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Abstract

Residential space cooling receives increasing attention in energy demand models, due to the considerable share of buildings' energy consumption it already represents in hot countries and its strong growth in mild climate countries such as France. Reliable estimates and predictions of market diffusion of cooling equipment are an essential part of such models. They require ownership and installation data from households, which is rarely collected in European countries. Existing European models are thus calibrated with data from the USA to account for variation due to climate and adjusted based on average household income. They assume that lower purchasing power may entirely explain the difference between the two continents and that similar level of market diffusion will be attained as wealth increases further. This usually implies eye watering growth rates in the coming decades when climate change and economic growth are considered. Survey data from France, Spain and the USA allows us to test this assumption and to propose a new model for France based on openly available data (cooling degree-days and GNI at purchasing power parity). This is likely to also be a more accurate model for other European countries. The evolution of cooling degree-days is predicted based on climate change scenarios. We identify the differences compared to the USA - those taken into account by the model and those due to other factors. It is found that significant variation exists which cannot be accounted for by the model variables, particularly in colder climates. Likely causes are attributed to "cultural" factors and the use of reversible heat pumps. We demonstrate the usefulness of US survey data and argue for the need of increased and better data collection for space cooling in Europe.

Keywords

Space cooling; Air conditioners; Energy demand modelling; Residential sector; Cooling demand; Energy system; Market Diffusion; Regression analysis; climate change; buildings

Contents

Introduction

Residential space cooling has long been considered a largely unnecessary luxury in most European countries [Noack, 2015]. This is not the case in the USA. Even in Europe's hottest countries, such as Greece, less than half of available residential floor area is cooled while in equally hot places in the US this figure exceeds 90% [Werner, 2016; Jakubcionis and Carlsson, 2017]. Comparing colder locations on both sides of the Atlantic the difference becomes even more striking with US rates more than 10 times as high as European ones [Werner, 2016; Jakubcionis and Carlsson, 2017]. However, while the American market has been mature since decades, sales of air conditioners are still increasing significantly every year in Europe [Huang et al, 2018]. As space cooling becomes more important, estimates of how much energy it requires receive increasing attention. They allow policy makers to assess the impact of potential measures aimed at reducing energy demand or at increasing energy efficiency. Such policies are of particular interest since the majority of energy used for cooling today originates from resources, which are limited, and the conversion is accompanied by the production of greenhouse gases.

The surge in energy demand for cooling in Europe exceeds the rate of household and floor area growth. Thus, it is driven primarily by increasing market diffusion of air conditioners. The question arises if (and if yes when) Europe will catch up with the US.

The US energy information administration (EIA) has since decades, kept rather extensive statistics on many aspects of the use of air conditioning by households [RECS 2015, Sailor and Pavlova, 2003]. Data on the subject from Europe is sparse given its administrative fragmentation and the historically low interest in space cooling. Numerous authors have therefore made use of American statistics to draw conclusions for Europe and/or the world [Santamouris, 2016; Jakubcionis and Carlsson, 2017; Hitchin et al., 2013, McNeil and Letschert, 2010; Isaac and Van Vuuren, 2009], usually assuming that income alone can account for the difference in residential cooling diffusion at equal climate. Some global models [McNeil and Letschert, 2010; Isaac and Van Vuuren, 2009] take into account other indicators such as electrification rates which are predictive of market diffusion rates of cooling equipment in developing countries but cannot account for intra-European or Europe/US differences. Climate and income indicators are the only variables used to model cooling energy demand in developed countries today. Equipment and electricity prices are sometimes considered [Santamouris, 2016], helping to create a cooling specific purchasing power variable, so essentially very similar to using household income at purchasing power parity (PPP) estimates.

When it comes to making predictions for future development the increase in income (at PPP) and climate change are the only quantifiable drivers of cooling demand growth. However, while climate and income are certainly in principle the most important factors (albeit sensitive to the quality of their indicators) the existing data for Europe clearly shows that solely they do not explain the large difference to the US and even intra-European differences, let alone the growth rates over the last decades. So, the question is how accurately can we estimate current and future space cooling energy demand across Europe as a function of widely available climate and income indicators only? Which US data may be used to calibrate such a model? Which other variables can account for the difference between Europe and the US? Is Europe eventually going to reach comparable levels of market diffusion?

By exploiting survey data from France, Spain and the US together with a review of the recent relevant literature, we will try to answer these questions. We propose a model to estimate current and future (up to 2050) market diffusion of residential space cooling equipment in France as a function of openly available climate (cooling degree-days) and income (GNI (PPP)) indicators. An equivalent model for the USA, calibrated with the latest data, is also developed to highlight and quantify the differences. Furthermore, we propose methods to project the models' variables into the future. Forecasting of cooling degree days is based on recently published methods that consider climate change scenarios of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

The paper is structured as follows. Section 1 lays out the methodological and theoretical foundation; data used is presented as well as hypothesis and calculations performed to obtain air conditioning penetrations and explanatory variables. In Section 2, obtained air conditioning penetrations are presented and an air conditioning penetration model is proposed. We examine the need to adapt the existing model (the fitted US model) for each country. In Section 3, the model is used to forecast market diffusion for France.

1. Modelling methodology and Data

1.1 Definitions

We start this section by introducing and defining the main terms and concepts referred to in this study.

Diffusion rate is the part of the residential sector equipped with cooling. Depending on the statistical information available, several ratios can be used to compute diffusion, e.g. number of households with air conditioning or share of total area that is cooled; these ratios are discussed below.

Market saturation is reached when cooling equipment sales increase only at the rate of growth of the number of households; therefore, the diffusion rate stays constant. In the literature, the term saturation rate is often used interchangeably with diffusion rate or penetration rate but here needs to be clearly distinguished.

Cooling degree-days (CDD) is a climate indicator based on daily average air temperatures defined as:

$$CDD = \sum_{i=1}^{N} \max\left(0, \frac{T_{\max}^{i} + T_{\min}^{i}}{2}\right) - T_{ref} \quad (1)$$

Where:

- *N : represents the number of days of a year*
- T_{max} *: high temperature of the day i (°C)*
- T_{min} *: low temperature of the day i (°C)*
- T_{ref} *: the reference temperature (usually 18 °C)*

Household Income (I_H) is the median or average income of a household.

Energy demand for cooling (E_c) is the amount of energy exchanged between the spaces to be cooled and the refrigerant fluids circulating in space cooling systems, per year (this is sometimes referred to as "useful" energy demand).

Three possible ways to decompose total cooling demand of any region into factors for which data is typically available are considered:

$$E_c = \frac{A_c}{A} \times \frac{E_c}{A_c} \times A \quad (2)$$

$$E_c = \frac{H_c}{H} \times \frac{E_c}{H_c} \times H \quad (3)$$

$$E_c = \frac{H_c}{H} \times \frac{E_c}{A \times H_c / H} \times A \quad (4)$$

Where:

- A_c *: floor area cooled*
- A *: total floor area*
- H_c *: number of households cooled*
- H *: number of total households*
- E_c *: energy demand for cooling*

Equations (2), (3) and (4) can be simplified with the following ratios:

- $X_c^{(A)} = A_c / A$ *: share of floor area cooled*
- $\widehat{E}_c = E_c / A_c$ *: specific energy demand for a cooled unit of floor area=*
- $X_c^{(H)} = H_c / H$ *: share of households (fully or partially) cooled*
- $\widehat{E}_{H_c} = E_c / H_c$ *: specific energy demand for a (fully or partially) cooled household,*
- $\widehat{E}_{H_c}^{(A)} = E_c / \left(A \times H_c / H \right)$ *: specific energy demand for a unit floor area of a (fully or partially) cooled household,*

Equations (2), (3) and (4) can then be written as:

$$E_c = X_c^{(A)} \times \widehat{E}_c \times A \tag{5}$$

$$E_c = X_c^{(H)} \times \widehat{E}_{H_c} \times H \tag{6}$$

$$E_c = X_c^{(H)} \times \widehat{E}_{H_c}^{(A)} \times A \tag{7}$$

Modelling energy demand using this framework is to approximate the above factors as accurately as possible with existing data. We can classify these as measures of diffusion (X_c), of intensity ($\widehat{E}_c$) and scale (H or A). Hence, in general we are looking for functions that map to diffusion from climate and income indicators and functions that map to intensity from climate indicators.

$$\widehat{E}_c = f_E(CDD) \tag{8}$$

$$X_c^{(A)} = f_E(CDD, I_H) \tag{9}$$

$$\widehat{E}_{H_c} = f_{E_H}(CDD) \tag{10}$$

$$X_c^{(H)} = f_H(CDD, I_H) \tag{11}$$

In this work, we derive the diffusion functions from survey data for the USA, France and Spain.

In equation (5), $\widehat{E}_c$ the average cooling energy required for a cooled unit of floor area, is primarily a function of climate [Sailor and Pavlova, 2003]. In the case of equations (6) and (7), $\widehat{E}_{H_c}$ and $\widehat{E}_{H_c}^{(A)}$ both depend as well on the average floor area per household and on the share of floor area cooled, however, if we assume:

$$A_{H_c} = X_c^{(H)} \times A \qquad (12)$$

Where:

- A_{H_c} *: is the total floor area of cooled households*

We can write:

$$E_c = X_c^{(H)} \times \frac{E_c}{A_{H_c}} \times A \times e \qquad (13)$$

Where:

- *e : signifies the factor of error due to the assumption of equation (8)*
- E_c / A_{H_c} *is the specific energy demand for a (fully or partially) cooled household per unit floor area* $\widehat{E}_{H_c}^{(A)}$

$$E_c = X_c^{(H)} \times \widehat{E}_{H_c}^{(A)} \times A \times e \qquad (14)$$

The advantage of equation (14) over equation (5) is that $X_c^{(H)}$, the usual indicator of market diffusion is more easily and more commonly measured than $X_c^{(A)}$, as in (INE, 2008), (INSEE, 2013), (Ürge-Vorsatz et al., 2015) and (Santamouris, 2016).

The error 'e' introduced has two main causes. First, assuming that equation (8) is true is to assume that the average floor area of a household is not correlated with the probability of it being cooled. This is not plausible if $X_c^{(H)}$ and the average floor area are both functions of another variable such as income. Therefore, we can expect an overestimate of E_c using equation (6) instead of equation (5) if higher income households have larger floor areas and are more likely to be cooled as well and vice versa. The error would be by a factor of:

$$e_A = \frac{\sum_{i=1}^{N} A_{H_c}^{(i)}}{X_c^{(H)} \times A} \qquad (15)$$

Where:

- $A_{H_c}^{(i)}$ *: is the floor area of cooled household i*

Second, if a value for $\widehat{E}_{H_c}^{(A)}$ modelled based on data for one region is used in equation (6) to estimate E_c of another region the result is further erroneous, if the average floor area and its correlation with $X_c^{(H)}$ are not the same for the two regions. This error corresponds to:

$$e_{\hat{E}} = \frac{e_A^{(1)}}{e_A^{(2)}} \frac{A^{(2)}}{A^{(1)}} \frac{H^{(2)}}{H^{(1)}} \quad (16)$$

Where *(1)* and *(2)* refer to two different regions. Hence, we can write:

$$E_c = X_c^{(H)} \times \hat{E}_{H_c}^{(A)} \times A \times e_A e_{\hat{E}} \quad (17)$$

Implying that:

$$X_c^{(A)} \times \hat{E}_c = X_c^{(H)} \times \hat{E}_{H_c}^{(A)} \times e_A e_{\hat{E}} \quad (18)$$

In addition, the use of data from one region in another to estimate $\hat{E}_{H_c}$ or $\hat{E}_c$ for another region is subject to a number of other sources of error due to differences in insulation and ventilation of building as well as different usage habits.

1.2 Data sources and processing

As seen above, the choice of cooling penetration variables may create undesirable biases. In order to compare the three countries, it is thus essential that the model variables are equivalent. At the same time, they need to indicate well the underlying drivers of market diffusion – climate and purchasing power - while being freely available to anyone. The surveys used in this work are:

- US : EIA Residential Energy Consumption Survey (RECS) 2015 (5 686 respondents) (EIA, 2015)
- FR : INSEE Enquête Logement en 2013 (27 137 respondents) (INSEE, 2013)
- ES : INE Encuesta de hogares y medio ambiente 2008 (INE, 2008)

For the US and France, the whole datasets where used which allowed for separate modelling of income groups while for Spain only the published results by region were used and the income dependence could not be analysed.

1.2.1 Cooling Degree Days

US survey data included CDD values from the National Climate Data Centre (NCDC), which correspond to measurements by the nearest weather station of each household. A value for 2015 was provided as well as a 30-year average (1982-2011) that we used as model variable. The source of the European CDDs was the 2009 ASHRAE Handbook, which gives average values of weather stations (1982-2006). For each region in France and Spain a weather station was available in large representative (centrally located) cities. The base was 65 °F (18.3 °C) for all sources. For the model inputs, all figures were converted to °C.

1.2.2 Household Income

Income data has been collected in the three surveys but definitions vary and, most importantly, we would like to compare the countries on purchasing power parity (PPP) basis. The World Bank [Word bank data, International Comparison Program database] estimates countries' gross national income (GNI) at PPP for every year. GNI is the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad. We have used GNI in international dollars of 2015. An international dollar has the same purchasing power over GNI as a U.S. dollar has in the United States.

The US survey of 2015 asked respondents to situate their household within gross income brackets consistent with the definition of GNI. We therefore took the responses as representative of the average GNI of the populations (weights) represented by the surveyed households.

The French survey asked for net household income values in euros of 2013. The total weighted sum was thus representative of the net income of the whole country. The ratio of the French GNI in international dollars of 2015 to this total net income was then multiplied by the value given by each household to obtain the GNI (PPP) per household that could be compared to the US data. The ratio therefore represents a currency exchange rate including the rates of inflation of US dollars and euros between 2013 and 2015 as well as the ratio of income including social charges and taxes to net income in France. Since this ratio is in reality almost constant with respect to income in France (Landais, 2011) this should introduce only a small error.
The ratio is 1.89 for France and 2.64 for Spain.

1.2.3 Share of households with cooling equipment

All three surveys directly recorded ownership of space cooling equipment of households.
In the US survey, the type of equipment is well distinguished between:

- Central air conditioning equipment with/without heat pump
- Wall /window air condition unit

Mobile air conditioning units are not mentioned in the US survey (included in the central air conditioned).
No distinction is mentioned between fix and mobile AC in the Spanish and French surveys

1.2.4 Share of floor area cooled

The US survey recorded the total floor area of households as well as the floor area cooled accurate to a square foot (the methodology can be found in the documentation of the EIA Residential Energy Consumption Survey (RECS) (EIA, 2015). It was therefore possible to estimate the share of floor area cooled of the represented populations (weights) directly from the responses.

The French survey (INSEE, 2013) recorded only the total floor area of households in square meters. The question of ownership was refined to “the whole property is cooled” and “a part of the property is cooled”. We assumed the second response corresponded to half of the total floor area on average to estimate the share being cooled.

The results of the Spanish survey (INE, 2008) do not give average floor area per dwelling of the different regions and so it was assumed homogeneous. Similar to the French survey the question of ownership was refined to "the whole property is cooled", "the majority of the property is cooled" and "a part of the property is cooled". We assumed the last two answers corresponded to two thirds and one third of dwelling floor area respectively.

1.2.5 Data processing for analysis

<u>USA</u>

The USA data was split into groups by CDD and income. The average CDD and average cooled floor area as well as the number of households owning air conditioners was calculated for each group. While the weights were conceived by the EIA such that representative averages could be taken over census divisions, their weighted averages did not cover CDDs fewer than 350 where most of French regions are found. The fit to census divisions was compared to that over CDD groups and coincided well. Given the reasonably large number of respondents in the CDD groups we assume that their weighted averages are representative.

Table 1: US survey (EIA, 2015), number of respondents, number of represented households, weighted average CCD by group

Inc. in k$ / CDD	*Number of respondents*			*Total number of households*			*Weighted average CDD*		
	0 – 40 k$	*40 - 80 k$*	*80 k$ <*	*0 - 40 k$*	*40 - 80 k$*	*80 k$ <*	*0 – 40 k$*	*40 – 80 k$*	*80 k$ <*
0 - 100	46	31	55	938 455	504 664	869 560	45	51	65
100 - 200	100	99	104	1 708 448	1 774 253	1 712 570	158	157	152
200 - 300	197	129	125	4 587 984	2 518 521	2 459 776	249	251	257
300 - 400	241	154	166	5 108 885	3 192 847	3 355 920	349	352	354
400 - 500	249	199	236	5 735 814	3 812 771	4 606 953	447	446	451
500 - 600	185	159	175	4 118 491	3 331 440	3 498 397	556	548	548
600 - 700	140	122	188	3 571 524	2 722 859	3 879 500	650	646	644
700 - 800	149	126	147	3 265 471	2 626 457	2 615 533	748	749	752
800 - 900	140	87	81	3 164 531	1 857 368	1 472 841	857	856	855
900 - 1000	140	95	100	3 279 673	1 944 372	1 790 637	939	953	954
1000 - 1100	71	56	46	1 510 369	1 159 872	1 024 789	1 046	1 043	1 041
1100 - 1200	50	41	33	1 016 633	835 210	698 955	1 144	1 143	1 144
1200 - 1300	55	24	16	1 057 188	466 170	257 867	1 245	1 245	1 260
1300 - 1400	67	48	48	1 495 261	938 713	842 620	1 360	1 359	1 358
1400 - 1500	96	57	33	2 364 563	1 387 019	723 207	1 452	1 442	1 446
1500 - 1600	47	37	43	1 094 505	755 124	884 661	1 551	1 554	1 543
1600 - 3219	278	192	183	6 147 910	3 810 296	3 710 806	1 980	1 989	1 993

France

The French data was split into groups by region and income. The average cooled floor area as well as the number of households owning air conditioners was calculated for each group. Given the reasonably large number of respondents in each region of France we assume that their weighted averages are representative.

Table 2: French survey (INSEE, 2013), number of respondents, number of represented households, and CCD of representative cities by region

Inc. in k$ / Regions	Number of respondents			Total number of households			Representative CDD	
	0 – 40 k$	40 – 80 k$	80 k$ <	0 – 40 k$	40 – 80 k$	80 k$ <	CDD	City
Picardie	144	253	337	150 873	271 704	384 734	63	Abbeville
Basse Normandie	108	182	246	128 197	216 688	319 379	76	Caen
Haute Normandie	128	219	327	167 245	241 262	397 002	82	Rouen
Nord Pas de Calais	764	1398	1948	312 983	588 269	795 493	113	Lille
Champagne Ardenne	122	213	177	129 906	249 024	224 671	152	Troyes
Bretagne	206	434	537	235 601	545 367	691 904	157	Rennes
Centre	118	254	408	150 735	372 731	625 726	189	Tours
Lorraine	135	274	359	178 457	367 527	495 441	190	Metz
Limousin	59	99	142	74 636	110 503	169 796	190	Limoges
Pays de la Loire	258	450	670	274 142	523 594	794 156	198	Nantes
Franche Comté	75	144	205	84 097	176 243	268 457	199	Besancon
Alsace	122	227	381	140 084	220 903	444 523	212	Strasbourg
Bourgogne	68	149	194	127 164	272 548	359 041	219	Dijon
Île de France	852	1878	4122	650 767	1407145	3 064 119	226	Paris
Auvergne	110	187	223	145 397	226 648	261 712	241	Clermont-Ferrand
Poitou-Charentes	140	233	287	186 736	283 672	354 230	252	La Rochelle
Aquitaine	188	371	507	285 073	522 323	691 197	351	Bordeaux
Rhône Alpes	368	665	1145	481 223	881 295	1 402 898	393	Lyon
Midi Pyrénées	158	263	418	284 808	417 941	633 820	419	Toulouse
Languedoc Roussillon	201	259	363	289 003	403 881	531 322	561	Montpellier
Corse	23	27	23	29 910	61 634	46 604	608	Bastia
Provence Alpes Côte-d'Azur	311	523	758	411 654	734 878	1 089 101	675	Toulon

Spain

CDD obtained by region using climatic data of main cities are presented in Table 3.

Table 3: CDDs of representative Spanish cities and results of the Spanish survey (INE, 2008)

Region	CDD city	CDD
Asturias	Gijon	120
Galicia	La coruna	128
Cantabria	Santander	208
Castilla y León	Valladolid	389
País Vasco	Bilbao	416
Navarra	Pamplona	454
Rioja	Logrono	491
Cataluña	Barcelona	623
Castilla La Mancha	Albacete	643
Madrid	Madrid	649
Aragón	Zaragoza	706
Balears	Palma	737
Comunitat Valenciana	Valencia	853
Extremadura	Merida	893
Murcia	Murcia	1139
Andalucía	Seville	1207

2. USA: air conditioning diffusion and model

2.1 Air conditioning diffusion rates (USA)

Results of RECs survey (EIA, 2015) treatment by CDD and income intervals are presented in Table 4. As expected, (Sailor and Pavlova, 2003), the share of households with AC increases rapidly with CDD increase to reach its maximum level between CDD values of 800 and 1200 and then stagnates. Impact of income is of second order. The same observations apply to the share of cooled area.

Table 4: Share of households with AC and share of area cooled (USA)

CDD	Share of households with AC				Share of area cooled in the USA			
	0 – 40 k$	40-80 k$	80 k$ <	All inc.	0 – 40 k$	40-80 k$	80 k$ <	All inc.
0 - 100	29.6%	52.1%	36.7%	37.2%	22.5%	32.9%	27.2%	27.3%
100 - 200	62.9%	64.0%	58.7%	61.9%	34.2%	36.6%	38.9%	37.0%
200 - 300	65.1%	81.7%	89.4%	75.7%	37.3%	43.6%	63.4%	48.3%
300 - 400	77.4%	78.5%	84.7%	79.8%	42.4%	53.1%	66.2%	54.3%
400 - 500	81.6%	88.0%	95.8%	87.9%	50.0%	58.6%	76.2%	63.3%
500 - 600	87.7%	91.5%	95.3%	91.3%	63.2%	66.8%	79.9%	70.9%
600 - 700	84.1%	89.8%	93.9%	89.3%	62.3%	70.5%	79.5%	73.3%
700 - 800	85.7%	95.8%	95.3%	91.8%	65.9%	73.5%	79.9%	74.1%
800 - 900	91.4%	98.0%	93.8%	93.8%	70.8%	86.2%	83.9%	79.5%
900 - 1000	84.7%	97.7%	98.9%	91.9%	64.9%	77.7%	81.6%	75.0%
1000 - 1100	93.0%	89.8%	96.1%	92.9%	76.5%	71.1%	80.6%	76.2%
1100 - 1200	91.7%	96.3%	100.0%	95.5%	65.5%	87.6%	88.3%	80.7%
1200 - 1300	93.3%	97.0%	100.0%	95.2%	75.4%	92.6%	88.9%	83.3%
1300 - 1400	92.9%	91.0%	97.9%	93.6%	79.2%	86.6%	88.3%	84.5%
1400 - 1500	90.2%	97.0%	97.9%	93.5%	76.2%	86.3%	97.0%	83.7%
1500 - 1600	93.6%	96.2%	98.5%	95.9%	75.9%	83.0%	94.5%	85.0%
1600 - 3219	90.0%	97.4%	97.7%	94.2%	80.9%	93.4%	91.0%	88.2%

Diffusion rates are lower in terms of cooled area than in terms of number of households. But this share increases with CDD (figure 1): in hotter climate not only the share of households with AC increases but the share of the household that is cooled also increases from about 60 % to 90 %.

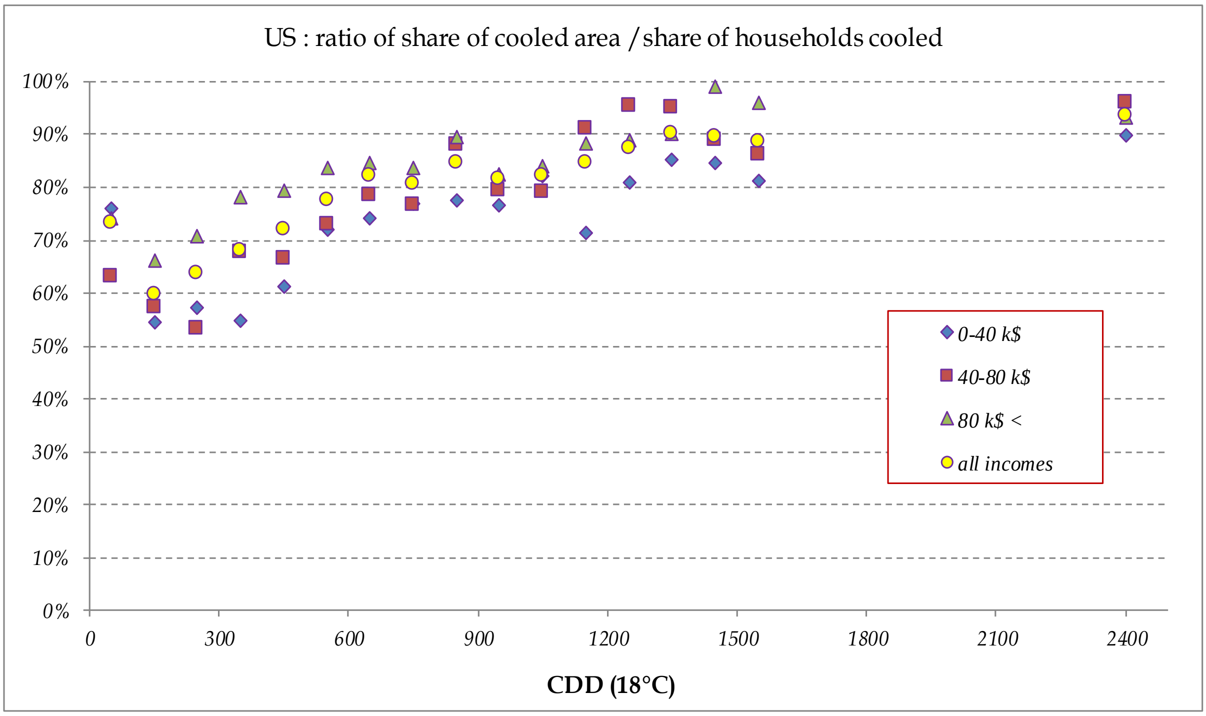

Figure 1: Ratio of the share of area cooled to the share of households with AC in the USA as a function of income, adapted from (EIA, 2015)

2.2 Air conditioning diffusion rates model (USA)

Diffusion rates in the US (for each income group) is based on the equation 19:

$$Diff_{cooled} = A - \exp(-k(CDD + c)) \qquad (19)$$

Where:

- *S : air conditioners diffusion for all end users in France (share of households or of floor area cooled)*
- *A: saturation level*
- *k: parameter related to the "steepness" of the logistic curve*
- *c: parameter corresponding to the CDD value at the inflection point of the logistic curve*

The model proposed is a generic version of the model used by (Sailor and Pavlova, 2003) and modified by (McNeil and Letschert, 2010) on RECS 2001 data.

Model fitting used non-linear least squared functions of the statistical software package R [R Core Team (2013)] with the default Gauss-Newton algorithm.

The following tables summarises all model parameters used for the USA:

Table 5: AC diffusion model fitting results (USA), share of households with AC

Share of households with AC	A	k	C	Residual standard error
All incomes	0.941	0.00529	54.14	1.5%
0 to 40 000$	0.910	0.00479	63.74	3.2%
40 000 to 80 000$	0.961	0.00410	144.44	3.3%
80 000$ <	0.976	0.00696	0	3.7%

As can be seen above residual standard errors are between 1.4% and 3.4% diffusion (absolute).

Table 6: AC diffusion model fitting results (USA), share of floor area cooled

Share of floor area cooled	A	k	C	Residual standard error
All incomes	0.867	-0.0023	16.53	2.2%
0 to 40 000$	0.820	-0.0018	24.03	3.7%
40 000 to 80 000$	0.949	-0.0016	207.0	5.0%
80 000$ <	0.899	-0.0034	71.90	4.2%

As can be seen above residual standard errors are between 2.3% and 5.0% diffusion (absolute).

Fitting results are show in Figure 2 for diffusion in terms of share of household with AC and in Figure 3 in terms of share of area cooled.

Comparison with (McNeil and Letschert, 2010) shows the evolution of AC diffusion since 2001, with a progression of diffusion at low CDD.

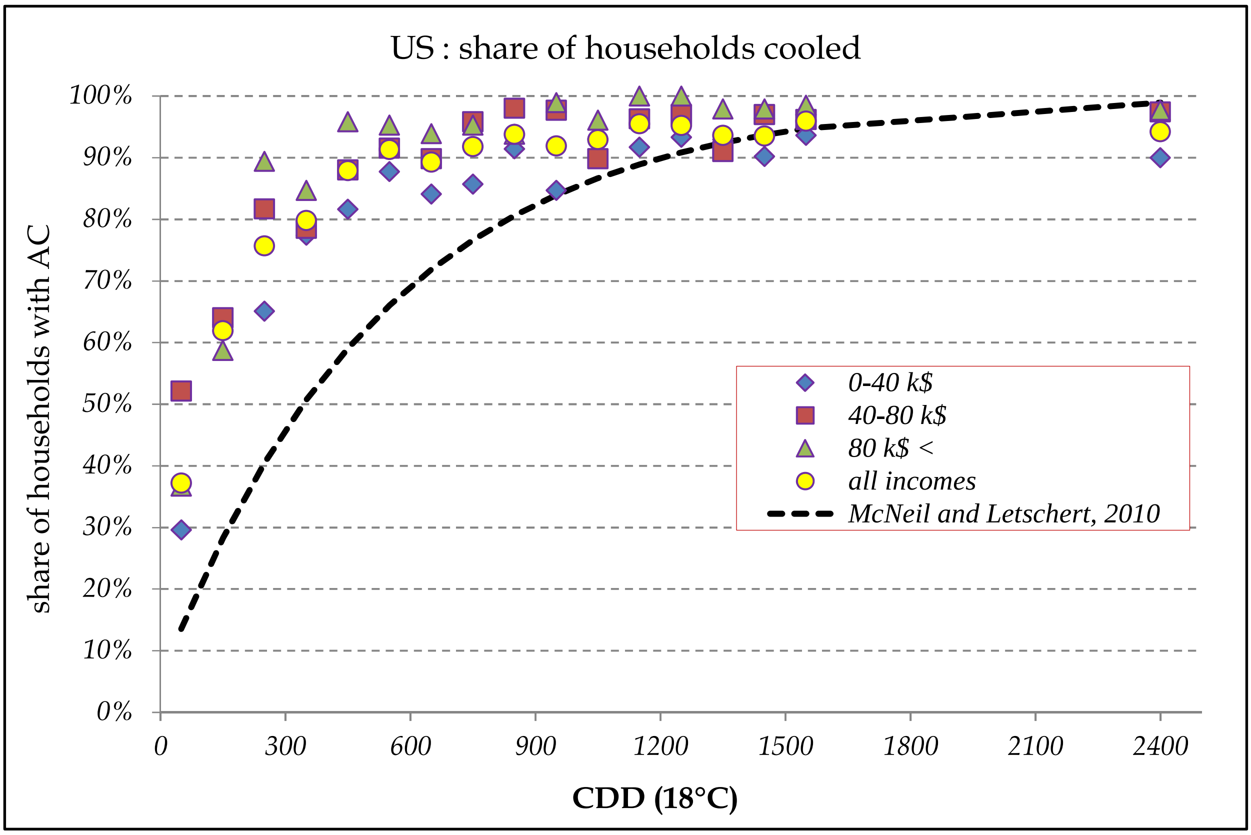

Figure 2: share of households cooled, in USA

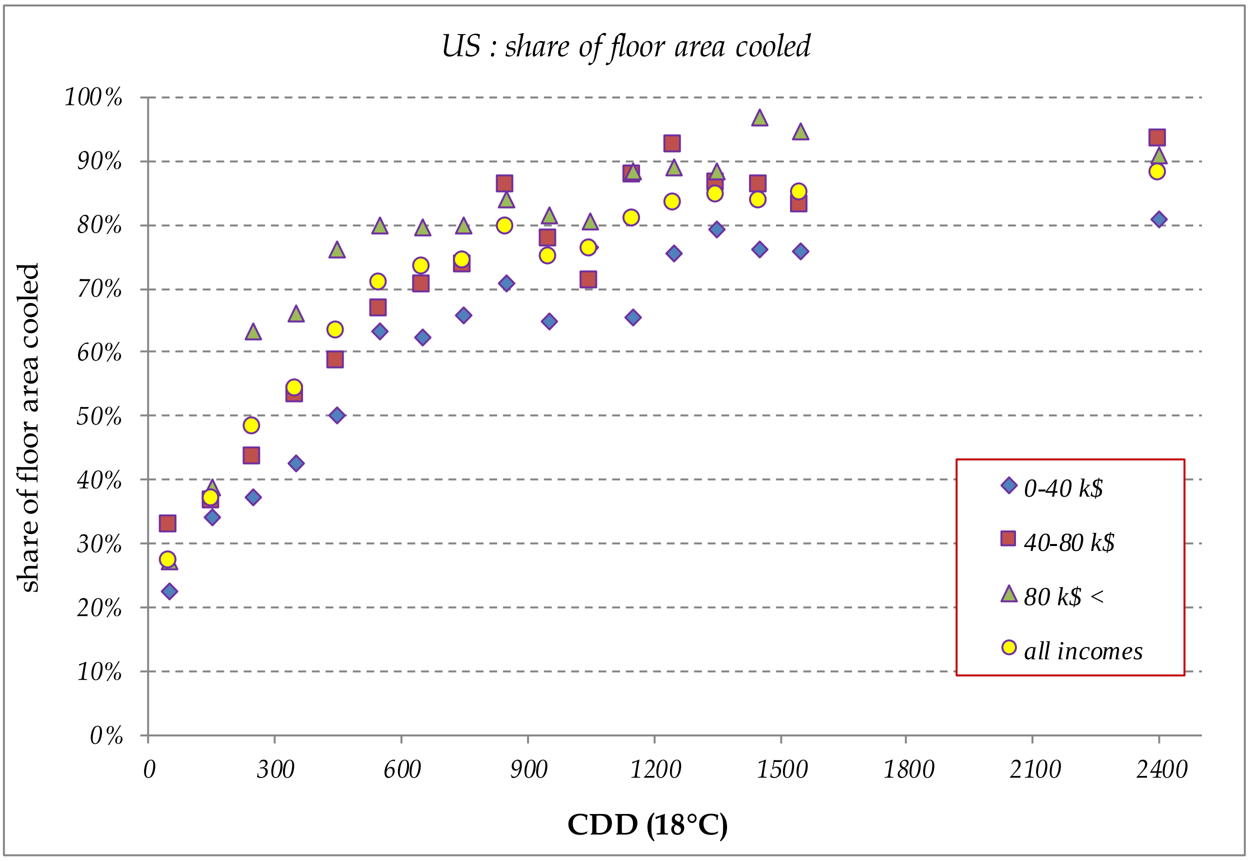

Figure 3: share of floor area cooled, for USA

3. France: air conditioning diffusion and model

3.1 Air conditioning diffusion rates (France)

Table 7: Share of households with AC and share of area cooled (France)

Region	CDD	Share of households with AC				Share of area cooled in the USA			
		0-40 k$	40-80 k$	80 k$ <	All inc.	0-40 k$	40-80 k$	80 k$ <	All inc.
Picardie	63	2%	2%	3%	2%	1%	2%	3%	2%
Basse-Normandie	76	0%	3%	2%	2%	0%	3%	1%	1%
Haute-Normandie	82	0%	1%	2%	1%	0%	0%	2%	1%
Nord-Pas-de-Calais	113	1%	1%	2%	1%	0%	1%	2%	1%
Champagne-Ardenne	152	0%	2%	4%	2%	0%	3%	3%	3%
Bretagne	157	0%	1%	1%	1%	0%	1%	1%	1%
Centre	189	1%	4%	8%	6%	2%	5%	6%	5%
Lorraine	190	2%	1%	4%	2%	1%	1%	2%	2%
Limousin	190	1%	2%	7%	4%	1%	1%	5%	3%
Pays-de-la-Loire	198	1%	1%	4%	3%	1%	1%	4%	3%
Franche-Comté	199	0%	3%	7%	4%	0%	3%	5%	4%
Alsace	212	1%	4%	9%	6%	1%	4%	7%	5%
Bourgogne	219	2%	2%	5%	3%	1%	3%	4%	3%
Île-de-France	226	1%	1%	3%	3%	1%	1%	3%	2%
Auvergne	241	0%	2%	5%	3%	0%	4%	4%	3%
Poitou-Charentes	252	1%	3%	8%	4%	1%	3%	6%	4%
Aquitaine	351	5%	4%	18%	11%	4%	3%	14%	9%
Rhône-Alpes	393	2%	4%	6%	4%	1%	4%	4%	4%
Midi-Pyrénées	419	2%	7%	19%	12%	1%	5%	15%	10%
Languedoc-Roussillon	561	16%	27%	38%	29%	16%	22%	30%	25%
Corse	608	20%	16%	69%	35%	10%	12%	41%	24%
Provence-Alpes-Côte-d-Azur	675	11%	20%	30%	23%	10%	15%	22%	18%

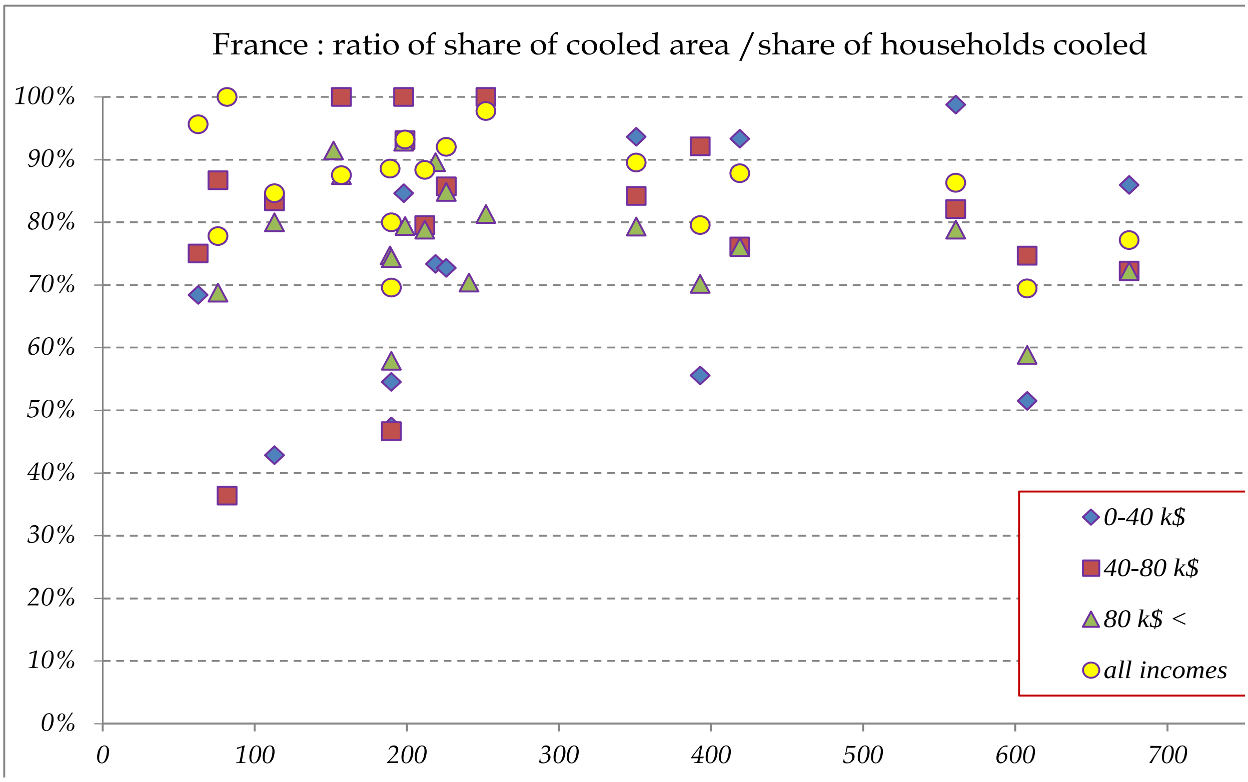

Figure 4: Ratio of the share of area cooled to the share of households with AC in France as a function of income

3.2 Air conditioning diffusion rates model (France)

The French (for each income group) and Spanish models are based on a logistic curve:

$$Diff = \frac{A}{1 + \exp(-k_c(CDD - c))} \qquad (20)$$

Where (for all equations above):

- *S : air conditioners diffusion for all end users in France (share of households or of floor area cooled)*
- *A: saturation level*
- *k_c : parameter related to the "steepness" of the logistic curve*
- *c: parameter corresponding to the CDD value at the inflection point of the logistic curve*

The models were fitted with non-linear least squared functions of the statistical software R with the default Gauss-Newton algorithm for the US and Spanish data and the Levenberg-Marquardt algorithm (without constraints) for the French data.

The following table summarises all model parameters used for the share of households cooled and the share of floor area cooled in France:

Table 8: AC diffusion model fitting results (France), share of households cooled

Share of households with AC	**A**	**k**	**C**	**Residual standard error**
All incomes	The data in this range did not allow fitting a logistic curve			
0 to 40 000$	0.385	0.0110	461.49	4.3%
40 000 to 80 000$	0.384	0.0090	395.63	4.2%
80 000$ <	0.342	0.0097	459.07	3.4%

Table 9: AC diffusion model fitting results (France), share of floor area cooled

Share of floor area cooled	**A**	**k**	**C**	**Residual standard error**
All incomes	The data in this range did not allow fitting a logistic curve			
0 to 40 000$	0.295	0.0096	454.68	3.5%
40 000 to 80 000$	0.254	0.0089	377.58	3.4%
80 000$ <	0.260	0.0089	443.75	2.8%

As can be seen above residual standard errors are between 2.8% and 4.3% diffusion (absolute). The choice of the logistic curve is somewhat speculative given the large gap in the data around the inflection point and the small amount of points at high CDD. The data shows nevertheless clearly that a model of the form used for the US with no inflection point (strictly negative second derivative) does not fit the data. The saturation value (parameter A) is possibly underestimated so the model should not be used for much hotter countries. An important source of error may be the CDDs of regions, which may not accurately represent the average household in them.

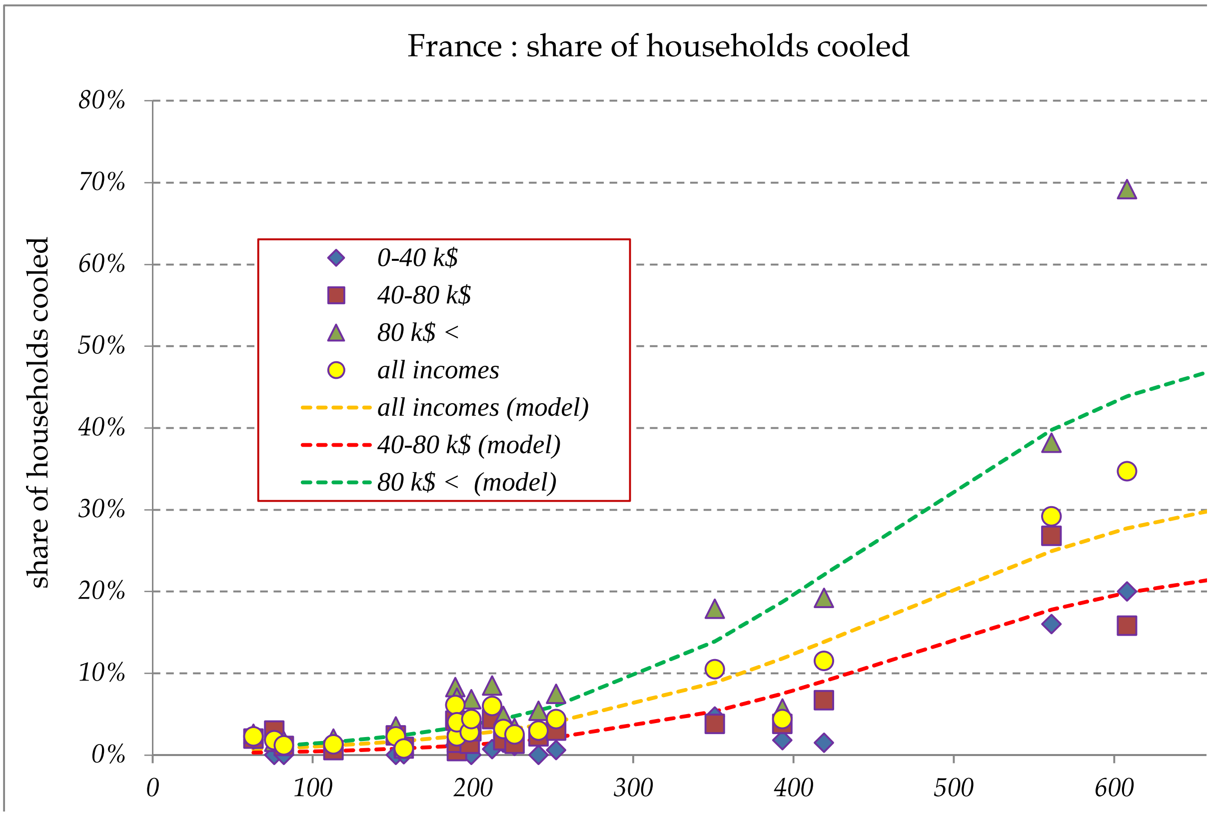

Figure 5: share of households with AC, for France, overall: 6.7%

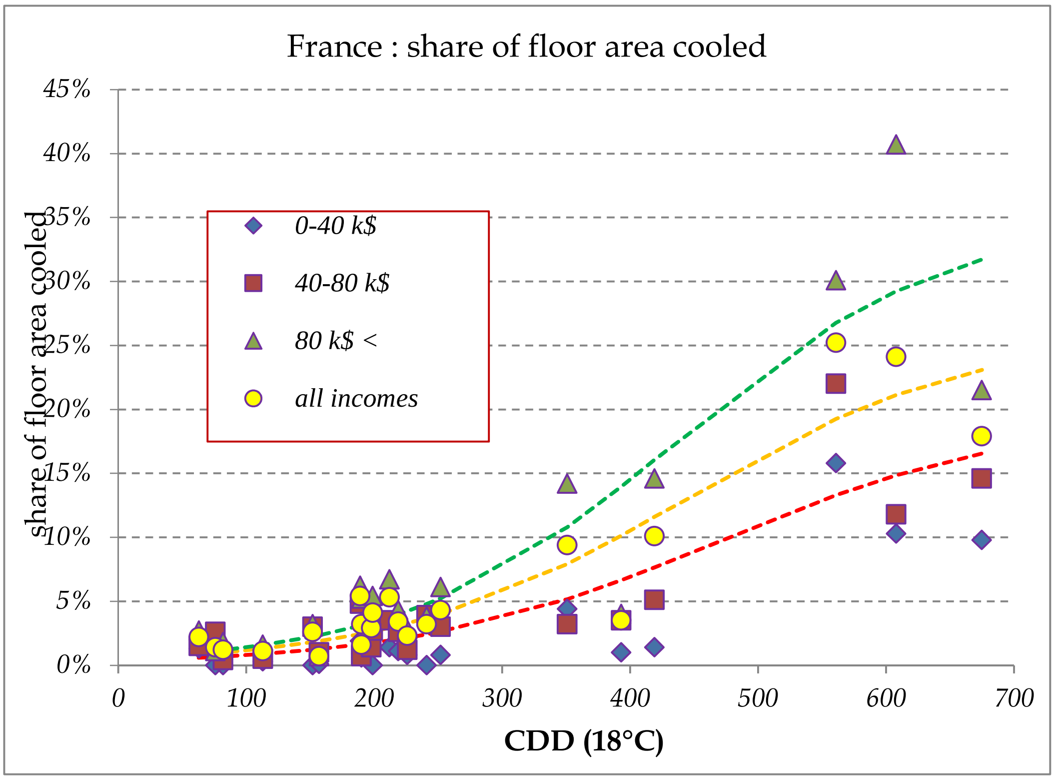

Figure 6: share of floor area cooled, for France, overall: 5.6%

4. Spain: air conditioning diffusion and model

4.1 Air conditioning diffusion rates (Spain)

Table 10: share of households with AC and share of floor area cooled (Spain)

Region	CDD city	CDD	Share of households	Share floor area cooled
Asturias	Gijon	120	0.4%	0.2%
Galicia	La coruna	128	1.0%	0.5%
Cantabria	Santander	208	0.7%	0.2%
Castilla y León	Valladolid	389	3.3%	1.4%
País Vasco	Bilbao	416	1.7%	0.7%
Navarra	Pamplona	454	11.4%	4.9%
Rioja	Logrono	491	13.3%	5.8%
Cataluña	Barcelona	623	36.1%	15.7%
Castilla La Mancha	Albacete	643	36.2%	14.6%
Madrid	Madrid	649	43.5%	20.3%
Aragón	Zaragoza	706	37.4%	17.2%
Balears	Palma	737	46.1%	21.0%
Comunitat Valenciana	Valencia	853	54.5%	25.3%
Ceuta y Melilla	Melilla	861	27.6%	13.7%
Extremadura	Merida	893	58.1%	22.8%
Canarias	Las Palmas	996	6.3%	2.7%
Murcia	Murcia	1139	63.9%	28.3%
Andalucía	Seville	1207	57.4%	24.8%

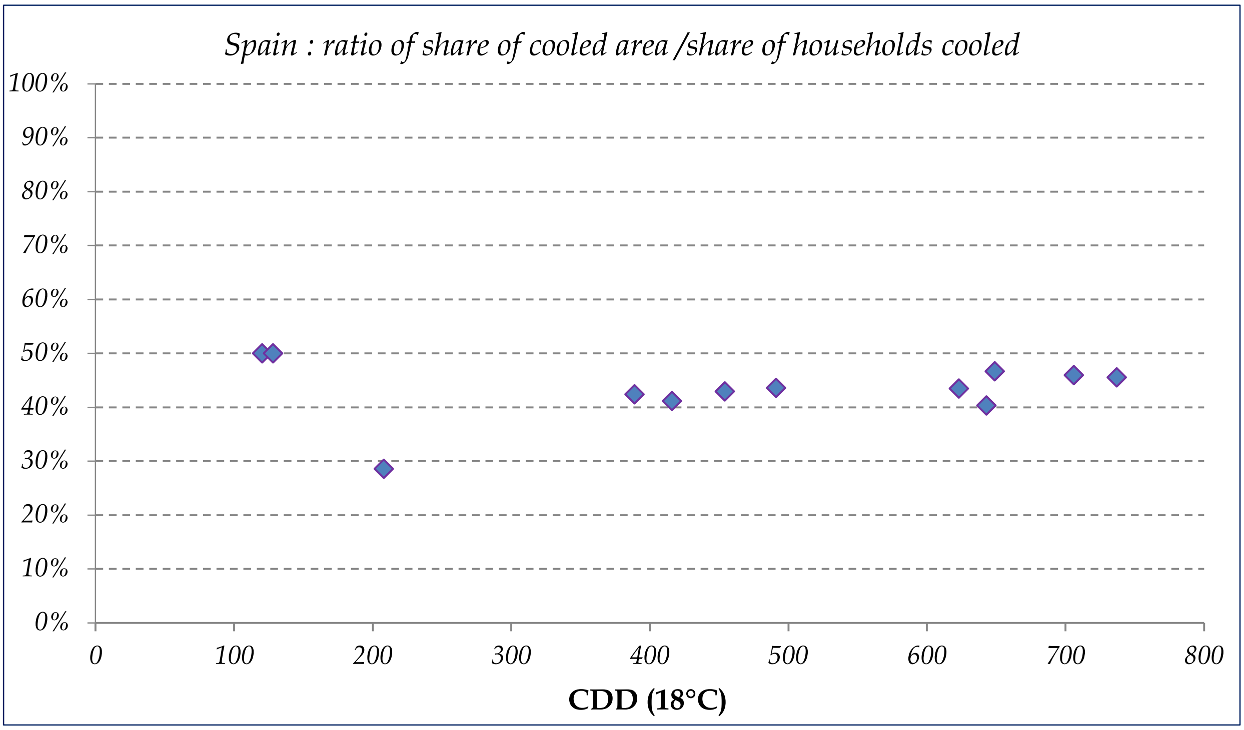

Figure 7: Ratio of the share of area cooled to the share of households with AC in Spain as a function of income

4.2 Air conditioning diffusion rates model (Spain)

Formula used to fit the share of households cooled and the share of floor area cooled models:

$$Diff = \frac{A}{1 + \exp(-k \times (CDD - C))}$$

The following table summarises all model parameters used for Spain (without the Canaries and Ceuta y Mellia):

Table 11: AC diffusion model fitting results (Spain), share of households cooled

Share of households with AC	A	k	C	Residual standard error
All incomes	0.569	0.0111	598.81	3.7%
0 to 1100 €	0.433	0.0087	677.25	3.2%
1101 to 1800 €	0.642	0.0114	618.69	5.1%
1800 € <	0.722	0.0115	574.70	4.5%

Residual standard error is 3.7% diffusion (absolute) without the Canaries and Ceuta y Mellia.

Table 12: AC diffusion model fitting results (Spain), share of floor area cooled

Share of floor area cooled	A	k	C	Residual standard error
All incomes	0.242	0.0120	590.14	1.8%
0 to 1100 €	0.159	0.0089	658.42	1.5%
1101 to 1800 €	0.269	0.0125	609.60	2.3%
1800 € <	0.357	0.0111	590.68	1.7%

Residual standard error is 1.8% diffusion (absolute) without the Canaries and Ceuta y Mellia.

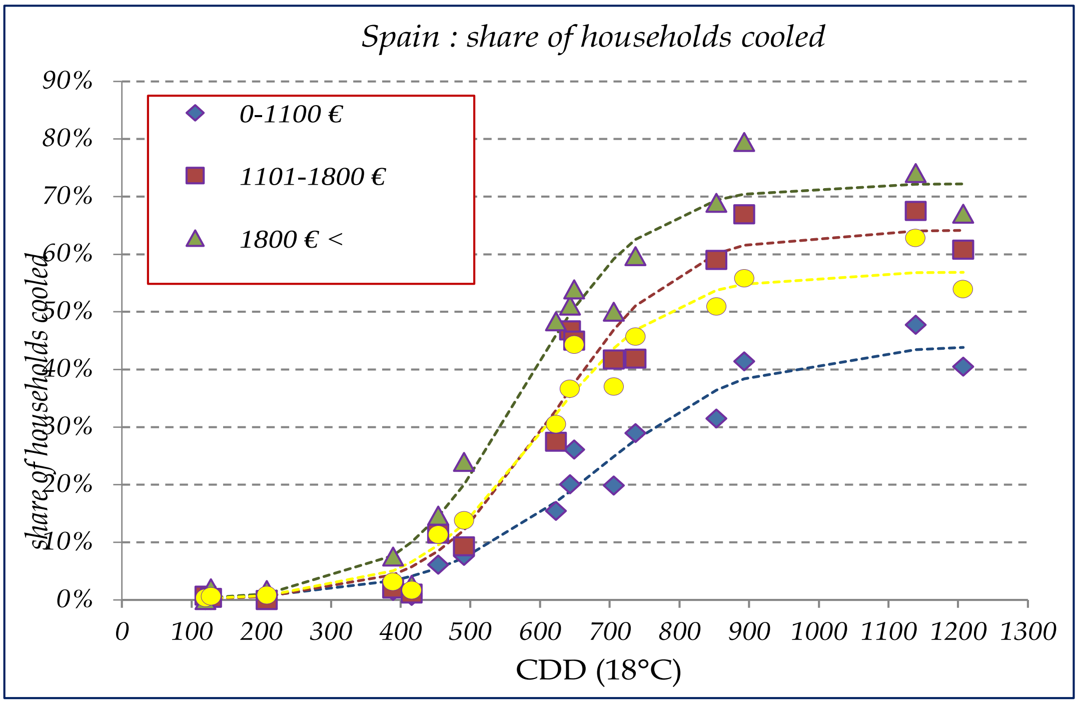

Figure 8: share of households with AC, for France, overall: 6.7%

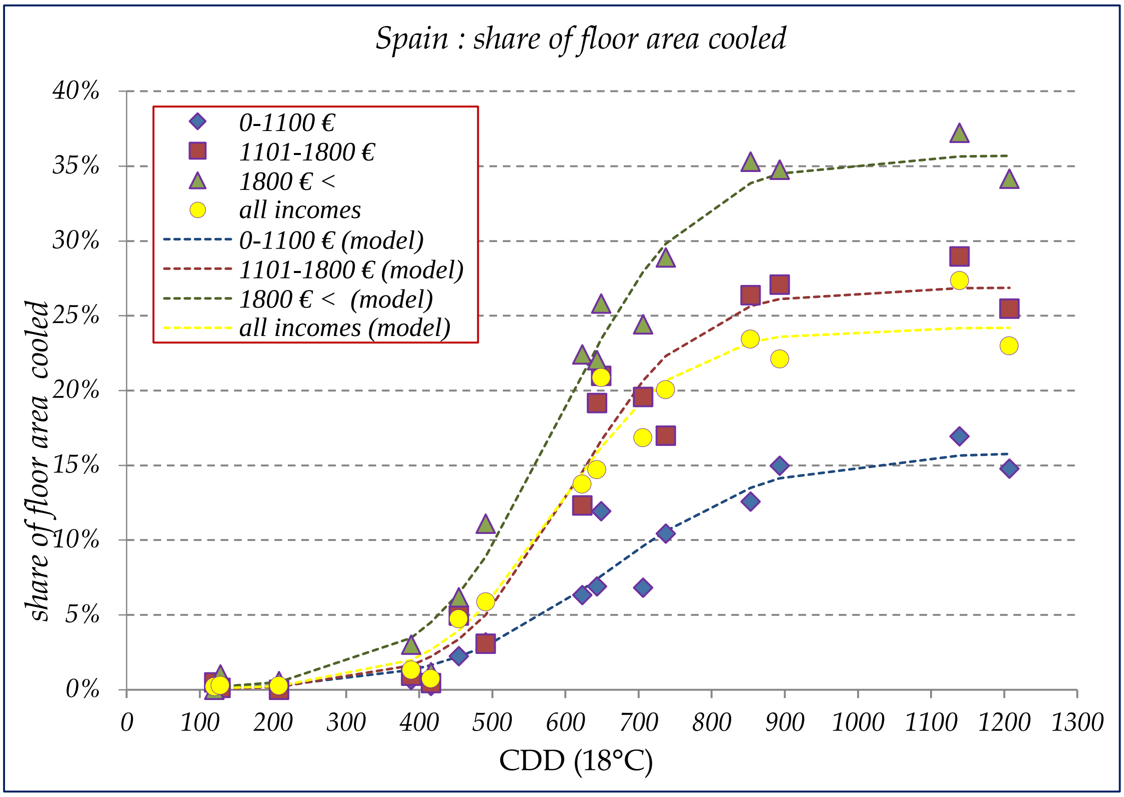

Figure 9: share of households with AC, for France, overall: 6.7%

5. Results and Discussion

By exploiting survey data from France and Spain, this paper proposed a model of diffusion of air conditioners, to estimate current and future residential space cooling demand in Europe. As the climate continues to change, and because of the importance of the diffusion rate of air conditioners for estimating energy savings in households. We need to ensure we use the most recent data and the latest methods and models, using local data instead of an adapted model that allows for estimations that are more accurate.

Local data for France and Spain show a low AC diffusion rate distribution compared to the fitted USA model. The average national diffusion rate (share of cooled floor) for France is about 6% from local data versus 25% from the fitted USA model. And for Spain is about 12% from local data versus 31% from the fitted USA model.

A possible limitation of this analysis is the accuracy of local data; the social survey in France considers three possible answers: the household is not air-conditioned, half is air-conditioned and the whole household is air-conditioned, remains representative to understand the use of these devices in France. For Spain, results of the social survey are more representative of the residential sector in Spain, compared to the French survey; another answer is possible, which improves the quality of the investigation, since the average number of rooms per household in Spain (and also in France) is between 3 and 4, which allows to the interviewee to better distinguish his answers; note that in the USA survey, only three answers were possible (no housing unit, one housing unit, two or more housing unit), but with more technical informations on the type of the equipment (central, window, wall), number of units for wall/window air conditioners, with/without heat pumps, age, maintenance, temperatures use, usage, …; these technical data are necessary to understand the difference of the market trend (and usage patterns) of space cooling equipments between the Europe and USA.

In France and Spain, most heating systems are decentralized (gas boiler), unlike the USA households who use largely air-to-air systems, which are often reversible. This could partly explain why the diffusion of air conditioners in USA is close to saturation comparing to France and Spain, and also why the USA model is not adapted to this European countries market.

The variables used represent a practical set of macroeconomic drivers for which AC diffusion model can be built. They do not represent all conceivable variables that may affect a household's choice of whether to purchase an air conditioning appliance. For example, air conditioners capacity is not differentiated in the diffusion model. The size of standard air conditioners, for example, has an influence on their price, and the desirability for owning more than one. The most significant determinant of future appliance diffusion rates not captured in the model is air conditioners price. It is widely known [Santamouris, 2016] that prices of air conditioners are not fixed over time. The continual decrease in price of AC appliances means that they become more affordable to households. Therefore, diffusion rates for a certain income may be higher than indicated by a model determined with current prices.

Evolution over time of the proposed models needs to be investigated to understand the most influential parameters on the diffusion rate, and why this considerable difference between Europe and USA.

Furthermore, CDD values do not represent all relevant climate related factors.

We attempted to fit a similar model to that of McNeil and Letschert by replacing the "climate maximum" by the model of the richest (>80 000$ GNI (PPP)/hh) French households. The data was however not sufficient to justify such a model. It appears that at equal CDD, average income in a region is only a weak predictor of market diffusion especially at the low CDDs in the majority of French regions.

6. Forecasting Market Diffusion

The purpose of this section is to use the new model developed in this paper to predict the future diffusion of residential space cooling equipment in France.

[Spinoni et al., 2017] investigated the evolution of CDD. The adjusted CDD values for France for IPCC emissions scenarios (RCP4.5 and RCP8.5) are estimated, using population weighting (from Eurostat data). The mean of the CDD trends over the period 1981-2100 for France is shown in table 15:

Table 13: the mean of the CDD trends over the period 1981-2100 for France

	RCP4.5	*RCP8.5*
CDD increase/year	***0.7±0.1***	***1.8±0.2***

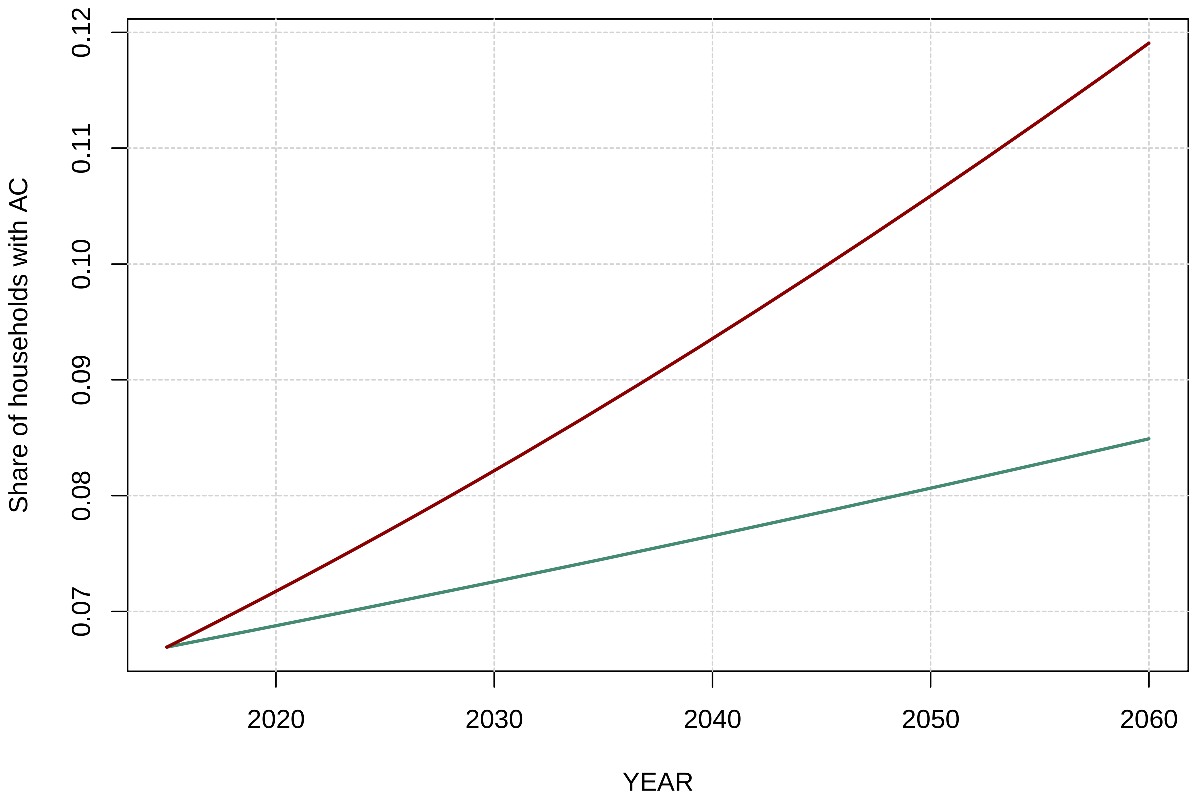

Figure 9: Air Conditioner Saturation for France regions for all end users, for rcp 45 and rcp 85 scenarios (share of households with AC)

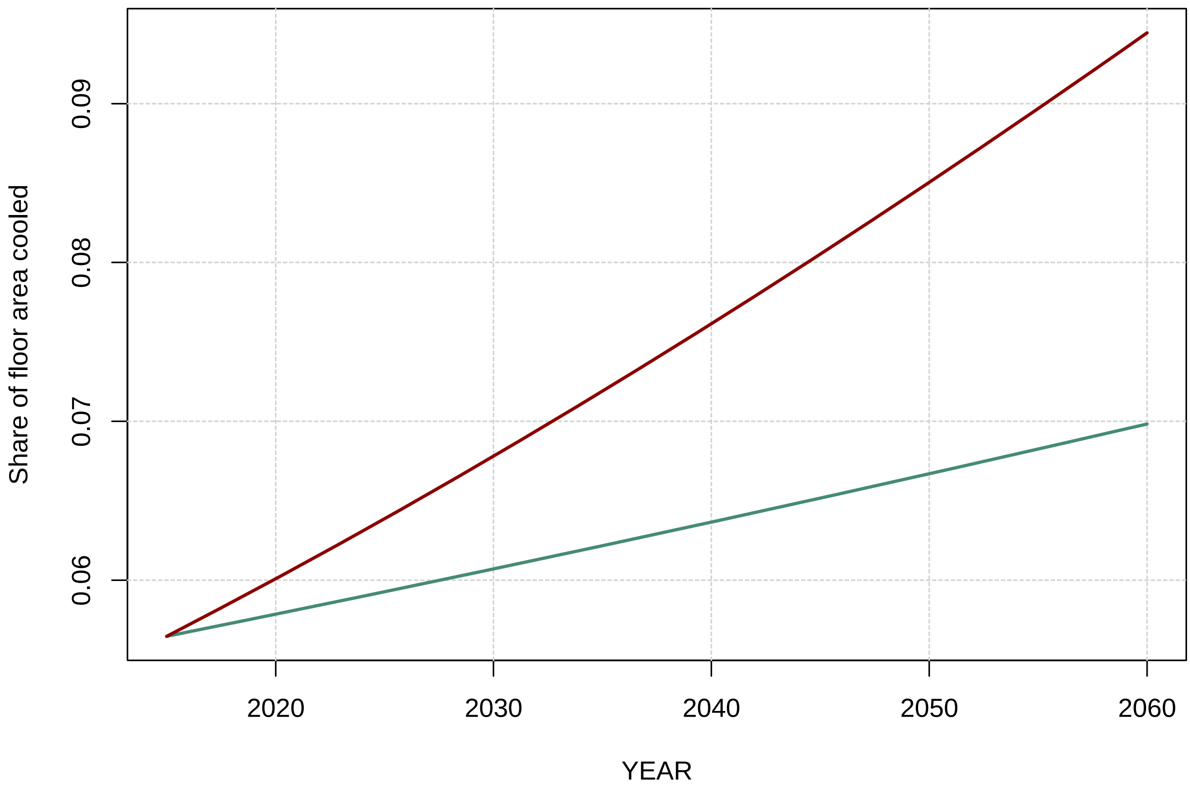

Figure 10: Air Conditioner Saturation for France regions for all end users, for rcp 45 and rcp 85 scenarios (share of households with AC)

For France, the average diffusion rate is about 6.7% of households and 5.6% of floor area in 2015 with a CDD around 300. Until 2050 this rate will increase considerably to 8.1% of households and 6.7% of floor area with a CDD around 325 for the IPCC scenario RCP4.5 and to 10.6% of households and 8.5% of floor area with a CDD around 362 for the IPCC scenario RCP8.5 (this forecasting study does not include the household income increase by 2050, only climate change is considered, however it is likely that AC prices will increase with income due to stricter efficiency regulation in Europe, keeping purchasing power not far from constant). And not the huge impact of heat waves (that leads to massive sales and tend to change the perception need for ac, probably more to quote).

7. Conclusion

In long-term scenarios, energy end use for air conditioners is often projected based on the fitted US model. However, additional information can be obtained by looking at the local data; such information not only leads to an improved understanding of the development of air conditioning energy consumption, but also provide the energy community with a foundation for further analysis, specifically in the development of end use energy demand forecasts, the possible impacts of changing climate and related projections of greenhouse gas emissions related to energy consumption.

This paper proposed a model of diffusion of air conditioners, to estimate current and future residential space cooling demand in Europe. As the climate continues to change, and because of the importance of the diffusion rate of air conditioners for estimating energy savings in households. We need to ensure we use the most recent data and the latest methods and models, using local data instead of an adapted model that allows for estimations that are more accurate.

As discussed above, local data for France and Spain show a low AC diffusion rate distribution compared to the fitted USA model. The average national diffusion rate (share of cooled floor) for France is about 6% from local data versus 25% from the fitted USA model. And for Spain is about 12% from local data versus 31% from the fitted USA model.

In France and Spain, most heating systems are decentralized (gas boiler), unlike the USA households who use largely air-to-air systems, which are often reversible. This could partly explain why the diffusion of air conditioners in USA is close to saturation comparing to France and Spain, and also why the USA model is not adapted to this European country market.

Evolution over time of the proposed models needs to be investigated to understand the most influential parameters on the diffusion rate, and why this considerable difference between Europe and USA.

Acknowledgment

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