6 °C
COP(Carnot)	6,6	8,7
Energy consumption (normalized)	100 %	76 %

Compressor rack control

The refrigeration system of the supermarket needs to deliver the refrigeration capacity that is demanded by refrigerated display cabinets and cold storage cells. Because this capacity demand is variable, the refrigeration system must supply a variable refrigeration capacity. In order to be able to do so, the refrigeration system is not equipped with a single compressor (with fixed capacity) but with a "compressor rack" consisting of 3 or 4 compressors. The compressors in the rack can be switched on and off to provide a variable refrigeration capacity, and often one of the compressors is equipped with a "variable frequency drive" to further refine the range of refrigerating capacities that can be delivered. The compressor rack control system controls the on / off switching of the compressors and the variable frequency drive to provide the desired refrigeration capacity. In a recent publication (S. Capanelli, 2017) the effect of a small adjustment in the compressor rack control was described. Before the adjustment, the compressor rack control did not react very quickly to changes in demand, resulting in frequent on / off switching of the two "fixed" compressors. After adjustment of the control reaction time, demand changes could be covered with the variable frequency compressor only, without need of additional on / off switching of the "fixed" compressors. This resulted in a much "smoother" evaporation temperature profile (Figure 54), but also in a 2-3 % decrease of refrigeration system energy consumption – due to improved system dynamics.

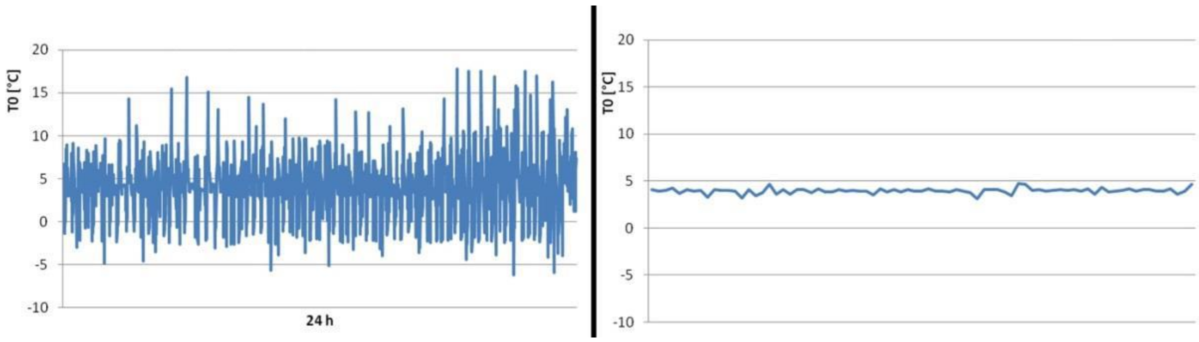


Figure 54: dynamic evaporation temperature profile before and after a small adjustment to the compressor rack control (from S. Capanelli, 2017).

These examples (for the refrigerated display cabinet control and for the compressor rack control) show how system dynamics can have an influence on the energy consumption. The relation between system dynamics and energy consumption is illustrated by these examples, but much further exploration of system dynamics and its consequences on energy consumption has yet to be done in the future.

Calculated versus measured (dynamic) performance

Another approach to estimate the dynamic losses has been performed on one of the Danish supermarkets described in the Danish data set (C. Heerup, K. Fredslund, 2016). In this case the measurements of the mass flows in the system enabled the calculation and mapping of the refrigeration load over a year. The compressors power consumption was mapped together with the condenser/ gascooler inlet temperature, suction and discharge pressures as well as the various temperatures in the system. From the mapped data it was possible to describe the load and the operating parameters to enable a calculation in a software simulation model (PackcalcPro) and compare the calculated compressor power consumption with the measured. This revealed a profound difference of approximately 25% higher consumption measured than the steady state values calculated from the compressor manufacturer data.

As this result showed a discrepancy much larger than anticipated, especially as the plant in question was performing quite well compared with other installations, a second calculation was made from a full set of data from a following year and this calculation gave a similar result.

Further to identify if the compressors was performing properly a control was made over a stable operating period. These data enabled the calculation of the isentropic efficiency which was very close to manufacturer data, in fact according to the measured data the compressor was slightly more efficient than expected based on the data from the manufacturer.

9. Conclusions and recommendations

The objective of the work in this Annex was to provide an estimate for the energy consumption of a supermarket, based on a variable number of performance indicators. With only one performance indicator used, the energy consumption will be a first estimate, but with more performance indicators used the estimated energy consumption will be more precise.

Based on the work in this Annex, we suggest to use the yearly total energy consumption per sales area unit as the performance indicator to best provide a first estimate of energy consumption. From data sets from Denmark, Sweden, and The Netherlands we have found the current value:

Average Energy Intensity = 400 kWh/m^2.year

Here the area (m^2) relates to the total supermarket area, and the energy consumption (kWh/year) to the sum of electrical energy and energy for heating. Combining electrical energy consumption and energy consumption for heating is necessary to account for heat recovery. A primary performance indicator based on supermarket area provides a better estimate than indicators based on refrigerated volume(s) or installed refrigeration capacity.

Secondary performance indicators can be used to refine the result given by the primary performance indicator. The overall idea is that the more performance indicators are used, the more precise the final estimate of energy consumption will be. The intention to provide secondary performance indicators with which it is possible to more precisely estimate the expected yearly energy consumption of a supermarket, has only been partly fulfilled. Only a few secondary performance indicators (P.I. ’s) could be quantified in our work, which is based on measured data from the field.

P.I. Deviation of the supermarket area from the average value (1360 m^2) :

$$E(\text{estimate } N) = E(\text{estimate } N\text{-}1) * (1 + (A_{total} – A_{total,mean})/100 * 0,01)$$

P.I. Actual opening hours compared to the average value (73 opening hours per week):

$$E(\text{estimate } N) = E(\text{estimate } N\text{-}1) * (1 + (OHW – 73,3) * 0,0047)$$

P.I. related to geographical location / outdoor climate:

No influence found from datasets or from (limited) modelling in Cybermart

P.I. related to supermarket indoor environment:

Relative Humidity (RH) is influential, but RH values are seldom measured in supermarkets

P.I. related to refrigerant type and/or refrigeration system type:

$$E(\text{new value}) = E(\text{initial value}) * (1 + (\text{if R404A=0} \mid \text{if other=1})) * (P.I._{effect}(REF))$$

$P.I._{effect}(REF)$ for partially indirect system = + 0,06 (only valid for Danish data set)

$P.I._{effect}(REF)$ for CO_2 system = - 0,11 (only valid for Danish data set)

P.I. on the basis of SEI or COP or SCOP values

Promising basis for effective P.I. but no measured values in supermarkets are yet available

P.I. related to sales volume:

Sales volume has no effect on supermarket energy efficiency

P.I. based on Year of Commissioning (YoC):

$E\ (\text{new value}) = E(\text{initial value}) * (1 + (\text{YoC} - \text{reference year})) * (\text{P.I.}_{\text{effect}}(\text{YoC}))$

Expected values for $\text{P.I.}_{\text{effect}}(\text{YoC})$ are in the range -1 % to -10 % per year

P.I. based on management attitude:

Management attitude has an effect on energy efficiency, but not yet quantifiable

P.I. related to optimization of control settings

Optimal control settings can considerably reduce refrigeration energy consumption, with amounts up to 10 – 20 % depending on the “uncontrolled” situation

P.I. related to optimization of system dynamics

Insufficient data at this stage to draw conclusions on importance of system dynamics.

In fact the “list” of performance indicators can be expanded, for every possible energy saving option an associated performance indicator can be defined. But even with a large data set containing measured yearly supermarket energy consumption in relation to a large number of energy saving options, it is not feasible to “distill” performance indicators relating to individual energy saving options by means of single regression analysis or multi variable regression analysis.

Variations in energy consumption between individual supermarkets relate to:

- Building thermal envelope
- Systems for ◦Lighting
    - Heating
    - Air conditioning
    - Ventilation
    - Refrigeration
- Commissioning, balancing and servicing of each individual system
- Behavioural characteristics of employees and customers

Within each of the above aspects, variations in the order of 30 % occur, which cause an overall spread in the energy performance data that mask the influence of any single energy saving option or that of a single factor of influence such as the outdoor climate.

The chosen approach, to investigate performance indicators based on measured “field data”, provides only a partial solution. For a more complete solution, the “field data” approach must be combined with an approach based on theoretical analysis and modelling of supermarket energy systems – which is beyond the scope of the Annex 44 work. By modelling, the influence of single energy saving options or single factors like outdoor climate can be traced. To reach the objectives targeted in annex 44, we recommend to use methods based on a combination of measured data and computer modelling of supermarkets.

In the validation of models based on field data however, the variations due to system commissioning, balancing and servicing, as well as behavioural characteristics of employees and customers will once again lead to discrepancies. We therefore recommend that when field data from different supermarkets is used for validations, the technicians and employees of these supermarkets are trained in a similar way before the measurements commence.

It is becoming a good practice to use heat recovery on supermarket refrigeration systems. Still, it is uncommon to look upon supermarket refrigeration systems as being heat pumps. By continuing research efforts concerning supermarket energy systems, the HPT can play a role in bringing the heat pump and refrigeration sectors closer together, to the mutual benefit of both sectors.

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Appendix A: Refrigeration system designs

Three main types of refrigeration systems are used in stores: condensing unit, centralised systems and stand-alone equipment. Condensing units are small-size refrigeration equipment with one or two compressors and a condenser installed on the roof or in a small machine room. Condensing units provide refrigeration to a small group of cabinets installed in convenience stores and small supermarkets.

Centralised systems consist of a central refrigeration unit located in a machine room. There are two types of centralised system: direct and indirect system. In a direct system (DX), racks of compressors in the machine room are connected to the evaporators in the display cases and to the condensers on the roof by long pipes with refrigerant. In an indirect system, the central refrigeration unit cools a fluid that circulates between the evaporator in the machine room and the display cases in the sales area. This fluid is known by different names, such as secondary refrigerant, secondary fluid, secondary coolant, heat transfer fluid, or brine.

Stand-alone (or “plug-in”) equipment is often a display case where the refrigeration system is integrated into the cabinet and the condenser heat is rejected to the sales area of the supermarket. Plug-in refrigerated display cabinets are often used to display ice cream or cold beverages such as beer or soft drinks.

Nowadays, a new system type is entering the market which uses refrigerated display cabinets with an integrated refrigerating system (like plug-in units), but instead of discharging the waste heat of the refrigerating system into the sales area, the waste heat is carried away by a “water loop”. The “water loop” temperature is kept at the desired temperature by means of a centralized heat pump system or simply by means of heat rejection to the ambient air (depending on outdoor conditions). The heat pump system can be used for space and water heating purposes.

The quest for increased energy efficiency and the phase-out of HFC refrigerants with high environmental impact have affected refrigeration system design for supermarkets considerably. A renewed interest in natural refrigerants and especially in CO_2 has resulted in the implementation of transcritical CO_2 refrigeration system designs in many supermarkets. Nevertheless, there are currently still many supermarket refrigeration systems containing HFC refrigerants in operation.

Direct System

The most traditional refrigeration system design in supermarkets is the direct system (Figure 55). In direct systems, the refrigerant circulates from the machine room, where the compressors are found, to the display cases in the sales area where it evaporates and absorbs heat. The system requires long pipes to connect the compressors to display cases and to the condensers on the roof. This implies very large refrigerant charges.

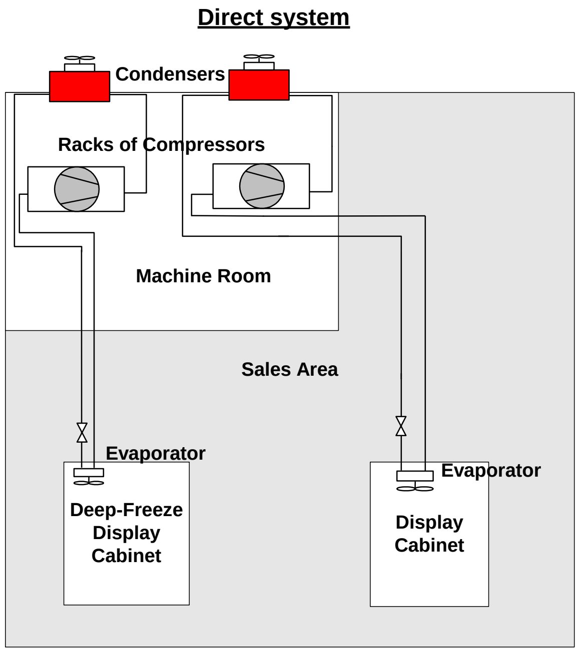

Figure 55: Direct System (Arias, 2005)

The most common direct system in supermarkets is the multiplex refrigeration system, which consists of a rack of compressors operating at the same saturated suction temperature with common suction and discharge refrigeration lines. The amount of refrigerant in a centralised direct system is typically 4-5 kg/kW of refrigeration capacity (Baxter, 2003). Another direct refrigeration system used in supermarkets is the single-compressor condensing system, which provides refrigeration to a small set of display cases.

Indirect System

System solutions with completely or partially indirect systems have been developed and introduced in supermarkets to reduce refrigerant charge and leakage.

Completely Indirect System

Refrigeration with indirect systems has been introduced in supermarkets to decrease the refrigerant charge and to minimize potential refrigerant leakage. Indirect systems have many forms; one of them is the completely indirect system. A design with a completely indirect system is presented in Figure 56. In this system design, there are two refrigeration systems (chillers) with different brines and levels of temperature.

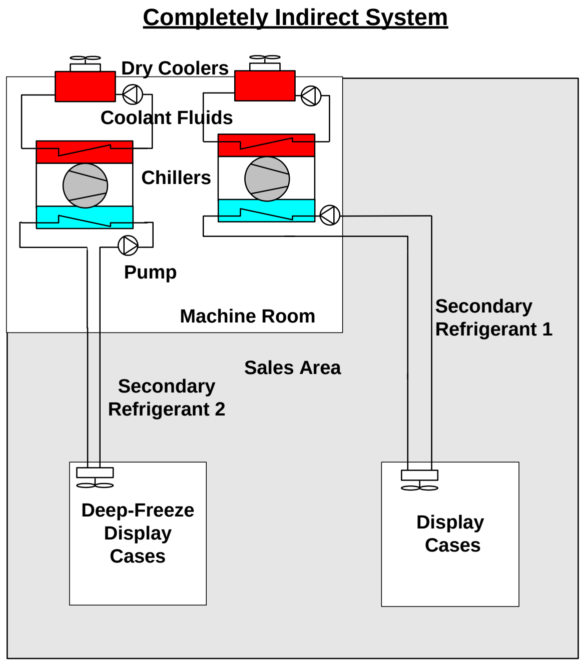

Figure 56: Completely Indirect System (Arias, 2005)

The secondary refrigerant in the medium temperature level often has an approach temperature around -8°C and a return temperature around -4°C. A typical value of secondary refrigerant temperature going to deep-freeze display cases is about -32°C and the return temperature is about -29°C. Secondary refrigerants based on potassium formate, potassium acetate, glycols, alcohols and chlorides are used as secondary refrigerants. Nowadays, CO_2 vapour-liquid is often used as secondary refrigerant in the low temperature system, CO_2 can also be used in the medium temperature level.

One or two other secondary loops (coolant fluids or dry cooler fluids) are used in the system to transport the heat rejected from the condensers, in the machine room, to two different dry coolers located on the roof of the supermarket. Typical out-going temperature of the coolant fluid is about 32°C and the return temperature is about 36°C.

The waste heat from the condenser can be recovered during the winter with substantial energy savings in cold climates.

Partially Indirect System

The most common partially indirect system in supermarkets in Sweden is shown in Figure 57.

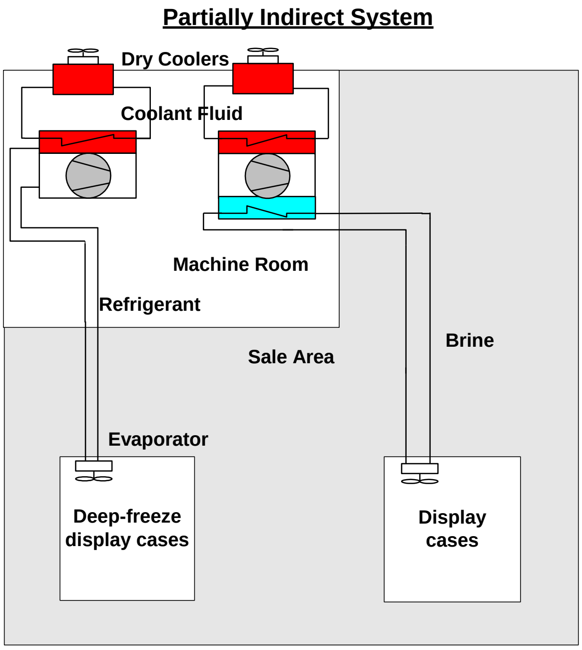

Figure 57: Partially Indirect System (Arias, 2005)

The heat from the condensers is rejected by a dry cooler on the roof of the supermarket to the environment. The low temperature system has a direct system between the compressors and the deep-freeze display cases, and the medium temperature system has an indirect system between the cabinets and the chiller.

Indirect Cascade System

The cascade system, shown in Figure 58 is a favourable solution that avoids the large pressure ratio in the low temperature system obtained in the completely indirect system. The installation operates with two different temperature levels and secondary loops. The temperature of the secondary refrigerant in the medium temperature unit has, as in completely indirect systems, an out-going temperature of about -8°C and a return temperature of about -4°C. The out-going temperature of the secondary refrigerant in the low temperature system is about -32°C and the return temperature is about -28°C.

The condenser heat from the low temperature system is rejected to the secondary refrigerant with the medium temperature. The condensing temperature of the low temperature system is about 0°C, which increases the coefficient of performance of the refrigeration cycle and decreases the energy consumption of the low temperature system. The drawback with this system is the increase of refrigeration capacity and compressor power of the medium temperature system due to the condenser heat from the low temperature system.

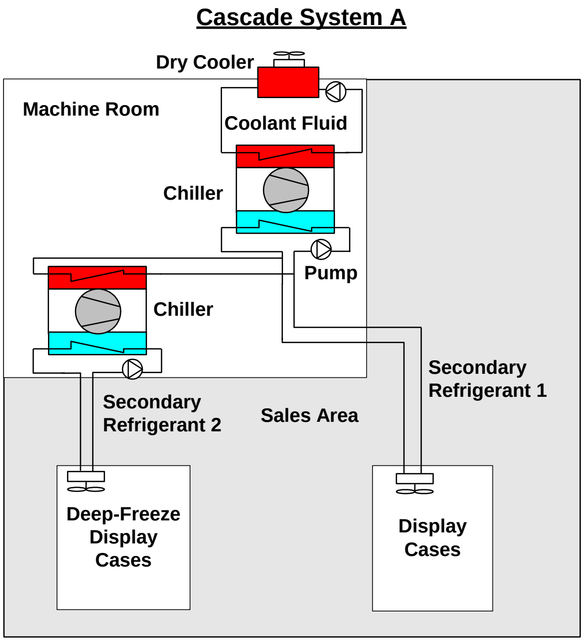

Figure 58: System Design 4: Cascade System (Arias, 2005)

The heat from the other condenser is rejected to the outside through a secondary loop that connects the condenser to a dry cooler located on the roof of the supermarket. The waste heat from the condenser can also be recovered during the winter.

CO_2 as the Only Refrigerant

CO_2 as the only refrigerant in the refrigeration system is an important alternative to HFC refrigerants in supermarkets. The CO_2 cycle might be trans-critical or sub-critical depending on ambient temperatures. The trans-critical temperature of CO_2 is 31°C. At higher ambient temperatures, the refrigeration system with CO_2 will operate at temperatures over the critical point. At low ambient temperature, as in cold climates, the operation of the refrigeration system will be in the sub-critical region.

The advantage with CO_2 as the only refrigerant in the refrigeration system in comparison with the cascade system is the absence of the heat exchanger between the low and medium temperature levels. The disadvantage is the high operating pressure of the high stage of the cycle.

Cascade System with CO_2

In order to decrease the pumping power in a low temperature system with CO_2 as secondary refrigerant, a system using CO_2 as refrigerant has been developed. A cascade refrigeration system with CO_2 in the low temperature stage and ammonia, propane, R404A or R407A in the medium temperature unit is an interesting solution that has been tested in several supermarkets with promising results (see Figure 59).

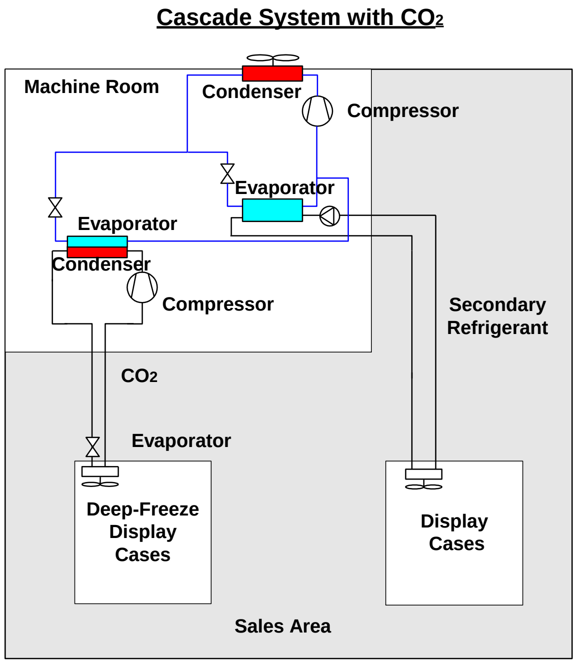

Figure 59: Cascade System with CO_2 in the Low Temperature Stage (Arias, 2005).

In Denmark, a cascade system operating with propane and CO_2 in the low temperature unit was implemented in two supermarkets. The propane is condensed directly in air-cooled condensers on the roof. The propane refrigeration system has two evaporators. In one evaporator (heat exchanger) the propane exchanges heat with an indirect system with glycol that covers the refrigeration requirement from the medium temperature unit (instead of glycol, it is also possible to use CO_2 as secondary refrigerant, which reduces pumping power and consequently MT compressor energy) . In the other evaporator (cascade heat exchanger) the evaporating propane condenses the CO_2 vapour of the low temperature subcritical CO_2 refrigeration cycle. Results from the system showed that the energy consumption decreased by about 5% compared to a conventional supermarket while the investment was 20% higher (back in 1999).

Multistage CO_2 system

A multistage CO_2 system is presented in Figure 60. The system has a two-stage compressor on the pressure side, an internal exchanger and a vessel with CO_2 in liquid and vapour state. A pump transports liquid CO_2 to cabinets and cold rooms in the medium temperature unit. Liquid CO_2 from the vessel goes to the direct expansion evaporator in cabinets and cold rooms in the low temperature level. After the evaporators, the CO_2 is compressed in the low pressure compressor and discharged as gas in the vessel (Schiesaro 2002).

Multistage System 1 with CO_2

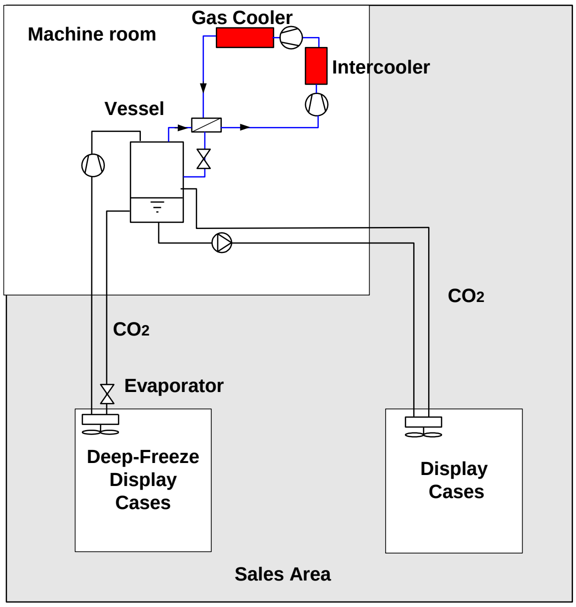

Figure 60: Multistage System 1 with CO_2 (Arias, 2005)

Another supermarket refrigeration system using CO_2 as the only refrigerant is the CO_2 trans-critical booster system. Simple schematic of a CO_2 trans-critical booster system with flash gas by-pass and its pressure-enthalpy diagram is shown in Figure 61. This system is an only-CO_2 solution which provides cooling in the medium temperature (MT) cabinets and low temperature (LT) freezers. The system is considered as state of the art system for CO_2 refrigeration in transcritical applications (i.e. suitable for higher outdoor temperatures). According to one of the main supermarket chains in Sweden, a supermarket built nowadays in Sweden will most probably be equipped with a CO_2 refrigeration system. System's independency of using other refrigerants such as HFCs, ammonia or hydrocarbons in indirect or cascade configurations results in less negative environmental impacts (compared to HFC) and better safety (compared to NH3-HC). Field measurements and performance comparison of five supermarkets using CO_2 and three advanced R404A systems have shown that CO_2 trans-critical booster systems have either higher or comparable COPs to conventional systems (Karampour, 2013).

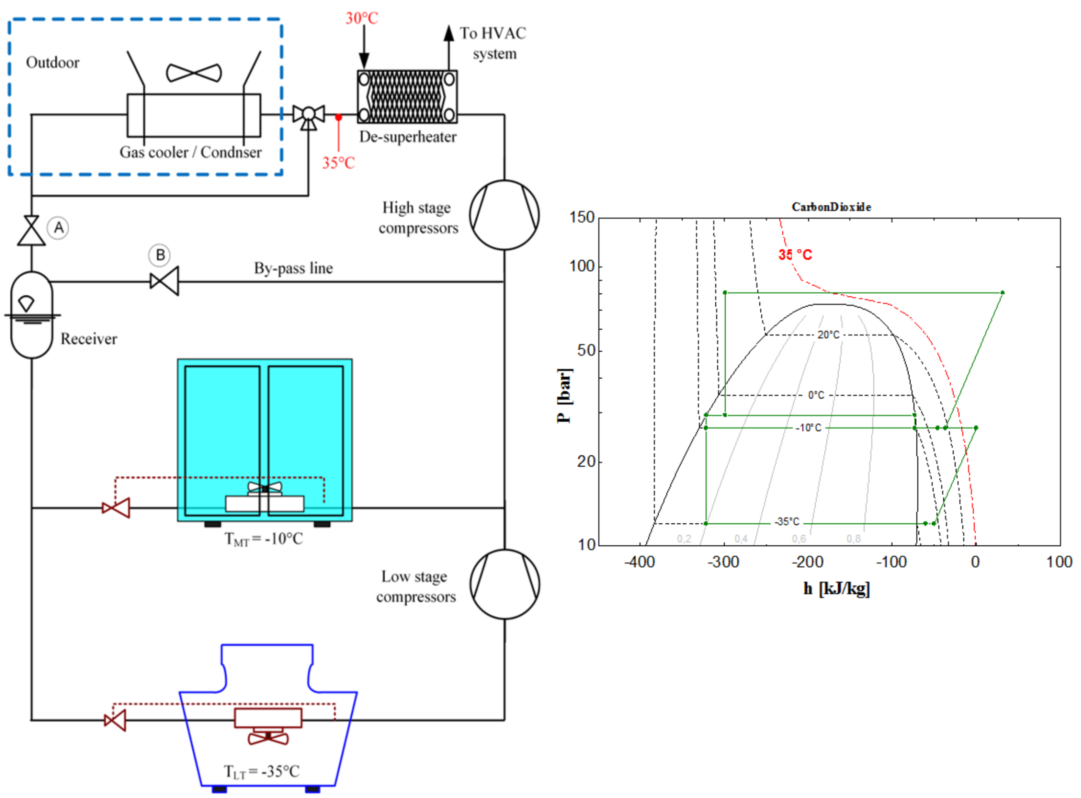

Figure 61: CO_2 trans-critical booster system schematic (left) CO_2 trans-critical booster P-h diagram (right)

As shown in the Figure 61, the refrigerant after the gas cooler/condenser enters a receiver. The liquid and vapour streams are separated in the receiver. The liquid is fed to the medium temperature (MT) and low temperature (LT) evaporators. CO_2 evaporation temperatures in medium temperature level and low temperature level are shown as -10°C and -35°C, respectively but the state-of-the-art CO_2 booster systems have few degrees higher evaporation temperatures.

The vapour compressed by the low temperature booster compressors is mixed with vapour outlet from MT evaporators and vapour from the by-pass line of receiver. The refrigerant is compressed in the high stage compressors to the high pressure level.

High pressure level is controlled by valve "A" depending on floating condensing or heat recovery mode. The system can be run in sub-critical or trans-critical zones, based on the ambient temperature and running mode.

Heat is recovered in a de-superheater; which is a heat exchanger after the high stage compressors and before condenser/gas cooler. There is a loop that connects the de-superheater to the HVAC system to transfer the required heat. The return temperature of the heat transfer fluid from the de-superheater is recommended to be as low as possible. The return temperature from the heating system is shown as 30°C, a typical value for Swedish supermarkets, and with 5K approach temperature, CO_2 temperature after the de-superheater is 35°C.

The development of CO_2 systems over the past few years is quite rapid, and much attention is given to designs that improve energy performance. An example is the use of parallel compression, which is used to compress the flash gas vapour directly from the receiver to the high pressure side, instead of the less efficient expansion to MT pressure level. Another efficiency improvement can be made with the use of ejectors. Ejectors are used to recover part of the expansion losses (which occur in all systems with standard expansion systems) and convert it to work for pre-compressing CO2 before the compressors suction line (vapour ejectors) or to allow higher evaporation pressures in flooded evaporators (liquid ejectors). These options and some additional state of the art options for increasing the energy efficiency are shown in Figure 62.

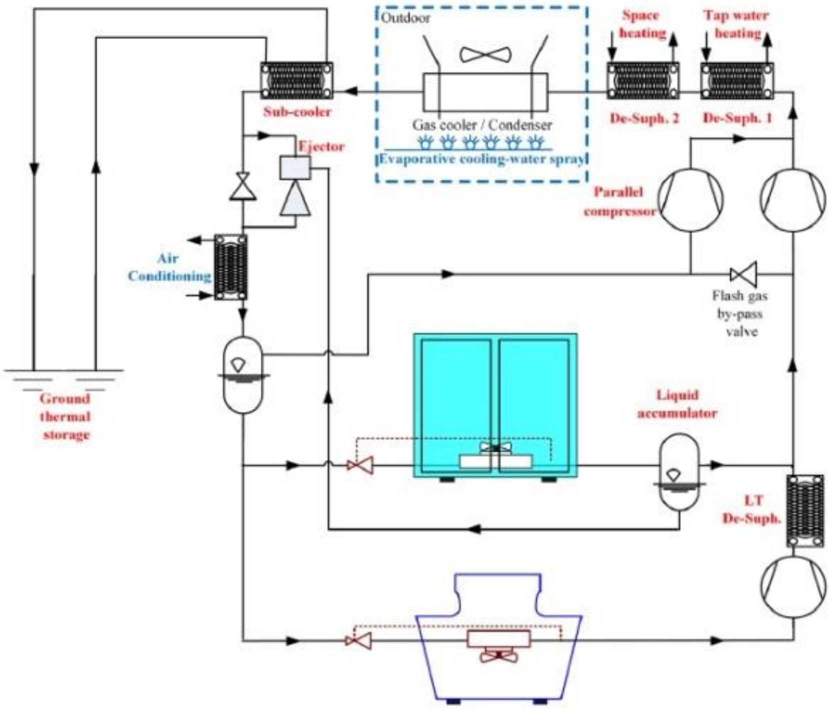

Figure 62: CO_2 booster system with a number of state of the art options to increase energy efficiency

<u>Designs for heat recovery or floating condensing pressure.</u>

Heat recovery in traditional refrigeration systems

The third heat recovery system design is shown in Figure 63. The heat from the condensers is rejected directly to the air system via a heat exchanger. The approach temperature to the heat exchanger is around 36°C, and the return temperature is around 32°C. The auxiliary heating is connected to the air system after the heat exchanger that recovers the heat from the refrigeration system.

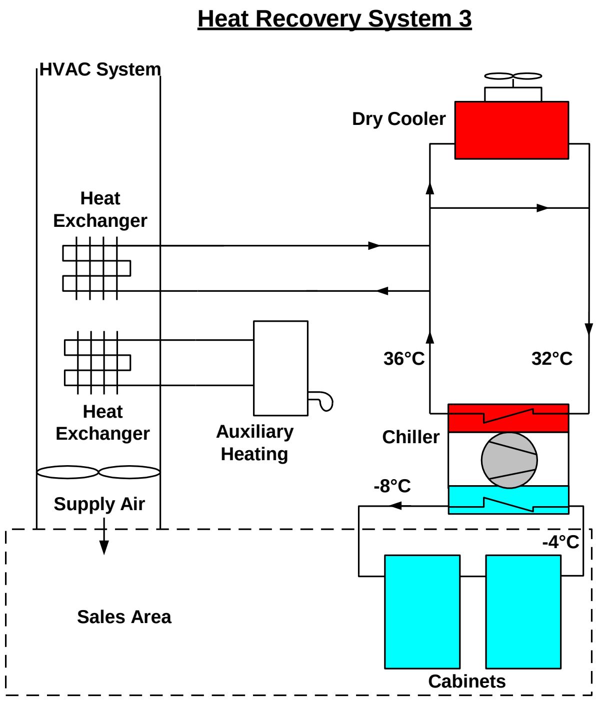

Figure 63: Heat Recovery System Design 3

Heat recovery in CO_2 transcritical booster system

CO_2 transcritical booster systems are one of the most energy-efficient systems in terms of heat recovery. The main reason for this fact is that by increasing the discharge pressure and switching from subcritical to transcritical zone, the amount of available heat increases considerably in CO_2 systems. To achieve an efficient heat recovery process and increase the heating capacity from the CO_2 booster system, a step-wise control of the refrigeration system is recommended. The steps are briefly described here but can be read more in detail in (Sawalha, 2013) and (Madsen and Bjerg, 2016):

- Step 1: Gas cooler should be run at full capacity to provide the lowest gas-cooler outlet temperature possible[6] – discharge pressure should be regulated to be able to cover the heating demand.
- Step 2: Discharge pressure should be fixed to a “max optimum” value and gas cooler capacity should be decreased by the following steps:
  - Step 2-1: Fan speed should be slowed down.
  - Step 2-2: Fans should be switched off.
  - Step 2-3: Gas cooler should be by-passed, via the three-way valve and the gas cooler by-pass line.

The “max optimum” discharge pressure value which is mentioned in step 2 is found based on the optimum discharge pressure algorithm but instead of using gas cooler exit temperature for the regulation, desuperheater exit temperature should be used (Sawalha, 2013).

[6] Minimum gas cooler exit temperature must not fall below +5 °C, otherwise the required receiver pressure cannot be maintained.

There have been several studies highlighting the importance and advantages of heat recovery in increasing the total efficiency of CO_2 transcritical booster system:

Floating Condensing System

A drawback with the heat recovery system is the high condensing temperature that increases the energy consumption of the refrigeration system. Another reason to use floating condensing is when heating costs are included in the rent of the building and there is not economic incentive to have heat recovery in the supermarket. In floating condensing systems (Figure 64), the condensing temperature changes with the ambient temperature The system is possible to implement with electronic expansion valves that are designed to operate over a wider range of pressure drops. At lower outdoor temperatures, the condensing temperature can float down properly. This increases the coefficient of performance, COP_2, and decreases the energy consumption of compressors. To cover the heat requirements of the premises, it is necessary to use an oil boiler or district heating.

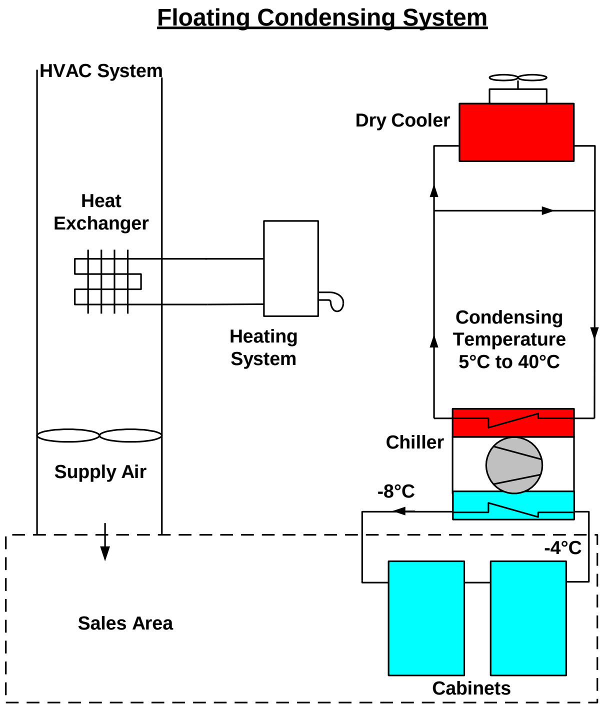

Figure 64:: Floating Condensing System

Appendix B. detailed analysis of the Danish data set

There are eight parameters in the Danish data set, some of which describe the refrigeration system and others the supermarket in general, such as sales area and number of sales receipts. Some of the parameters are already described in other chapters, and may be repeated here for completeness.

Firstly, for each parameter, the effect on electricity use is analysed, using a linear trend line with intercept, and no normalization.

With a multi-variable regression analysis, different models will be tested against the data set. The goal is to predict electricity usage with as low an intercept and as high an R^2 as possible, with as few parameters as possible.

Individual parameter study

Sales and extra area

As seen in Figure 65, the sales area seems to predict non-refrigeration electricity use quite well. The electricity used by the refrigeration system correlates quite poorly to sales area, indicating that better parameters are needed to predict that half of the total electricity use.

Data for the storage area was also made available, but as expected from paragraph 6.7**Fel! Hittar inte referenskälla.**, was found to correlate poorly with refrigeration or other electricity use.

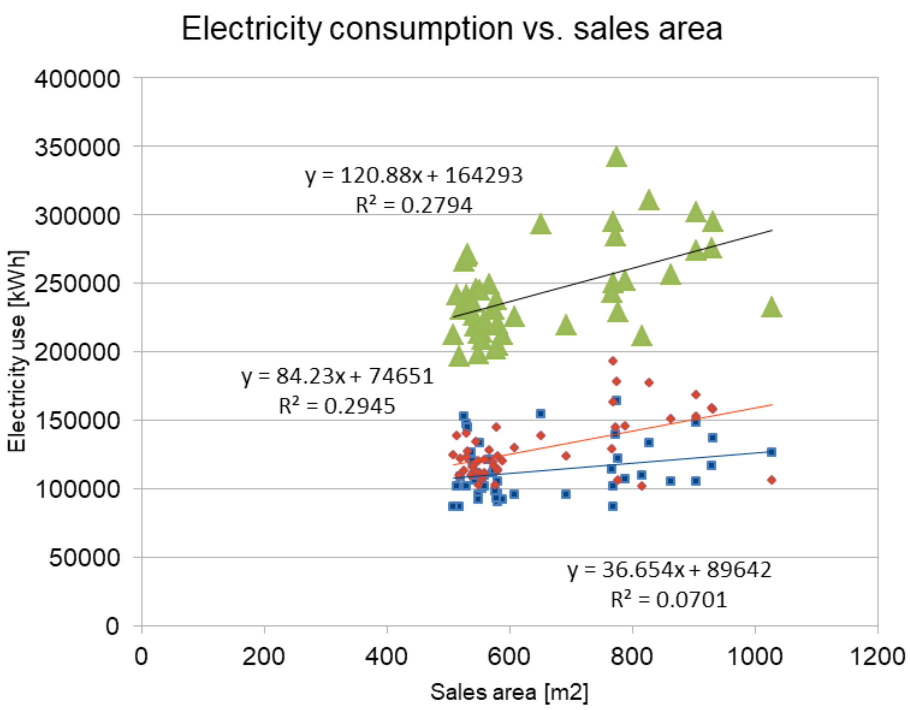

Figure 65: Electricity consumption as function of sales area. Blue square is refrigeration; orange diamond is non-refrigeration; green triangle is total

Nominal refrigeration system load

The nominal cooling load on the refrigeration system in kW is available at the chilled (MT) and frozen (LT) temperature levels. It is the sum of nominal cooling load of all installed refrigeration cabinets, storage rooms etc., as provided by the equipment manufacturers, for the two evaporation temperature levels.

The nominal chilled load is, surprisingly, not showing a clear correlation with refrigeration electricity use (Figure 66). A slight negative trend is shown, but this is neither statistically significant, nor something that can be explained from theory.

The nominal frozen load does correlate with the refrigeration electricity use, and shows that a higher freezing load causes higher electricity use, as expected (Figure 67).

When looking at the combined cooling and freezing load in Figure 68, no clear trend is found – the trends seen for cooling and freezing separately seem to cancel each other out. A further look however shows that the two largest refrigeration system type groups, R404a and CO2 (1), do have a clear correlation between total refrigeration load and refrigeration-related electricity use (Figure 69).

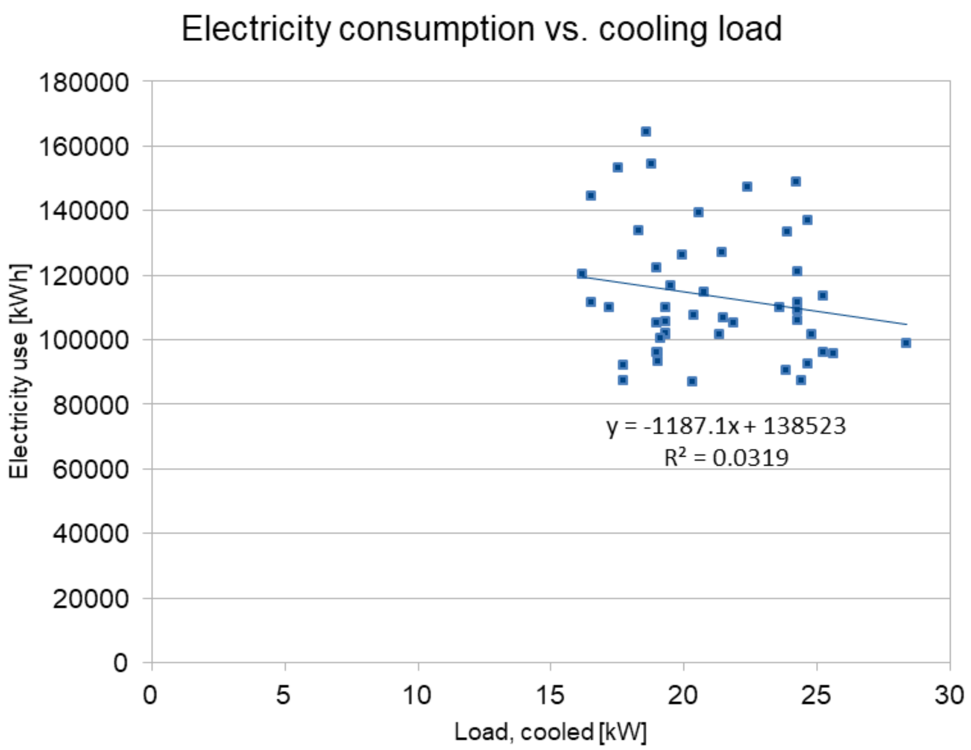

Figure 66: Refrigeration system electricity consumption as function of nominal chilled load.

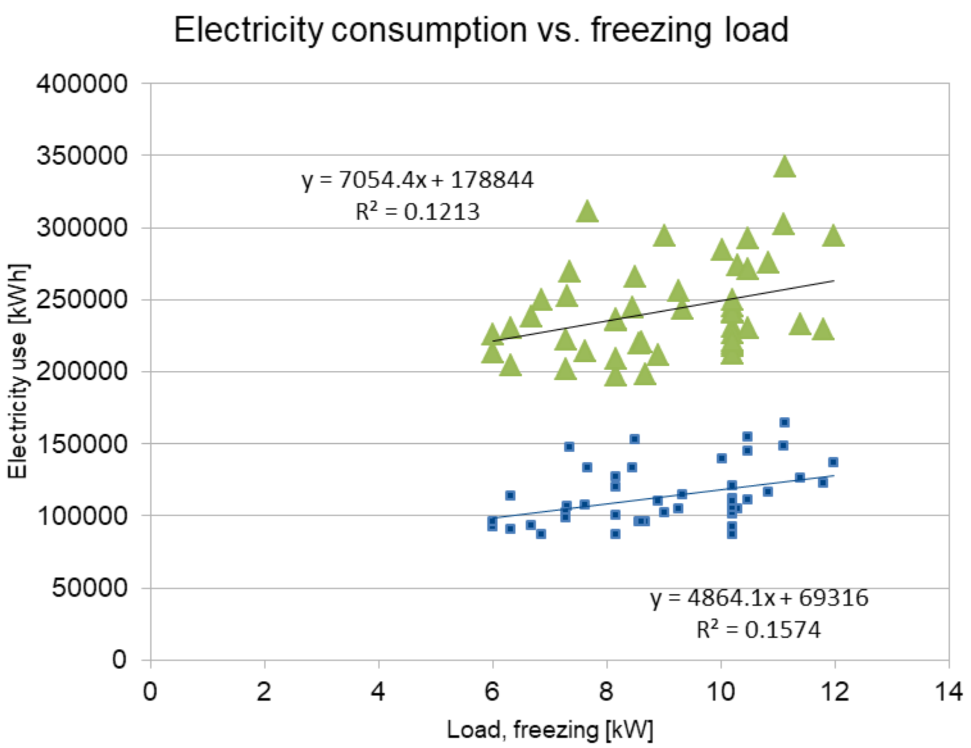

Figure 67: Electricity consumption as function of nominal frozen load. Blue square is refrigeration; green triangle is total

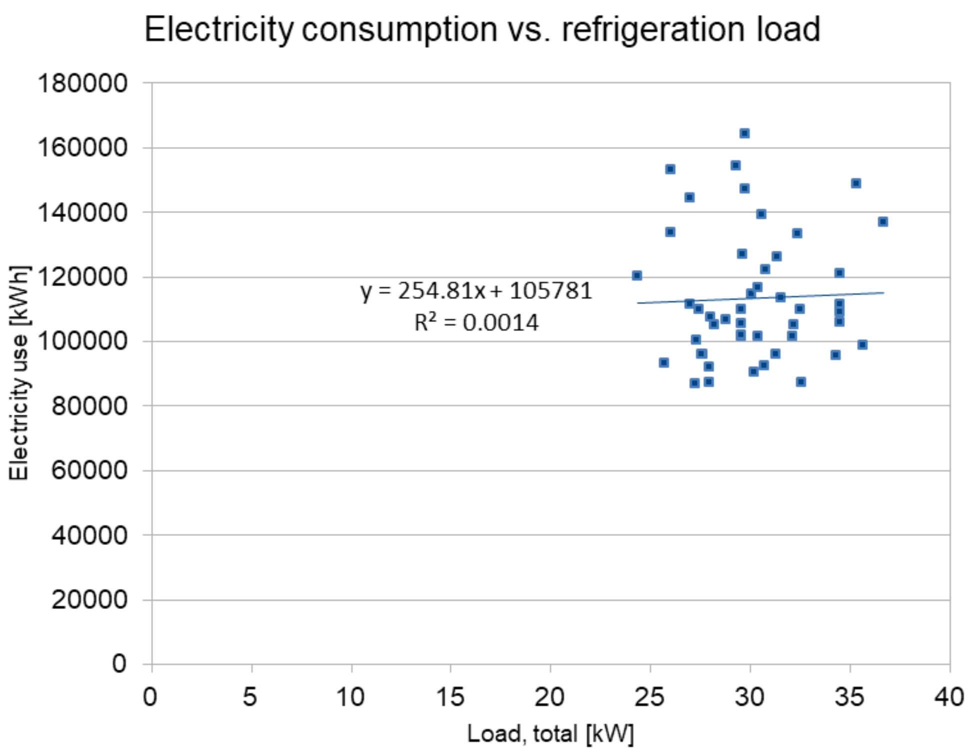

Figure 68: Refrigeration electricity consumption as function of nominal refrigeration load

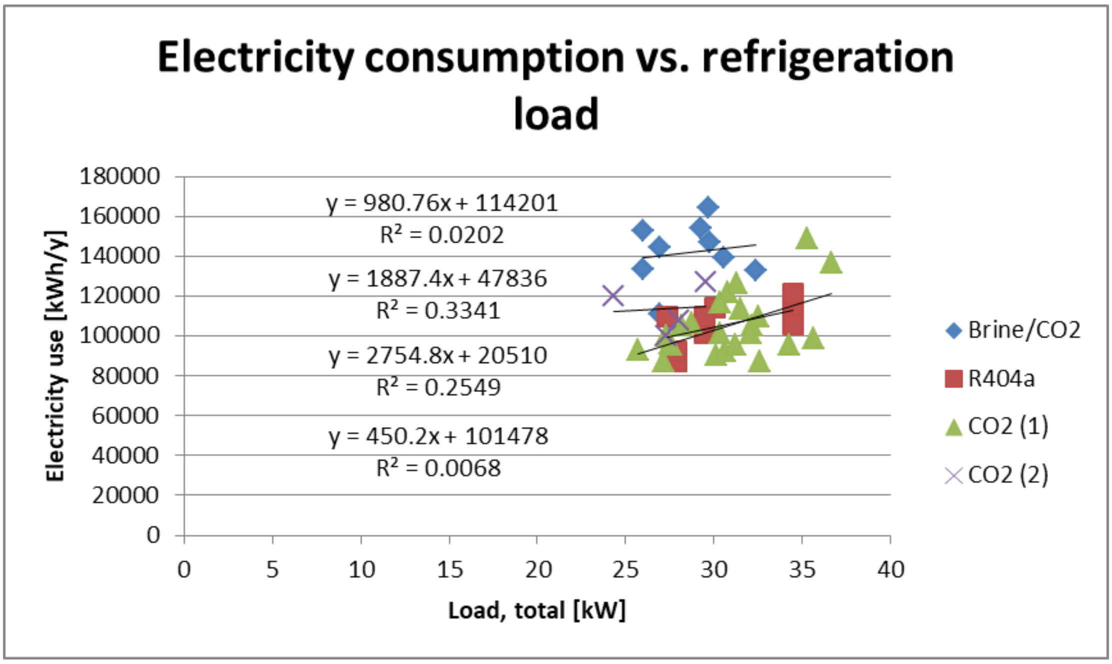

Figure 69: Refrigeration electricity use as function of nominal refrigeration load, grouped by refrigeration system type. Trend line functions in same order as legend

Installed refrigeration capacity

The installed cooling capacity in kW of the refrigeration plant is available at the two common temperature levels: chilled (Medium temperature; or MT) and frozen (Low Temperature; or LT). For most systems in this analysis, the LT and MT capacity are related: With a higher LT load, the MT capacity increases too because the MT system needs to discharge the heat from the LT level as well. Therefore, only the combined capacity is investigated.

In Figure 70 a slight negative correlation between installed capacity and electricity use is found. The clustering on the x-axis is due to refrigeration system standardization within the supermarket chain of the Denmark (2015) data set, where each cluster matches with a refrigeration system type – there is little or no variation in capacity with the same refrigeration system type within the data set.

Normally, installed refrigeration capacity is a function of nominal load, as capacity is installed based on expected load. Within the current data set however, it turns out capacity is almost the same for all plants, even though the demand varies.

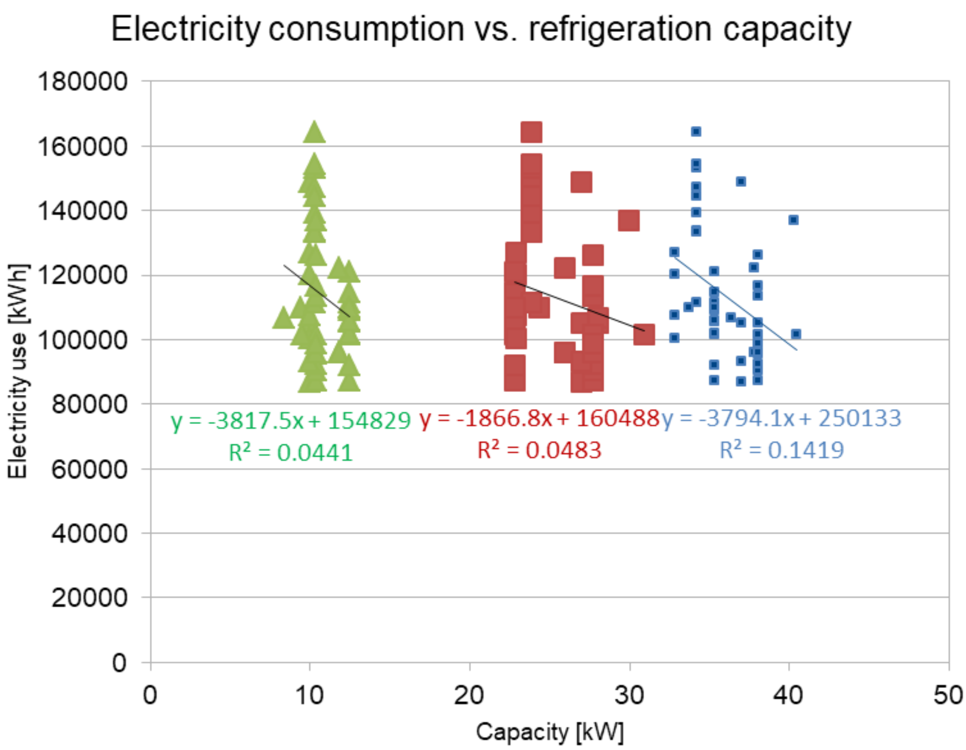

Figure 70: Refrigeration system electricity use as function of installed capacity. Green is LT, red is MT, blue is total refrigeration capacity. Significant clustering per refrigeration system type, due to low or no capacity variation with same system type

Refrigeration system overcapacity

In this paragraph, it is investigated whether looking at capacity as a function of nominal load gives clearer information than looking at only the installed capacity.

In Figure 71 the overcapacity percentage, found by subtracting the nominal load from the installed capacity and dividing by the nominal load, is plotted against the electricity use intensity per kW of nominal load, found by dividing the refrigeration electricity use with the nominal load. The reason for the latter is that the overcapacity is inversely proportional to the nominal load within the current data set, due to almost equal capacity for all plants, which masks any effect the overcapacity itself might have. This also applies to multi-variable regression analysis.

A slight positive trend is found, indicating that the electricity use per kW of nominal load slightly increases with increasing overcapacity, as expected. As seen earlier, the CO2/Brine plants perform slightly worse than the other ones – though they also seem more sensitive to overcapacity than for instance the CO2 (1) plants. This is probably due to the use of speed controlled compressors in this group of systems which makes them better to adapt to variations in the load.

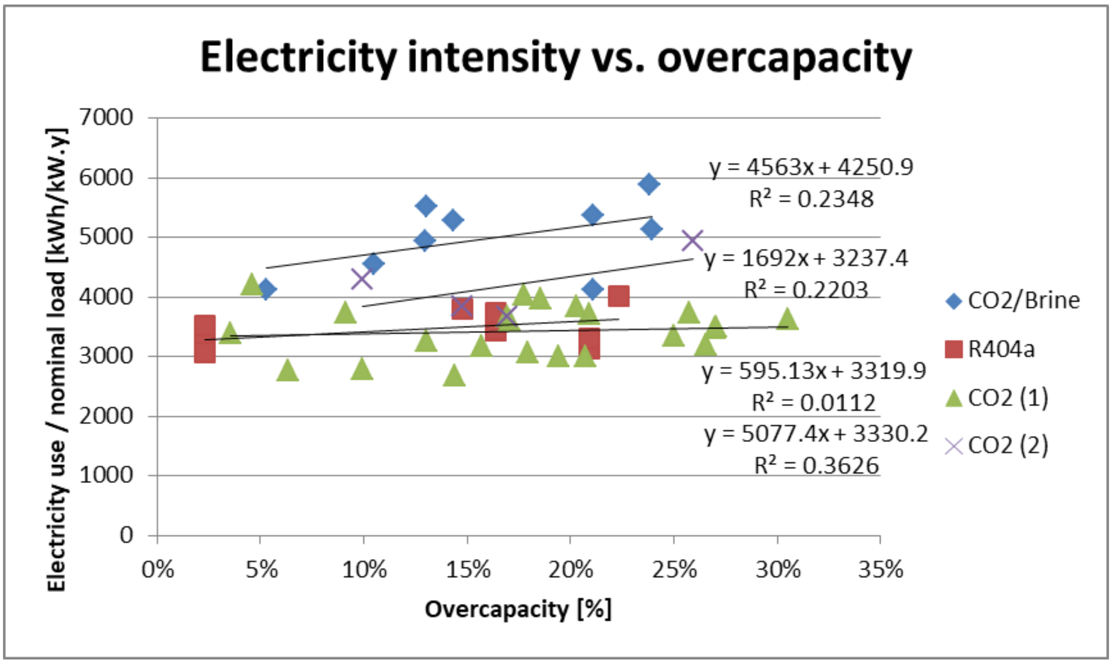

Figure 71: Refrigeration electricity use per kW of nominal load, as a function of overcapacity per kW of nominal load. Trend line functions in same order as legend

Seasonal Performance Factor (SPF)

Using a theoretical Seasonal Performance Factor was proposed in paragraph 7.9. For the Danish data set, a parameter with the nature of the Seasonal Coefficient of Performance (SCOP) was calculated per refrigeration system type, by modelling them in a tool called Pack Calculation Pro. The SPF performance indicator needs further development, and another approach may be more reproducible and easier to apply. Despite its limitations, the modelled SCOP is analysed qualitatively here.

The relation between electricity use and modelled SCOP is displayed in Figure 72. A strong inverse correlation between refrigeration electricity use and SCOP is found for refrigeration-related and total electricity use, which is expected.

In the regression analysis, it is desired to only have parameters that are directly proportional to electricity use. As an increasing SCOP decreases electricity use, everything else left equal, the inverse of the SCOP could be used instead; this can be regarded as a cost function for refrigeration. As shown in Figure 73, this increases the R-squared for both refrigeration and total electricity use slightly, however that effect is attributed to the distribution of data points.

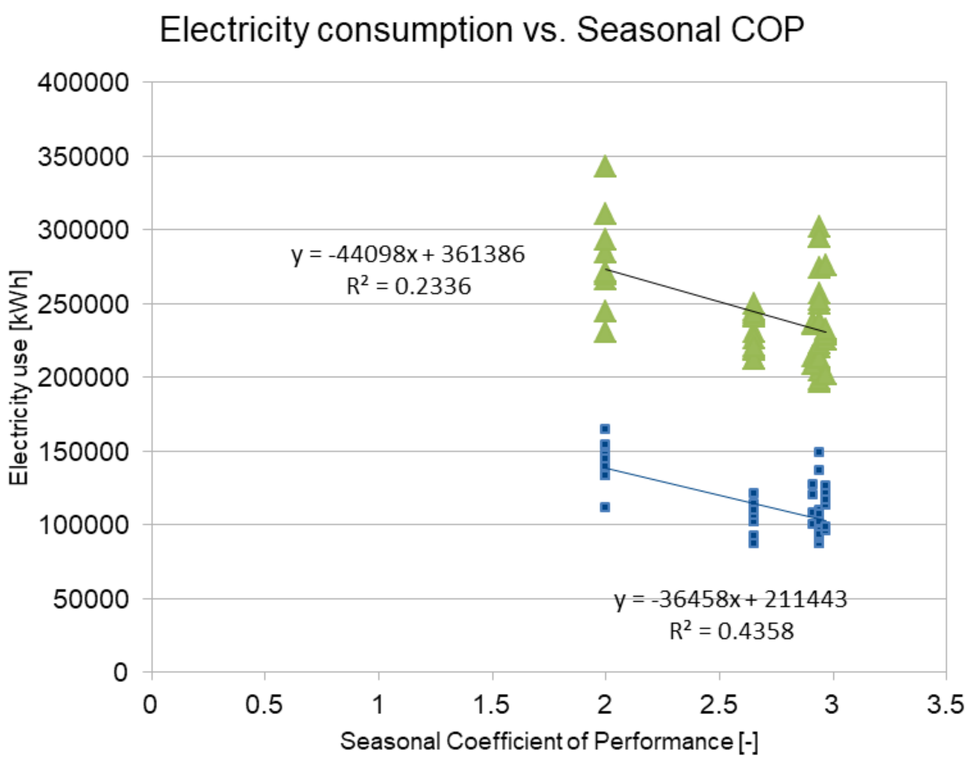

Figure 72: Electricity consumption as function of Seasonal Coefficient of Performance (SCOP). Blue square is refrigeration; green triangle is total

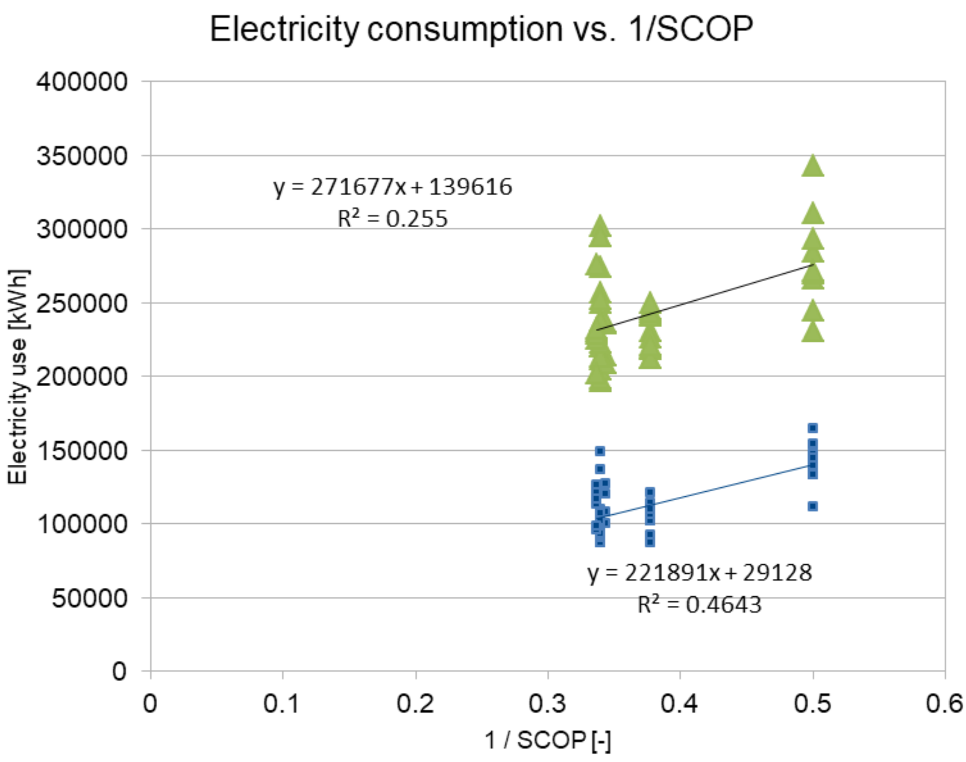

Figure 73: Electricity consumption as function of the inverse of SCOP. Blue square is refrigeration; green triangle is total

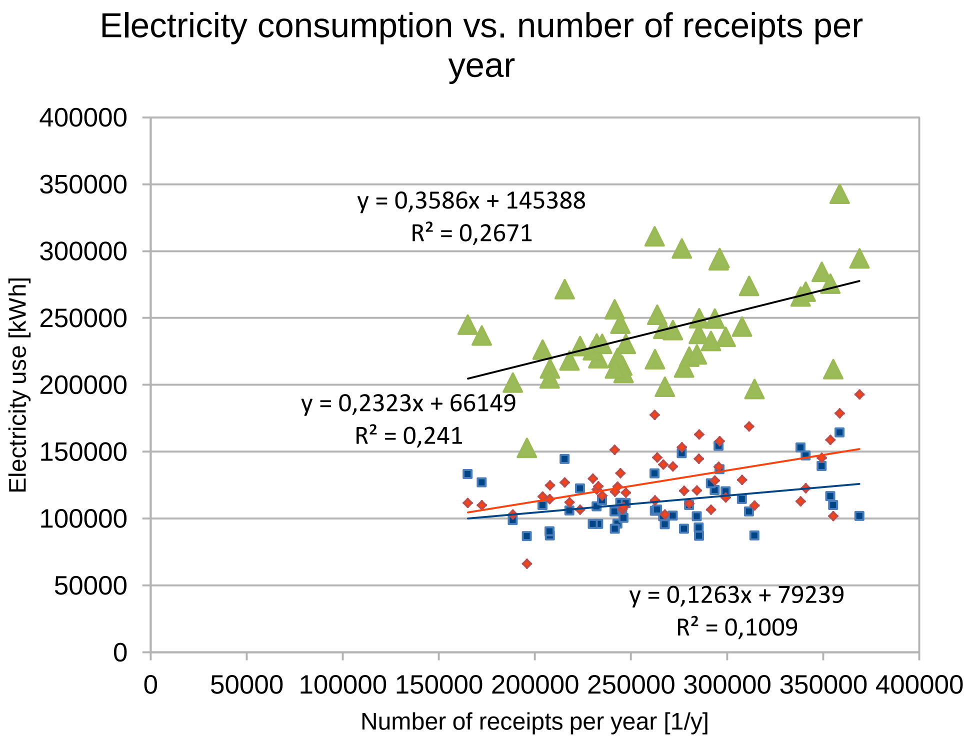

Figure 74: Electricity consumption as function of number of receipts per year. Blue square is refrigeration; orange diamond is non-refrigeration; green triangle is total

Sales volume, footfall

For the sales volume, or footfall, data is available in the form of number of receipts per year, which at least within the analysed supermarket chain are comparable as they are similar in purchase pattern and store layout. The numbers are presented in Figure 74, and the correlation for non-refrigeration electricity use is stronger than for refrigeration-related electricity use. However, the trend is completely removed when normalizing by dividing the number of receipts with the sales area.

Summary

The R-squared values found for each predictor in the data set, when used as the only predictor, are listed in Table 20.

Table 20: Coefficient of determination (R^2) for each predictor and electricity use group in the Danish Annex 44 data set

	Refrigeration	Non-refrig.	Total
Sales area [m2]	7.01%	29.45%	27.94%
Extra area [m2]	2.68%	6.32%	7.27%
Installed capacity [kW]	14.19%	-	-
Nominal load [kW] all	(0.14)%	-	-
Nominal load [kW] R404A	33%		
Nominal load [kW] CO2(1)	25%		
1/SCOP [-]	46.43%	-	25.5%
Number of receipts [1/y]	8.38%	20.76%	23.47%

The sales area, the inverse of SCOP, and the number of receipts seem useful as standalone parameters. The extra area and the actual installed capacity for LT/MT seem neither to be strong predictors when used individually, nor is it expected that they get more value when combining with other indicators.

For reference the two best represented systems are included in the table for nominal load versus electricity use. The systems R404A and CO2(1) are best represented by 12 respectively 22 out of the 49 plants and for these systems there is a relatively high coefficient of determination.

As seen in Figure 69 and Figure 71, there are large differences in how well the nominal load and the overcapacity fit with electricity use, depending on refrigeration system type. These two parameters can perhaps be of value once the data is corrected for differences in refrigeration system type, i.e. by SCOP.

Multi-variable regression analysis

The goal of the multi-variable regression analysis is to combine the parameters from Table 20 into one model, describing the supermarket electricity use better than each parameter individually due to the inter-play between parameters. As an example, the Seasonal Coefficient of Performance may vary strongly for shops with an almost equal sales area or number of receipts, so where SCOP alone might not explain electricity use, the combination of SCOP and sales area might explain it much better.

Another goal is to end up with a model that has as few artefacts as possible of the Danish data set, and can be applied as generally as possible. This for instance means that a large intercept is not ideal, so it should be investigated whether the intercept can be removed altogether in the final model. Also, it should be possible for others to compare their supermarket with the Danish data set benchmark using the same model, so the parameters should be well-defined so they can be collected reproducibly.

For each group of electricity use, as a start, a model with all parameters and an intercept will be created. This model is optimized by removing parameters from it step by step, starting with the parameter contributing the least to the model, and stopping when removing further parameters would worsen the model's predictive power significantly.

The intercept is the last parameter to be removed, and can only be removed if it is insignificant for the model.

To trim the model to a minimum set of parameters that gives an acceptable representation of the data set, we can look at the 't value', which is a value describing how well a parameter contributes to the model, and is calculated for each parameter by dividing its coefficient estimate by its standard error. The further the t-value is from zero, the better is the contribution of the parameter to the model.

Refrigeration system electricity use

An initial model with all parameters and an intercept was set up in the statistical analysis language R. Both the model and the outcome are shown in Figure 75.

Except for cooled and frozen capacity, and cooled demand, the value under 'Estimate' has a similar sign and order of magnitude as found in the single-parameter analysis. The negative correlation between capacity and electricity use is not adequately understood, so we'll try to remove those from the model.

Looking at the t-value column, we can see that the intercept, the extra area, the installed chilled capacity, and the number of receipts seem to predict refrigeration system electricity use poorly. One by one, we'll try to remove parameters with a low t-value from the model as well.

With a few steps, we end up with the very minimal model in Figure 76, which by its form assumes refrigeration load is adequately predicted by sales area, and uses the inverse of SCOP as a cost function for refrigeration.

Removing the intercept from the model in Figure 76 can still be defended, as the intercept is only slightly more than one standard deviation away from zero. The final model for refrigeration-related electricity, after removing the intercept, is listed in Table 21.

Coefficient	**Estimate [kWh/y/unit]**	**Standard error**
Sales area [m2]	49.31	9.571
1/SCOP [-]	211600	16300

Table 21: Final model for refrigeration energy use

```
model_refrig = electricity_refrig ~ area_sales + area_extra cap_total + demand_total + scop_inv +
num_receipts

Call:
lm(formula = model_refrig, data = mydata)

Residuals:
   Min     1Q Median     3Q    Max
-22851  -7742  -2172   5397  22149

Coefficients:
               Estimate    Std. Error   t value  Pr(>|t|)
(Intercept)    -3.448e+03  5.245e+04    -0.066   0.9479
area_sales     4.378e+01   1.665e+01    2.630    0.0121 *
area_extra     3.797e+01   2.308e+01    1.645    0.1078
cap_total      -1.602e+03  1.273e+03    -1.258   0.2156
demand_total   1.357e+03   6.713e+02    2.021    0.0500 .
scop_inv       2.307e+05   3.744e+04    6.162    2.8e-07 ***
num_receipts   2.492e-02   3.990e-02    0.624    0.5358
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 11950 on 40 degrees of freedom
Multiple R-squared:  0.6862,    Adjusted R-squared:  0.6392
F-statistic: 14.58 on 6 and 40 DF,  p-value: 9.72e-09
```

Figure 75: Regression analysis results for refrigeration energy with all parameters

```
model_refrig = electricity_refrig ~ area_sales + scop_inv

Call:
lm(formula = model_current, data = mydata)

Residuals:
   Min     1Q Median     3Q    Max
-25932  -7041  -1748   7439  32082

Coefficients:
               Estimate     Std. Error    t value     Pr(>|t|)
(Intercept)    -16053.80    15975.71      -1.005      0.32
area_sales     58.56        13.27         4.412       6.53e-05 ***
scop_inv       237136.02    30154.71      7.864       6.33e-10 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 12650 on 44 degrees of freedom
Multiple R-squared:  0.6134,    Adjusted R-squared:  0.5959
F-statistic: 34.91 on 2 and 44 DF,  p-value: 8.3e-10
```

Figure 76: Optimized model for refrigeration electricity use

Non-refrigeration electricity use

The only predictors with relation to non-refrigeration electricity use are the sales and extra area, and the number of receipts.

Only the final model is shown in Figure 77. The residuals are quite large, and the intercept is around 45000 kWh/y, so the predictive quality of the model is not very good – which also is reflected by the much lower R-squared value compared to the refrigeration-related electricity use models.

The lower ability to predict non-refrigeration electricity use is expected with the Danish data set, as there has been focus on collecting data about the refrigeration system, and not on e.g. energy saving measures.

```
model_extra = electricity_extra ~ area_sales + num_receipts
Call:
lm(formula = model_extra, data = mydata)

Residuals:
   Min     1Q Median     3Q    Max
-53911  -9579   -928   9272  42036

Coefficients:
               Estimate      Std. Error     t value  Pr(>|t|)
(Intercept)    4.534e+04     1.559e+04      2.908    0.005625 **
area_sales     7.531e+01     2.015e+01      3.738    0.000522 ***
num_receipts   1.288e-01     6.041e-02      2.133    0.038431 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 18570 on 45 degrees of freedom
Multiple R-squared:  0.4208,    Adjusted R-squared:  0.3951
F-statistic: 16.35 on 2 and 45 DF,  p-value: 4.603e-06
```

Figure 77: Optimized model for non-refrigeration electricity use

Total electricity use

For the total electricity use, Figure 78 indicates that almost only the sales area, number of receipts, and SCOP have reasonable predictive power.

Using the same approach as before, the model is trimmed until the resulting model in Figure 79 is found.

Earlier in this chapter it was noted that normalizing the number of receipts by dividing it with sales area (so going from sales volume to sales density) showed there was no correlation between electricity use and sales density. Removing the number of receipts from the model in Figure 79 decreases the R-squared from 0.6323 to 0.6099, and doubles the intercept from 1.12e4 to 2.47e4 (which is still less than one standard deviation from zero).

```
model_total = electricity_total ~ area_sales + scop_inv + demand_total + cap_total + num_receipts

Call:
lm(formula = model_total, data = mydata)

Residuals:
   Min     1Q Median     3Q    Max
-47495 -11145   1301  12465  40934

Coefficients:
              Estimate    Std. Error   t value  Pr(>|t|)
(Intercept)   -8.860e+04  8.755e+04    -1.012   0.3175
area_sales    1.217e+02   2.449e+01    4.969    1.24e-05 ***
scop_inv      3.384e+05   6.125e+04    5.525    2.04e-06 ***
demand_total  9.455e+01   1.108e+03    0.085    0.9324
cap_total     2.378e+03   2.119e+03    1.122    0.2684
num_receipts  1.243e-01   6.695e-02    1.857    0.0705 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 20060 on 41 degrees of freedom
Multiple R-squared:  0.6679,    Adjusted R-squared:  0.6274
F-statistic: 16.49 on 5 and 41 DF,  p-value: 6.626e-09
```

Figure 78: Initial regression model for total electricity use

```
model_total = electricity_total ~ area_sales + scop_inv + num_receipts

Call:
lm(formula = model_total, data = mydata)

Residuals:
   Min     1Q Median     3Q    Max
-49579 -10019   3210  11572  39581

Coefficients:
              Estimate    Std. Error   t value  Pr(>|t|)
(Intercept)   1.116e+04   2.614e+04    0.427    0.6716
area_sales    1.294e+02   2.346e+01    5.517    1.83e-06 ***
scop_inv      2.942e+05   4.855e+04    6.061    2.98e-07 ***
num_receipts  1.272e-01   6.635e-02    1.917    0.0619 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 19930 on 43 degrees of freedom
Multiple R-squared:  0.6562,    Adjusted R-squared:  0.6323
F-statistic: 27.36 on 3 and 43 DF,  p-value: 4.669e-10
```

Figure 79: Optimized regression model for total electricity use

With the above in mind, and given the expected difficulty in comparing number of receipts between different supermarket chains, it's chosen to not include number of receipts in the final model. Also, the intercept is low enough to be removed. Coincidentally, this results in the same set of parameters as found for refrigeration electricity use in the preceding section – though of course with different values, see Table 22.

Coefficient	**Estimate [kWh/y]**	**Standard error**
Sales area [m2]	164.01	15.52
1/SCOP [-]	3.524e5	2.64e4

Table 22: Final model for total electricity use

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