Analysis of HVAC retrofit layouts including solar cooling system with adsorption heat pump
Modelling, dynamic simulation, and multi-criteria evaluation

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Abstract
This work deals with the HVAC systems retrofitting of a residential building located in Valencia (Spain), that is a pilot site in the European R&D project Heat4Cool. Using TRNSYS 17, the proposed layout has been modelled including a solar thermal system and a solar thermally driven adsorption chiller and varying the collectors’ surface. The simulations demonstrated that the renewable share of the generation energy can reach 51% for heating and 20% for cooling. Furthermore, the results obtained have been compared with the pre-retrofit status according to energy, environmental and economic perspectives.

Key Innovations
- Dynamic simulation of a multi generation system for heating, cooling and DHW with a high percentage of renewable energy sources
- Use of flat plate collectors for solar cooling
- Use of a silica gel adsorption chiller

Practical Implications
The auxiliary energy consumption of a solar cooling system should always be evaluated. Beware of the limited operation ranges of chillers and heat pumps. Always do parametric cost-benefit analysis.

Introduction
Currently, the construction sector is identified as crucial in terms of energy consumptions, buildings are responsible of about 40% of total final energy consumptions in the European Union (Gynther, Lapillonne, and Pollier, 2015) and their long lifecycle leads to a very small rate of replacement of the existing stock, namely 1-2% per year (Eichhammer et al., 2009). Thus, it is necessary to pursue the objective of building retrofitting, starting from the older buildings stock, which has the largest energy saving potential.

The European R&D project Heat4Cool addresses the specific construction segment of residential buildings, proposing innovative, efficient, and cost-effective solutions for the space heating and cooling retrofitting. Among the Heat4Cool pilot sites, this paper concerns the HVAC systems retrofitting of a residential building located in Valencia (Spain), including solar thermally driven adsorption chiller.

Currently, the use of solar collectors for domestic hot water production and space heating is widespread, while the solar cooling technologies are still fairly uncommon (Daßler and Mittelbach, 2012). This latter can be realized by coupling solar collectors with thermal adsorption units, so that, the solar heat is used to perform the endothermic desorption process necessary to regenerate the adsorbent material and restart the adsorption process (Chua et al., 1999). Dynamic modelling and simulation of the performances under different conditions (installation site, load profile, design parameters, etc.) have been theoretically investigated in various papers (Buonomano et al., 2017; Palomba et al., 2017), while studies on pilot projects are more limited (e.g. the Shanghai Institute of Building Science analysed by Zhai and Wang (2009)).

This paper summarizes the steps of definition, modelling and evaluation of the Heat4Cool pilot renovation layout of the heating and cooling system, with the aim to identify the optimal configuration in terms of energy consumptions, costs, and environmental impact.

Methodological approach
The building under analysis has been modelled in TRNSYS 17 (Solar Energy Laboratory, 2010) through Type 56 - TRNBuild. The simplified building model considers only the typical floor plant, the top level, and the unheated attic, while the commercial spaces at the ground level are not modelled and considered imposing adiabatic boundary conditions to the first floor. Subsequently, the simulation results have been processed to represent the whole building. The energy needs estimation for space heating and space cooling has been carried out through the Type 56 considering an ideal heating and cooling systems with unlimited power, able to keep the zones temperature at the scheduled set point.

Then, in TRNSYS Simulation Studio the HVAC layout has been modelled and connected to the TRNBuild building model, running six minutes time-step simulations. Parametric simulations are performed for the implementation of solar assisted thermal driven adsorption chiller.

To analyse and compare the results, a set of performance indicators have been considered investigating the performances of the HVAC system, the primary energy (PE) consumptions, the environmental impact in terms of CO₂ emissions, and the economic implications and financial feasibility of the investment. From the values of the delivered energy, the unit coefficients reported in
Table 1 have been used to calculate the primary energy, the \( CO_2 \) emissions, and the energy costs. In addition, a cost-benefit analysis has been performed; the annual saving for energy (\( R_0 \)) and the investment cost (\( C_0 \)), have been estimated, then, imposing annual incentive fee (\( I_k \)) and assuming values for the interest rate (\( i \)), inflation (\( f \)) and energy costs growth rate (\( e \)), the Discounted Payback Period (DPP) has been identified as the minimum number of years (\( k \)) where the Net Present Value (NPV, calculated according to Eq.(1)) is higher or equal to zero.

\[
NPV_n = \sum_{k=1}^{n} \left( R_0 \cdot (1 + e)^k + I_k \right) \cdot \frac{(1 + f)^k}{(1 + i)^k} - C_0 \quad (1)
\]

Table 1: Conversion coefficients – Sources: Eurostat; Ministerio de Industria Energia y Turismo (2016)

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Natural gas</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-renewable PE factors ( f_{PE, ren} ) [kWh PE/kWh]</td>
<td>1.190</td>
<td>1.954</td>
</tr>
<tr>
<td>Renewable PE factors ( f_{PE, ren} ) [kWh PE/kWh]</td>
<td>0.005</td>
<td>0.414</td>
</tr>
<tr>
<td>( CO_2 ) emission factors [kg CO(_2)/kWh]</td>
<td>0.252</td>
<td>0.331</td>
</tr>
<tr>
<td>Energy prices (household consumers, taxes, and levies incl.) [€/kWh]</td>
<td>0.086</td>
<td>0.228</td>
</tr>
</tbody>
</table>

Building modelling

The building is located in Valencia’s city centre (TMY climatic data used are referred to the station 82850) and consists of commercial spaces at the ground floor, 12 apartments divided on four levels with a total floor area of 610 m\(^2\), and an unheated attic; the typical floor plan zoning is reported in Figure 1. The building is a portion of a block, adjacent to other two building units; its exposed façades address to South-East and North-West. It was constructed in 2001 and the opaque and transparent envelope has been recently refurbished as summarized in Table 2.

Table 2: Building envelope thermal transmittance

<table>
<thead>
<tr>
<th>Construction</th>
<th>Ext. walls [W/m(^2)K]</th>
<th>Int. walls [W/m(^2)K]</th>
<th>Slabs [W/m(^2)K]</th>
<th>Windows [W/m(^2)K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>0.47</td>
<td>0.52</td>
<td>0.45</td>
<td>2.89</td>
</tr>
</tbody>
</table>

The annual and daily profiles for internal gains, air changes, and set point temperature have been defined according to the Spanish technical building document DB HE (Código Tecnico de la Edificacion, 2017). A maximum value of 8.80 W/m\(^2\) is associated to equipment and lighting, while for the internal gains due to people occupation 75 W/person of sensible gains are considered, neglecting the latent heat since the systems installed do not control the hygroscopic internal comfort. A ventilation rate equal 1.2 vol/h has been accounted, in addition to the summer night ventilation. From October to May, the heating set point is 20\(^\circ\)C from 8:00 to midnight and the set back is 17\(^\circ\)C. While during the cooling season (June-September), the set point is fixed to 25\(^\circ\)C between 16:00 and 0:00, raised to 27\(^\circ\)C from 0:00 to 8:00; there is no set point for the remaining hours.

DB HE establishes for DHW residential use 28 litres/day/person at 60\(^\circ\)C and a reduction of the 10% have to be considered for multi-family centralized plants. The daily Load Profile M of European Standard EN 13203-2 (CEN, 2015) has been re-modulated to obtain the total daily value of the Spanish regulation.

Building energy needs

Figure 2 reports the monthly values specific to the building floor area of the thermal energy needs, divided into space heating (SH), space cooling (SC) and domestic hot water (DHW) production. The annual values for each use are similar: 21.5 kWh/m\(^2\)/y for space heating (29% of the needs), 25.4 kWh/m\(^2\)/y for DHW (35%) and 26 kWh/m\(^2\)/y for space cooling (36%), corresponding to a total annual value of 73 kWh/m\(^2\)/y (45 MWh/y).

The heating peak power is equal to 33.50 kW while the maximum cooling power is 42.57 kW.

HVAC system description and modelling

The pre-existing building plant includes a centralized natural gas boiler (seasonal efficiency 0.88) for space heating and domestic hot water production. Instead, the summer space cooling is operated by split air conditioners, with average seasonal EER equal to 2.9. The
annual energy consumption for thermal purposes is 53 kWh/m² from natural gas and 9 kWh/m² from electricity. In Figure 3 the scheme of the retrofitted system layout is reported. Heating and cooling emission devices are fan coil units, fed by a cold (1000 litres) and a hot (1500 litres) water tank. The latter also provides hot water to the DHW circuit. The hot tank is fed by a solar thermal power plant integrated on the roof (flat plate solar collectors – slope 24° and azimuth -66° – with 2000 litres solar tank) and by two reversible electric heat pumps (revEHP). In cooling mode, the electric heat pumps work in parallel with an adsorption chiller (AdChiller), exploiting the solar cooling technology. An optimization process has been developed varying the solar field area. Table 3 reports the list of the simulations performed.

<table>
<thead>
<tr>
<th>Sim. ID</th>
<th>Number of collectors</th>
<th>Total collectors’ area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layout A 6</td>
<td>6</td>
<td>13.86 m²</td>
</tr>
<tr>
<td>Layout A 9</td>
<td>9</td>
<td>20.79 m²</td>
</tr>
<tr>
<td>Layout A 12</td>
<td>12</td>
<td>27.72 m²</td>
</tr>
<tr>
<td>Layout A 15</td>
<td>15</td>
<td>34.65 m²</td>
</tr>
<tr>
<td>Layout A 21</td>
<td>21</td>
<td>48.51 m²</td>
</tr>
<tr>
<td>Layout A 27</td>
<td>27</td>
<td>62.37 m²</td>
</tr>
</tbody>
</table>

Fan coil units operating at constant speed have been modelled according to the bypass factor approach, using the TRNSYS component model (Type) 600. The design water supply and return temperatures are 50/45°C for SH and 10/15°C for SC.

Differential controllers with hysteresis (Type 2b) have been used to regulate the zones temperature according to the seasonal hourly profiles previous introduced. Upper and lower dead-band temperature differences are fixed at ±1°C.

Domestic hot water production

The DHW supply temperature is fixed at 50°C. The flow rate profile is regulated through Type 14h (time dependent forcing function).

Water storages

The thermal storages have been modelled using Type 4b (stratified fluid storage tank), assuming 3 fully-mixed equal volume segments.

Generation systems

The heating and cooling generation systems have been modelled on the basis of manufacturers’ performance maps and load curves, read by Type 42 (Conditioning Equipment), which enable to assess the generation power and the performance coefficient (COP or EER) at the specific conditions of inlet water and/or air temperatures. The electric reversible heat pump (Carrier AquaSnap reversible 30AW - size 015 - nominal heating/cooling capacity: 15/16 kW) has been modelled evaluating separately the heating and cooling mode, imposing the priority of the heating mode through a control function. In heating mode, the set point temperature has been fixed at 51°C, and the control function is based on the temperature at the top of the hot tank, with a dead-band between 49°C and 51°C. On the other hand, the temperature at the bottom node of the cold tank (with a dead-band between 8-11°C) determines the functioning of the chiller mode with a supply water set point fixed at 10°C.

Emission system and air temperature control system

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Figure 4: Performance map of the adsorption chiller eCoo by FAHRENHEIT GmbH
The performances of the two-bed silica gel water adsorption chiller are reported in Figure 4, in function of the inlet water temperatures of the three circuits: LT (low temperature circuit), MT (medium temperature circuit), and HT (high temperature circuit). A constant parasitic electric consumption, due to the chiller electric components and the cooler, has been accounted in the total delivered energy. The adsorption machine operates only in the cooling season and the working conditions are restricted by limit temperatures on the three circuits: $T_{IN} \geq 55^\circ C$, $T_{IN} \geq 10^\circ C$, and $T_{IN} \leq 37^\circ C$. The heat rejection device on the MT circuit has been modelled as a crossflow heat exchanger with unmixed fluids (Type 5e) using the ε-NTU approach.

**Solar system model**

The efficiency curve of the Flat Plate Collectors (FPC) reported in Figure 5 have been implemented with Type 539. This type, setting the control specification equal to 2, allows the flow rate modulation and outlet temperature control; the model attempts to keep the collectors outlet as close to the user-specified temperature as possible by varying the flowrate (between defined minimum and maximum values), when the collectors are gaining energy; the flow rate is set to zero if they are losing energy (TESS - Thermal Energy Systems Specialists, 2010). The possibility of using vacuum tube collectors had to be excluded due to urban and aesthetic constraints imposed by the municipality. Then, preliminary analyses regarding the solar field configuration and set point temperature have been performed to evaluate the collectors’ performances. Decreasing the number of collectors in series and the outlet set point temperature, the total energy produced by the solar thermal system increases. For this reason, in the following simulations the collectors have been arranged in series of 3, keeping the outlet set point temperature equal to $70^\circ C$. Additionally, a cut-off temperature is fixed at $95^\circ C$. Circulating pumps P1 and P2 operate simultaneously so that the solar system feeds the hot water tank whenever possible, while P3 works only when required by the adsorption chiller.

**Solar Fraction**

The greater is the solar field area, the higher is the electrical energy saved and thus the SF, but the lower is the specific collectors output energy, since the solar tank size is constant; passing from 6 to 27 collectors, the solar fraction passes from 0.30 to 0.54, while the productivity decreases of the 49%. The value of the SF is particularly influenced by the mismatch of solar radiation availability and heating demand; the solar thermal contribution covers high percentages of the DHW energy in summer, even reaching 100% for the layouts with more than 12 collectors, while in winter the percentages are reduced in any case, due to low availability of the solar radiation and, at the same time, high heating needs for DHW and SH.
Analysing in detail the input and output energy of all the generation subsystems, Figure 8 summarises the delivered and generation energy of the HVAC system in function of the number of collectors. The solar thermal plant size clearly affects the energy required to the heat pumps in the heating season, while in the cooling season the generation energy of the EHP is minimum in any case since the DHW production is almost fulfilled by the solar system already with six collectors. For the cooling production, the contribution of the adsorption chiller rises with the solar collectors’ area, but this leads to values of electric consumptions (due to the adsorption chiller itself and the dry cooler) that almost counterbalance the electric saving of the electric chiller. This fact is correlated to the high performances of the electric reversible heat pump, whose seasonal EER in cooling mode (around 4.75) is higher than the adsorption chiller’s EER in the cases with less than 15 collectors (Figure 9). Actually, the electric consumptions of the adsorption technologies are assumed constant in the simulations, without any correlation between the useful thermal output and the necessary electricity inlet; thus, the actual results obtained onsite could show lower values of global electric consumptions. Under these conditions, the increase of the collectors’ area installed leads to a reduction of the total delivered energy equal to 17% passing from 6 to 27 collectors.

Cost-benefit analysis

To evaluate the impact of the HVAC system renovation, a comparison with the pre-retrofit status have been carried out in terms of primary energy, CO2 emissions and energy costs (Figure 10). The saving in terms of non-renewable PE varies between 64% and 70%, corresponding to values between 6.9 and 7.4 tons of avoided CO2 emissions in a year. The value of the specific energy cost is almost halved in all the cases, passing from 6.63 €/m²/year for the pre-retrofit to values lower than 3 €/m²/year.

To calculate the Net Present Value (Eq. (1)) and consequently obtain the Discounted Payback Period, the costs of the HVAC retrofit have been estimated according to producers’ price lists, not including plumbing and auxiliaries (pumps, controls, etc.), and the public incentives of the Community of Valencia have been considered. The incentives amount, granted for retrofit actions that include the installation of renewable systems, varies from the 20% (provided in four annual rates) to the 45% (discounted immediately) of the total investment cost, according to the kind of stakeholders (taxpaying citizens or legal entities). In addition, knowing the strict dependence of the DDP on the rates of interest, inflation and growth of energy costs, different scenarios (Table 4) have been supposed to evaluate the possible effects related to the variation of political, financial and economic conditions that influence the rates: Scenario I is considered as the reference case, Scenario II is intended to represent a period of economic downturn with increase of interest rates, while Scenario III takes into account high increase of energy costs that can be related to financial and international issues and agreement about the energy delivery.
The NPV trend is reported in Figure 11 only for the reference scenario, while, to avoid redundancy, Table 5 summarizes the DDP in all the cases analysed. For the reference scenario with 20% incentive, the payback period varies between 14.5 (layout A_6) and 18.2 (layout A_27) years, while the 45% incentive guarantees lower DPP, between 10.3 and 13.0 years. On the other hand, higher interest rate of Scenario II leads to longer time to return of the capital invested (between 19.0 and 25.6 years with an incentive of the 20%, 12.2 and 16.2 years with 45% incentive fee). Lastly, the scenario III is the most profitable one, with DPP between 12.1 and 14.6 years for the 20% case and 8.9 and 11.0 years in case of 45% incentive. In fact, the exploitation of the renewable energy sources allows to become independent from the energy costs growth, increasing the saving margin compared to the pre-retrofit case.

**Table 5: Discounted Payback Period [years]**

<table>
<thead>
<tr>
<th>Incentive</th>
<th>Scenario</th>
<th>A_6</th>
<th>A_9</th>
<th>A_12</th>
<th>A_15</th>
<th>A_21</th>
<th>A_27</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>Sc. I</td>
<td>14.5</td>
<td>14.8</td>
<td>15.3</td>
<td>15.8</td>
<td>17.0</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>Sc. II</td>
<td>19.0</td>
<td>19.5</td>
<td>20.3</td>
<td>21.3</td>
<td>23.4</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td>Sc. III</td>
<td>12.1</td>
<td>12.3</td>
<td>12.6</td>
<td>13.0</td>
<td>13.8</td>
<td>14.6</td>
</tr>
<tr>
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<td>10.3</td>
<td>10.5</td>
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<td>12.2</td>
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<td>14.9</td>
<td>16.2</td>
</tr>
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<td></td>
<td>Sc. III</td>
<td>8.9</td>
<td>9.1</td>
<td>9.4</td>
<td>9.7</td>
<td>10.3</td>
<td>11.0</td>
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**Conclusion**

In this paper, a HVAC system retrofitting layout have been defined and modelled in TRNSYS 17, implementing a solar thermal system and a solar thermally driven adsorption chiller, for a residential pilot building located in Valencia, in the framework of the European project Heat4Cool. Varying the collectors' surface, the simulations results were analysed and then compared with the pre-retrofit status according to energy, environmental and economic perspectives. The results have shown how the percentage of the solar energy used for the heating (SH+DHW) reaches values till 51%; further exploitation is restricted by the mismatch between radiation availability and heating demand. On the other hand, the use of a solar assisted adsorption chiller has proved its potentialities providing a contribution on the total cooling energy production that reaches the 20%.

![Figure 10: Comparison of Key Performance Indicators between pre-retrofit and retrofit scenarios characterized by an increasing solar field area](image)

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Then, the simulations outcomes have been evaluated in a cost-benefit analysis to highlight if the costs of the retrofit action are commensurate to the useful effects. In comparison with the pre-retrofit system, the non-renewable primary energy saving varies between 64% to 70%, passing from 6 to 27 collectors, leading to the halving of the energy costs and to annual avoided CO₂ emissions around 7 tons. Among the layouts, the relative differences in the overall performances are limited compared to the improvement from the pre-retrofit situation; this demonstrates the great advantage given by implementation of high efficiency heat pump combined with solar collectors. On the other site, there are high differences in terms of investment costs and subsequently discounted payback period with values between 9 and 25 years, depending on the rates considered, and average difference from the case with 6 collectors to the 27 ones around 3 years.

Acknowledgement
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