Energy savings and economic benefits of using electronic expansion valves in supermarket display cabinets

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Abstract This paper reports on the energetic and economic comparison between electronic and thermostatic expansion valves in a centralized refrigeration plant of a supermarket. Adopting electronic expansion valves enables an appreciable energy saving, due to the fact that electronic valves allow a lower condensation pressure in systems equipped with air cooled condensers, which is adjusted to variations in outside air temperature. Furthermore, superheating at the evaporator is lower and more stable, increasing cooling capacity and decreasing refrigerant temperature at the compressor discharge (the latter ensures better efficiency and lower wear and tear for the compressor).

This study is supported by experimental work where the cabinets of a supermarket, located in the northern Italy, have been equipped with both thermostatic and electronic expansion valves, alternatively activated by solenoid valves on a daily basis, in order to compare the two systems in the same environment and at similar load conditions. This allowed the building of a simulation model of the application to evaluate the performance, energy and economic savings in different climates (the energetic analysis considers total electricity consumptions – compressors, fans and electrical switchboards).

Keywords electronic expansion valve; thermostatic expansion valve; refrigeration plant; energy savings

1. Introduction

Storage of cold and frozen food accounts for approximately 40–50% of the electricity used in supermarkets. Open vertical display cabinets are common and are also large users of electrical energy. One of the reasons for their popularity is the possibility of displaying a large amount of food on a small floor area. An open design and a large display are important factors for the retailer who wants to display food in an attractive way for the customer. However, an open design also makes the display cabinet sensitive for infiltration of warm ambient air, responsible for 60–70% of the heat gain of the cabinet.

Numerous actions can be taken to reduce energy consumption, from design, construction and installation of the refrigeration systems to their operation and maintenance. Regarding the construction, it is well known that all refrigerating machines, both for air conditioning and refrigerating applications, have widely used thermostatic expansion valve (TEV). Though this is a useful expansion device, it reveals some characteristics that can limit versatility and performance of the machines.

Some kinds of plants are more sensitive to negative aspects of TEV regulation, because of plant specifics, kind of duty or distribution of cooling load during the year.

One solution to face nearly all these shortcomings is the electronic expansion valve (EEV). While TEV can work in a very restricted range of condensation temperature values (around its nominal value), EEV allows a very important increase in the compressor output: on/off compressors reduce their on operating periods, part load operation or inverter driven compressors decrease their electrical consumptions at given output. This is due to the longer stroke of the control nozzle, which may reach the tens of millimetres and more: the control of the refrigerant benefits from this significant resolution and precision, resulting in thus much more precise control than the best traditional TEV.

This electrically driven control device has been studied experimentally and theoretically in recent years ([1], [2], [3]) and it is now widely available on the market; it controls the refrigerant flow at the evaporator by means of a pressure and a temperature sensor, both at the outlet of evaporator. The two signals are elaborated by a regulator that control, in real time mode, the opening of the valve.

In this paper EEV application is analysed for a refrigeration plant in a large supermarket located in the Tirrenic coast of Italy, not far from Pisa, in the North Italy. The plant has been retrofitted with the EEVs installed in parallel to the TEVs, in order to operate alternatively the plant with the two technologies [4]. A simulation model has been developed to compare the two technologies on an annual basis from the energetic and economic point of view under different conditions. The comparison has been made for three different Mediterranean climates, Milano, Roma and Trapani (for which hourly Test Reference Year data are available [5]), to investigate the behaviour of the innovative system varying the condensation conditions.

2. Refrigeration system

The supermarket refrigeration system is divided into two independent circuits: low temperature (LT, $T_{ev} = -34$ °C) and medium temperature (MT, $T_{ev} = -13.5$ °C) with, respectively, 75 kW and 325 kW refrigerating capacity. Refrigerant is R404a and its heat rejection is provided by two rooftop condensers: three units for MT circuit and one unit for LT circuit (476 kW, 77,000 m^3/h each unit). The retrofit solution has involved the creation, in each display cabinets, of two parallel expansion lines, one with a TEV and the other with an EEV, activated alternately by solenoid valves on a daily basis; this has allowed comparative tests to be conducted between the two systems in the same environmental and load conditions. A remote machine room hosts the compressors (three per circuit) that work in parallel with an inverter-based control system. Desuperheating of the refrigerant allows heat recovery: two heat exchangers in LT circuit for hot water production for the tap water circuit and for space heating and one heat exchanger in MT circuit for space heating (Figure 1).

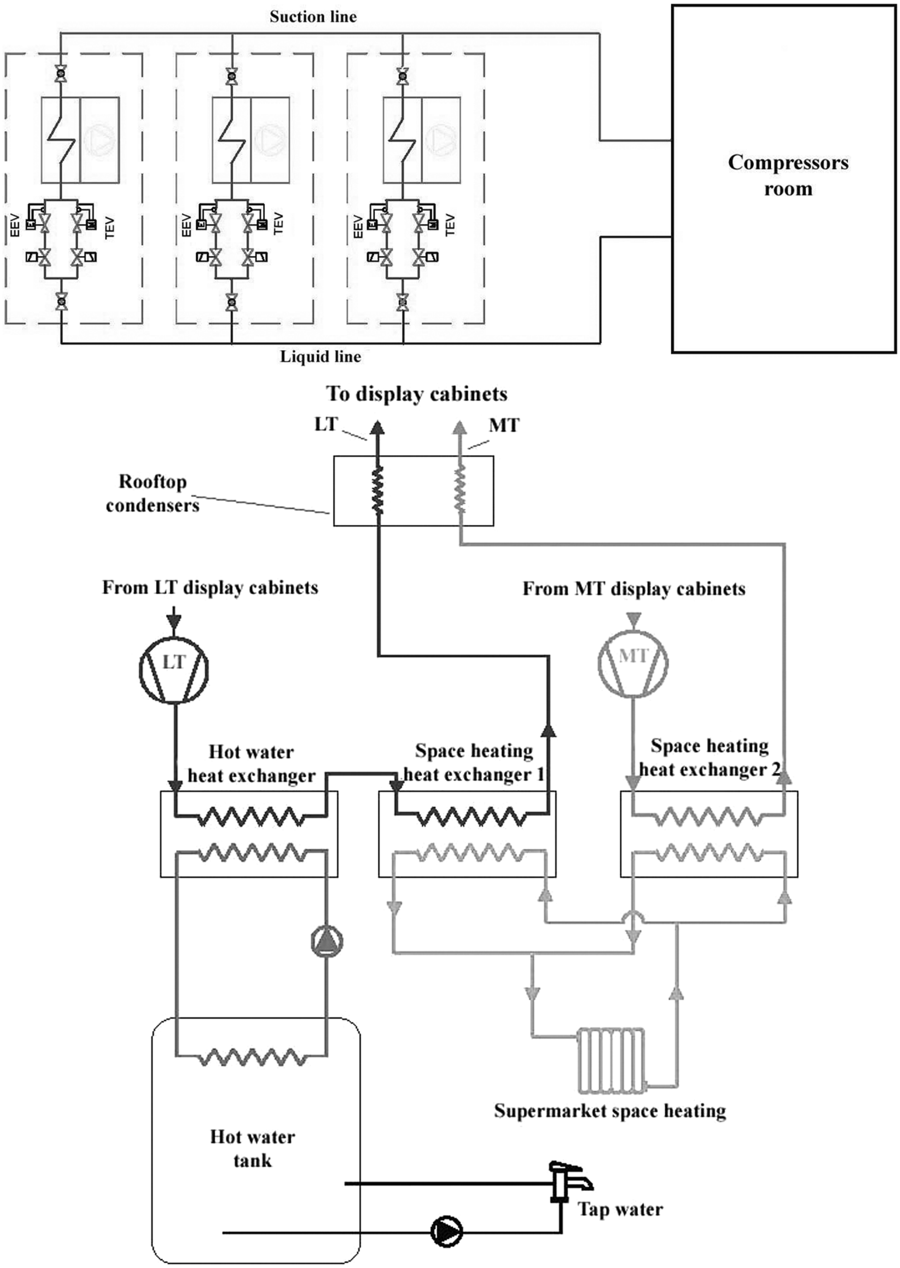

Figure 1. *Refrigeration system: machine room layout with heat recovery.*

3. Energetic analysis

An experimental survey started in December 2004 and extended for one year. Much data has been logged and recorded (temperatures, pressures, electrical consumption, state of compressors, fans and drivers, etc.) with a very small time interval (varying from 5 to 120 s depending on the variable) [4].

The display cabinets refrigerating load is difficult to foresee exactly, due to several reasons. Refrigerating capacity is very influenced by customer frequency, by thermal and physical characteristics of the packaged goods (dimension, material, emissivity, thermal inertia, etc.) and by internal gain of the building (lights, number of people, etc.). So, for all these and other stochastic reasons, refrigerant mass flow rates at the cabinet evaporators and so electrical consumption of compressors as a function of outside air temperature are quite difficult to predict on the basis of recorded data. It is also true that the daily alternating operation of the plant with the two valves technologies can mitigate this uncertainty on the electrical consumption of compressors. Anyway, instead of developing a formula based on recorded data, it has been preferred to calculate compressors power consumption on the basis of the thermodynamic cycle by means of CoolPack software, assuming, for the two circuits and for the two kinds of valves, the hypotheses summarized in Table 1. Behaviour of the cycle with EEV has been simulated by means of a lower superheating (Table 1) and, above all, by a lower condensation pressure than TEV (see further on this paragraph). Condensation temperatures for EEV and TEV have been considered about 10 °C higher than outside air temperature.

Electrical power consumption is a function of thermodynamic cycle conditions, mainly evaporation and condensation temperatures and superheating:

$$P_{el} = f(T_{ev}, T_{cond}, SH)$$

In centralized plants, evaporation is quite constant, due to cabinet classification [6]. In such a way, it is possible to simplify the above equation:

$$P_{el} = f(T_{cond}, SH)$$

Table 1. *Hypotheses of the thermodynamic cycle for the calculation of the specific compression power (values are applicable both for the experimental cabinet and for the hypothetical simulation). Subcooling and isentropic efficiency are considered decreasing in the respective ranges increasing the condensing (and so outside air) temperature*

	Low Temperature		Medium Temperature	
	TEV	EEV	TEV	EEV
T_{ev} (°C)	−34	−34	−13.5	−13.5
Superheating (°C)	10	5	14	14
Subcooling (°C)	20–17	10–9.5	5–4	3–1
Isentropic efficiency	0.85–0.73	0.85–0.78	0.85–0.70	0.85–0.75
Pressure drop at suction and discharge lines (°C)	0.5	0.5	0.5	0.5

It is possible to do a further simplification, because in centralized plant superheating is a design parameter and so it is held quite constant during the year:

$$P_{el} = f(T_{cond})$$

In such a way it is possible to evaluate specific (that is referred to 1 kW cooling capacity of the cycle) compressor power consumption for various values of the condensing temperature. So electrical power consumption of the compressors can be considered a function of the condensing temperature and so, because the latter is allowed to float in response to outside air temperature, a function of the outside air temperature (obviously, electrical energy consumption is a function also of the total refrigerating load on the evaporators because of the real operating conditions of the display cabinets: these conditions will be considered constant in the three climates in the following analysis). The results of the simulations are depicted in Figure 2 and Figure 3, where P_{el} of compressors is the specific power per unit of refrigeration capacity.

Note that, for outside air temperature higher than 37–38 °C, the two curves (in both circuits) intersect, so EEVs give no energetic advantages over TEVs. This result is in agreement with previous works ([7], [8]), in which it has been verified that energy saving is very high (due to the great modulation and adjustment capability of EEV with respect to TEV) at low condensation pressure (so low outside air temperature), while energy saving is decreasing with the increasing of condensation

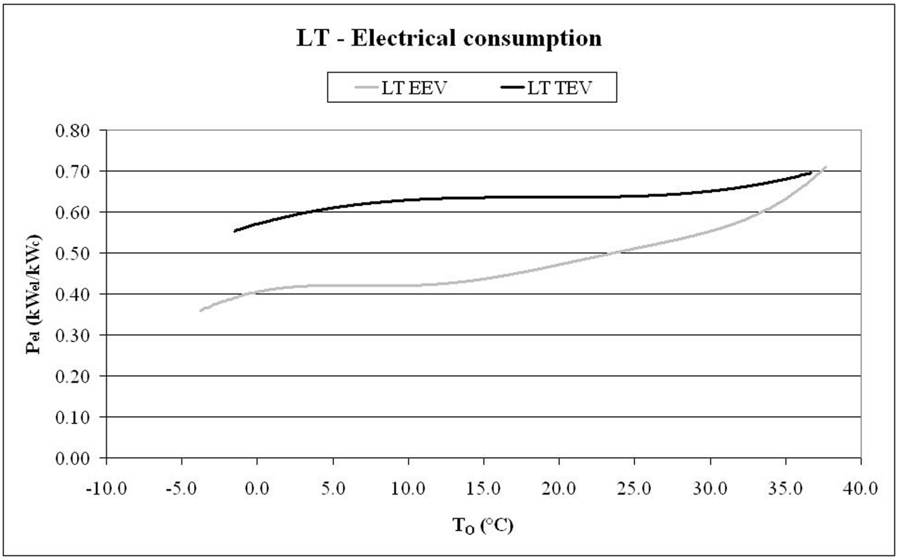

Figure 2. *Specific electrical power consumption of compressors for the low temperature circuit, both for thermostatic and electronic expansion valves.*

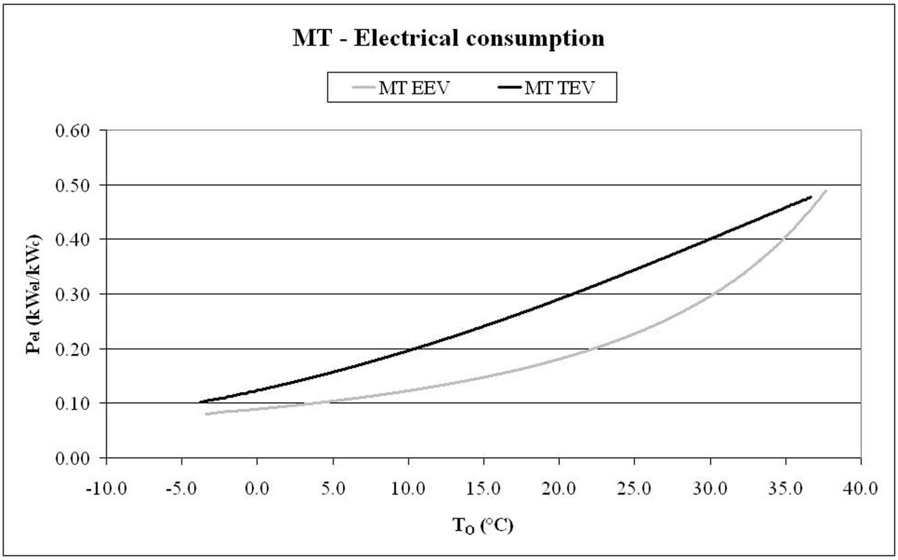

Figure 3. *Specific electrical power consumption of compressors for the medium temperature circuit, both for thermostatic and electronic expansion valves.*

temperature. This is directly connected to a refrigerating capacity increase of the cabinets with EEV, because of:

– higher refrigerant mass flow rate for lower condensation pressures;
– more steady operation;
– lower superheating of the refrigerant at the evaporator outlet.

Such mathematical functions allow to calculate the Primary Energy Saving (PES) of EEVs with respect to TEVs. Figure 4 reports the PES for the two circuits and the total for the entire supermarket, still considering only the electrical consumption of the compressors. Note how increasing outside air temperature decreases savings dramatically, going to zero for temperature around 37–38 °C as just said. Note also that decreasing outside air temperature beneath −10 °C reduces savings to zero: this is because also EEV has a limit to condensation pressure, that is about 6.5 bar in our simulations. Savings are higher with medium temperature cabinets than low temperature ones, reaching almost 40% in the range of 10–20 °C outside air temperature (the most frequent temperatures range in Mediterranean climate). This is due to MT circuit greater sensitivity to outside air temperature because of lower compression rate of the thermodynamic cycle than LT circuit. Anyway, PES for the compressors consumption for the entire supermarket is very high, above 35% in that range of temperatures.

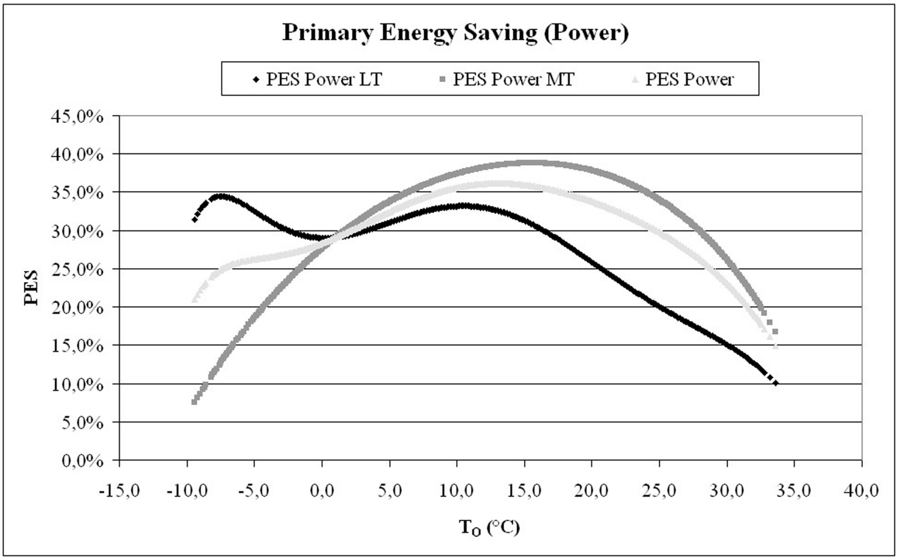

Figure 4. *Primary Energy Saving (related to compressors consumption only) for both circuits (low and medium temperature) as function of outside air temperature.*

In these figures consumption refers only to compressors. Here we indicate as 'power' the sum of consumptions of compressors, condensers fans and electrical switchboards. Electrical consumption of condensers fans is higher with EEVs, because they use cut phase speed controllers that allow a greater capacity of following outside air temperature and so to operate the condensation at lower values if possible. Anyway, fans electrical consumption is less than 1/10 of compressors consumption and electrical switchboards consumption is quite constant with the two valves, so their influence in PES is almost negligible.

For this application there is other electrical consumption linked to the operation of the plant, called 'auxiliaries', such as evaporators fans, anti-misting resistors, cabinets light, etc. These are quite constant with EEVs and TEVs: again they can be neglected in PES calculation.

Table 2 reports all the annual electrical consumption and heat recovery for all the 118 cabinets and for the three climates analysed (as written in previous paragraph desuperheating heat is recovered by heat exchangers in the two circuits for tap hot water and for space heating). Values are expressed in terms of primary energy (in Megajoule), taking into account an electrical efficiency production of 0.4 and a thermal efficiency production of 0.9 of the natural gas boiler used to provide the same quantity of heating energy.

Electrical consumption for the compressors has been calculated by multiplying values of Figure 2 and Figure 3 by the total cooling capacity of the two circuits

Table 2. *Electrical energy for the compressors and heat recovery by refrigerant desuperheating for the two circuits (Low Temperature and Medium Temperature) for all the 118 cabinets and for the three climates. On the last columns on the right the Primary Energy Saving using EEVs with respect to only electrical consumption, heat recovery and the total. Values are all expressed in Megajoule*

	Low Temperature EEV		Low Temperature TEV		PES		
	Compressors	Heat rec.	Compressors	Heat rec.	electrical	heat rec.	total
MI	2,619,294	365,315	3,670,574	552,605	1,051,280	–187,290	863,990
RM	2,702,324	366,920	3,737,550	575,875	1,035,226	–208,955	826,271
TR	2,769,102	368,128	3,765,236	580,584	996,134	–212,456	783,678
	Medium Temperature EEV		Medium Temperature TEV		PES		
	Compressors	Heat rec.	Compressors	Heat rec.	electrical	heat rec.	total
MI	3,446,230	479,841	5,737,701	675,857	2,291,471	–196,016	2,095,455
RM	4,197,532	493,130	6,353,658	696,074	2,156,126	–202,944	1,953,182
TR	4,749,422	498,569	6,850,745	707,660	2,101,323	–209,091	1,892,232
	EEV (LT + MT)		TEV (LT + MT)		PES (LT + MT)		
	Compressors	Heat rec.	Compressors	Heat rec.	electrical	heat rec.	total
MI	6,065,524	845,156	9,408,275	1,228,462	3,342,751	–383,306	2,959,445
RM	6,899,856	860,050	10,091,208	1,271,949	3,191,352	–411,899	2,779,453
TR	7,518,524	866,697	10,615,981	1,288,244	3,097,457	–421,547	2,675,910

(respectively 75 and 324 kW) and by the number of hours for each outside air temperature value; they are in good agreement with experimental data [9]. They are increasing from Milano to Trapani, both for low and medium temperature circuits, but more for the latter in relative terms. Auxiliaries consumption is assumed to be the same (obtained from experimental data), while heat recovery (obtained by means of regression functions on the basis of experimental data [9]) is also increasing from colder to milder climates (due to a greater number of hours with higher outside air temperature and so higher refrigerant condensation temperature, as can be seen in Table 3). In terms of Primary Energy Saving (the last three columns in Table 2), heat recovery is considered as negative, because of the larger quantity of heat recoverable with TEV due to higher condensation pressure with outside air temperature lower than 37–38 °C (the greater part of annual hours for all the three climates). It is worth reminding that the higher condensing pressure with the TEV is due to the constraint of a higher pressure differential across the TEV to provide proper refrigerant flow control.

Considering all the energy elements (‘compressors’, ‘power’, ‘auxiliaries’ and ‘heat recovery’), Figure 5 reports the Primary Energy Saving for the three climates.

Table 3. *Number of annual hours for each outdoor air temperature T_O range for the three climates*

	Number of hours		
T_O ranges [°C]	MI	RM	TR
$T_O \leq -10$	0	0	0
$-10 < T_O \leq -5$	66	0	0
$-5 < T_O \leq 0$	664	114	0
$0 < T_O \leq 5$	1344	567	7
$5 < T_O \leq 10$	1550	1625	697
$10 < T_O \leq 15$	1558	2095	2873
$15 < T_O \leq 20$	1699	2022	2162
$20 < T_O \leq 25$	1228	1431	2116
$25 < T_O \leq 30$	542	701	839
$30 < T_O \leq 35$	109	204	66
$35 < T_O \leq 40$	0	1	0
Total	8760	8760	8760

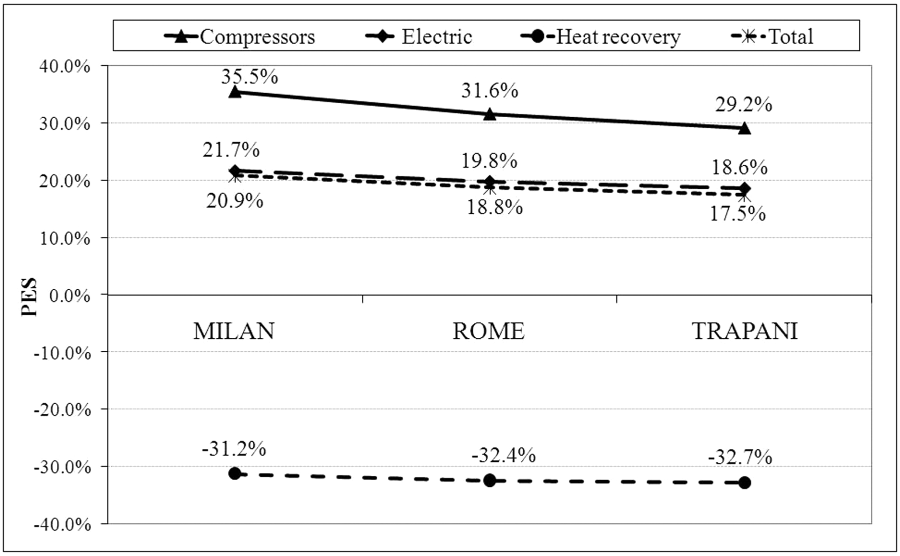

Figure 5. *PES for the supermarket for compressors, electrical (power + auxiliaries), heat recovery and the total for the three climates.*

Note that, for this application, total PES for compressors consumption is around 36% for Milano, decreasing to 29% for the milder city of Trapani. Considering all the electrical consumption ('power' and 'auxiliaries') energy saving is respectively 22% and 18.5%; it does not suffer too much of the greater heat recovery with TEVs for this particular application (PES decreases only by 1% considering heat recovery).

4. Economic analysis

Investment costs of the innovative system were obtained from estimates by manufacturers. Total cost is composed of components (mainly EEVs) and labour. Cost of EEV solution is approximated €350 for each of the 118 display cabinets in the supermarket studied. This results in €41,300 total investment cost for the plant. Of course the total cost is definitely lower when EEVs are directly installed by cabinets manufacturers.

Electrical energy cost is fixed at 0.10 €/kWh, interest rate at 5% and investment period 15 years. Table 4 reports the results of the economic analysis for the 'base case' just described, in terms of annual savings, Net Present Worth (NPW) and Discounted Payback Period (DPP). Because the NPW is always positive, investment is advantageous for all the climates; initial costs are recovered in a very short period, about 1.4 year for Milano and more for the other climates. Because of the uncertainty of the investment cost, it is appropriate to extend these considerations with a 'sensitivity analysis'. Table 4 reports the results: increasing investment cost (1.5 times the value before reported) results in a decrease of NPW and an increase of DPP, greater in the milder climate of Trapani with respect to the colder one of Milano, while a decrease in investment cost (0.5 time the value before reported) allows a DPP of more than half a year for all the cities.

5. Conclusions

Application of EEV technology to display cabinets of a large supermarket demonstrated considerable energy savings, due to the superior control characteristics of the EEV and the favourable type of application, with operating conditions in which the condensing temperature is allowed to drop with the outdoor temperature. A simulation model demonstrated that very similar advantages are possible under different Mediterranean climate conditions. For this particular case, with heat recovery on

Table 4. *Annual savings, Net Present Worth and Discounted Payback Period for the three climates varying the EEV investment cost*

Investment cost [€]	City	Annual savings [€/year]	NPW [€]	DPP [years]
61,950	MI	31,590	265,947	2.1
(50% increase	RM	29,494	244,188	2.3
from base case)	TR	28,311	231,909	2.4
41,300	MI	31,590	286,597	1.4
(base case)	RM	29,494	264,838	1.5
	TR	28,311	252,559	1.6
20,650	MI	31,590	307,247	0.7
(50% drop from	RM	29,494	285,488	0.7
base case)	TR	28,311	273,209	0.8

desuperheating of refrigerant, only a very slight penalization is introduced. As the required investment cost is not particularly high, energy savings allow also important economic savings and a very short payback period (1.5 year and probably shorter if EEVs are installed directly by cabinets manufacturers).

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