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

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Context

In housing sector:

- In EU, few *ex-post* evaluations of local energy efficiency programs
- Less studies about **indirect rebound effect** linked to air conditioning than studies about direct rebound effect linked to space heating (Sorrell 2007)
- Whereas direct electric heating space heating systems replaced by **reversible air-to-air heat pumps** in France
- In 2012 **1,3 millions air-to-air heat pumps sold in UE including** 80,000 in France (EurObservER 2013)

Our approach:

- **Statistical modeling** of the annual energy consumption change where air-to-air heat pumps have been installed
Aims of this study

• To quantify energy savings generated by air-to-air heat pump installations in southern France

• To assess the robustness of observed energy savings

• To study potential rebound effects (direct and/or indirect) occurring after such refurbishment
The operation studied…
and the dedicated inquiry

- The energy efficiency operation:
  - Southern regional energy efficiency programme in France in Provence-Alpes-Côte d’Azur launched by EDF in 2009
  - Target: an annual rate of refurbishment of 10%/y instead of 3%/y actually, within a building stock of 200,000 houses built before 1990 and heated by electricity

- The inquiry:
  - Telephone survey during 2012
  - Informations required: building typology, energy systems, behaviour, retrofitting actions (with and outside the program), total energy bills (on the last three years)
  - 212 filled questionnaires
The sample

- 91 questionnaires presenting both situations ("before" and "after")

- Type of dwellings: recent (built >1975 and <2001) single family housing mainly initially equipped with direct electric heating

- 84% of the dwellings without air conditioning system

- Type of refurbishment: installation of heat pump coupled with a second action (roof insulation, solar water heater)
Energy savings calculations

\[ ES_i = C_{i,be}^{\text{norm}} - C_{i,af}^{\text{norm}}. \]

- with \( ES_i \) annual energy savings of case \( i \) (in kWh, final energy)
- \( C_{i,\vartheta}^{\text{norm}} \): \textbf{climate adjusted} annual \textbf{total} energy consumption (in kWh) with \( \vartheta = \text{before (be) or after (af) retrofitting} \)

- Total end-uses consumption = sum of declared consumptions for different energies (electricity, gas, LPG, wood...)(in kWh_{LCV})

- Climate normalization only done on space heating consumption:
  - Normal climate (average over 20 years): HDD between 1600 and 1300 °.day per year
  - Space heating consumption share: 70% of total final consumption (average national value for individual housing)
  - No Cold Degree Day adjustment, not reliable (Day 2004)
Existence of energy savings?

A large majority presents positive energy savings (i.e. consumption drop)

Nevertheless, a large share of cases presents energy savings in an interval between -50 and 50 kWh/m²
Robustness of energy saving: methodology

- Calculation of uncertainties linked to energy savings by propagation of uncertainties from:
  - Declared consumptions of fuel oil, LPG, wood (lack of proper metering)
  - Share of space heating consumption in the all end-uses consumption used for the climate adjustment

- Definition of the uncertainties by the confidence intervals at level 95%:
  - Are robust, energy savings with a reliable sign (+ or -), i.e. the lack of zero in the confidence interval at level 95%
Robustness of the energy savings: results

- Given the difficulty to choose a value of uncertainty, we performed a sensitivity analysis based on three scenarios of uncertainties.

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

<table>
<thead>
<tr>
<th>Uncertainty scenario</th>
<th>Optimistic</th>
<th>Realistic</th>
<th>Pessimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-robust</td>
<td>5.5</td>
<td>10.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Robust with - sign</td>
<td>13.0</td>
<td>10.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Robust with + sign</td>
<td>81.5</td>
<td>80.0</td>
<td>78.0</td>
</tr>
</tbody>
</table>

- Whatever the uncertainty scenario, the cases with robust and positive energy savings are predominating.
Does it exist declared rebound effects?

\[ \text{variable}^{\text{explained}}_i = \alpha + \sum_{j=1}^{N_j} a_j \cdot \text{variable}_{j,i}^{\text{quantitative}} + \sum_{k=1}^{N_k} \sum_{l=1}^{m_k} b_{kl} \cdot \text{variable}_{k}^{\text{qualitative \_modality}_{l,i}} + \varepsilon_i \]

- **Response variable**: total annual energy consumption after retrofitting at normal climate and for 1 m\(^2\) of surface area (in kWh/m\(^2\))

- **Change model type**: include the annual energy consumption **before** retrofitting

- **Explanatory variables linked to rebound effects**:
  
  - **Declared change of heating set temperature** in the living rooms between before and after retrofitting (in °C) ⇒ **Direct rebound effect**
  
  - **Declared use of air conditioning after** retrofitting (a coupling between the declared time of use during summer and declared set temperature) ⇒ **Indirect rebound effect**
Statistical method used

- Quantitative and qualitative variables → covariance analysis (ANCOVA, general linear statistical modeling)

- Backward selection to retain significant variables with at least a significance level of 0.05 on Student’s test

- Reference of the quantitative variables with constraint «coefficient of the first category = 0»

- It is verified that:
  - Explanatory variables do not present collinearity (Variat. Inflat. Factor ≤ 3)
  - Residuals are homoscedastic (graphic verification)
  - Residuals are normally-distributed (Jarque-Bera’s test)

Model highly significant (Pr to Fisher’s test <0.0001)

Explanation and prediction capacities limited (adj. $R^2 = 0.37$ ; RMSE* = 36.5 kWh/m²)

* RMSE= Root-Mean-Square Error
Results of the statistical model

\[
C_{i,af}^{\text{norm,} m^2} = \alpha + a_1 \times C_{i,be}^{\text{norm,} m^2} + \sum_{l=1}^{4} b_{1l} \times \text{declared use air conditioning}_l + \varepsilon_i
\]

- **Energy savings** of 69.2 kWh/m² for the reference case**

- Only **two variables kept** by the selection procedure amongst 8 variables:
  - Energy consumption before retrofitting
  - Declared use of air conditioning after retrofitting

- “Energy consumption before retrofitting” effect: 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)

- **Direct** rebound effect: **no statistical evidence**

*confidence interval at level 95 %: [59.5; 78.9])
**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)
Indirect rebound effects

- An **important use** of air conditioning after retrofitting presents **higher energy** consumptions after retrofitting:
  - around an increase of +39.5 kWh/m²
  - but with a large uncertainty: confidence interval at level 95%=[21.9 ; 57.1]
  - and representing **only 31%** of studied households

- **Indirect rebound effect quantification:**
  - energy savings losses estimated with declared air conditioning use
  - energy savings estimated with no air conditioning use

- **Average** on every cases of the sample: 29% with a confidence interval at level 95%=[12% ; 46%]
Conclusions

This study of a regional operation promoting air-to-air heat pumps in a Mediterranean area has shown:

• Whatever the uncertainty scenario, the vast majority of studied households presents robust and positive energy savings

• Only 31% of the sample declaring an important use of air conditioning after retrofitting have significant energy savings losses BUT the quantified effect presents a high uncertainty

Future works needed in order to enhance the validity of those results:

• To increase the samples from a new survey

• To reduce the uncertainties linked to the information about households behaviours
Many thanks for your attention!

Your comments and suggestions are welcome at:

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References


Appendix

Synthesis of the three uncertainty scenarios:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Bounds $[a_-; a_+]$</th>
<th>Probability distribution</th>
<th>Standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimistic (interval/2)</td>
<td>$[0.9C_e; 1.1C_e]$</td>
<td>Symmetric trapezoidal distributions having equal sloping sides, with bases of width $a_+ - a_-$ and tops of width $(a_+ - a_-)*0.5$</td>
<td>$\sqrt{\frac{(a_+ - a_-)^2 * (1 + 0.5^2)}{24}}$</td>
</tr>
<tr>
<td>Realistic</td>
<td>$[0.8C_e; 1.2C_e]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pessimistic (interval*2)</td>
<td>$[0.6C_e; 1.4C_e]$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Bounds $[a_-; a_+]$</th>
<th>Probability distribution</th>
<th>Standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimistic (interval/2)</td>
<td>$[0.665; 0.74]$</td>
<td>Rectangular distributions with widths $a_+ - a_-$</td>
<td>$\sqrt{\frac{(a_+ - a_-)^2}{12}}$</td>
</tr>
<tr>
<td>Realistic</td>
<td>$[0.63; 0.78]^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pessimistic (interval*2)</td>
<td>$[0.56; 0.86]$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Observed consumptions for oil ($C_{oil}$), LPG ($C_{LPG}$), wood log ($C_{woodl}$) or wood pellets ($C_{woodp}$)

Hypothesis on space heating share in total consumption (0.7)
Appendix

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

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

- Air-to-air (85% of the sample) vs air-to-water (15%): variable found **non statistically significant** BY THE MODEL

- Whereas a **difference exists** according to energy savings calculations:

<table>
<thead>
<tr>
<th>$ES_i$ (in kWh/m²)</th>
<th>Mean</th>
<th>Confidence interval at level 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of heat pump installed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air-to-air</td>
<td>47.3</td>
<td>[31.2; 63.4]</td>
</tr>
<tr>
<td>Air-to-water</td>
<td>115.0</td>
<td>[70.8; 159.3]</td>
</tr>
</tbody>
</table>

- **Difference taken into account** by the statistical model via:
  - A higher initial energy consumption for air-to-water installations than for air-to-air installations (averages: 244.4 kWh/m² vs 162.5 kWh/m²)
  - Declarations of more intensive use of air conditioning for air-to-air installations than for air-to-water installations (all households declaring important use installed air-to-air)