Limiting the Impact of Increasing Cooling Demand in the European Union: Results from a Study on Room Air-Conditioner Energy Efficiency

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ABSTRACT

The traditionally low demand for artificial cooling in Europe is rapidly giving way to a new 'air conditioning culture', especially in southern European countries, where the climate and the improving living conditions are driving up demand. As a consequence, RACs are flourishing and policy actions are needed to reduce their growing energy consumption. This paper presents the results of a study sponsored by the European Commission to investigate the potential to improve the energy efficiency of room air-conditioners (RACs) sold in the EU and to recommend policy measures. Representatives from eight countries, the main manufacturers' associations and the two largest European utilities participated in the study.

The market and stock of RACs are estimated for both the residential and tertiary sectors. Energy and CO_2 projections are made for the next 20 years that predict rapidly growing but still moderate penetration rates compared to the levels seen in the USA or Japan today. Nevertheless, RAC-related CO_2 emissions in the EU are forecast to increase 11-fold by 2010, the deadline for compliance with the Kyoto protocol targets. An extensive technical and economic analysis of potential energy efficiency options revealed a cost-effective saving potential of +25% over current average energy efficiency levels. Consumer surveys and a manufacturer policy impact analysis were also conducted.

Market-transformation policies outside Europe are reviewed and the policy actions required to realize the economic optimum savings potential are discussed. Potential energy and CO_2 savings from the enactment of these policy measures are estimated. Lastly, policy recommendations at the EU level are described, including minimum efficiency standards and labelling.

Introduction

Around the world, room air-conditioners (RACs) have become more and more commonplace in public, commercial and residential buildings. In Europe, there has traditionally been a very low demand for artificial cooling, but there are now clear signs of a growing 'air conditioning culture' and of the rising energy use associated with it. Many studies have made the link between building design, climate and comfort and the extent to which cooling demand can be avoided through passive building design measures. Nonetheless, the reality is that air-conditioner ownership and use is continuing to grow and therefore effort also needs to be directed at improving the efficiency of the appliances themselves.

There are currently about 7.5 million RACs installed in the EU, but with annual sales reaching 1.6 million by 1996 and growing at an average of 12% each year, this is expected to rise dramatically in the coming decades. Sales in 1996 were dominated by Italy and Spain, which accounted for 47% of the EU total, while Germany, France, Greece and the UK accounted for another 41% (Adnot et al. 1999).

Since 1990 the RAC stock in the EU has grown by a startling average of 35% per annum, and annual RAC sales have doubled over the same period. The factors affecting overall RAC energy consumption are the size of the stock, the average annual hours of equivalent full-power usage, the average RAC cooling capacity and the average energy efficiency ratio (EER). The EU stock is projected to grow to 21 million units by 2010, although this forecast is highly uncertain due to the immaturity of the market (Adnot et al. 1999).

Aiming at limiting the damage of this growing end-use, the European Commission mandated a group of research centres, energy agencies, consultants, manufacturers' associations and Europe's two largest utilities to perform a study entitled 'Energy Efficiency in Room Air Conditioners' (EERAC). The present paper presents the results of this study that was concerned with investigating ways to improve the energy efficiency of European RACs and involved resepresentives from the following eight EU countries: France, Spain, Italy, Portugal, Greece, Austria, the United Kingdom and Germany.

RAC Types and Technology

There are a variety of RAC types on the market, and consumer preferences show considerable regional variation in response to different traditions. The prevalent RAC types on the European market are very similar to those in Japan, South East Asia and Australasia. In this study, RACs have been categorised into four major types: split-packaged, multi-split-packaged, single-packaged and single-duct (Figure 1).

Split-packaged units. This type dominates sales in the EU (69% in 1996) and accounts for an estimated 61% of the RAC stock. It was originally developed in Japan and has the advantage of being reasonably simple to install, comparatively unobtrusive and moderately priced while being among the most energy efficient. Split-packaged systems comprise an indoor and an outdoor unit linked by flexible piping through which the refrigerant is circulated. The outdoor unit contains the condenser and usually also houses the compressor, while the indoor unit comprises an evaporator, air-handling unit and control system. The indoor units can be either high-wall or floor mounted (i.e. 'cassette', ceiling-suspended, built-in horizontal or built-in vertical), or mobile. The outdoor units can also be either fixed or mobile.

Multi-split-packaged units. An important and growing share of the market is taken by multi-split-packaged RACs, which accounted for 7% of EU sales in 1996, even though they had not been on the market for very long. Multi-splits are similar to single-splits but are comprised of several interior units connected to one exterior unit via flexible refrigerant piping and are usually used to cool up to four different rooms or spaces.

Single-packaged units are commonly known as either 'window' or 'wall' air-conditioners. They comprise a single unit, one side of which is in contact with the outside air for condensation, while the other side houses the evaporator and provides direct cooling of the inside air with a fan. The two sides of the appliance are separated by a dividing wall, which is insulated to reduce heat transfer between them. Single-packaged RACs usually fit under or over a window or above a door. A distinction is generally made between those units with louvered sides, designed to be installed in a window opening, and those without louvered sides, which are designed to be installed in an opening in the exterior wall. The share taken by single-packaged window systems is diminishing in Europe, accounting for 6% of sales in 1996, and they are usually less efficient than split-packaged RACs, partly because of size constraints but mostly because it is a relatively old technology.

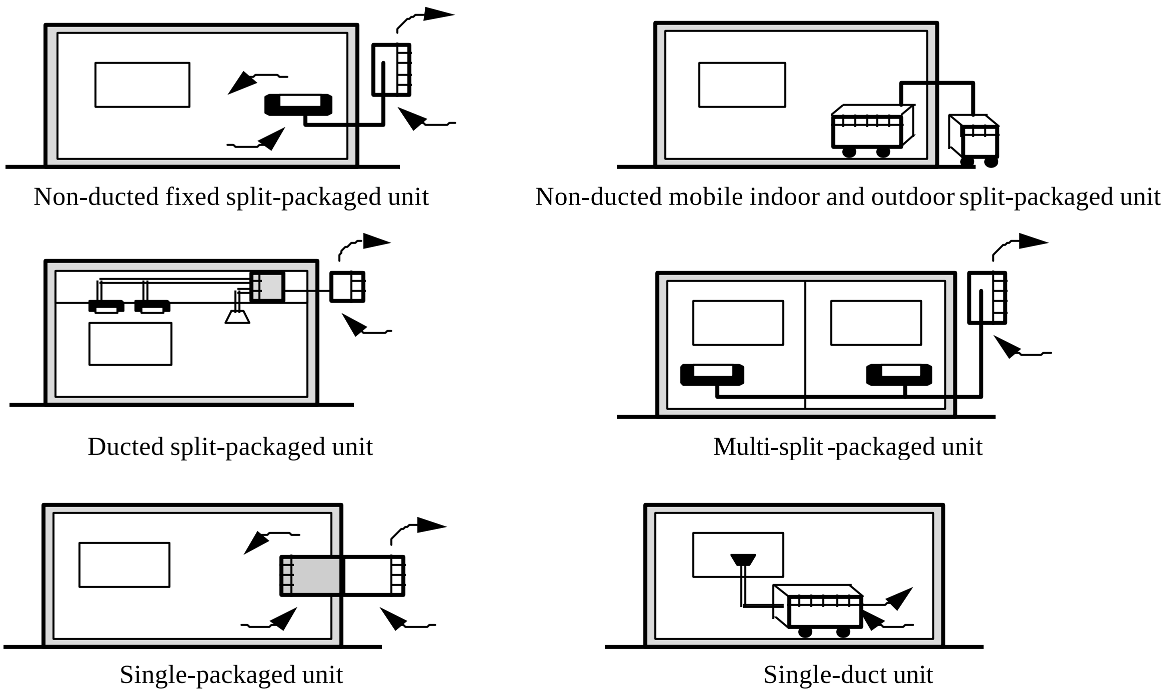

Figure 1. Diagrammatic Representations of Different RAC Types

Single-duct units. These RACs are small, low-cost and are aimed at the occasional user. The condenser, evaporator and air-handling system are all packaged into a single unit. Hot air from the condenser is ejected outside the room through a flexible duct running from the indoor unit to the exterior. They are usually mobile, but in order to operate they must be set close to a window or a door through which the duct is passed. In practice the duct is usually hung through an open window, which lowers the system's efficiency by allowing hot air to enter the room. This practice is not simple to incorporate in the energy efficiency test standard and therefore there is some debate about how single-duct RAC performance should best be measured. Single-ducts accounted for 18% of EU RAC sales by volume in 1996.

All of the above-mentioned RAC types can be either water- or air-cooled, although the vast majority of them use air as the heat-transfer medium. Water-cooled units can have considerable energy efficiency advantages but require connection to a water source (most commonly potable water), with its associated environmental impact. Furthermore, as air-conditioners are essentially heat pumps operated in the refrigeration mode, it is a simple matter to design them to operate in reverse as electric space heaters. Almost half the RACs sold on the EU market are reversible (i.e. they have the option to heat a space as well as cool it) and in some regions (such as Japan or central China) the market share of reversible RACs is much higher.

The definition of what makes a 'room' air-conditioner as opposed to say a 'central' air-conditioner is somewhat arbitrary in terms of the maximum cooling capacity of the unit. RACs also have to be 'packaged', which means that the various components are sold together in a single system. In the EU a packaged air-conditioner can be classified as a 'room' air-conditioner providing it has a maximum cooling capacity of 12 kW. Similar distinctions are applied in other regions, with a maximum cooling capacity of 7-19 kW; however, in US and Canadian energy efficiency regulations, RACs are only window or wall single-packaged units, while split systems are always treated as central air-conditioners regardless of their cooling capacity.

The EERAC study made use of two databases, supplied by the European manufacturers' associations, Eurovent (Eurovent 1998) and CECED (CECED 1997), that contained technical information on 80–90% of the RACs on the EU market in 1997/98.

RAC Energy Efficiency

RAC energy efficiency is generally defined by the energy efficiency ratio (EER):

EER = *Pc* (cooling) / *Pe* (electrical)

where *Pc* is the total cooling capacity of the air-conditioner in Watts and *Pe* is the electrical input power, also in Watts. A similar index, the COP (coefficient of performance), is used for reversible units to describe their performance in the heating mode.

The European Standard EN 814 specifies the terms, definitions and methods for the rating and performance of air- and water-cooled air-conditioners and largely mirrors the international RAC test standard ISO 5151, although there are some significant differences in the applicability of the standards. In both EN 814 and ISO 5151 the RAC EER is usually measured at the T1 test condition, wherein the indoor side set temperatures are 27 °C dry bulb and 19 °C wet bulb, and the outdoor side conditions are 35 °C dry bulb and 24 °C wet bulb. The same steady-state test conditions are generally used for RACs around the world (with the important exception of split-packaged RACs in North America, for which a seasonal EER is applied) and hence RAC test data are generally comparable.

Inspection of the distribution of RAC EERs about the average EER by type (i.e. split-packaged, multi-split-packaged, single-packaged and single-duct) on the European market shows that there are clear energy efficiency performance differences between comparable products (Figure 2).

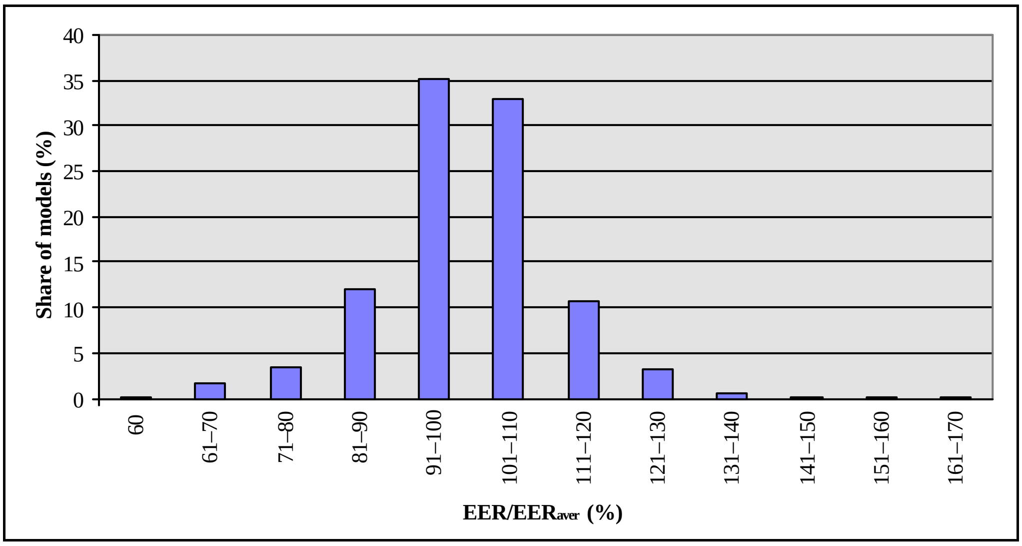

Figure 2. Distribution of the EER about the EU Market Average for the Four RAC Types

The most efficient products use only 35% of the electricity of the least-efficient products when providing the same cooling service. This range is typical of the performance differences that can exist in an unregulated market and shows that there is a considerable potential to save energy through policy intervention.

The average, minimum and maximum EERs found on the 1997/98 European Union market are shown by RAC type in Table 1. It should be noted that the present permitted measurement tolerances for the EER are ±6%, that variable-speed units are not accommodated by the test procedure, and that some uncertainties about practical test conditions remain for single-duct RACs. Following one of the new EU study's recommendations, the European Commission has prepared a mandate (M/274) to CEN, the European standard body responsible for maintaining EN 814, in order to improve the standard's accuracy and applicability. The mandate also mentions the necessity of considering multi-split packaged units in the new testing protocol.

Table 1. Energy Efficiency Performance of RACs on the EU Market in 1997–98

RAC category	Cycle type and cooling mode	Heat-transfer fluid	EER		
			Minimum	Average	Maximum
Multi-split-packaged	Cooling only	Air	1.91	2.70	3.74
	Reverse	Air	2.08	2.53	2.94
Split-packaged	Cooling only	Air	1.54	2.53	3.56
		Water	2.70	2.75	2.88
	Reverse	Air	1.45	2.48	3.45
Single-packaged	Cooling only	Air	1.88	2.38	2.77
		Water	2.11	3.32	5.42
	Reverse	Air	1.93	2.32	2.84
		Water	2.26	3.20	5.31
Single-duct	Cooling only	Air	1.35	2.07	3.09
		Water	2.10	2.33	3.62

Technical Means to Raise Efficiency

With the exception of the use of an inverter system, the technical options to improve RAC energy efficiency are generally well understood and quantifiable. In this section, we divide the technical options into design options that improve heat transfer, using inverters and other options. The problems of the part load and the impact of the refrigerant are also treated.

Design options improving heat transfer. The majority of viable design options are concerned with improving the heat transfer of the condenser and evaporator(s), lowering the temperature difference between the two and thereby raising the efficiency of the vapour-compression cycle. The options for improving heat exchange are to increase the frontal coil (heat exchanger) area, increase the density of the fins in the heat exchanger, add additional refrigerant tubing (i.e. increase the coil depth), and improve heat exchange between the refrigerant and coil through better tubing design (e.g. add internal grooving to raise the effective heat-transfer surface area).

Other options and inverters. Other design options include using a higher-efficiency compressor and higher-efficiency fans. There is less certainty about the efficiency gains that might be expected through changing the refrigerant (which must be done in tandem with a re-optimization of the whole system if any efficiency gains are to be achieved), using an electronic expansion valve, and using a variable-speed compressor (inverter).

According to values reported in the literature, the use of a variable-speed compressor (inverter type) in place of a conventional single-speed compressor could lead to seasonal cooling energy savings ranging from 10% to 40%. The wide range in reported values (Table 2) is largely attributable to the typical range of conditions under which the air-conditioners are assumed to operate.

Table 2. Energy Savings Achievable with RAC Inverter Technology

Reference	Method of assessing savings	Mode studied	RAC input power (kW)	Energy savings
Senshu et al. 1985	Experimentation	Heating	4.4	29%
Miller 1988	Experimentation	Cooling/heating	8.8	15–20%
MacArthur 1988	Simulation	Heating	-	15%
Hori et al. 1985	Experimentation	Cooling/heating	3	15%
Torikoshi et al 1987	Experimentation	Heating	6.9	7–15%[a]
Senshu 1988	Simulation	Cooling	14.5	30%
Shimma et al. 1985	Simulation	Heating	6.3	20–40%
Parkes 1988	Experimentation	Cooling	3–5	17–18%[a]
LBNL 1996	-	Cooling	-	10%[b]

[a] Gains in terms of EER (or COP) and not in terms of energy consumption.
[b] The report took into account 'a conservative value'.

Part-load treatment. At present there is no general consensus about how part-load RAC performance should be measured and incorporated into the overall EER or COP performance declarations. This makes it difficult to quantify the expected savings from using inverters and hinders the evaluation of the design option. It is for these reasons that the European Commission, following the recommendations from this study, has issued a mandate asking CEN to modify EN 814 to take into account part-load conditions.

Impact of refrigerant. The impact of changing the refrigerant is also hotly disputed. Almost all RACs currently use R-22 for the refrigerant, but this is an HCFC with an ozone depletion potential (ODP) of 5% and will be phased out by 2015 in the EU under the terms of the Montreal protocol. The leading replacement candidate is an HFC (R-410a) and some R-410a RACs have already appeared on the market. Computer simulations of expected RAC energy efficiency performance using R-410a carried out under the EERAC (Adnot et al 1999) study showed a gain of 5% compared to R-22, but some manufacturers have queried this result.

Technical and Economic Analysis of High-Efficiency Options

The Oak Ridge National Laboratory Mark V RAC energy simulation software was used to simulate the impact of each of the above-mentioned higher-efficiency design options on four base-case RACs, for which participating manufacturers had supplied detailed design data. The simulation model was first validated by comparing its predicted EER values with the measured values for the base-case RACs, which were found to agree by an average of ±2.8%. The discrepancy fell to only 1.3% when considering only the three base-case RACs for which all the required input data were available. The estimated average energy savings from implementing the improved-efficiency design options on base-case appliances, which have EER and cooling capacities near to the average for RACs of their type on the EU market, are shown in Table 3. The figures presented are averaged over the four base-case models that were studied.

Table 3. Estimated RAC Efficiency Gains with Potential Improved-Design Options

Option	Technological improvements	Increase in EER
1 (a)	15% increase in frontal coil area	4%
1 (b)	30% increase in frontal coil area	8%
1 (c)	45% increase in frontal coil area	11%
2 (a)	Addition of one extra row of refrigerant tubing in the frontal coil	10%
2 (b)	Addition of two extra rows of refrigerant tubing in the frontal coil	16%
3 (a)	10% increase in coil fin density	10%
3 (b)	20% increase in coil fin density	16%
4	Addition of subcooler to condenser coil	1%
5	Improved coil fin design (modified fin pattern)	11%
6	Improved refrigerant tubing heat transfer	8%
7a	Use of high-efficiency fan motor	1%
7b	Electronically commuted motor	2%
8 (a)	5% more efficient compressor	3%
8 (b)	10% more efficient compressor	5%
8 (c)	15% more efficient compressor	8%
9	Use of R-410a with optimized system	5%?
10	Use of variable-speed compressor	10-40%[a]
11	Use of electronic expansion valves	5%[b]
12	Use of (fuzzy) controls	4%[c]

[a] c.f. table 2.
[b] Adnot et al. 1999.
[c] Adnot et al. 1999.

Simulations of these design options were also conducted in combination, taking the most cost-effective first, to calculate the life-cycle cost implications from the consumer's perspective of buying a more efficient RAC. The simulations were made for average European prices of electricity, RAC purchase and installation, and also for average usage patterns. The results show that a combination of design options 5, 6 and 2b was always cost-effective, regardless of the basic RAC type and usage sector (residential, commercial, hotel, public), providing average annual energy savings of 25% compared to the base-case models. The simple payback period is 3.7 years, while the product life is typically 12 years. The change in marginal net present value for the implementation of each additional design option from the consumer's perspective is shown in Figure 3.

If the primary concern is to reduce CO_2 emissions rather than lower consumer costs, a combination of design options are possible that would halve average RAC energy consumption but still not cost the typical EU RAC consumer any more overall than they are paying today.

Energy Consumption and CO_2 Projections in the EU

Cooling needs. An evaluation of air-conditioner demand and usage patterns has enabled estimates of an equivalent number of hours of full-load air-conditioner operation per year by user sector and country, using computer simulations based on knowledge of the building stock, climate, occupancy patterns and comfort thresholds. These were used to predict RAC energy consumption and to evaluate the cost-effectiveness of the technical variations under investigation. Figure 4 shows the equivalent cooling hours in the office sector and illustrates the large differences in cooling needs throughout the European Union, varying from 147 hours in Vienna (Austria) to 1402 hours in Murcia (Spain). Similar simulations have been made for the residential, commercial and hotel sectors, giving annual average usage values of 519 hours for the residential sector, 768 hours for hotels, 803 hours for offices and 1019 hours for other commercial uses. This gives an EU average of 773 hours across all sectors. Electricity load curves have also been produced. Furthermore, average usage was estimated in the study from two extensive consumer telephone surveys in Italy and Spain. Perhaps surprisingly, the two independent methods produced similar results.

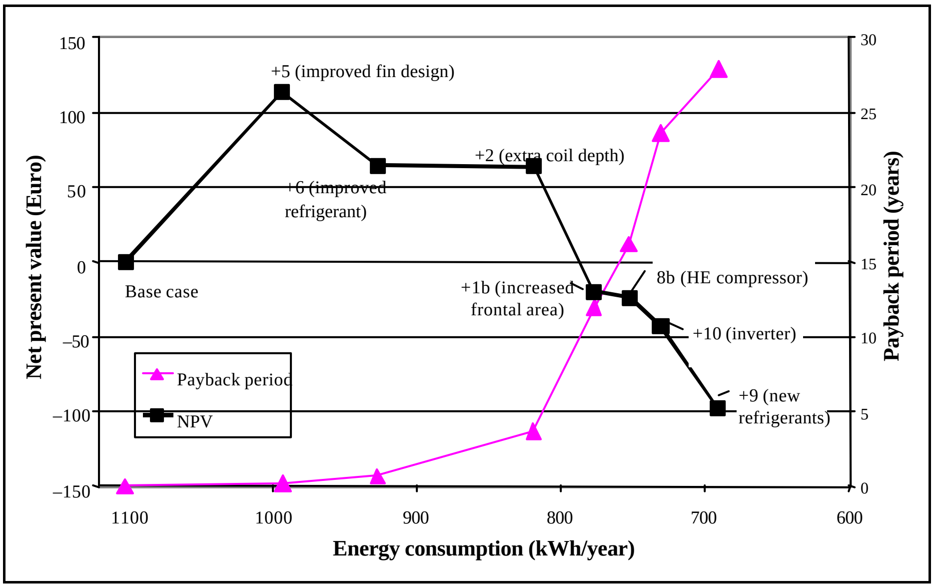

Figure 3. Estimated Residential Consumer Marginal Net Present Value Achievable by Improving the Energy Efficiency of an Average, Cooling-Only, Split-Packaged RAC in the EU Energy Consumption.

A base-case, business-as-usual scenario has been defined in order to analyse the technical and economic potential of single or combined policy measures in several alternative energy-efficiency scenarios. The year 2010 has been chosen for projection purposes in accordance with the deadline for the implementation of the Kyoto protocol. Longer-term projections are given up to the year 2020. The base year for the study was 1996, but backwards projections have been made to 1990 to be consistent with the base year used under the terms of the Kyoto protocol. Very conservative assumptions have been made about future market growth, but despite this the estimated growth for some countries is still very rapid. The results are shown in Table 4.

CO_2 emissions. Without policy intervention, RAC-associated CO_2 emissions in the EU are conservatively projected to increase by a factor of 20 from 1990 to 2010 (the time-scale used in the Kyoto protocol), rising from 0.6 million to 12 million tonnes. The projected increment in RAC-related CO_2 emissions is about 11 Mton (3000 Mton being the initial CO_2 emissions from all fuels in the EU). The direct effect of the growth of the RAC market on total EU emissions is therefore projected to be +0.37% without policy intervention, as compared with the –8% target for the EU as a whole.

Table 4. Estimated RAC Electricity Consumption (TWh/year) in the European Union

Country	1990	1996	2010	2020
Austria	0.02	0.02	0.21	0.42
France	0.52	1.68	5.49	9.03
Germany	0.05	0.16	0.86	1.64
Greece	0.14	1.32	3.29	5.14
Italy	0.36	4.39	5.72	7.09
Portugal	0.25	0.61	1.78	2.60
Spain	0.18	2.40	9.34	15.20
UK	0.08	0.35	1.11	1.84
Other EU	0.03	0.10	0.51	0.98
Total EU	**1.63**	**11.03**	**28.30**	**43.93**

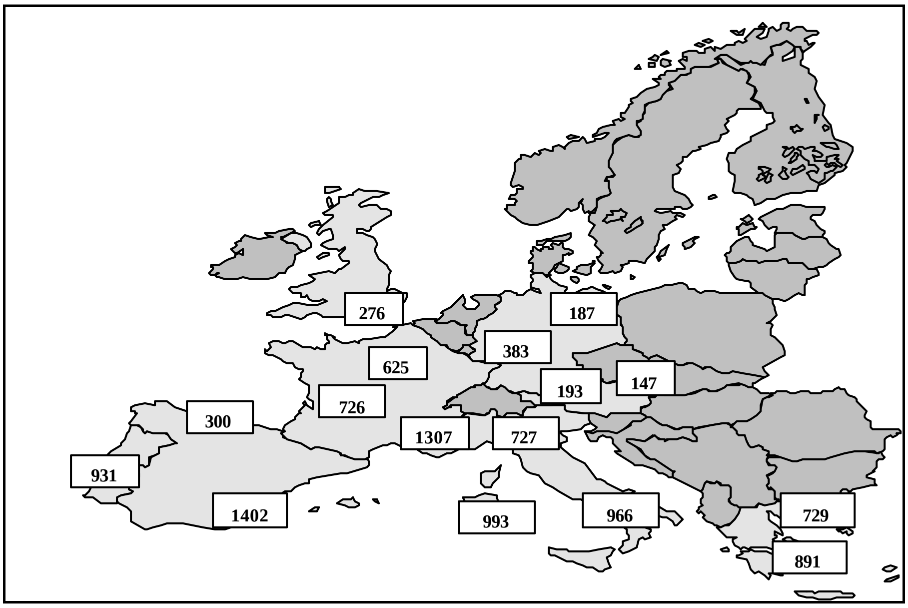

Figure 4. Estimated Weighted Annual Average Hours of RAC Usage in the EU Office Sector

Conclusions and Policy Recommendations for Europe

Despite some national efforts in France and Portugal to regulate RAC energy efficiency, the EU study has found that there is a compelling need to introduce policies at the EU level. The study recommends the introduction of two tranches of minimum energy efficiency standards (MEES): one to be enforced by 2003 and the other by 2010 at the latest. In addition, it is proposed that an energy label should be developed, based on the existing European energy label (Figure 5).

Market-Transformation Policies Outside Europe

The principal conclusion of the comparative work performed is that there has been considerable legislative activity to improve air-conditioner efficiency outside the European Union. Table 5 summarises known energy-performance test protocols, mandatory and voluntary energy-rating labelling programmes, minimum efficiency standards and voluntary agreements applicable to RACs in various countries around the world, including many developing ones. This comparative work also shows that a large proportion of RACs currently available for sale in the EU would not satisfy efficiency requirements in many other countries around the world. This suggests that there is significant scope to improve RAC energy performance in the EU and that to do so requires not technological innovation but merely implementation of well-established higher-efficiency design options. European efforts, either at national or EU level, appear very limited when compared with the schemes being applied in any country or group of countries considered in Table 5.

Table 5. RAC Energy-Performance Programmes Around the World

Country	Energy	Energy label		Minimum efficiency standards	
	protocol	Mandatory	Voluntary	Mandatory	Voluntary
Australia	Y[a]	Y	N	N[a]	N
Canada	Y	Y	N	Y	N
China	Y	N	N[a]	Y[a]	N
EU	Y[a]	N[a]	N[a]	N[a]	N[a]
Hong Kong	Y	N[a]	Y	N	N
Indonesia	Y	N[a]	N[a]	N	N
Israel	Y	N[a]	N	N	N
Japan	Y[a]	Y[a]	N	N	Y
Mexico	Y	Y	N	Y	N
New Zealand	Y[a]	N[a]	Y	N[a]	N
Philippines	Y	Y	N	Y	N
Russia	Y	N	N	Y	N
South Korea	Y[a]	Y	N	Y	Y
Taiwan	Y	N	N	Y	N
Thailand	Y[a]	N[a]	Y	N[a]	N
USA	Y	Y	Y	Y	N

[a] Under review.

The recommended MEES levels are shown in Table 6 and are quite conservative, such that even the second set of MEES falls some 15% short of the current estimated point of least life cycle cost and is still only typically 75% of the new ‘Top Runner’ target values for cooling-only RACs that will have to be met by 2007 in Japan (see Table 5).

The estimated impact of introducing these policies is indicated in Table 7.

As an alternative to MEES, the study has concluded that voluntary agreements with industry would be satisfactory, but only provided the market-weighted EER of all RAC sales in the EU can demonstrably reach 2.75 W/W by 2000 and 3.06 W/W by 2005.

It is a sobering thought that if RAC ownership in the EU were to climb to just 0.5 units per household, residential electricity demand could rise by 120–160 TWh annually, at which point air conditioning would supplant refrigeration as the largest domestic electricity demand.

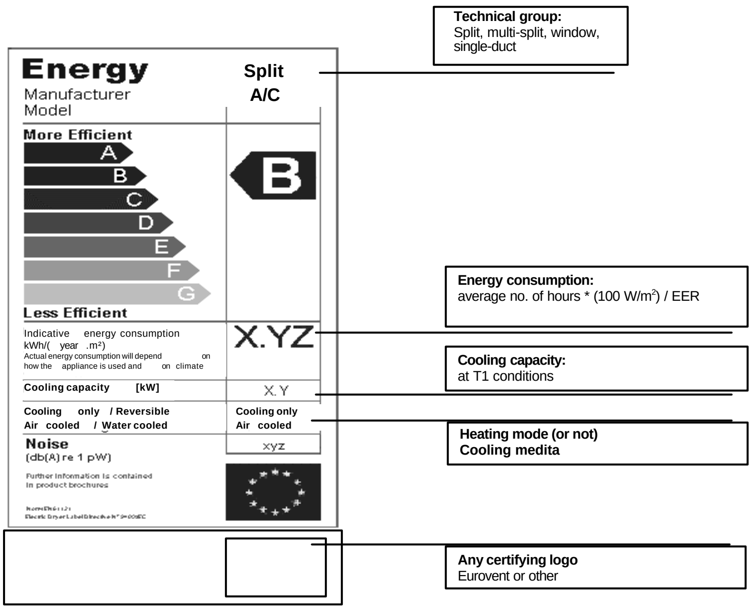

Figure 5. Potential EU RAC Labelling System

Table 6. Recommended MEES Applicable to RACs Sold in the EU

RAC type	First MEES level[a] [EER (W/W)]	Current best EER (W/W)	Second MEES level[b] [EER (W/W)]
Multi-split, air-cooled	2.63	3.74	2.89
Packaged, air-cooled	2.38	2.97	2.62
Packaged, water-cooled	3.32	5.42	3.55
Single-duct, air-cooled	1.80	3.09	2.28
Single-duct, water-cooled	2.36	3.62	2.60
Split, air-cooled	2.48	3.56	2.73
Split, water-cooled	2.75	2.88	3.03

[a] Set at the current average EER.
[b] Set at 10% above the current average EER.

Table 7. Projected Energy and Cost Savings Achievable with the Recommended MEES for RACs in the EU

Policy measures (labelling present in all cases)	**Scenarios**				
	BAU	**'First Step'**	**'Target 2020'**	**'Target 2015'**	**'Target 2010'**
	No measure	1st MEES: 2003+labeling	MEES: 2003 & 2007+labeling	MEES: 2000 and 2005+labeling	2nd MEES: 2000+labeling
	Consumption	Savings	Savings	Savings	Savings
TWh/year in 2010	28.3	-0.6	-2.8	-3.3	-4.4
TWh/year in 2020	43.9	-1.6	-8.6	-9.4	-10.3
CO_2 emis. 2010 Mton	12.0	-0.9	-1.0	-1.5	-2.0
CO_2 emis. 2010 – % of 1990	+1890%	–145%	–160%	–240%	–320%
Manufacturers' revenue increase in 2010 (MEuro/year)	–	12	57	67	90
Consumer benefits in 2010 (MEuro/year)	–	72	336	396	528
Avoided risk in 2020 [Southern utilities] (MEuro)	–	88	411	485	646

If industry and policy-makers act quickly, future air-conditioner demand could potentially be halved over the levels that might otherwise be attained – all through raising energy efficiency. High energy savings are possible, as well as significant CO_2 emissions reductions, **at no (in fact negative) cost**, such that all parties (manufacturers, consumers and utilities) would benefit from the marketing of efficient RACs.

References

Adnot J., Orphelin M. 1999. 'Hungry cooling: room air-conditioners', *Appliance Efficiency* 3 (3): 6.

Adnot J., (Coordinator), Orphelin, M., Waide, P. et al. 1999. *EERAC – energy efficiency in room air conditioners*. Armines, France: Ecole des Mines de Paris Available at www-cenerg.ensmp.fr.

CECED. 1997. Data Base on Room Air-Conditioners. Brussels, Belgium.

DOE (US Department of Energy). 1996. *General methodology for the analysis of alternative efficiency levels for room air conditioners and residential cooking products*. Berkeley, Calif.: Lawrence Berkeley National Laboratory, Energy and Environment Division, Technology and Market Assessment Group.

Eurovent-Certification. 1998. *Annuaire des Produits Certifiés.* www.eurovent-certification.com.

Hori M, Akamine I., Sakai T. 1985. Seasonal efficiencies of residential heat pump air conditioners with inverters-driven compressors. *ASHRAE Transactions*.

LBNL (Lawrence Berkeley National Laboratory). 1996. *Potential impact of alternative efficiency levels for room air.* Berkeley, Calif.: LBNL, prepared for the US DOE.

MacArthur J. & Gerald E.. Optimal comfort control for variable-speed heat pumps. *ASHRAE Transactions* 1988 (Part 2): 1283–97.

Miller WA. 1988. Laboratory examination and seasonal analyses of the dynamic losses for a continuously variable-speed heat pump. *ASHRAE Transactions*.

Parkes R. 1988. *The scroll effect*. *Refrigeration, Air Conditioning and Heat Recovery.*

Senshu T., Terada H. 1988. *Research and development on packaged heat pump air-conditioners in Japan*.

Senshu T., Arai A, Oguni K, et al. 1985. Annual energy-saving effect of capacity-modulated air conditioner equipped with inverter-driven scroll compressor. *ASHRAE Transactions*.

Shimma Y., Tateuchi T, Sugiura H. 1985. Inverter control systems in the residential heat pump air conditioner. *ASHRAE Transactions*: 1541–53.

Torikoshi K., Uemura S, Yajima R, et al. 1986. *Prediction using equivalent ratio in estimating of the performance of heat pump air conditioner*.

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