Evidence of an indirect rebound effect with air-to-air heat pump: to have and not to use ?

M.Raynaud, EDF-R&D and CES – MINES ParisTech, Moret-sur-Loing, France
D.Osso, EDF-R&D, Moret-sur-Loing, France
B.Bourges, GEPEA – Ecole des Mines de Nantes, Nantes, France
B.Duplessis, CES – MINES ParisTech, Paris, France
J.Adnot, MINES ParisTech, Paris, France

Abstract

Regional energy efficiency programmes are of particular interest as they tackle local constraints which are not always targeted by national energy policy. In this frame, an energy efficiency programme for existing dwellings has been implemented in a southern European region, providing financial incentives for a combination of energy efficiency actions (reversible air-to-air heat pump combined with insulation and/or solar hot water). *Ex-post* evaluation results of this pilot programme are reported here.

More than 200 households were surveyed regarding their individual energy consumption and building as well as household characteristics. Likewise, the survey highlights household behaviours concerning both space heating and air conditioning, before and after refurbishment. A three years billing analysis is used to calculate the energy savings attributed to the operation. Evaluations are carried out taking into account critical parameter like climate differences between years or direct (enhanced space heating comfort) and indirect (use of air conditioning) rebound effect via a statistical model. Moreover, an uncertainty assessment of energy savings was realized on the basis of three scenarios (low, median and high).

Particularly, this study points out the use of air conditioning by households, data rarely found in the literature, whereas this end-use should increase in the residential sector especially in southern regions.

These results contribute answering questions about installation of air-to-air heat pump in existing buildings: energy savings and direct rebound effect as well as indirect rebound effect and household motivation for implementing energy efficiency actions.

Introduction

The question of observed energy savings (*ex-post* evaluation) is of great importance in order to derive experience feedback from national energy policies or from local energy efficiency programmes as well. But major difficulties (cost, measurement vs. enquiry, representativeness, uncertainty…) explain why so few studies can be found in the European literature, especially studies about energy efficiency programmes in France.

Moreover, regional energy efficiency programmes are of particular interest as they tackle local constraints which are not always targeted by national energy policy. In this frame, an energy efficiency operation for existing dwellings has been implemented in the southern France area, providing financial incentives for a combination of energy efficiency actions (reversible air-to-air heat pump (AAHP) combined with insulation and/or solar hot water).

The specificity of this operation dedicated to dwellings located in a Mediterranean climate region helps us to study behavioural change of households after implementations of a reversible AAHP: space heating and air conditioning uses.

If beyond the assessment of energy savings, the question of direct rebound effect (dRE) (*i.e.* thermal comfort, space heating, increase correlated with lower energy expenditure) is usually discussed, the question of indirect rebound effect[1] (iRE) (*i.e.* air conditioning use) is not so often discussed (Sorrell 2007). This paper is an attempt to study these two phenomena.

Energy efficiency operation

The operation, called "wellness solution" studied here, is part of an energy efficiency programme conducted in France in the *Provence-Alpes-Côte d'Azur*[2] region and launched in 2009 for six years. This energy programme aims at limiting the growth of electricity demand, diversifying energy sources and promoting behavioural changes as the PACA region produces only 40% of its consumed electricity and is located at the end of the high voltage grid[3]. This programme, amongst other aims, targets a cumulated electricity saving of 1.5 GWh[4] over the six years.

In the framework of the studied operation, EDF provides a financial incentive to the households for retrofitting their dwelling with at least two kinds of energy efficiency action. These refurbishment actions achieved by a craftsman/installer could be:

- space heating system replacement by an heat pump or a wood boiler or a wood stove[5], coupled with;
- insulation improvement (wall or roof insulation or double glazing windows), Solar Water Heater (SWH) or hot water heat pump installation.

From October 2009 to March 2012 (start date of the survey), according to official's operation a little more than 4,200 dwellings were retrofitted.

To investigate this operation a survey was conducted on some of the participants especially those who had installed a heat pump. Our primary objective is to quantify the energy savings generated by the implemented actions and to assess their uncertainty, following an *ex-post* evaluation process.

As the installed heat pump could be reversible (*i.e.* to provide space heating or cooling) and the operation taking place in a region with a Mediterranean climate with high temperature[6] during summer, the survey covers the household's behaviour concerning both space heating and air conditioning managements before and after retrofitting.

Thus, through our study we seek to identify and quantify potential rebound effects (direct and/or indirect) occurring after the refurbishment. We consider a dRE concerning the change of space heating management and an iRE for the additional air conditioning use.

Method

After presenting the dataset used, we will discuss the *ex-post* evaluation of the energy efficiency actions by describing the calculation methods used to assess the energy savings and their uncertainty. The analysis of dRE and iRE will be conducted through a statistical modeling of the annual energy consumption after retrofitting.

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[1] Indirect rebound effect means that "the lower effective price of the energy service may lead to changes in the demand for other goods, services and factors of production that also require energy for their provision" (Sorrel & Dimitropoulos 2008). In our case, air conditioning is considered as a new energy service provided by the reversible heat pump.

[2] See: http://fr.edf.com/demarche-en-regions/energie-efficace-en-paca/accueil-81197.html.

[3] See: http://fr.edf.com/demarche-en-regions/energie-efficace-en-paca/notre-ambition-81216.html.

[4] *Ibid.*

[5] The surface area heated had to be at least 60 % of the net floor area or a minimum of 80 m².

[6] For example, in the city of *Aix en Provence* (*Bouche du Rhône*), from 1981 to 2010 (Météo Climat 2011), the average temperatures in July and August were respectively 22.9 °C and 22.5 °C. The average daily minima and maxima temperatures were 15.1 °C and 30.6 °C in July and 14.9 °C et 30.1 °C in August.

Available data

The data were provided by a dedicated phone survey, during the year 2012, requiring households information about their dwelling, their behaviours concerning space heating and air conditioning, the retrofitting actions done and their energy bills over the last three years.

A selection of respondents was done according to the type of energy efficiency actions realized: installation of a heat pump coupled with a second action (SHW, roof or external wall insulation). Moreover, the survey was restricted to household located in 3 *départements* (administrative division): *Bouche du Rhône* [code 13], *Var* [code 83] and *Alpes Maritimes* [code 06], which provided the major part of participants to the operation.

Finally, with an initial sample of 212 filled questionnaires, 91 presenting both "before" and "after" retrofitting data are usable for this study. The surveyed dwellings are mainly "recent"[7] single-family housings initially equipped with direct electric heating. Moreover, it should be noted that the majority of the dwellings (84 %) had not initially an air conditioning system.

The questionnaire used for this study is based on the version presented in a previous paper of the IEPEC Conference (Raynaud et al. 2012) and will be not fully presented here. However, modifications have been necessary to adapt this survey to the air conditioning end-use by adding questions on:

- The type of air conditioning system, year of installation and air conditioned space area.
- The air conditioning management: summer time of use, set temperature in the living rooms and others rooms before and after the retrofit during daytime presence, hours of absence during the day and at night.

Concerning the refurbishment measures, two types of action were included: those realized under the umbrella of the operation and those realized outside the operation (from 2009, the beginning of the operation).

Energy savings calculation

In the context of this paper, we focus on the unitary energy savings achieved by a participant of the operation. With one year of energy consumption both for the periods before and after retrofitting, we calculate the resulting annual energy savings. Specifically, we choose to study the total energy consumption (all end-uses) collected through the survey.

All end-uses annual energy consumptions are directly reported by the household during investigation as explained by equation 1. At the scale of one participant and its housing, we calculate the energy savings expressed in final energy. Consumptions of different energy sources (gas, oil, LPG and wood) expressed in different units (liters, tonnes, etc.) are converted into kWh_{LCV} (Lower Calorific Value)[8].

$$C_{i,\vartheta}^{obs.} = \sum C_{i,\vartheta,e} \qquad \text{eq. 1}$$

with $C_{i,\vartheta}^{obs.}$: observed (climate unadjusted) annual energy consumption for all end-uses of case i (kWh) with ϑ = before (*be*) or after (*af*) retrofitting.

$C_{i,\vartheta,e}$: annual energy consumption before or after retrofitting of energy e declared by respondent i, (kWh), with e = electricity, gas, LPG, domestic oil, wood logs or pellets.

In order to assess the efficiency of actions and not only the direct changes in consumption between before and after situations, we adjust the consumption according to a normal climate corresponding to an average climate over 20 years. Climate correction is only done on space heating consumption according to equation 2:

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[7] Built after the first thermal regulation (*i.e.* >1975) and before 2001.

[8] Gas: 0.9 kWh_{LCV}/kWh_{HCV} (Higher Calorific Value) ; Domestic oil: 10 kWh_{LCV}/liter ; LPG: 12720 kWh_{LCV}/tonne ; Wood logs: 1710 kWh_{LCV}/stere ; Wood pellets: 4700 kWh_{LCV}/tonne.

$$C_{i,\vartheta}^{norm.} = C_{i,\vartheta}^{obs.} * (X_{shs} * \frac{HDD^{norm.}}{HDD^{obs.}} + (1 - X_{shs})) \qquad \text{eq. 2}$$

with $C_{i,\vartheta}^{norm.}$: climate adjusted annual energy consumption for all end-uses of case i (kWh) with ϑ = before (*be*) or after (*af*) retrofitting.

$HDD^{norm.}$: annual Heating Degree Days[9] of the normal climate[10], (°C.day),

$HDD^{obs.}$: annual Heating Degree Days of the observed year (°C.day),

X_{shs} : space heating consumption share in total final consumption (all end-uses), value = 0.7 (average national share for individual housing).

Although in some cases, there is a linear correlation between air conditioning consumption and Cold Degree Day (CDD), climate adjustment does not seem to be reliable (DAY 2004). Moreover, to our knowledge, there is no French reference concerning the share of air conditioning in the total consumption to help us to realize a climate normalization as it does for space heating. Finally, the annual energy savings (ES_i in case i) are calculated using equation 3:

$$ES_i = C_{i,be}^{norm.} - C_{i,af}^{norm.} \qquad \text{eq.3}$$

Uncertainty assessment of energy savings

To assess the robustness of the calculated energy savings an uncertainty analysis is carried on. Uncertainties concerning the energy savings are coming from:

- the consumptions directly reported by the household for the following energies: oil, LPG, wood (log or pellets) due to the lack of proper metering. Uncertainties concerning electricity and gas are considered negligible.
- the share of space heating consumption in the all end-uses consumption (see equation 2) used for the climate adjustment.

Those uncertainties are *a priori* highly variable from one participant to another. Therefore, given the difficulty to choose a value for each variable, we performed a sensitivity analysis based on three scenarios: a “realistic” one framed by a “pessimistic” one and an “optimistic” one. Establishing these scenarios of uncertainties needs the definition of standard uncertainties[11] associated to each variable. Standard uncertainty u linked to the consumption C of energy e reported by the case i is written $u(C_{i,e})$. Standard uncertainty linked to the space heating share is written $u(X_{shs})$. Unable to give a value to these uncertainties, assumptions are made on the basis of lower and upper bounds and their probability distribution (see Table 1).

From the standard uncertainties defined by the scenarios, the law of propagation of uncertainty (JCGM/WG1 2008) and the equations used for estimate the energy savings (equations 1 to 3), we can calculate the combined standard uncertainties linked to the energy savings ($u_c(ES_i)$):

$$u_c\left(C_{i,\vartheta}^{obs.}\right) = \sqrt{u^2\left(C_{i,\vartheta,oil}\right) + u^2\left(C_{i,\vartheta,LPG}\right) + u^2\left(C_{i,\vartheta,woodl}\right) + u^2\left(C_{i,\vartheta,woodp}\right)} \qquad \text{eq.4}$$

$$u_c\left(C_{i,\vartheta}^{norm.}\right) = \sqrt{\left[X_{shs}\left(\frac{HDD^{norm.}}{HDD^{obs.}} - 1\right) + 1\right]^2 {u_c}^2\left(C_{i,\vartheta}^{obs.}\right) + \left[C_{i,\vartheta}^{obs.}\left(\frac{HDD^{norm.}}{HDD^{obs.}} - 1\right)\right]^2 u^2(X_{shs})} \qquad \text{eq.5}$$

$$\mathrm{u_c}(ES_i) = \sqrt{{u_c}^2\left(C_{i,be}^{norm.}\right) + {u_c}^2\left(C_{i,af}^{norm.}\right) + 2 * 1 * (-1) * u_c\left(C_{i,be}^{norm.}\right) u_c\left(C_{i,af}^{norm.}\right) * \mathrm{r}\left(C_{i,be}^{norm.}, C_{i,af}^{norm.}\right)}$$

eq.6

with $\mathrm{r}(C_{i,be}^{norm.}, C_{i,af}^{norm.})$: correlation coefficient between $C_{i,be}^{norm.}$ and $C_{i,af}^{norm.}$, it is 0.403 for the studied sample.

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[9] Base 18 °C.

[10] *Département* 06: 1372 °C.day; *Département* 13: 1627 °C.day; *Département* 83: 1309 °C.day.

[11] The standard uncertainty of a quantity is defined as the estimated standard deviation associated to an estimation of its value.

In order to have results more understandable that the combined standard uncertainties, we choose to express the uncertainties linked to ES_i by the confidence intervals at level 95 % $\pm U_i$ framing ES_i:

$$U_i = 2 * u_c(ES_i) \qquad \text{eq.7}^{12}$$

Table 1. Synthesis of the three uncertainty scenarios.

	Scenario	Bounds $[a_- ; a_+]$	Probability distribution[13]	Standard uncertainty
Observed consumptions for oil (C_{oil}), LPG (C_{LPG}), wood log (C_{woodl}) or wood pellets (C_{woodp})	Optimistic (interval/2)	$[0.9C_e ; 1.1C_e]$	Symmetric trapezoidal distributions having equal sloping sides, with bases of width $a_+ - a_-$ and tops of width $(a_+ - a_-)*0.5$	$\sqrt{\frac{(a_+ - a_-)^2 * (1 + 0.5^2)}{24}}$
	Realistic	$[0.8C_e ; 1.2C_e]$		
	Pessimistic (interval*2)	$[0.6C_e ; 1.4C_e]$		
Hypothesis on space heating share in total consumption (0.7)	Optimistic (interval/2)	[0.665 ; 0.74]	Rectangular distributions with widths $a_+ - a_-$	$\sqrt{\frac{(a_+ - a_-)^2}{12}}$
	Realistic	[0.63 ; 0.78][14]		
	Pessimistic (interval*2)	[0.56 ; 0.86]		

To determine the existence or not of the energy consumption reductions associated to the energy efficiency actions realized, we define as robust, ES_i values with a reliable sign (+ or -). More precisely, it means the lack of zero in the confidence interval at level 95 % of ES_i ($[ES_i - U_i ; ES_i + U_i]$).

Statistical analysis

The study of dRE and iRE is done with a covariance analysis (ANCOVA), a general linear statistical modeling merging quantitative and qualitative variables to explain a specific variable:

$$variable_i^{explained} = \alpha + \sum_{j=1}^{N_j} a_j * variable_{j,i}^{quantitative} + \sum_{k=1}^{N_k} \sum_{l=1}^{m_k} b_{kl} * variable_k^{qualitative} * \_modality_{l,i} + \varepsilon_i \quad \text{eq.8}$$

The used sample is reduced to 82 cases due to some particular cases[15]. The response variable of ANCOVA analysis is the total annual energy consumption after retrofitting at normal climate and for 1 m² of surface area (in kWh/m²). For the case i, it will be noted $C_{i,af}^{norm.,m^2}$.

Explanatory variables used in the ANCOVA analysis are presented in the appendix (Table 6). The total annual energy consumption before retrofitting at normal climate ($C_{i,be}^{norm.,m^2}$) is one of these variables in order to realize a statistical analysis of "Change Model" type (TecMarket Works et al. 2004). The dRE is studied with the declared change of heating set temperature in the living rooms between before and after retrofitting (in °C). The iRE is studied with the declared use of air

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[12] In the frame of this study, we can hypothesize that the probability distribution characterizing ES_i follows a normal distribution because of the central limit theorem and secondly that $u_c(ES_i)$ is a reasonably reliable estimate of the standard deviation of the normal law.

[13] "Because there was no specific knowledge about the possible values of X_i within its estimated bounds a_- to a_+, one could only assume that it was equally probable for X_i to take any value within those bounds, with zero probability of being outside them. Such step function discontinuities in a probability distribution are often unphysical. In many cases, it is more realistic to expect that values near the bounds are less likely than those near the midpoint. It is then reasonable to replace the symmetric rectangular distribution with a symmetric trapezoidal distribution having equal sloping sides." (JCGM/WG1 2008).

[14] Minimum and maximum values of the space heating share in the average all end-uses consumption for the *Provence-Alpes-Côte d'Azur* region (CEREN 2009).

[15] 6 cases having installed an air-to-air heat pump and realized two others energy efficiency actions, 2 cases having installed a water-to-water heat pump and 1 case having installed an air conditioning system out of the operation.

conditioning after retrofitting[16]. This variable is a coupling between the declared time of use during summer (no use, low[17] or important[18]) and declared set temperature of air conditioning (less than 23 °C or 23 °C and more[19]).

In the aim to retain only the significant variables, a backward selection is applied with a significance level of 0.05 at Student's t-test. The constraint "coefficient of the first category= 0" is used for the qualitative variables in order to assure an easy understanding of the effects found by the model. For the presented model, it is verified that:

- explanatory variables do not present colinearity (Variation Inflation Factor ≤ 3),
- residuals are homoscedastic (graphic verification),
- residuals are normally-distributed (Jarque-Bera's test).

It is important to keep in mind the definition of what is statistically significant or not in a statistical model: a non-significant coefficient does not mean "absence of effect in the real life". It only means that the uncertainty linked to the effect estimation remains higher than some level.

Results

Energy savings

A large majority of the 91 cases (85 %) presents positive energy savings (Figure 1), *i.e.* an energy consumption reduction. Nevertheless, a large share of cases (58 %) presents energy savings in an interval between -50 and 50 kWh/m². The robustness of these relatively small energy savings linked with the energy efficiency actions realized must be analyzed to be sure of their reality.

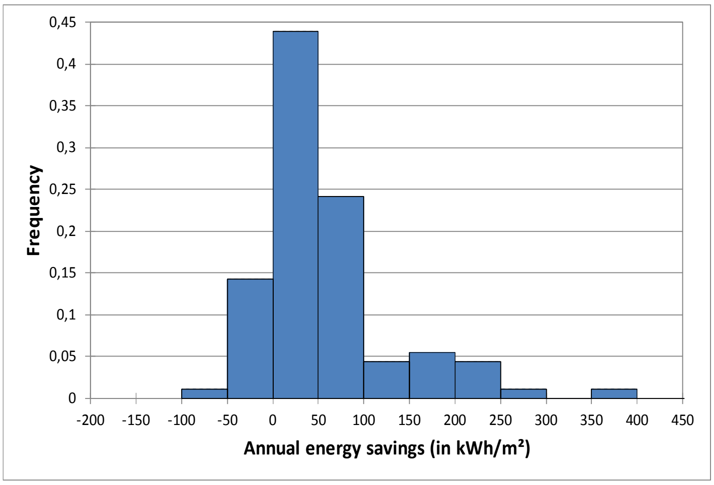

Figure 1. Histogram of energy savings.

Robustness of energy savings.

Whatever the uncertainty scenario, the cases with robust and positive energy savings (*i.e.* energy consumption reduction) are the large majority (Table 2).

For the "optimistic" scenario, the part of cases with robust and negative energy savings (*i.e.* energy consumption increase) is higher than the part of cases with no robust energy savings (Table 2). With the increase of uncertainty through the "realistic" or the "pessimistic" scenarios, the share of non-robust energy savings increases at the expense of robust and negative ones whereas the share with

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[16] 90 % of the sample do not have or do not use air conditioning before retrofitting.

[17] Cumulated duration: 1 week and less.

[18] In reason of too low separately representativeness (respectively less of 17 % and less of 14 % of the sample), this category regroups two cumulated duration categories 2 to 3 weeks (regularly) and 1 month and more (very often).

[19] The two categories represent 50 % of the sample.

robust and positive energy savings stays relatively stable according to the scenarios.

Table 2. Breakdown of 91 cases according to energy savings robustness (in %).

	Uncertainty scenario		
Share (%)	Optimistic	Realistic	Pessimistic
Non-robust	5.5	10.0	18.0
Robust with - sign	13.0	10.0	4.0
Robust with + sign	81.5	80.0	78.0

Statistical Model.

The ANCOVA analysis of $C_{i,af}^{norm.,m^2}$ supplies a significant model ([Pr > F] < 0.0001) with limited explanation and prediction capacities (adjusted R² = 0.370; RMSE[20] = 36.5 kWh/m²). Amongst the statistically significant variables kept by the selection procedure (amongst two quantitative and six qualitative variables; see Table 6 in appendix for definition), there are only the variables "energy consumption before retrofitting" and "declared use of air conditioning after retrofitting". *Inter alia*, the variable "declared change of heating set temperature" is not significant from a statistical viewpoint.

The intercept (value = 105.3 kWh/m², confidence interval at level 95 %: [95.6; 115.0]) corresponds to an annual energy consumption after retrofitting for an hypothetical case with an annual energy consumption before retrofitting equals to the sample mean (174.5 kWh/m²) and a household having declared to not use air conditioning after retrofitting (and for all categories or values of non significant variables). For this case, the energy savings are estimated at 69.2 kWh/m² (confidence interval at level 95 %: [59.5; 78.9]).

The values of significant categories or variables have to be added to this intercept to obtain the annual energy consumptions after retrofitting and consequently the energy savings calculated by the model (Table 3).

Table 3. Qualified variables from the ANCOVA model of $C_{i,af}^{norm.,m^2}$ (sample=82, [Pr > F] < 0.0001, adjusted R² = 0.37, RMSE = 36.5 kWh/m², Cv_{RMSE} = 31 %[21]).

Source of parameter (reference unit)	Value	Confidence interval at level 95 %	Significance (Pr > |t|)
Intercept	105.3	[95.6; 115.0]	< 0.0001
Energy consumption before retrofitting (1 kWh/m² more than the sample mean)	0.30	[0.20 ; 0.40]	< 0.0001
Declared use of air conditioning after retrofitting – No use	Reference (coefficient = 0)		
Declared use of air conditioning after retrofitting – important use with set temperature <23 °C	40.2	[17,7 ; 62,7]	0,001
Declared use of air conditioning after retrofitting – important use with set temperature ≥23 °C	38.7	[15,4 ; 62,0]	0,001

Discussion

First, we can affirm that the energy efficiency actions realized in this operation lead to effective energy savings for the vast majority of studied households (about 80 %). Moreover, a negative energy savings observed for some households (about 15 %) seem in many cases non-robust values, *i.e.* for which we are not able to decide between energy savings or consumption increase.

Nevertheless, we can notice that the sample presents highly scattered energy savings. Thus, with the help of the statistical model, we will try to understand the explanatory factors of this scatter.

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[20] RMSE (Root Mean Square Error) is an unbiased estimate of the standard-deviation of model error.

[21] CV_{RMSE}=RMSE/(mean of $C_{i,af}^{norm.,m^2}$ on the sample).

The ANCOVA model finds an effect of the energy consumption before retrofitting: 0.3 kWh/m² after retrofitting (confidence interval at level 95 %: [0.2; 0.4]), meaning an additional energy savings of 0.7 kWh/m², per each kWh/m² of initial overconsumption relative to the sample mean (174.5 kWh/m²). Thus, higher energy consumption before retrofitting leads to a greater energy savings. Energy savings obtained depend directly on the initial heating needs and on the efficiency of the initial heating system as the implemented energy efficiency actions target space heating. Heating consumption represents the main share of a single-family housing's energy consumption (see footnote 14 in Table 1), a high total energy consumption corresponds to a high space heating consumption and consequently to large heating needs and/or a low efficient heating system.

On the other side, no effect of the characteristics of the energy efficiency actions implemented is identified: the variables "type of heat pump installed" and "type of second action realized" are not significant from a statistical viewpoint. Thus, the ANCOVA model does not find significant difference in terms of energy savings, *ceteris paribus*, on the one hand, between installations of AAHP and of air-to-water heat pump (AWHP) and on the other hand, between roof insulation and SWH installation.

Comparison of the mean energy savings obtained according to the energy efficiency actions only partly confirms this former result (Table 4). We find again that the energy savings difference according to the type of the second action realized is not statistically significant (overlap of the confidence intervals). But conversely, on average, installation of AWHP significantly leads to more energy savings than installation of AAHP (non-overlap of the confidence intervals), as it can be expected from technical analysis[22]. Consequently, we may be surprised by the result of the statistical model.

Table 4. Means of energy savings according to the type of heat pump installed and to the type of second action realized.

ES_i (in kWh/m²)		Mean	Confidence interval at level 95 %[23]
Type of heat pump installed	Air-to-air	47.3	[31.2; 63.4]
	Air-to-water	115.0	[70.8; 159.3]
Type of second action realized	Roof insulation	50.9	[32.7; 69.1]
	SHW	81.4	[50.0; 112.8]

In fact, the level of the energy consumption before retrofitting seems to be at least part of the explanation. The initial energy consumption of households having installed AWHP is significantly higher than the initial consumption of households having installed AAHP (Table 5). Amongst the AWHP cases, the share of houses built before the first French thermal regulation (*i.e.* <1975) and initially equipped with combustible boiler (50 % of houses built before 1975 and 83 % of non electrical systems) is greater than amongst the AAHP cases (14 % of houses built before 1975 and 16 % non electrical systems). From a technical viewpoint, it is logical that an AWHP replaces heating systems with a hydraulic loop.

Table 5. Energy consumption before retrofitting according to the type of installed heat pump.

$C_{i,be}^{norm.,m^2}$ (in kWh/m²)	Type of heat pump installed	
	Air-to-air	Air-to-water
Mean	162.5	244.4
Confidence interval at level 95 %[24]	[145.2; 179.8]	[182.4; 306.4]

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[22] According to the French EPC (Arrêté 17 octobre 2012) default Coefficient of Performance for AAHP = 2.2 and for AWHP = 2.6.

[23] They are calculated with an assumption of normal distribution in reason of impossibility to know precisely the actual probability distributions (number of cases too small) especially for the subsamples, "air-to-air" (12 cases) and "SHW" (17 cases).

[24] *Ibid.*

Thus, the difference of energy savings obtained between installations of AAHP and of AWHP is imputes by the statistical model no to the type of heat pump but to the difference of energy consumptions before retrofitting.

The variable "declaration of action realized outside the operation" is not statistically significant too. The type of actions realized within the operation (replacement of heating system coupled with roof insulation or SHW installation) only leaves the place for additional actions with limited impacts: amongst the households declaring an third additional action (22 % of the 82 studied cases), 61 % are concerning a DHW system replacement (mainly an electrical storage tank by the same kind of system) and 39 % consist of insulation actions (mainly double glazing windows). Such supplementary energy savings can be "hidden" by the uncertainties of data. Moreover, the Mediterranean climate with low HDD (see footnote 10) can also explain a weaker impact of insulation actions.

This mild climate in winter is also certainly an explanation of the non statistical significance of the variable linked to the dRE, "declared change of heating set temperature". Another possible part of the explanation seems due to the relatively well-insulated dwellings after retrofitting: only 5.5 % of sample households declare to not have wall insulation, only 5.5 % declare to have at least a share of single glazing windows and all households declares to have roof insulation. These relatively well-insulated housings reduced the impact of climate (HDD) on energy consumption.

While the variable linked to the iRE, "declared use of air conditioning after retrofitting", is statistically significant for two categories amongst the four (the first is the reference with a coefficient equals to zero). Households declaring an important use of air conditioning after retrofitting present higher energy consumptions after retrofitting than household declaring to not use air conditioning (Table 3): +40.2 kWh/m² with set temperatures less than 23 °C (confidence interval at level 95 %: [17.7 ; 62.7]) ; +38.7 kWh/m² with set temperatures greater than 23 °C (confidence interval at level 95 %: [15.4 ; 62.0]). These overconsumptions are directly reductions of energy savings.

From these results, firstly, we can note that the declared set temperature does not seem to have an effect on air conditioning consumption (the difference between the two coefficients is not significant)[25]. It is difficult to assess the uncertainty of the declared values and even the actual nature of the declared values (set temperature or indoor temperature). This explains certainly the absence of a significant effect.

Between the 45 % and the 24 % of households declaring respectively no use or low use of air conditioning after retrofitting (75 % of these 24 % did not use air conditioning before), no significant difference of energy savings is found. We can suppose that a low use of air conditioning causes a small energy overconsumption and thus, the effect –if any- is masked by uncertainties.

At the opposite, for the 31 % of the sample declaring important use of air conditioning after retrofitting (84 % of these 31 % did not use air conditioning before) significant decreases of energy savings are detected. Nevertheless, from the confidence intervals at level 95 % of the two coefficients (respectively ±56 % and ±60 % of the coefficients), we must note the high uncertainty of the effect quantification.

For every cases of the sample, we can define the iRE estimated by the model as ratio between energy savings losses estimated with declared air conditioning use after retrofitting and energy savings estimated with no air conditioning use after retrofitting (even if it is not a pure iRE because the variable used does not allow to know if it is a completely new use or an increased use of air conditioning). According to this iRE definition, we calculate a mean value of 29 % on the sample (mean of the individual effects) but with a high uncertainty (confidence interval at level 95 %: [12 % ; 46 %]).

Moreover, we can observe that all households with important use of air conditioning after retrofitting have installed AAHP. Thus, the difference of energy savings obtained between installations of AAHP and of AWHP (Table 4) is also probably taken into account by the statistical model via the

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[25] A model with a variable "Declared use of air conditioning after retrofitting" defines by only the three categories of declared time of use during summer (no use, low use and important use) obtains similar results that the presented model: adjusted $R^2=0.38$, RMSE=36.3 kWh/m², category "low use" non significant and category "important use" significant (value= 39.5 kWh/m², confidence interval at level 95 %=[21.9 ; 57.1], p-value<0,0001).

effects of these two categories (declarations of more intensive use of air conditioning for AAHP cases than for AWHP cases).

We have found only one literature reference with data before and after retrofitting enabling to analyze use of air conditioning with installations of AAHP in single-family houses (Gram-Hanssen, Christensen & Petersen 2012). This study concerns a sample of 67 Danish houses (principal dwellings), initially equipped with electrical heating system. The declared number of days of air conditioning use has no statistically significant effect on the annual electrical consumption after retrofitting. The declared moderate use of air conditioning (21 % declare using it and amongst them, only 17 % declare a time-use of 15 days and more during summer) coupled with a relatively mild[26] summer climate explain that additional energy consumptions are too low to be significant.

Finally, we can note that the statistical model detects as non statistically significant the variables "declared change in occupation" and "bad workmanship".

Conclusion

Firstly, this study of a regional energy efficiency operation promoting heat pumps in a Mediterranean area has shown that, whatever the uncertainty scenario, the vast majority of studied households presents robust and positive energy savings, *i.e.* energy consumption reduction after implementation of energy efficiency actions. Moreover, a great part of the cases with negative energy savings (*i.e.* energy consumption increase) seems to have in reality non-robust values, meaning that we are not able to decide between energy savings or consumption increase.

Then, it has been found by a statistical model that only the energy consumption before retrofitting and the declared use of air conditioning after retrofitting (iRE, indirect rebound effect) are significant explanatory variables of the energy savings scatter. Thus, the declared change of heating set temperature (dRE, direct rebound effect), presents for only 22 % of the sample, is found not significant. The Mediterranean climate of the operation (low HDD) coupled with relatively good insulation levels of the sample's housings can explain this lack of effect.

Concerning the iRE, air conditioning has been declared as a new energy use after the retrofit by 44 % households of the sample, but only the 31 % of the sample declaring an important use[27] of air conditioning after retrofitting have a significant effect. Nevertheless, the quantified effect presents a high uncertainty for all these cases of AAHP installation (air-to-air heat pump).

It has been highlighted that the higher energy savings on average with AWHP installations (air-to-water heat pump) than with AAHP installations are not explained by the type of heat pump. For a part, the difference seems to be linked to the higher energy consumptions before retrofitting for the AWHP cases than for the AAHP cases. Amongst the AWHP cases, the share of houses built before the first French thermal regulation and initially equipped with combustible boiler is greater than amongst the AAHP cases. The other part of the difference seems taking into account by the declarations of less air conditioning use after retrofitting for the AWHP cases than for the AAHP cases.

As a final remark, it is important to come back to the definition of what is statistically significant or not in a statistical model: it enables to remind that a non-significant coefficient does not mean "absence of effect in the real life". It means that the uncertainty linked to the effect estimation remains higher than some level. This uncertainty increases with the scattering of the data (caused by uncontrolled phenomena) and is higher with small sub-sample size. Scattering of household energy consumption data is very important and the smaller relative errors (ratio between half of confidence interval at level 95 % and estimated coefficient) for the best predictive statistical models are generally around 25 % or 30 % (Raynaud et al 2013). Thus it is difficult identifying small influencing factors

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[26] From 1981 to 2010 (Météo Climat 2011), the average temperature in July (the hottest in Denmark) were 18.2 °C for Copenhagen (Denmark) whereas for *Aix en Provence* (*Bouche du Rhône*), it were 22.9 °C. On the same month, the average daily minima and maxima temperatures were respectively 14.2 °C and 22.0 °C for Copenhagen and 15.1 °C and 30.6 °C for *Aix en Provence*.

[27] Cumulated duration in summer: 2 weeks to 1 month and more.

using statistical models, unless sample size is high enough and unless most influencing factors (building characteristics, energy systems characteristics, occupant behaviour) are well monitored and included in the model.

This remark is a key for future works: in order to enhance the validity of those results, we have to increase the samples from a new survey and work to reduce the uncertainties linked to the information about households behaviours.

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Appendix

Table 6. Explanatory variables used for the statistical model of $C_{i,af}^{norm.,m^2}$ (sample=82).

Variable	Definition
Quantitative variables	
Energy consumption before retrofitting	Difference between the total annual energy consumption before retrofitting at normal climate ($C_{i,bf}^{norm.,m^2}$) and 174.5 kWh/m² (mean of the sample); reference unit: 1 kWh/m² (final energy); [-118.2 ; 360.1]
Declared change of heating set temperature	Declared change of heating set temperature due to the retrofitting; reference unit: 1°C; [-3.5 ; 5.5] (22 % of a value different to zero with 17 % of a positive value and 5 % of a negative value).
Qualitative variables and their categories	
Type of heat pump installed	0- air-to-air heat pump (85 % of the sample); 1- air-to-water heat pump (15 %)
Type of second action realized	0- roof insulation (79 % of the sample); 1- SHW (21 %)
Declaration of action realized outside the operation	0- no additional action(s) declared (78 % of the sample); 1- additional action(s) declared (22 %)
Declared use of air conditioning after retrofitting	0- no use declared (45 % of the sample); 1- low use declared with set temperature <23 °C (13 %); 2- low use declared with set temperature ≥23 °C (11 %); 3- important use declared with set temperature <23 °C (16 %); 4- important use declared with set temperature ≥23 °C (15 %)
Declared change in occupation	0- no change declared between before and after retrofitting (77 % of the sample); 1- increase declared (8 %); 2- decrease declared (15 %)
Bad workmanship	0- no bad workmanship declared (90 % of the sample); 1- bad workmanship declared (10 %)