

Oropeza-Perez, Ivan

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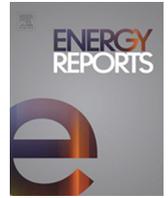
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Comparative economic assessment of the energy performance of air-conditioning within the Mexican residential sector



Ivan Oropeza-Perez

Department of Architecture, Universidad de las Américas Puebla, Ex Hacienda Sta. Catarina Mártir 72810, San Andrés Cholula, Puebla, Mexico

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ABSTRACT

This work shows a sensitivity analysis of the economic impact of different energy performances of air-conditioning within the Mexican housing sector. For this purpose, a cooling-load calculator program in function of the indoor temperature is developed. The program also calculates the electricity consumption along with the expenditure with the different residential rates of the Mexican Federal Commission of Electricity (CFE, initials in Spanish) set according to the season of the year and zone of the country. After the results onto the national-scale scenario are validated with the literature, a sensitivity analysis is carried out by changing three parameters that are considered as influential on the consumption and which can be considered as energy saving strategies. With these strategies, it is found that the indoor temperature decrease due to the use of a passive cooling system is the most important characteristic to take into account followed by the coefficient of performance (COP) of the air-conditioning and the increase of the comfort temperature set-point, respectively. Thereby, an economic analysis is carried out, finding an annual saving up to 770 USD within a single air-conditioned dwelling having a payback period of 3 years for using a combination of passive cooling techniques and increasing the comfort temperature set-point; or a 2 years payback period if the air-conditioning is changed by a high-efficient equipment.

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1. Introduction

The use of air-conditioning (AC) to achieve indoor thermal comfort is a common practice in countries which are mainly under warm conditions (Shin and SL, 2016; Rana et al., 2015). Several reasons drive to the use of this type of active cooling method: its reliability, its control and its efficiency to reach thermal comfort under extreme conditions are amongst of them (Zhou et al., 2015). Nevertheless, the utilization of this cooling technique increases the electricity demand of the building (International Energy Agency, 2013).

Because of a great extent of the most consuming countries of AC have a mostly fossil-fuel-based electricity generation (International Energy Agency, 2013), the extensive use of AC increases the climate change effect (International Energy Agency, 2013). Mexico is amongst these countries, having an electricity demand for AC within the residential sector calculated at 8.9 TWh in 2011 (3% of the total national demand) (Oropeza-Perez and Østergaard, 2014).

Thereby, different cooling passive strategies have been developed in Mexico and other countries in order to have thermal comfort by not using energy and thus to meet the international agreements that consider the decrease of greenhouse gases emissions such as Kyoto and Paris (Bastide et al., 2006; Cancino-Solórzano et al., 2010; Lokey, 2009; Huacuz, 2005; Assimakopoulos et al., 2002; Oropeza-Perez and Morillon-Galvez, 2011; Haase and Amato, 2009; Yik and Lun, 2010; Cardinale et al., 2003; Laverge et al., 2011; Florides et al., 2002; Garde et al., 1999; Tablada et al., 2009). This passive cooling strategies are often, however, not affordable enough for all building' users, especially regarding the initial investment (Yik and Lun, 2010; Cardinale et al., 2003; Laverge et al., 2011; Florides et al., 2002; Garde et al., 1999; Tablada et al., 2009).

Nonetheless, different methods along with the passive cooling techniques can be used in order to achieve indoor thermal comfort and still saving energy and money. Moreover, different low-carbon scenarios have been analyzed in order to find their feasibility of implementation (Kwon and Østergaard, 2012; Østergaard, 2009, 2010; Østergaard and Lund, 2011). The purpose of this document is to show the economic feasibility of using techniques of energy saving and to achieve a payback period taking case studies within the Mexican residential sector as examples.

E-mail address: ivan.oropeza@udlap.mx.

Nomenclature

| | |
|-------------------|--|
| ρ | Density of the indoor air (kg/m ³) |
| COP | Coefficient of performance of the air-conditioning [dimensionless] |
| C_p | Specific heat of the indoor air (kJ/kg K) |
| D_{AC} | Electricity rate of the air-conditioning (W) |
| E_{Conv} | Convective heat transfer rate from the surfaces (J/s) |
| E_{Vent} | Heat transfer rate due to natural ventilation, controlled and not controlled (J/s) |
| E_{AC} | Cooling rate due to air conditioning/heating (J/s) |
| E_{Int} | Internal heat loads, including direct solar gains (J/s) |
| ED_{AC} | Annual electricity demand of the air-conditioning (Wh) |
| $Q_{gained/lost}$ | Heat rate gained or lost without considering mechanical systems (J/s) |
| T | Indoor temperature (C) |
| T_1 | Indoor temperature at 0 s (C) |
| T_2 | Indoor temperature at 3600 s (C) |
| T_{indoor} | Indoor temperature calculated by EnergyPlus (C) |
| $T_{set-point}$ | Comfort indoor temperature set-point (C) |
| t | Time (s) |
| V | Volume of the thermal zone (m ³) |

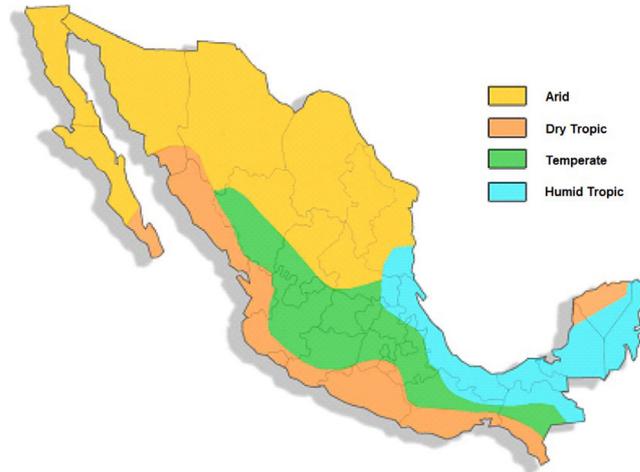


Fig. 1. Main climatic regions in Mexico (Vidal-Zepeda, 2005; Servicio Meteorológico Nacional, 2015).

purchase power in the last years combined by the depletion of the AC prices (Lezama, 2014). There is even the fact that for some sector of the Mexican society, having an AC means achieving a higher social status (Lezama, 2014).

2.3. Air-conditioning demand calculation

To carry out the economic analysis of the AC consumption, a cooling-load calculator program is developed. The program starts with the heat balance of the thermal zone, considering that a single dwelling is the thermal zone and that the indoor air temperature is well-mixed (Etheridge, 2012):

$$\begin{aligned} \rho \cdot c_p \cdot V \cdot \frac{dT_{cond}}{dt} &= \{E_{Int} + E_{Conv} + E_{Vent} + E_{AC}\} \\ &\approx \rho \cdot c_p \cdot V \cdot \frac{dT_{free}}{dt} \\ &= \{E_{Int} + E_{Conv} + E_{Vent}\}. \end{aligned} \quad (1)$$

If it is considered that the zone is on a free-running building (not using AC), the sum of the different heat rate of gains/losses can be simplified as a general heat rate of gain/loss and be equaled to the heat rate by using AC/heating, i.e. the heat transfer by using AC/heating:

$$Q_{gained/lost_free} \approx Q_{gained/lost_cond} \approx -E_{AC}. \quad (2)$$

This is valid if $[E_{Int} + E_{Conv} + E_{Vent}]_{free} \approx [E_{Int} + E_{Conv} + E_{Vent}]_{cond}$ and assuming that internal heat loads are dominating the heat transfer. Therefore, if the total of gain/loss by E_{Int} , E_{Vent} and E_{Conv} is removed/added by AC/heating, the general heat rate of gain/loss can be shown as follows:

$$\rho \cdot c_p \cdot V \cdot \frac{dT_{free}}{dt} = -E_{AC}. \quad (3)$$

The differential equation is rearranged as:

$$\frac{dT_{free}}{dt} = -\frac{E_{AC}}{\rho \cdot c_p \cdot V}. \quad (4)$$

The differential of temperature of the thermal zone shown in Eq. (4) can be determined within an hour (3600 s) if the equation is solved by integrating the differentials, setting an interval from 0 to 3600 for dt and an interval of $T_2 - T_1$ for dT , and considering that the term $E_{AC}/\rho \cdot c_p \cdot V$ has a constant value during the period of one hour (Blanchard et al., 1998):

$$\int_{T_1}^{T_2} dT_{free} = -\frac{E_{AC}}{\rho \cdot c_p \cdot V} \int_0^{3600} dt. \quad (5)$$

2. Cooling load calculator

2.1. Climatic regions in Mexico

In the country four main climatic regions are defined as shown in Fig. 1 (Vidal-Zepeda, 2005; Servicio Meteorológico Nacional, 2015). These regions are described by their mean monthly temperatures as shown in Fig. 2 (Vidal-Zepeda, 2005; Servicio Meteorológico Nacional, 2015). It is noticed that for the temperate region there are only two months with temperatures somewhat higher than 30 °C, whereas for the dry tropic and hot humid regions all the months have the highest temperature above 31 °C. The arid region presents five months below 30 °C.

With Figs. 1 and 2 one can claim that Mexico is mostly under warm conditions therefore the use of AC is mainly necessary.

2.2. Air-conditioning consumption in the Mexican housing sector

According to a prior study, in 2011 in Mexico there were 5.2 million air-conditioned dwellings, being 26.7 million the total Mexican households (Oropeza-Perez and Østergaard, 2014). Therefore, conditioned dwellings accounted for 19.5% of the total residential stock. If the annual growing rate was estimated at 7.5% (Rosas-Flores et al., 2011), the number of household with AC by 2015 is calculated at 6.9 million.

Furthermore, the electricity demand of AC is estimated at 11.8 TWh for 2015. This is considering that in 2011 the consumption was determined at 8.9 TWh (Oropeza-Perez and Østergaard, 2014) and that the AC devices have the same energy performance than 2011, i.e. same COP and same daily period of use. This figure has the same order of magnitude than the calculated by Rosas-Flores et al. (2011) and the CFE (Comisión Federal de Electricidad, 2015; Comisión Nacional para el Uso Eficiente de Energía, 2007; Secretaría de Energía, 2015) considering the annual growing rate calculated by the same authors, i.e. 7.5% (Rosas-Flores et al., 2011).

The distribution of the air-conditioned dwellings by climatic region is shown in Table 1. Notice that by 2015 there are 30.2 million dwellings, i.e. an annual growing rate of 3.1%. This is less than the half of the growing rate of conditioned dwellings. This is explained by the fact that Mexican people has reached a higher

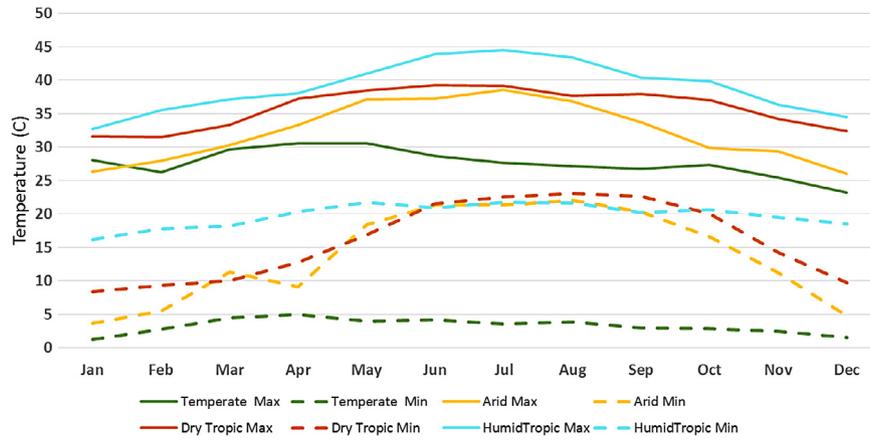


Fig. 2. Average maximum and minimum temperatures (C) gathered by climatic region (Vidal-Zepeda, 2005; Servicio Meteorológico Nacional, 2015).

Table 1

Number of air-conditioned dwellings gathered by climatic region in 2015 (Rosas-Flores et al., 2011; Secretaría de Energía, 2015).

| Climatic region | No. of dwellings | Share of total (%) | Distribution of population (%) | Air-conditioned dwellings | Electricity consumption for AC (GWh) | Share of total (%) |
|-----------------|-------------------|--------------------|--------------------------------|---------------------------|--------------------------------------|--------------------|
| Arid | 6 979 171 | 23.1 | 21.9 | 3 597 747 | 6 152 | 51.9 |
| Dry tropic | 4 803 845 | 15.9 | 12.0 | 1 247 773 | 2 134 | 18.0 |
| Temperate | 14 471 962 | 47.9 | 53.7 | 6 169 55 | 1 055 | 8.9 |
| Humid tropic | 3 957 885 | 13.1 | 12.4 | 1 469 600 | 2 513 | 21.2 |
| Total | 30 212 863 | 100.0 | 100.0 | 6 932 075 | 11 854 | 100.0 |

Thereby, T_2 is the temperature at $t = 3600$ and T_1 is the temperature at $t = 0$. The temperature difference is thus shown as:

$$T_2 - T_1 = -\frac{E_{AC}}{\rho \cdot c_p \cdot V} \cdot 3600. \quad (6)$$

From Eq. (6) the heat rate to be removed/added by AC/heating can be solved:

$$E_{AC} = -\frac{\rho \cdot c_p \cdot V \cdot (T_2 - T_1)}{3600}. \quad (7)$$

Thereby, the heat rate to be removed/added necessary in order to achieve from a certain indoor temperature to the temperature of comfort (temperature set-point) within an hour is given by:

$$E_{AC} = -\frac{\rho \cdot c_p \cdot V \cdot (T_{set-point} - T_{indoor})}{3600}. \quad (8)$$

When the indoor temperature is over the comfort temperature set-point, the heat rate E_{AC} is positive, which means that certain indoor heat must be removed, using AC, in order to be in comfort. On the other hand, when E_{AC} is negative a heat rate has to be added.

For calculating the electricity demand, an average simplified COP, i.e. the ratio of the cooling rate provided over the energy rate, of the AC system is given (Etheridge, 2012):

$$COP = \frac{|E_{AC}|}{D_{AC}}. \quad (9)$$

As in the model the cooling rate can be also a heating rate, a COP was chosen instead of an energy efficiency ratio (EER), which is only suitable for refrigerant pumps (Etheridge, 2012). Furthermore, a seasonal coefficient of performance (SCOP) or a seasonal energy efficiency ratio (SEER) is not used due to the knowledge that the AC generally works at full capacity in order to achieve the low temperature set-points (around 17 °C) set by the users (Comisión Nacional para el Uso Eficiente de Energía, 2007) (the SCOP and the SEER are suitable for equipment that works with partial capacities). The electricity rate D_{AC} can be estimated as:

$$D_{AC} = \frac{|E_{AC}|}{COP}. \quad (10)$$

Thereby, an electric cooling demand given in watt-hour (Wh), an aggregate of the hourly D_{AC} during a year, is calculated:

$$ED_{AC} = \sum_{n=1}^{8760} \frac{|E_{AC}|}{COP}. \quad (11)$$

The hourly indoor temperature in each case study are determined by running simulations with the thermal simulation program EnergyPlus (U. S. Department of Energy, 2015) and according to the simulation modeling set up by the building design (materials of construction, size, geometry, etc.) and occupants' behavior (schedule, number of occupants, internal heat gains, etc.) statically distributed within the four main climatic regions. In the modeling, three sizes of dwellings were set (45 m², 75 m², 100 m²); six types of materials of construction of the walls and roof were considered (brick-concrete, brick-corrugated roofing, brick-clay tile, adobe-concrete, adobe-clay tile, wood-clay tile); an average of 4 occupants per dwelling with a home-schedule (full occupancy at night and partial at daytime) and 12 W/m² by electrical equipment and 1000 W by gas equipment with the home-schedule were set as well (Oropeza-Perez and Østergaard, 2014; Oropeza-Perez et al., 2012).

The 8760 h with the indoor temperature are set down on an Excel spreadsheet where Eqs. (8)–(10) are solved. For this document the cooling-load calculator program only takes into account a heat rate of loss (cooling) into the buildings. The calculation of the cooling loads is made in an hourly way during the entire year.

The air density and the air heat capacity are considered as constant and under regular conditions (1.2 kg/m³ and 1.012 kJ/kg °C, respectively) (Rao, 2012). The volume of the thermal zone is given by the corresponding case study.

The comfort temperature set-point depends on the users' necessities and willingness, for this document, the range is from 20 °C to 27 °C. This in accordance with the surveyed results of the AC use gathered by the Mexican Commission of the Efficient Use of Energy (CONUEE, initials in Spanish) (Comisión Nacional para el Uso Eficiente de Energía, 2007); and with the different retrieved standards of thermal comfort (see the following section). The COP is a national-wide averaged value and is set at 2 according

Table 2

Annual simulated AC electricity consumption for a single dwelling with EnergyPlus and the cooling-load calculator program.

| Climate conditions | EnergyPlus consumption (MWh) | Cooling-load calculator consumption (MWh) |
|--------------------|------------------------------|---|
| Arid | 5.38 | 5.39 |
| Dry tropic | 5.73 | 5.36 |
| Temperate | 3.10 | 4.31 |
| Humid tropic | 6.46 | 5.79 |

to the latest estimations (Comisión Nacional de Vivienda, 2014). This value is not yet available as a regional estimation even though it depends on the outdoor air temperature (Etheridge, 2012).

In summary, the calculation method uses the indoor air temperature of the free-running building, calculated by EnergyPlus, in order to estimate the cooling load based on the heat balance of the free-running building and then considered as an air-conditioned building.

3. Analysis of results

3.1. Validation of the cooling-loads calculator program

By solving Eqs. (8)–(11) for hourly time-steps, an annual aggregated electricity demand of AC is found for every case study. The case studies are set up according to the climate conditions presented in Mexico: temperate, arid, dry tropic and humid tropic. Thus, four case studies are carried out.

The simulation modeling of each case study is statistically distributed among the four climate conditions and according to its building design and occupants' behavior. This means that for every climate condition, the number of conditioned dwellings are statistically distributed depending on the materials of construction, the built area, the building geometry, the people schedule and the internal heat gains schedule (Oropeza-Perez and Østergaard, 2014; Oropeza-Perez et al., 2012). Furthermore, the temperature set-point was set at 23 °C while the COP was set at 2.

For the validation of the model, a comparison between simulations of the cooling-load calculator and EnergyPlus was carried out. At the same climate conditions, a single dwelling with the same characteristics was simulated. In Table 2 the results of the annual AC electricity consumption are shown. It can be seen that the simulations with EnergyPlus are somewhat lower than the calculated with the cooling program for temperate conditions, while for dry tropic and hot humid are slightly higher. This discrepancy is attributed to the limitations that the cooling-load program has in comparison with EnergyPlus, where the heat flows within the building energy balance are hourly estimated and taking into account the relative humidity of the place, whereas in the program developed here the consumption is only a function of the indoor temperature. There is, however, a sufficient agreement between the results.

Thereby, Table 3 can be constructed. It is seen that both simulated consumptions of AC are somewhat higher than the estimated previously, i.e. 11.8 TWh. This discrepancy is attributed to various factors such as the uneven regional values of the air-conditionings' COP and the different comfort temperature set-points, among others. The estimated consumption, however, has the same order of magnitude. Hence, the program is considered as validated.

3.2. CFE rates of electricity consumption

The CFE establishes every year the rates of electricity consumption for residential buildings according to the zone of the country (1, 1A, 1B, 1C, 1D, 1E and 1F), the season of the year (off-summer

Table 3

Simulated electricity consumption in 2015 by climatic region.

| Climatic region | Air-conditioned dwellings | Estimated electricity consumption by AC (GWh) | Simulated electricity consumption by AC with EnergyPlus (GWh) |
|-----------------|---------------------------|---|---|
| Arid | 3597747 | 6517 | 5568 |
| Dry tropic | 1247773 | 2250 | 3357 |
| Temperate | 616955 | 921 | 1768 |
| Humid tropic | 1469600 | 2591 | 4747 |
| Total | 6932075 | 12279 | 15438 |

and on-summer) and the level of consumption (basic, intermediate, surplus and high-consumption) (Comisión Federal de Electricidad, 2015). Furthermore, when the household reaches the high-consumption level, a monthly fixed fee has to be paid (Comisión Federal de Electricidad, 2015).

The rates by zone are set according to the mean minimum outdoor temperature on summer of the place. Also, the rates by zone differ in the criteria to set the level of consumption. The mean temperature and the level of consumption of each rate can be seen in Table 4.

According to the rates of the CFE in 2015, the price of each rate is shown in Table 5.

Thereby, according to Fig. 2 and Tables 4 and 5, the distribution of the rates by climatic region are set as follows: rate 1 and 1A, temperate; rate 1B, arid; rate 1C and 1D, dry tropic; rate 1E and F, humid tropic. These rates are set as inputs in the cooling-loads calculator programs along with the electricity demand by AC.

3.3. Economic analysis of the AC consumption

With the rates set by CFE for 2015 and the electricity demand of AC for each case study, a sensibility analysis can be carried out by using the cooling-load calculator program. The changing input variables are the following: the comfort temperature set-point, the air-conditioning COP and the indoor temperature decrease by using a passive cooling system. The output variable is the annual expenditure for consuming electricity.

A baseline consumption of 120 kWh per month is added for all case studies. This is in accordance with the monthly averaged consumption by other appliances apart from AC in a Mexican household (Comisión Federal de Electricidad, 2015). The baseline consumption takes into account the fact that devices such as fridges and freezers may vary their performance with respect the outdoor temperature (Comisión Federal de Electricidad, 2015).

When the comfort temperature set-point, controlled by the AC thermostat, varies, Fig. 3 can be displayed. The range of the comfort temperature is set between 20 °C and 27 °C according to two standards, ASHRAE-55 and EN-15251 that claim this range as the threshold of cooling temperature, depending on the metabolic rate and clothing of the occupants (CEN, 2007; American Society of Heating, 2015; Olesen, 2006). Furthermore, the range is in accordance with the experience gotten from the CONUEE. The national COP of the AC is set at 2. From Fig. 3 it can be seen that, apart from rate 1F, all the rates have an annual saving over 300 USD if there is an increase from 20 °C to 27 °C in the AC thermostat. Rate 1F remains almost within the same expenditure.

If the air-conditioning COP varies, Fig. 4 is displayed. The COP was set according to the AC equipment that is available in the market. The temperature set-point was set at 23 °C. It can be seen that there is a convergence point of less of 200 USD while increasing the COP value. It is also noticed that, apart from rate 1F, the slope of the expenditure is higher between 1 and 3. Beyond 5, the expenditures have a soft decreasing.

When there is an indoor temperature drop due to the use of one or various passive cooling systems, Fig. 5 is plotted. The COP and

Table 4

Criteria for the seven domestic rates of electricity in Mexico in 2015 (Comisión Federal de Electricidad, 2015).

| Rate | Mean minimum outdoor temperature on summer (C) | Climate | Basic off-summer (kWh) | Basic on-summer (kWh) | Intermediate off-summer (kWh) | Intermediate on-summer (kWh) | Surplus off-summer (kWh) | Surplus on-summer (kWh) | High (kWh) |
|------|--|--------------|------------------------|-----------------------|-------------------------------|------------------------------|--------------------------|-------------------------|------------|
| 1 | - | Temperate | 1-75 | 1-75 | 76-140 | 76-140 | 141-250 | 141-250 | > 251 |
| 1A | 25 | Temperate | 1-75 | 1-100 | 76-150 | 101-150 | 151-300 | 151-300 | > 300 |
| 1B | 28 | Arid | 1-75 | 1-125 | 76-175 | 126-225 | 226-400 | 175-400 | > 400 |
| 1C | 30 | Dry tropic | 1-75 | 1-150 | 76-175 | 151-450 | 176-850 | 451-850 | > 850 |
| 1D | 31 | Dry tropic | 1-75 | 1-175 | 76-200 | 176-600 | 201-1000 | 601-1000 | > 1000 |
| 1E | 32 | Humid tropic | 1-75 | 1-300 | 76-200 | 301-750 | 201-2000 | 751-2000 | > 2000 |
| 1F | 33 | Humid tropic | 1-75 | 1-300 | 76-200 | 301-1200 | 201-2500 | 1200-2500 | > 2500 |

Table 5

Prices (USD) by kWh of the seven domestic rates of electricity in Mexico in 2015 (Comisión Federal de Electricidad, 2015).

| Rate | Climate | Basic off-summer | Basic on-summer | Intermediate off-summer | Intermediate on-summer | Surplus off-summer | Surplus on-summer | High | Monthly fixed fee |
|------|--------------|------------------|-----------------|-------------------------|------------------------|--------------------|-------------------|-------|-------------------|
| 1 | Temperate | 0.049 | 0.049 | 0.059 | 0.059 | 0.173 | 0.173 | 0.211 | 5.043 |
| 1A | Temperate | 0.049 | 0.043 | 0.059 | 0.051 | 0.173 | 0.173 | 0.211 | 5.043 |
| 1B | Arid | 0.049 | 0.043 | 0.059 | 0.051 | 0.173 | 0.173 | 0.196 | 5.043 |
| 1C | Dry tropic | 0.049 | 0.043 | 0.059 | 0.051 | 0.173 | 0.173 | 0.193 | 5.043 |
| 1D | Dry tropic | 0.049 | 0.043 | 0.059 | 0.065 | 0.173 | 0.173 | 0.198 | 5.043 |
| 1E | Humid tropic | 0.049 | 0.036 | 0.059 | 0.059 | 0.173 | 0.173 | 0.204 | 5.043 |
| 1F | Humid tropic | 0.049 | 0.036 | 0.059 | 0.109 | 0.173 | 0.173 | 0.193 | 5.043 |

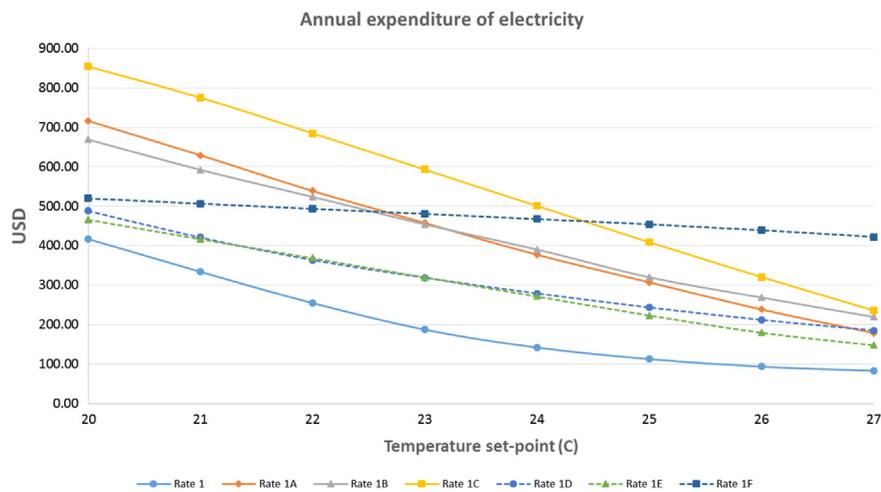


Fig. 3. Annual expenditure of electricity at different temperature set-points and different electricity rates for a conditioned dwelling.

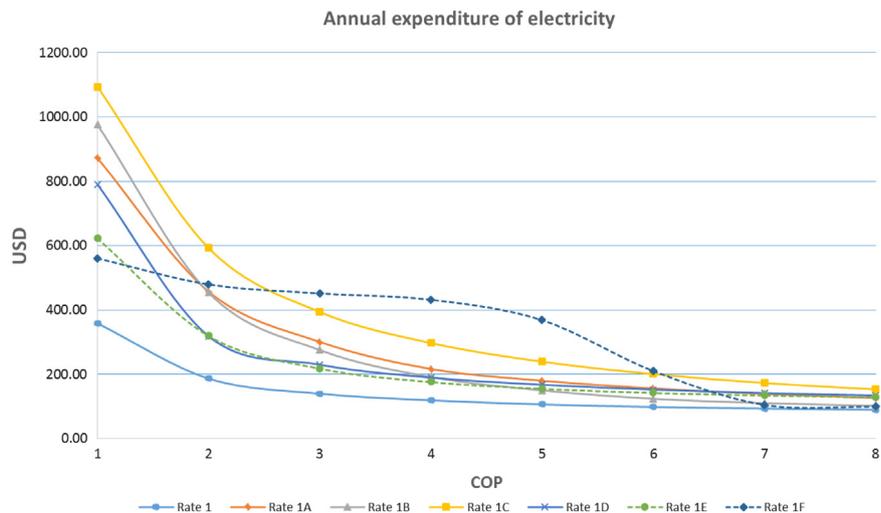


Fig. 4. Annual expenditure of electricity at different COP of the AC and different electricity rates for a conditioned dwelling.

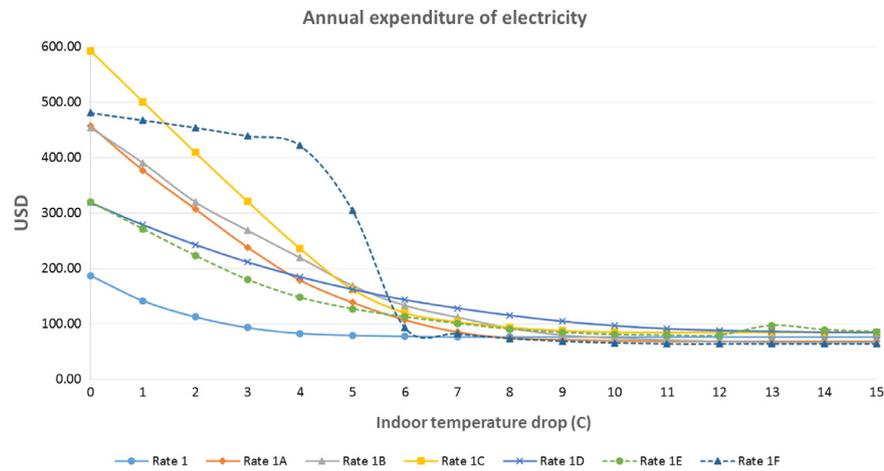


Fig. 5. Annual expenditure of electricity at different indoor temperature decreases by passive cooling and different electricity rates for a conditioned dwelling.

Table 6

Annual consumption and money saving for increasing the indoor temperature set-point from 20 °C to 25 °C at a conditioned dwelling.

| Rate | Consumption 20 °C (MWh) | Expenditure 20 °C (USD) | Consumption 25 °C (MWh) | Expenditure 25 °C (USD) | Saving (USD) |
|------|-------------------------|-------------------------|-------------------------|-------------------------|--------------|
| 1 | 3.24 | 417 | 1.77 | 113 | 304 |
| 1A | 4.92 | 717 | 2.87 | 307 | 410 |
| 1B | 5.37 | 669 | 3.46 | 320 | 349 |
| 1C | 5.67 | 854 | 3.43 | 409 | 445 |
| 1D | 5.78 | 488 | 3.73 | 243 | 245 |
| 1E | 5.85 | 466 | 3.62 | 224 | 242 |
| 1F | 5.92 | 520 | 3.68 | 454 | 66 |

Table 7

Annual consumption and money saving for changing the COP of the AC from 2 to 5 at a conditioned dwelling.

| Rate | Consumption COP-2 (MWh) | Expenditure COP-2 (USD) | Consumption COP-5 (MWh) | Expenditure COP-5 (USD) | Saving (USD) | Payback period (years) |
|------|-------------------------|-------------------------|-------------------------|-------------------------|--------------|------------------------|
| 1 | 2.20 | 187 | 1.74 | 107 | 80 | 8 |
| 1A | 3.62 | 458 | 2.31 | 181 | 277 | 2 |
| 1B | 4.18 | 454 | 2.53 | 150 | 304 | 2 |
| 1C | 4.33 | 593 | 2.59 | 240 | 353 | 2 |
| 1D | 4.49 | 319 | 2.66 | 168 | 151 | 4 |
| 1E | 4.51 | 320 | 2.67 | 156 | 164 | 4 |
| 1F | 4.58 | 480 | 2.69 | 369 | 111 | 6 |

the temperature set-point were set at 2 and 23 °C, respectively. It can be noticed that there is a convergence for every rate to around 100 USD when there is an indoor temperature drop higher than 15 °C. The expenditure of rate 1F is suddenly dropped if there is an indoor temperature decrease of 6 °C, further this point, the expenditure is practically the same.

From Figs. 3 to 5 it is concluded that there are significant amounts of saving for the three strategies. Nonetheless, rate 1F presents different behaviors for the three saving strategies. This is because rate 1F is fixed by the CFE in order to help the users who live on this climate by making the AC affordable and therefore not undergoing issues such as unhealthy environments (Comisión Federal de Electricidad, 2015). This is important because 21% of the energy consumption by AC is under this rate (cf. Table 1).

3.4. Feasibility of implementation of the saving strategies

Three case studies of conditioned dwellings according to the CFE rates are set in order to find out what would be the economic feasibility of implementation of the three main strategies to reduce the AC demand, presented in the prior section. For this purpose, rough estimations are carried out.

It is important to mention that the estimations have the purpose to show a basic economic analysis of implementation within a

single dwelling. For an accurate national-scale analysis, a full-length article may be necessary.

Thereby, for the first strategy the increase of the temperature set-point from 20 °C to 25 °C in the AC thermostat is carried out. For this case none investment is considered since it only depends on the action of the occupants. The COP was set at 2. With this, Table 6 can be constructed. In the table it is seen that the annual saving range is from 66 USD (rate 1F) to 445 USD (rate 1C).

For the second strategy, a change of the AC by equipment with higher COP is analyzed. It is proposed the change of the COP from 2 to 5. An AC equipment with a COP of 5 was found with a price of 615 USD (Oropeza-Perez and Østergaard, submitted for publication). The temperature set-point was set at 23 °C. In Table 7, where the results are shown, it is noticed that the payback period of all cases is low, from 2 to 8 years.

For the third strategy the implementation of three passive cooling techniques is analyzed. The three selected methods are: a light building color on the envelope (as radiant heat barrier), eco-evaporative cooling and a shading system. These passive methods, all together, are lowering the temperature by 8 °C, in accordance with a prior analysis (Oropeza-Perez and Østergaard, submitted for publication) and according to the heat flux block and/or expelled on the building heat balance shown in Eq. (3). It is important mentioning that this temperature drop depends in a great extent on the outdoor conditions (solar radiation, wind

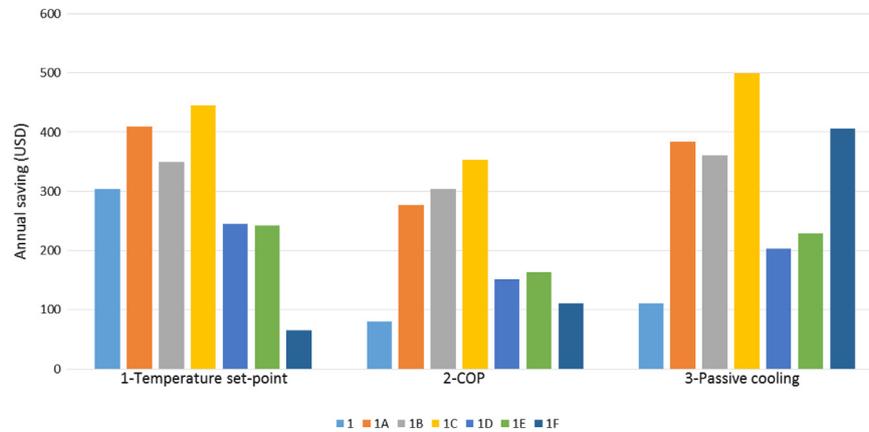


Fig. 6. Summary of Tables 5–7. In the x-Axis, the histogram 1 corresponds to the increase of the temperature set-point, the 2 to the change of a 2 COP AC by a 5 COP AC and the 3 to the use of passive cooling systems. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 8

Annual consumption and money saving for using three passive cooling methods that decrease the indoor temperature by 8 °C at a conditioned dwelling.

| Rate | Consumption no passive (MWh) | Expenditure no passive (USD) | Consumption passive (MWh) | Expenditure passive (USD) | Saving (USD) | Payback period (years) |
|------|------------------------------|------------------------------|---------------------------|---------------------------|--------------|------------------------|
| 1 | 2.20 | 187 | 1.44 | 76 | 111 | 19 |
| 1A | 3.62 | 458 | 1.56 | 74 | 384 | 6 |
| 1B | 4.18 | 454 | 1.86 | 93 | 361 | 6 |
| 1C | 4.33 | 593 | 1.57 | 94 | 499 | 4 |
| 1D | 4.49 | 319 | 2.04 | 116 | 203 | 11 |
| 1E | 4.51 | 320 | 1.64 | 91 | 229 | 9 |
| 1F | 4.58 | 480 | 1.68 | 74 | 406 | 5 |

Table 9

Annual consumption and money saving for using a combination of three passive cooling methods that decrease the indoor temperature by 8 °C and the increase of the indoor temperature set-point from 20 °C to 25 °C at a conditioned dwelling.

| Rate | Consumption no strategies (MWh) | Expenditure no strategies (USD) | Consumption three strategies (MWh) | Expenditure three strategies (USD) | Saving (USD) | Payback period (years) |
|------|---------------------------------|---------------------------------|------------------------------------|------------------------------------|--------------|------------------------|
| 1 | 3.24 | 417 | 1.44 | 76 | 341 | 6 |
| 1A | 4.92 | 717 | 1.46 | 69 | 648 | 3 |
| 1B | 5.37 | 669 | 1.60 | 74 | 595 | 4 |
| 1C | 5.67 | 854 | 1.45 | 86 | 768 | 3 |
| 1D | 5.78 | 488 | 1.70 | 97 | 391 | 5 |
| 1E | 5.85 | 466 | 1.47 | 81 | 385 | 6 |
| 1F | 5.92 | 520 | 1.49 | 66 | 454 | 5 |

speed, relative humidity, outdoor temperature etc.), considering that the indoors remains. Nonetheless, there is not a study, to the best of our knowledge, which gathers all the information beyond the simulation modeling mentioned in this work. For further analysis, a full-length article regarding the topic is proposed.

Thereby, the cost of the passive methods is 2140 USD in total (Oropeza-Perez and Østergaard, submitted for publication). The COP and the temperature set-point were set at 2 and 23 °C, respectively. The results, displayed in Table 8, show payback periods of 6 years or lower for rates 1A, 1B, 1C and 1F. For rates 1, 1D and 1E the periods are higher than 9 years.

Fig. 6 shows the summary of Tables 6–8. In the figure it can be seen that in all cases the highest saving is presented in rate 1C. It is also noticed that the savings are not equality distributed. For instance, in case 3, rate 1F presents a very high saving, while in case 1 the same rate has the lowest saving. This unequal distribution is attributed to two facts: the not-uniform distribution of the rates by the CFE, and the different climate conditions presented in the country, where the performance of both the AC and the passive methods varies.

From Tables 6 to 8 and Fig. 6 one can realize that although the three saving strategies are actually saving money, the investment is sometimes not returned at short term. For these cases, a combination of two or more strategies is proposed. As example, the

combination of two strategies (increase of temperature set-point from 20 °C to 25 °C, and the use of building color, eco-evaporative cooling and a shading system that lower by 8 °C the indoor air temperature) are shown in Table 9.

Table 8 shows that all case studies have a relative short period of payback. This is due the investment only consists in the passive strategies (2140 USD).

4. Conclusions

An economic analysis of the AC energy performance within the Mexican residential sector has been carried out. For this, a program that calculates the AC demand according to the hourly indoor temperatures and other features such as the COP of the AC and the comfort temperature set-point, was developed. As the program also calculates the expenditure for consumption with the corresponding electricity rates set by the CFE, the economic analysis is done after the program is validated.

The sensitivity analysis showed that the indoor temperature decrease by using passive cooling techniques has a great extent of influence on the electricity expenditure. Nonetheless, the money saving is more evident when the decrease reaches 6 °C. Beyond this drop, the expenditure remains almost constant.

If the strategy is changing the AC by one with a higher COP value, the saving is also very suitable. Furthermore, the initial investment could be payable at short term.

When there is an increase of the indoor temperature set-point, it can be an annual saving up to 600 USD, with the great advantage that there is not an initial investment.

Thereby, for getting shorter payback periods of investment it is recommended to combine two or the three saving strategies presented in this document when this could be possible. Furthermore, it was found that the use of passive cooling is almost as affordable as a highly efficient AC, with the advantage that with passive techniques there are not energy consumption and emissions of gases such as chlorofluorocarbons (CFC).

Finally, as the performance of the passive methods is not analyzed by climate condition, it is proposed, as future work, a study of the efficiency of these methods onto the four main Mexican climate conditions in order to establish which one(s) is the most suitable technically and economically.

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