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Technical, environmental, and economic evaluation of a solar/gas driven absorption chiller for shopping malls in the Caribbean region of Colombia

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ABSTRACT

This study discusses the technical, environmental, and economic feasibility of using absorption chillers driven by solar energy and/or natural gas, in selected shopping malls in Barranquilla, Caribbean region of Colombia. The high solar irradiation and the low prices of natural gas in the cities of the Caribbean region of Colombia are attractive conditions for the use of absorption chillers. To prove the feasibility of absorption chillers in the Caribbean region of Colombia, the use of water/LiBr absorption chillers of 352 kW cooling capacity was investigated considering the cooling loads in selected malls. A thermodynamic model was developed to study the performance of the absorption chiller and evaluate different scenarios proposed. The results evidenced that the absorption chiller could reach a maximum COP and SCOP of 0.77 and 0.52, respectively. The different alternatives could reduce gas emissions between 17% and 76% depending on the cooling load covered by the absorption chillers and driving energy input as compared to the current use of mechanical compression chillers. The economic results indicated that the best scenario, considering a lifetime of 20 years, is the gas-driven absorption chiller with IRR varying from 40% to 54.6% depending on the mall cooling load covered.

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Nomenclature

$\mathbf{A_c}$	Collector surface area of a system [m^2]
A_{coll}	Collector surface area [m^2]
C	Cost [USD]
C_p	Specific heat of water [kJ/kg·K]
COP	Coefficient of performance
GHGs	Greenhouse Gases
h	Specific enthalpy [kJ/kg]
HVAC	Heating, ventilation, and air conditioning
I_s	Solar irradiation [W/m^2]
IRR	Internal rate of return
LHV :	Lower heating value [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
N°_c	Total number of solar collectors
NPV	Net Present Value
P	Pressure [kPa]
$\dot{Q}$	Heat transfer [kW]
shx	Heat exchanger
$time_{use}$	Operating time or use [hours]
U	Global heat transfer coefficient [kW/m^2 K]
υ	Specific volume [m^3/kg]
V	Volume [m^3]
$\dot{W}$	Power consumption [kW]
X	Concentration of LiBr in the solution

Subscripts

a	Absorber
abs	Absorption system
Amb	Environment
c	Solar collector
cond	Condenser
el	Electricity
e	Evaporator of the absorption system
e comp :	Evaporator of the compression system
Exp	Experimental
d	Desorber
inst	Installation
inv	Investment
L	Losses
NG	Natural gas
p	Pump
proy	Useful life or projection
op	Operation
s	Solar
sist	System
u	Useful

Greek letters

ε	effectiveness
η_o	Efficiency of the solar collector
η_{GN}	Overall efficiency of the natural gas burner
μ	repair rate/1000 h
λ	failure rate/1000 h

1. Introduction

Rising energy consumption, the main driver of global warming and climate change, is one key issue globally [1,2]. Particularly, the increased demand for fossil fuels (i.e. coal, gas, and oil) accounting for 49% of greenhouse gas (GHG) emissions and supporting 65.2% of the global electricity production [3], stands as an issue requiring urgent attention.

The building sector accounts for around 32% of the total energy used globally [4], whereas, in developed countries, around half of the buildings energy demand is due to air-conditioning systems [5]. Moreover, it is forecasted that the energy demand from the building will be increased by up to 50% by 2030, which will result in higher emissions of GHGs [6,7].

Shopping malls are required to provide specific comfort standards in large areas to satisfy the needs of customers and visitors and thus account for high energy demands within the buildings sector [8]. Consequently, malls use large amounts of electricity in high-powered cooling systems for air conditioning in large areas [6,7,9].

The vapour compression cooling systems are currently the most widely used for air conditioning in shopping malls [6,9,10]. These systems demand large amounts of electricity per unit area [6,9]. The performance of the alternative absorption cooling technology has improved during the last years, and it stands as an option to reduce the electricity requirements for air conditioning and refrigeration, and might eventually replace mechanical compression systems [11,12]. Absorption cooling systems require a small fraction of the electricity consumed by vapour compression cooling systems and can be powered by heat sources like solar energy, natural gas, waste heat, or geothermal energy, which is beneficial to reduce the carbon footprint from current refrigeration systems [13–16]. This is the most widely non-conventional refrigeration technology used on a global scale [17]. The basic configurations of absorption refrigeration and vapour compression refrigeration cycles are similar, but they mainly differ in how the vapour compression process takes place to reach adequate conditions for its condensation [18]. While vapour compression refrigeration systems use mechanical compression, absorption refrigeration systems use a thermal compressor consisting of a vapour absorber, a solution pump, a heat exchanger, and a vapour generator. From these components, the vapour absorber and generator are the most critical components in the absorption system due to the heat and mass transfer processes involved there [19–21].

The potential of solar cooling systems depends strongly on local climate conditions and buildings characteristics [22]. Therefore, a case by case study should be conducted for each climatic region [23]. Tropical and equatorial regions generally show favourable conditions for air-conditioning of buildings using solar-based non-conventional technologies [24,25]. There are different studies in the literature discussing the use of absorption cooling systems in different scenarios. The promotion of solar absorption cooling is of especial interest and a challenging task due to the high investment costs and the needs of the system performance optimization [26]. Moreover, the effectiveness of solar collectors is higher than photovoltaic systems, making solar thermal systems environmentally and economically more suitable to power absorption cooling systems [22]. Comparing a vapour compression refrigeration system powered by a photovoltaic array with a vapour absorption refrigeration system powered by a solar evacuated tube thermal unit is evidenced that both systems are cost-effective [27]. However, vapour compression systems require less space, use a simpler technology, require easier maintenance, and thus result in higher economic benefits over their life cycles. Moreover, absorption refrigeration systems are sustainable energy technologies and more advantageous than vapour compression systems when powered by various available thermal energy [12,28]. For instance, Florides et al. [29] reported the modelling of a solar absorption chiller for Nicosia, Cyprus. The authors concluded that around 49% of the energy required for cooling and water heating can be covered by solar energy. The authors also highlighted the need for sustainable energy technologies even when the economic benefits are marginal given the pollution problem that humanity faces. Dispenza et al. [16] presented a case study of the use of an absorption refrigeration system powered by residual heat from a gas turbine in an industrial consortium in Sicily. The economic analysis showed that the time of return on the initial investment would be less than 4 years. Shafieian & Khiadani [30] proposed a multipurpose absorption unit for cooling and water desalinisation powered by heat waste coming from a diesel motor. The authors reported a coefficient of performance up to 0.88. Balghouthi et al. [31] simulated a solar-assisted 11 kW single effect water/LiBr absorption chiller at the environmental conditions of Tunisia proving its suitability under Tunisian climates. Calise [32] evaluated the energetic and economic feasibility of a solar heating and cooling water/LiBr absorption system for Italian school buildings. Results indicated that around 20% of the cooling load covered could come from solar energy whereas the payback period of the systems proposed was 12 years considering public feed-in tariff. Gomri [33] investigated the performance of a 10 kW water/LiBr absorption chiller driven by solar energy and natural gas in Algeria. The authors employed flat solar collectors to obtain the main energy input while natural gas was used as an auxiliary backup. The maximum COP of the system was around 0.82 while the maximum energy input covered by the solar energy was around 58%.

Lubis et al. [34] reported the performance of a solar-driven single/double effect absorption chiller in a research centre building in Indonesia. The authors reported energy savings potentials up to 58% for tropical Asia areas. Alhamid et al. [35] experimentally evaluated the performance of a solar/gas driven single/double effect absorption chiller in Indonesia and reported a coefficient of performance up to 1. Saleh and Mosa [36] optimized the performance of a single-effect absorption chiller driven by solar flat collectors. The authors concluded that the system coefficient of performance can be up to 0.8 for hot water temperatures between 75 °C and 80 °C.

Al-Falahi et al. [37] investigated two configurations of solar-powered absorption air conditioning systems and concluded that parabolic trough collectors are more adequate for solar water/LiBr absorption cooling systems than evacuated tube collectors. In general, the area required for solar collectors to power absorption systems differs depending on environmental conditions and cooling demand and affects the life cycle costs and viability of the cooling system [24]. For instance, Al-Ugla et al. [9] evidenced that absorption cooling systems are technically and economically viable in commercial buildings in Saudi Arabia. Ghaith and Razzaq [38] evaluated the performance of a solar-powered double-effect absorption chiller for cooling in residential buildings in the United Arab Emirates and evidenced payback periods around 2.5 years. Allouhi et al. [22] concluded that the payback period of the solar collectors for absorption cooling systems varies from 5.8 to 37 years. Moreover, Narayanan et al. [39] reported a feasibility study on the use of solar-driven absorption chillers in student residential buildings in Australia's subtropical climate region. This study evidenced a payback period of 15.8 years. In any case, there are few studies in the literature showing a detailed economic assessment of absorption cooling systems powered by solar energy and/or fuels like natural gas. Moreover, most studies fail to consider maintenance factors like failure rates and recovery rates.

While there is a great potential for solar energy and low-cost natural gas in South America, it is been hardly exploited to drive absorption cooling systems because of the high investment costs, and the lack of knowledge about the potential of these systems in the region [40]. Colombia has a high solar energy potential and low-cost natural gas [41], which are attractive conditions to promote the use of absorption cooling systems. Particularly, the Caribbean region of Colombia has a tropical climate, thus mechanical compression air-conditioning systems are highly employed. On average, the electricity demand for air conditioning in shopping malls in the city of Barranquilla, one of the main cities in the Caribbean region, is around 8 kWh/ m^2. This is significantly higher than that in other regions of the country [42,43].

Emerging technologies like absorption cooling systems stand as an alternative to reduce the demand for electricity and CO_2 equivalent emissions in shopping malls. However, the technical and economic potential of absorption chillers for air-conditioning in the Caribbean region of Colombia has not been explored. Therefore, this study aims to investigate the technical and economic feasibility of solar and/or gas-driven absorption chillers for air conditioning of shopping malls in the Caribbean region of Colombia where the climate is Tropical Savanna. This study also includes recommendations of adequate control strategies for the operating conditions of the absorption chillers in the shopping malls. Moreover, an environmental study in terms of CO_2 equivalent emissions is presented under various scenarios. Finally, an economic study is approached for different case studies considering the net present value and internal rate of return.

2. Methodology

This section presents the characteristics of the shopping malls selected for the study. Additionally, it describes and presents the validation of the thermodynamic model used to simulate the operation of water/LiBr absorption cooling systems. Finally, it shows the economic indicators used for the feasibility study.

2.1. Environmental variables in Barranquilla

Colombia includes different climate zones which depend on the altitude and landscape. Barranquilla, which is located in the Caribbean Coast of Colombia and has a population of around 1.2 million people, is one of the largest and most important cities in Colombia in terms of economic development and projection. In Barranquilla, the climate can be classified as Tropical Savanna, the environmental temperature ranges between 24 °C and 35 °C while the relative humidity varies over 70% [41,44,45]. Fig. 1 shows the average hourly solar radiation per month in the city.

Fig. 1 shows peak irradiation during January and February with the lowest irradiation between August and October, and March and April, which coincides with the two periods of precipitations that reduce irradiation in the city. Solar irradiation ranges from 600 Wh/ m^2 to 1000 Wh/m^2 through the year, with peaks of 800 Wh/m^2 to 1000 Wh/m^2. Daily irradiation peaks occur between 11:00 and 15:00 h, the daily sunlight period yearly averages 7.18 h, resulting in a daily average irradiation of 846.4 Wh/m^2 [46].

2.2. Characteristics of selected shopping malls

The three shopping malls selected are in the Riomar area, which concentrates about 54% of the shopping malls in Barranquilla.

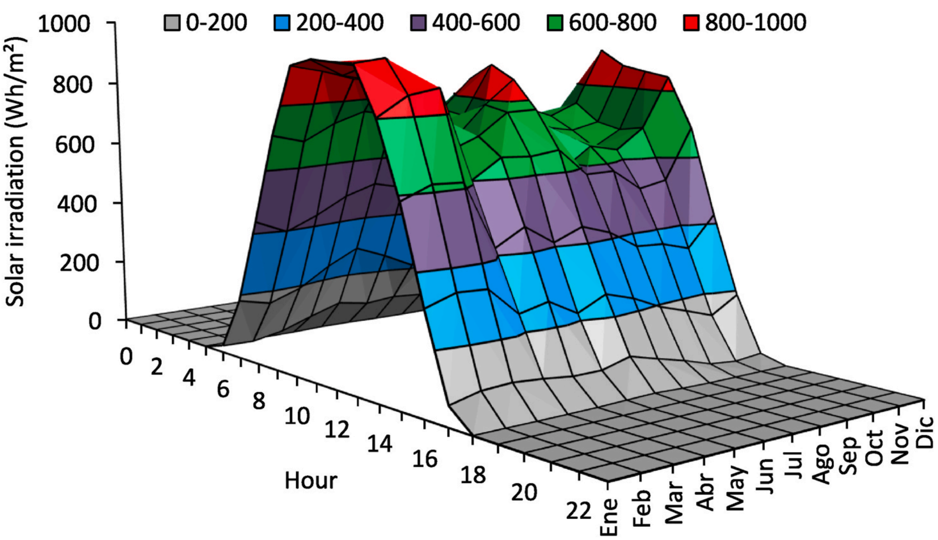

Fig. 1. Average hourly solar irradiation per month [46].

Table 1
Characteristics of selected shopping malls.

Shopping mall	Air-conditioned area (A_{CA}) (m^2)	Available area for solar collectors (A_{SC}) (m^2)	Ratio (A_{CA}/A_{SC})
C.C.1	28,390	4043	7
C.C.2	21,000	2391	9
C.C.3	19,800	1214	16

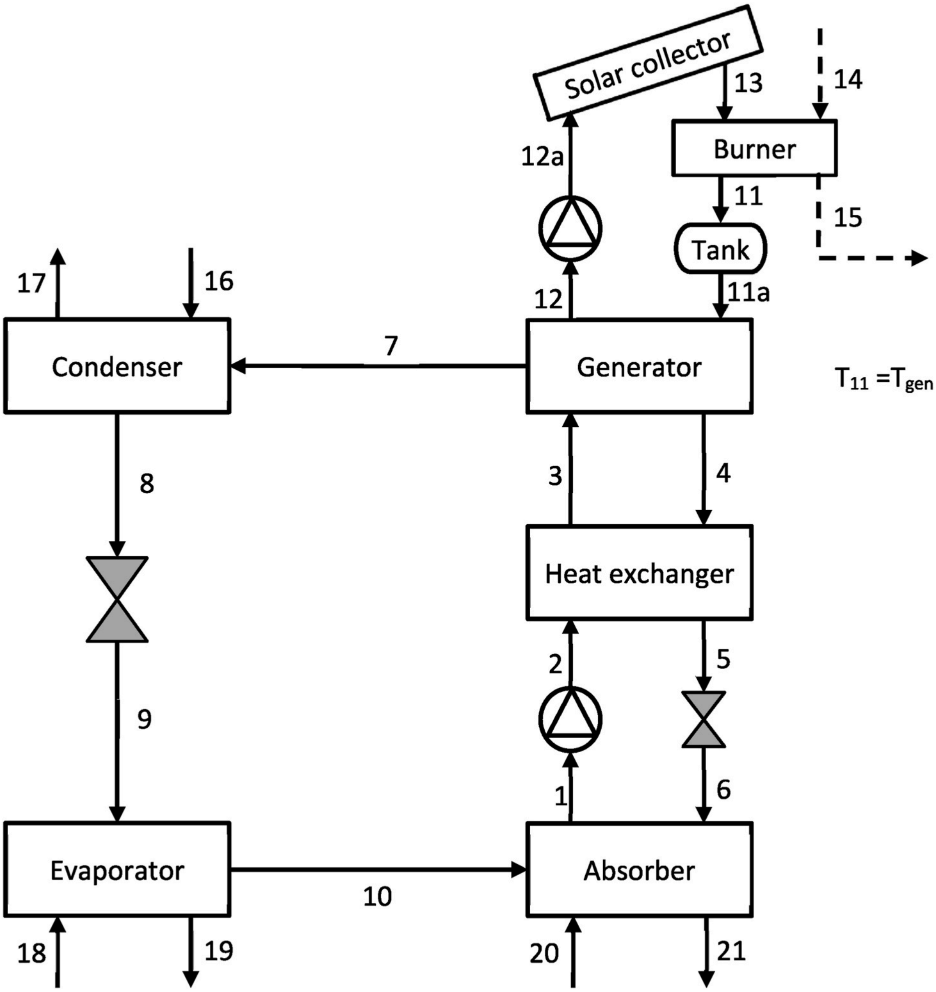

Fig. 2. Absorption cooling system configuration.

From here on will the shopping malls will be referred to as C.C.1, C.C.2, and C.C.3. Table 1 shows the main characteristics of the shopping malls selected.

The ratio A_{CA}/A_{SC} for C.C.3 is about 2 times higher than for C.C.1 and C.C.2. Thus, for C.C.3 is reasonable to expect lower potentials for absorption chillers powered by solar energy.

The power consumption of the vapour compression cooling systems in the shopping malls was measured with a power analyser FLUKE 435 II, during the daily operation of the malls between 7:00 a.m. and 8:30 p.m. (at 1-min intervals). Measuring campaigns in shopping malls C.C.1 and C.C.3 were carried out in October 2019, while in shopping mall C.C.2 was conducted in March 2019.

2.3. Absorption chiller configuration

Fig. 2 shows the configuration of the absorption cooling system considered in the present study.

The system consists of a solar collector and a natural gas burner used to power the absorption chiller. In the absorption chiller, the refrigerant vapour leaves the evaporator and enters the absorber, where it is absorbed by the absorbent solution of water/LiBr weak in refrigerant (from here on such weak solutions will be referred to as 'weak solution'). During the absorption process, heat is released and dissipated by the cooling water flow (streams 20 and 21). The absorbent solution of water/LiBr (strong in refrigerant, from here on such solutions will be referred to as 'strong solution') in stream 1 leaves the absorber driven by the small solution pump and enters the heat exchanger (stream 2, strong solution) where it exchanges heat with stream 4 (weak solution). The strong solution enters the generator (stream 3) and receives heat from the input energy source. Then, the refrigerant partially separates from the solution because of its lower vapour pressure. The refrigerant vapour flow leaves to the condenser (stream 7) while the weak solution (stream 4) leaves to the solution heat exchanger. The condensed refrigerant leaving the condenser (stream 8) flows to an expansion valve where it expands while reducing its pressure and temperature and leaves to the evaporator (stream 9) where it absorbs heat causing the cooling effect (streams 18 and 19). Finally, the refrigerant flows to the absorber (stream 10), where the cycle starts again. Streams 11 and 12 consist of pressurized water used to transport the thermal energy input from the solar collector and gas burner to the generator (streams 12, 12a, 13, 11, and 11a). Streams 14 and 15 correspond to the natural gas and exhaust gases flow.

In total, 4 scenarios were considered to assess the integration of absorption chillers:

1. Baseline scenario: Cooling demand of the shopping malls using mechanical compression chillers.
2. Solar-activated scenario: Cooling demand supported by combining absorption chillers (powered with ETC systems) and mechanical compression chillers.
3. Hybrid activated: Cooling demand supported by combining absorption chillers (powered with ETC and natural gas systems) and mechanical compression chillers.
4. Gas activated scenario: Cooling demand supported by combining absorption chillers (powered with natural gas systems) and mechanical compression chillers.

In these scenarios, when the absorption chillers can support 100% of the cooling demand, the mechanical compression chillers are excluded from the assessment. For scenarios 2 and 3, using ETC systems to power absorption chillers, the cooling capacity will be limited by the available area for solar collectors.

2.3.1. *Thermodynamic model*

The model considers the components of the absorption cooling system depicted in Fig. 2.

The energy potential of a solar thermal collector ($\dot{Q}_s$), is calculated as [47]:

$$\dot{Q}_s = A_c I_s \tag{1}$$

where A_c is the area of the solar collectors, and I_s is the total solar irradiation on the surface of the solar collector. The database of solar irradiation in Barranquilla is constant per hour.

Table 2
Mass and energy balances of the absorption chiller.

Components	Mass Balance	Eq.	Energy balance and effectiveness	Eq.
Pump	$\dot{m}_1 = \dot{m}_2$	6	$\dot{W}_p = n_p \cdot \dot{W}_e$	16
			$\dot{W}_p = \dot{m}_1 \cdot \upsilon_1 \cdot (P_2 - P_1)$	17
Heat Exchanger	$\dot{m}_2 = \dot{m}_3$	7	$\dot{Q}_{shx} = \dot{m}_2 \cdot (h_3 - h_2)$	18
	$\dot{m}_4 = \dot{m}_5$	8	$\dot{Q}_{shx} = \dot{m}_4 \cdot (h_4 - h_5)$	19
			$\varepsilon = \frac{T_4 - T_5}{T_4 - T_2}$	20
Generator	$\dot{m}_3 = \dot{m}_7 + \dot{m}_4$	9	$\dot{Q}_{gen} = \dot{Q}_u + \dot{Q}_{GN}$	21
	$\dot{m}_3 X_3 = \dot{m}_7 + \dot{m}_4 X_4$	10	$\dot{Q}_{GN} = \dot{m}_{GN} \cdot LHV \cdot \eta_{GN}$	22
			$\dot{Q}_{GN} = \dot{m}_{11} \cdot C_p \cdot (T_{11a} – T_{13})$	
			$\dot{Q}_{gen} = \dot{m}_7 \cdot h_7 - \dot{m}_3 \cdot h_3 + \dot{m}_4 \cdot h_4$	23
			$\dot{Q}_{gen} = \dot{m}_{11} \cdot C_p \cdot (T_{11a} – T_{12})$	24
			$\varepsilon = \frac{T_4 - T_3}{T_{11a} - T_3}$	25
Absorber	$\dot{m}_{10} = \dot{m}_1 - \dot{m}_6$ $\dot{m}_6 X_6 + \dot{m}_{10} = \dot{m}_1 X_1$	11	$\dot{Q}_a = \dot{m}_{10} \cdot h_{10} + \dot{m}_6 \cdot h_6 - \dot{m}_1 \cdot h_1$	26
			$\dot{Q}_a = \dot{m}_{20} \cdot C_p \cdot (T_{21} – T_{20})$	27
			$\varepsilon = \frac{T_6 - T_1}{T_6 - T_{20}}$	28
Condenser	$\dot{m}_7 = \dot{m}_8$	12	$\dot{Q}_{cond} = \dot{m}_7 \cdot h_7 - \dot{m}_8 \cdot h_8$	29
			$\dot{Q}_{cond} = \dot{m}_{16} \cdot C_p \cdot (T_{17} - T_{16})$	30
			$\varepsilon = \frac{T_7 - T_8}{T_7 - T_{16}}$	31
Evaporator	$\dot{m}_9 = \dot{m}_{10}$	13	$\dot{Q}_e = \dot{m}_{10} \cdot h_{10} - \dot{m}_9 \cdot h_9$	32
			$\dot{Q}_e = \dot{m}_{18} \cdot C_p \cdot (T_{18} - T_{19})$	33
			$\varepsilon = \frac{T_{18} - T_{19}}{T_{18} - T_{19}}$	34
Valve 1	$\dot{m}_8 = \dot{m}_9$	14	$h_8 = h_9$	35
Valve 2	$\dot{m}_5 = \dot{m}_6$	15	$h_5 = h_6$	36

The thermal efficiency of solar collectors is defined as the ratio of heat flow absorbed by the working fluid in the collector ($\dot{Q}_u$) to the solar energy flow irradiated on the collector ($\dot{Q}_s$):

$$\eta_c = \frac{\dot{Q}_u}{\dot{Q}_s} = \frac{\dot{m}_{11} c_p (T_{12} - T_{13})}{A_c I_s} \tag{2}$$

In this study, incidence angles smaller than 35° are considered, so equation (2) can be simplified as [47]:

$$\eta_c = n_o - \frac{a_1 \Delta T_{avg}}{I_s} - \frac{a_2 (\Delta T_{avg})^2}{I_s} \tag{3}$$

where η_o represents the optical efficiency of the collector; a_1 and a_2 are coefficients of heat loss, and ΔT_{avg} is the difference between the average temperature in the solar collector and the ambient temperature.

Since ΔT_{avg} has a linear variation with the thermal efficiency of the collector, the efficiency for flat plate solar thermal collectors can be finally simplified to Ref. [48]:

$$\eta_c = 0.75 - \frac{5 \cdot \Delta T_{avg}}{I_s} \tag{4}$$

Moreover, for evacuated tube collectors, the efficiency is calculated as [48,49]:

$$\eta_c = 0.82 - \frac{2.198 \cdot \Delta T_{avg}}{I_s} \tag{5}$$

The model of the absorption chiller is based on the mass and energy balances in its components (see Fig. 2). The general considerations used in this study are:

- The refrigerant flow in the generator (stream 7) is a superheated vapour.
- The refrigerant flow leaving the condenser (stream 8) is saturated liquid.
- Heat losses in pipes are neglected.
- The efficiency of the gas heater (η_{GN}) is 0.85 [33].
- The efficiency of the solution pump is 0.6.

The EES software was used for the simulation. The thermodynamic properties of the water/LiBr solution such as density, specific volume, and enthalpy were provided by the EES and obtained from Ref. [50]. Table 2 shows the mass and energy balances for the different components.

The heat reservoir tank (see Fig. 2) is considered adiabatic. Therefore, the outlet temperature of the tank (T11a) is equal to the input temperature (T11). The volume of the tank is calculated as follows [24]:

$$V_{tank} = \frac{A_c}{30} \tag{37}$$

where A_c is the area of thermal solar collectors in m^2.

The length of the heat reservoir is considered equal to its diameter [49]. The mass of the thermal reservoir is calculated using the water density and tank volume.

The coefficient of performance (COP) and the solar coefficient of performance (SCOP) of the absorption chiller are estimated as:

$$COP = \frac{\dot{Q}_{ev}}{\dot{Q}_{gen} + \dot{W}_p} \tag{38}$$

$$SCOP = \frac{\dot{Q}_{ev}}{\dot{Q}_s} \tag{39}$$

where $\dot{Q}_{ev}$ is the heat transfer rate in the evaporator, $\dot{Q}_{gen}$ is the heat transfer rate in the generator, and $\dot{W}_P$ is the power consumption of the pump.

The area required for the solar collectors must be less than the available area ($A_{available} > A_c$) in the shopping malls. The share of the cooling demand supported by absorption cooling systems is calculated as:

$$\text{Share of cooling demand covered } (\%) = \frac{\dot{Q}_{ev}}{\dot{Q}_{e\ comp}} \cdot 100 \tag{40}$$

When applicable, the environmental impact of natural gas is assessed with the $CO_{2\ eq}$ emissions, which are calculated as [51]:

$$CO_{2\ eq} = \left(\dot{m}_{GN} \cdot C_{em\ GN} + \dot{W}_{pump} \cdot C_{em\ el}\right) \cdot time_{use} \quad (41)$$

Where $C_{em\ el}$ is the emission factor of kg of CO_2 due to electricity supply (kWh). Its value is considered 0.181 kg CO_2/kWh. $C_{em\ GN}$ is the CO_2 emission factor of kg due to the natural gas consumption (Nm^3). Its value is 2.15 kg CO_2/Nm^3 [51].

To determine the $CO_{2\ eq}$ emissions associated with mechanical compression systems, the following equation is used [51]:

$$CO_{2\ eq} = \left(\dot{Q}_{e\ comp} \middle/ \left(COP_{\ comp}\right)\right) \cdot time_{use} \cdot C_{em\ el} \quad (42)$$

To determine the $CO_{2\ eq}$ emissions associated with the electricity consumed by systems absorption powered by solar energy, the following equation is used [51]:

$$CO_{2\ eq} = \left(\dot{Q}_{e\ comp} \middle/ COP + \dot{W}_{pump}\right) \cdot time_{use} \cdot C_{em\ el} \quad (43)$$

To determine the $CO_{2\ eq}$ emissions associated with the electricity and natural gas consumed by systems absorption, the following equation is used [51]:

$$CO_{2\ eq} = \left(\left(\dot{Q}_{e\ comp} \middle/ COP + \dot{W}_{pump}\right) \cdot C_{em\ el} + \dot{m}_{GN} \cdot C_{em\ GN}\right). \cdot time_{use} \quad (44)$$

2.4. *Economic assessment*

The economic analysis is developed assessing the net present value for the life cycle of the absorption cooling system, using the equations reported in Table 3. The maintenance costs of both the absorption cooling system and the heat activation system were considered [49,52].

The discount rate (*i*) is taken as 3.5% while a project lifespan (Y_{proy}) of 20 years is considered for the NPV [24]. The operational availability of the system is calculated with the failure and repair rates for each configuration. For the cooling system, a failure rate of 0.219375 per thousand hours and a repair rate of 20.83 per thousand hours were considered. Moreover, for the natural gas supply network system a failure rate of 0.11986 per thousand hours and a repair rate of 41.67 per thousand hours were considered. Finally, the failure rate for the electricity supply network is taken as 0.12742 per thousand hours, while the repair rate is considered as 41.67 per thousand hours [52]. Data regarding the capital costs considered in the study are presented in Table 4.

The conversion of € to USD was taken as 1.16 USD/€. The cost of natural gas was taken as 0.19 USD/m^3 whereas the electricity cost was taken as 0.15 USD/kWh.

3. Results

This section shows the validation of the simulation model and the results from the techno-economic assessment.

3.1. *Validation of the simulation model*

The validation of the thermodynamic model is carried out using the operation data of the Thermax series absorption chillers. The

Table 3
Economic model.

Cost	Equation	Eq.	Reference
Capital cost (solar collector)	$C_c = A_c \cdot C_{Uc}$	45	[24,53]
	$N_c^{\circ} = \frac{A_c}{A_{\ coll}}\ (A_{\ coll} = 2.2\ m^2)$	46	
Capital cost (absorption chiller)	$C_{abs} = C_{conv\ USD} \cdot C_{esp\ abs} \cdot \dot{Q}_{ev\ nom} \cdot N^{\circ}_{\ abs}$	47	[24]
Capital cost (heat reservoir tank)	$C_{tank} = (Vol) \cdot C_{tank\ u}$	48	[24]
Capital cost	$C_{inv} = C_{abs} + C_c + C_{inst} + C_{tank}$	49	[54]
Maintenance cost (natural gas-solar systems)	$C_{maint} = 0.04 \cdot C_{inv}$	50	[52]
Maintenance cost (solar system)	$C_{maint} = 0.01 \cdot C_{inv}$	51	[49]
Operation	$C_{op} = \dot{W}_b \cdot time_{use} \cdot C_{el} + C_{NG}\ V_{NG} + C_{maint}$	52	[54,55]
Insurance cost	$C_{ins} = 0.02 \cdot C_{inv}$	53	[54]
Installation Cost	$C_{inst} = 0.05(C_{abs} + C_c + C_{tank})$	54	[56]
Electric savings	$AE = \frac{\dot{Q}_{ev} \cdot time_{use} \cdot C_{el}}{COP_{comp}}$	55	–
Net Present Value	$NPV = C_{inv} + \sum_{y=1}^{y=Y\ proy} \frac{(C_{ope} + C_{insurance}) - AE}{(1+i)^Y}$	56	[49,54]
Operational availability or use time	$time_{use} = Business\ days \cdot \frac{1}{\frac{\lambda_{sist}}{\mu_{sist}} + 1}\ Business\ days = 360\ \ days$	57	–
System failure rate	$\lambda_{sist} = \lambda_{el} + \lambda_{sist.GN} + \lambda_{sist.abs}$	58	[52]
System repair rate	$\mu_{sist} = \frac{\lambda_{el} + \lambda_{sist.GN} + \lambda_{sist.abs}}{\frac{\lambda_{el}}{\mu_{el}} + \frac{\lambda_{sist.GN}}{\mu_{sist.GN}} + \frac{\lambda_{sist.\ abs}}{\mu_{sist.\ abs}} + 1}$	59	[52]
Inactive time	$Inactive\ \ time = 365\text{-}time_{use}$	60	

Table 4
Capital costs.

Unit	Capital costs	Reference
FPC $\left({}^{€}/_{m^2}\right)$	200	[53]
ETC $\left({}^{€}/_{m^2}\right)$	250	[24,48]
Tank $\left({}^{USD}/_{m^3}\right)$	580	[24]
$C_{esp\ abs}$ $\left({}^{€}/_{kW}\right)$	300	[24]

Table 5
Thermax series chillers [57].

Series	Cooling capacity (kW)	Mass flow rate of water/LiBr estimated at the absorber outlet (kg/s)
LT-10C	352	1.66
LT-12C	422	1.90
LT-14C	492	2.30
LT-16C	563	2.60
LT-18C	633	2.90
LT-20C	738	3.40

mass flow rates and inlet temperatures of the external streams were set as recommended by the manufacturer, for instance: 6.7 °C for chilled water temperature, 29.4 °C for the heat dissipation temperature, and 90.6 °C for the hot water circuit (input energy) [57]. The characteristics of Thermax absorption chillers and the estimated solution mass flow rates leaving the absorber are shown in Table 5. It can be observed that the solution mass flow rate leaving the absorber increases almost linearly with the cooling capacity of the chiller. Adequate values from literature are considered for the effectiveness of the solution heat exchanger, evaporator, condenser, generator, and absorber (see Table 6).

Fig. 3 compares the heat flows (data at nominal capacities (see Table 5) and values estimated with the model using the effectiveness from Table 6) in the generator and evaporator of different Thermax absorption chillers.

Results show a linear relationship between the nominal data and simulated results, with a slope of 45° and relative errors lower than 1% for the generator and evaporator heat flows. This validates the model to be used to simulate the process of absorption cooling for the selected case studies.

Table 6
Effectiveness of the absorption chiller components [58–60].

Component	Effectiveness
Evaporator	0.815
Condenser	0.676
Absorber	0.500
Generator	0.302
Solution Heat Exchanger (SHX)	0.640

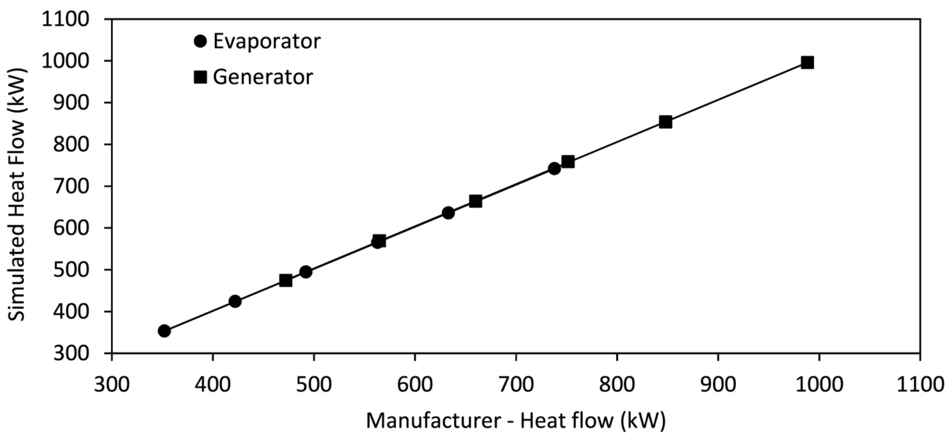

Fig. 3. Scatter plot of experimental and simulated heat flows in the evaporator and generator of different Thermax absorption chillers.

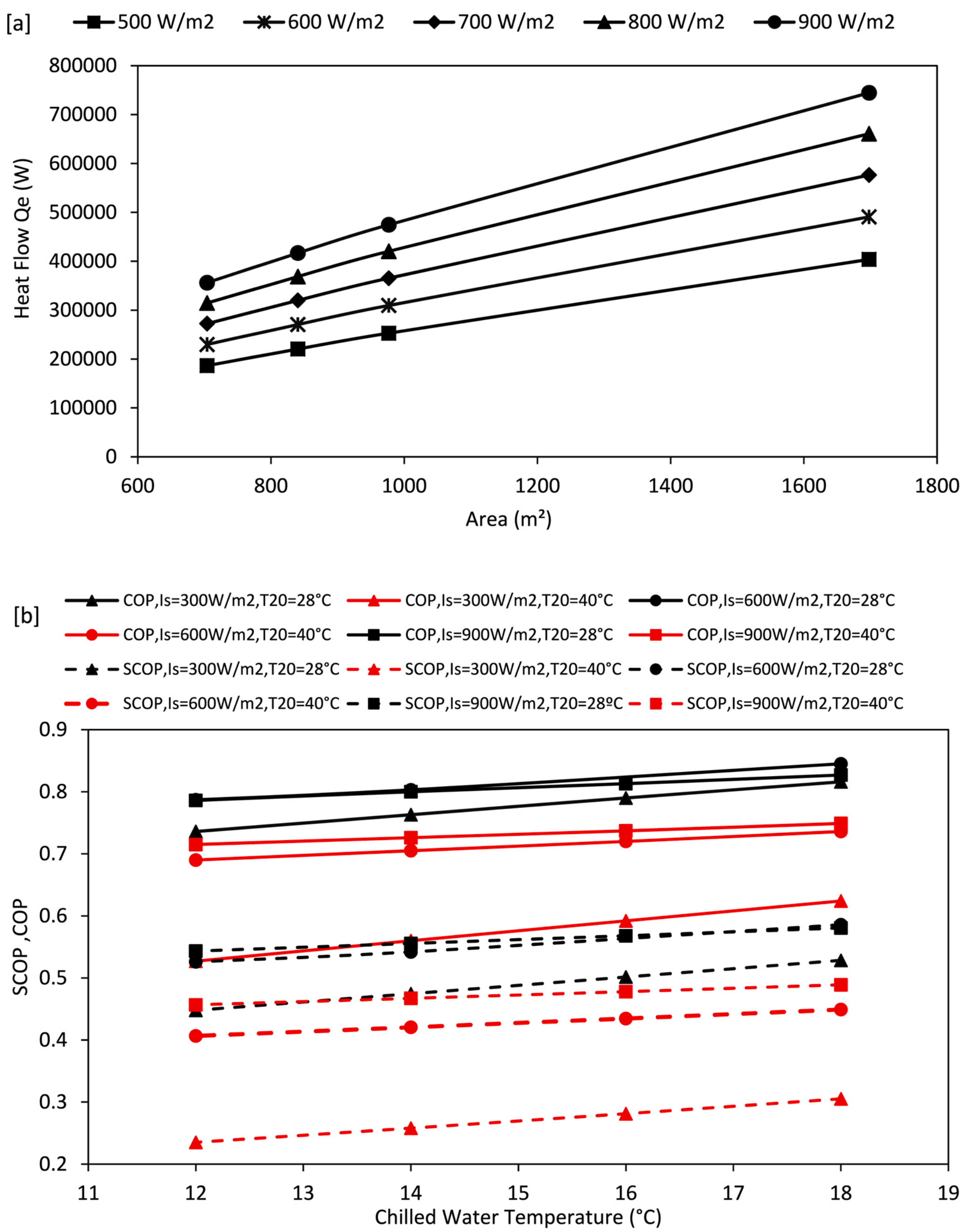

Fig. 4. [a] Area of solar collectors for different thermal loads and irradiation values, [b] sensitivity study applied to the absorption cooling system with ETC.

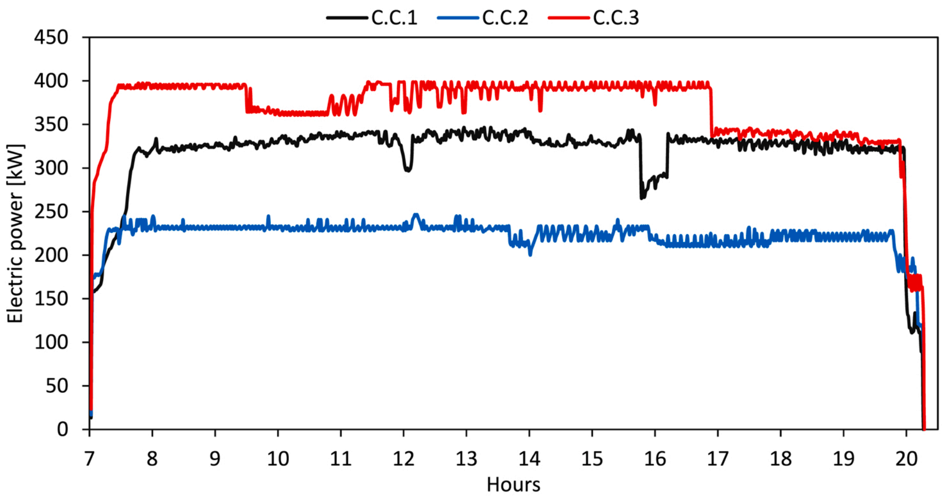

Fig. 5. Power demand from mechanical vapour compression chillers.

3.2. Sensitivity analysis

A sensitivity analysis is developed to quantify the influence of the different operating parameters on the system performance. The effects of solar radiation, the temperature of heat dissipation in the condenser and absorber, and refrigeration temperature in the evaporation are carefully assessed. To this end, the operation of the series LT-10C was simulated, considering the annual average irradiation of 846.48 W/m^2, the average daily sunlight period of 7.18 h [46], and its nominal operating conditions. If the absorption chiller is connected to flat plate solar collectors (FPC), an area of 1412 m^2 is required for installing the collectors, whereas if evacuated tube collectors (ETC) are used, an area of 840 m^2 is required. The differences between the area required for FPC and ETC imply a difference in capital cost of 83,914 USD. The use of ETC results in lower capital costs and higher efficiency. Therefore, this type of collector was selected for the following simulations.

Fig. 4a shows the heat flow in the evaporator of the absorption chiller, with the minimum area of ETC used to drive the system at different solar irradiations. Fig. 4b shows that absorption chiller reaches the highest performance (COP between 0.78 and 0.85, and SCOP between 0.53 and 0.59) at irradiation of 600–900 W/m^2, and a dissipation temperature of 28 °C. Moreover, the performance of the system drops with the increase of the heat dissipation temperature in the condenser and absorber, and by reducing the evaporation temperature. It is worthy of note that while the nominal chilled water temperature reported by the thermal series systems manufacturer is 6.7 °C, higher chilled water temperatures were considered in this study which implies higher performances of the system. With the operational parameters in these ranges, no crystallization of the water/LiBr solution occurs. Moreover, increasing the cooling water (T_{19}) setpoint by 2 °C improves the COP between 1.6% and 3.7%. On the other hand, this system can operate at low irradiations above 300 W/m^2, with dissipation temperatures between 28 °C and 40 °C, with T_{19} temperatures equal to or above 12 °C. These results can be used to define adequate control strategies of the absorption cooling system at the environmental conditions in Barranquilla.

3.3. Energy consumption from mechanical compression chillers in shopping malls

Fig. 5 shows the data measured with the power analyser. These data correspond to the electricity consumption of the mechanical vapour compression chillers in the selected shopping malls during a typical operation day.

The data collected shows that the power consumption remains relatively stable during the day. In the city, shopping malls operate around 13 h a day. The C.C.3 showed the highest power consumption varying between 330 kW and 400 kW for most of the day. After 5 p.m. cooling demand decreased because some backup equipment was shut down. Moreover, in C.C.1 the power consumption of chillers varied from 267 kW to 330 kW for most of the day. In C.C.2, the power consumption of chillers ranged between 200 and 240 kW for most of the day. In the three malls, variations in the power consumption are observed, which are the result of the mall functioning, i.e. flow of people, environmental conditions, etc. A COP_{comp} of 3 was considered to calculate the thermal load dissipated by mechanical vapour compression cooling systems in the shopping malls, [24,52]. Consequently, the maximum cooling loads provided by the mechanical compression cooling systems in the C.C.1, C.C2, and C.C.3 are around 1001 kW, 735 kW, and 1187 kW, respectively. These results are used as the cooling targets to be covered with the absorption cooling system configurations investigated. These results are presented in section 3.4.

It must be pointed that there is a low cooling demand when the system starts at 7 a.m. as well as when the system is shut down at 8:30 p.m. This demand increases rapidly after the system starts, from some 20 kW to 200 and 400 kW, in the C.C.2 and C.C.3, respectively. The opposite occurs before the system shutdown.

3.4. Absorption chillers driven by solar and/or natural gas: case studies

In this section, the results from simulating the operation of the absorption chillers in shopping malls are presented. The cooling load estimated from the power consumption measurements is used to define the absorption chillers requirements in each shopping mall. For the simulations, the chilled water temperature was set to 12 °C, while the heat dissipation temperature was set to 29.4 °C. The LHV of natural gas was taken as 47,040 kJ/kg [58]. Given that the chilled water temperature was set to 12 °C in the absorption chillers, the chillers could operate above their nominal cooling capacity. Table 7 shows the number of chiller units and solar collector areas used in each shopping mall of each case study.

To define the chiller units needed for each mall the cooling load covered by mechanical compression chillers and the available area for solar collectors in each building were considered. For instance, in C.C.1 the mechanical compression chillers cover a cooling load of 1001 kW, thus 3 absorption chillers LT-10C of 352 kW operating at nominal capacity could be used to cover the same cooling capacity. However, the performance of the chiller depends on the solar radiation and the possibility to operate close to the nominal conditions. In the case of chillers powered by both, solar energy, and natural gas, they can operate at nominal or higher conditions since the outlet temperature of chilled water was set at higher values. Therefore, only two absorption chillers powered by solar energy and natural gas were used in the C.C.1. A similar analysis was conducted in the C.C.2 and C.C.3. However, in C.C.3 the number of chiller units was limited to 1 when including solar energy due to the little area available for solar collectors. When powered with natural gas, the area available for absorption chillers is not an issue, plus they can also operate above nominal conditions due to a higher chilled water temperature.

Results from the simulations of the absorption chillers powered by solar energy show that the maximum COP is 0.77, while the maximum SCOP is 0.52. The highest performance is obtained between 10:00 and 11:00 h when the chillers can operate near their nominal cooling capacity. In the remaining hours, the irradiation decreases, providing less power to the generator reducing the performance of the chillers. The cooling capacity of absorption chillers varies during the day because of the variations of solar irradiation. Fig. 6a shows the share of cooling demand supported by solar-driven absorption chillers for each shopping mall.

Results in Fig. 6a show that, because of the limitations of the area available for ETC in the shopping malls, absorption cooling systems can support from 3% to 97.5% of the cooling demand between the hours of 7 a.m. and 5 p.m., which coincides with the period of highest demand within the day. In C.C.1, absorption chillers can support from 40% to 97.5% of the cooling demand between 8 a.m. and 3 p.m., dropping to 10.9% afterwards. In C.C.2, absorption chillers can support from 40% to 87.57% of the cooling demand between 8 a.m. and 3 p.m., dropping to 10.94% afterwards. Finally, in C.C.3, absorption chillers can support from 11.58% to 29% of the cooling demand between 8 a.m. and 3 p.m., dropping to 3% afterwards. These results highlight that the main limitations of using ETC to power absorption chillers are the area for solar collectors and the solar radiation variations. Thus, in this case, it is required to use mechanical vapour compression cooling units to meet the cooling demand of the shopping malls.

Results from the simulations of the absorption chillers powered by natural gas show that the COP of the absorption chillers in the shopping malls was around 0.77 based on a stable energy supply. Fig. 6b shows the share of the cooling demand supported by the absorption systems for each shopping mall.

In this case study, 2 absorption chillers were used in each shopping mall given that there is no limitation in the area for the installation of the whole system. In C.C.2, the absorption chillers can support 100% of the cooling demand during the day. Moreover, in C.C.1 the system can supply from 81 to 100% of the cooling demand during the day (8:00–18:00 h). Finally, in C.C.3 absorption chillers can support from 70 to 83% of the cooling demand during the day (8:00–18:00 h). In C.C.1 and C.C.3 is possible to meet 100% of the cooling demand by adding an absorption chiller but it would increase the investment costs whereas the additional system may not work at full load conditions, affecting the economic feasibility of the investment.

Fig. 6c shows the cooling energy supported by the absorption chillers powered by solar energy and natural gas for the three shopping malls. Results show that in C.C.1 and C.C.2, the cooling effect provided by the absorption chillers is like the obtained using natural gas to power the chillers. This is because the same number of chillers were used in this case study and their operation above the nominal capacity was possible thanks to the stable energy input.

Results show that in C.C.1, the absorption chillers can support around 81% of the cooling demand for most of the day, including peak hours. Moreover, in C.C. 2, the absorption chillers can support 100% of the cooling demand during the day. Finally, in C.C.3 the absorption chillers can support around 35% of the cooling demand. The low cooling demand in C.C.3 as compared to C.C.1 and C.C.2 is because, given the limitations of available area for solar collectors, only 1 absorption chiller can be powered with solar energy and natural gas.

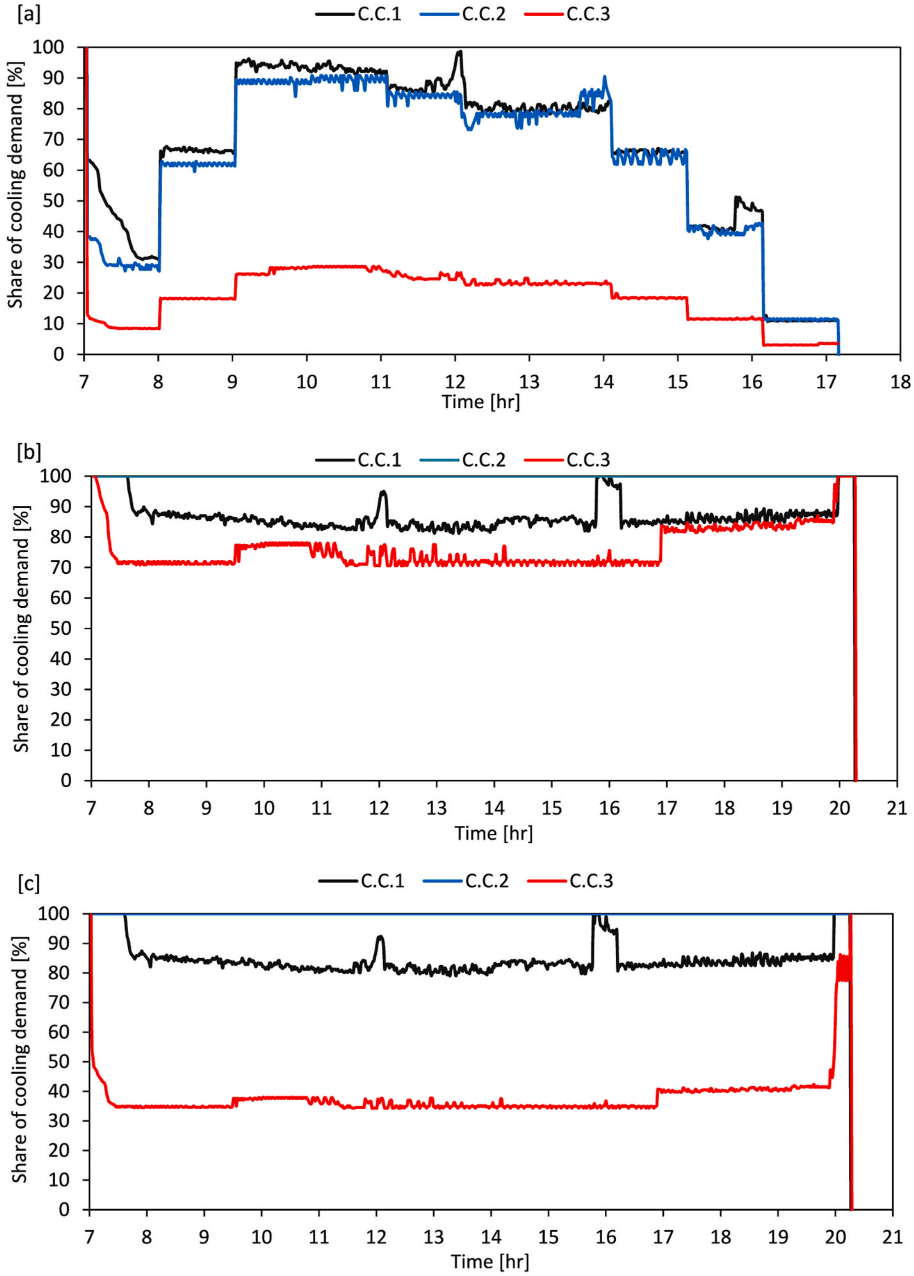

Fig. 6. Share of cooling demand supported by absorption chillers powered by [a] solar energy, [b] natural gas, and [c] solar energy and natural gas.

Table 7
Requirements for absorption chillers and solar collector area.

Mall	Power source	Number of chillers	Solar collector area (m^2)
C.C.1	ETC	3	2521.2
	Natural gas	2	–
	Combination	2	1680.8
C.C.2	ETC	2	1680.8
	Natural gas	2	–
	Combination	2	1680.8
C.C.3	ETC	1	840.4
	Natural gas	2	–
	Combination	1	840.4

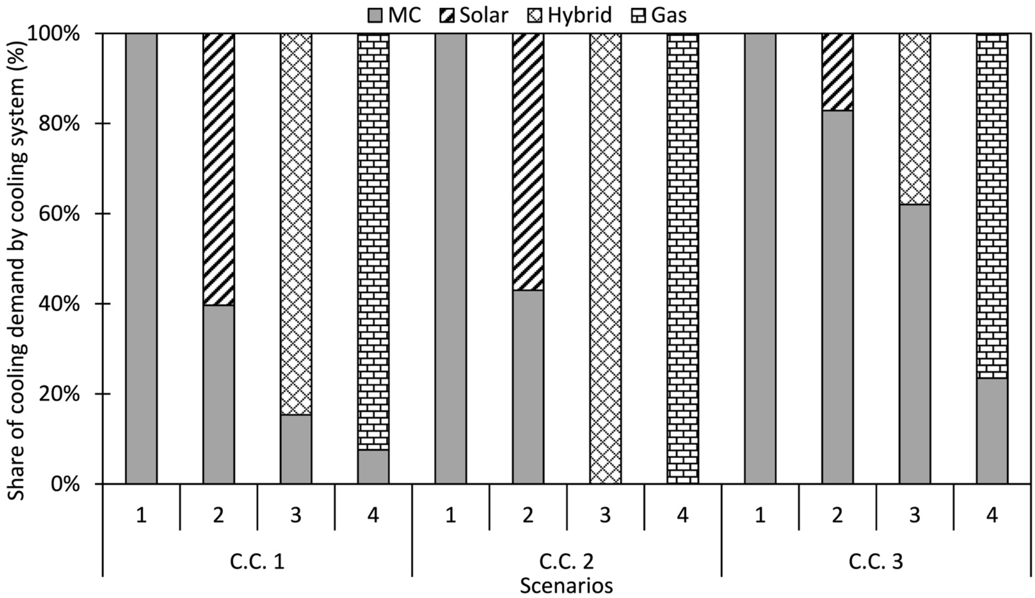

Fig. 7. Share of cooling demand supported by absorption chillers.

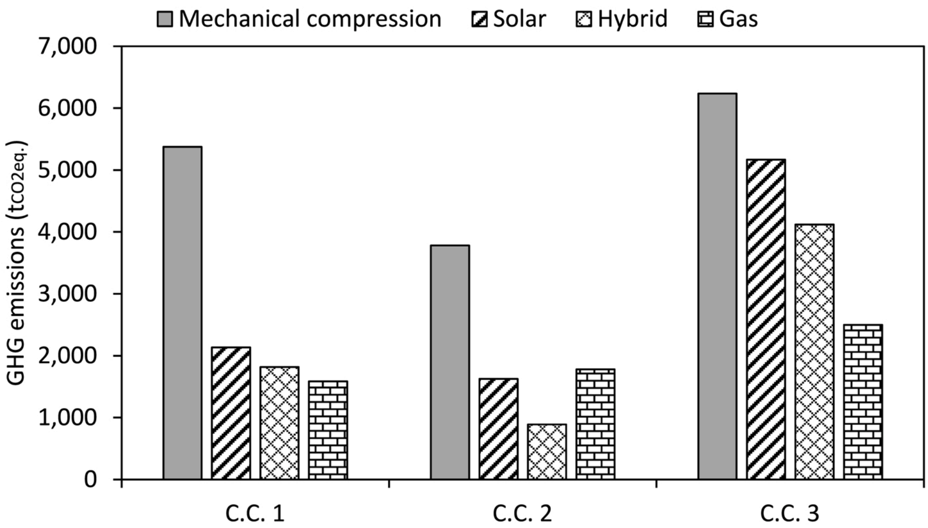

Fig. 8. Greenhouse gas emissions estimated for the cooling systems during their life cycle.

The share of the cooling demand supported by absorption or mechanical compression chillers for the scenarios considered is depicted in Fig. 7.

In general, absorption chillers can support from 57 to 100% of the cooling demand in C.C.1 and C.C.2. However, in C.C.3 it is possible to support a lower 17–76% given the area constraints for the use of ETC.

3.5. Greenhouse gas emissions

During the life cycle of the absorption chillers, the GHG emissions result mainly from the combustion of natural gas. Moreover, the use of electricity for the mechanical vapour compression cooling systems also implies the emission of GHGs.

Fig. 8 shows the greenhouse gas emissions from the mechanical compression systems electricity use and absorption chillers powered by natural gas (gas), and both solar energy and natural gas (hybrid).

In C.C.1, the use of absorption chillers activated by ETC to support a share of the cooling demand could reduce GHGs by 60%, while using a hybrid heat source to drive the chillers could reduce GHG emissions by 66% and using natural gas could reduce emissions by

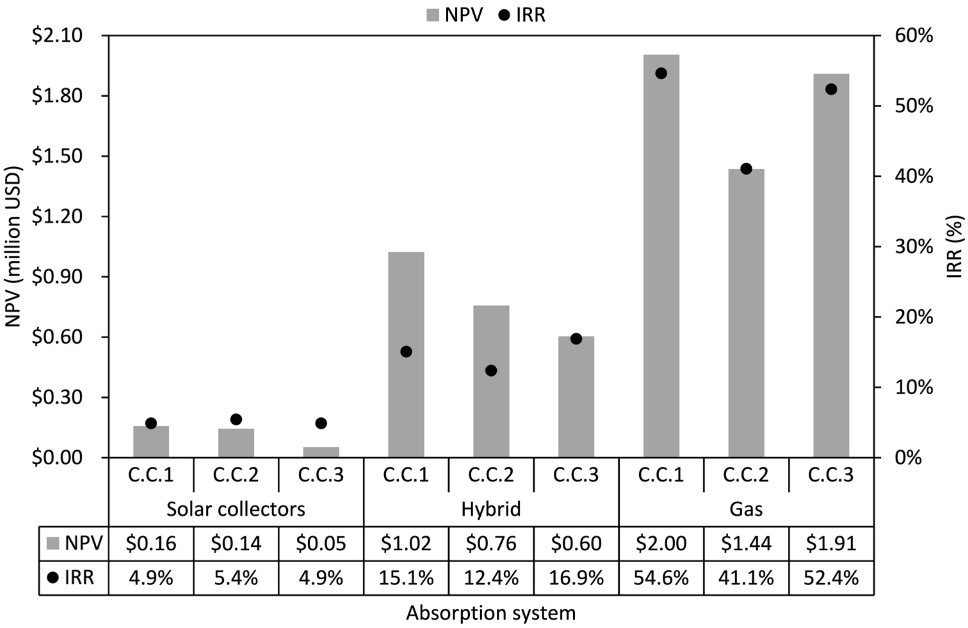

Fig. 9. Net present value and internal rate of return for scenarios 2, 3, and 4 in C.C.1, C.C.2, and C.C.3.

71%. As compared, in C.C.2 GHG emissions could be reduced by 57%, 76%, and 53% using the same systems, while in C.C.3 GHG emissions could be reduced by 17%, 34%, and 60%, respectively. The lower reduction of GHG emissions using absorption chillers in C. C.3 contrasted to C.C.1 and C.C.2, is because in C.C.3, considering the cooling demand supported by mechanical compression chillers, using absorption chillers can support from 28 to 83% of the demand supported by absorption chillers in C.C.1 and C.C.2.

3.6. Economical analysis

The net present value (NPV) and Internal rate of return (IRR) were calculated for scenarios 2, 3, and 4 considering a lifetime of 20 years. The IRR is a measure to assess the profitability of investments (i.e. the highest the IRR the more desirable is an investment) [61]. An investment is considered profitable for values of IRR > risk [62]. Fig. 9 shows the evolution of the NPV and IRR for the different scenarios in the three shopping malls.

The economic results indicated that the best scenario is the use of natural gas-driven absorption chillers with IRR varying from 40% to 54.6% depending on the mall characteristics. The solar/gas (hybrid) driven chillers accounted for IRR values from 12% to 16.9% for the studied scenarios, whereas the solar-driven chillers provided IIR values up to 5.6%.

Results show that the use of natural gas results in an NPV from 2 to 3 times higher than for hybrid systems, and 10 to 36 times higher than for solar collectors. The use of only solar collectors reduces significantly the NPV and IRR in the scenarios. In scenario 2, solar collectors account for 58% of the capital costs. Therefore, while the three scenarios can be considered profitable investments, scenarios 4 and scenario 3 are preferable to scenario 2. Particularly, the use of solar collectors requires more equipment (e.g. pumps, pipes, collectors, etc.), thus, the use of solar systems increases the financial risk of the investment in absorption chillers.

All in all, the use of natural gas looks like a very attractive investment, which can additionally provide an environmentally friendly corporate image.

4. Discussion

The implementation of absorption chillers can be promoted as one climate change mitigation strategy to meet the 20% reduction target established for 2030 [63]. However, absorption cooling systems are rather unknown by potential users as shopping malls, and in general, there is scarce information available on the maintenance and reliability of these systems. Therefore, demonstration projects at different scales could serve to provide more information and promote the wider use of absorption chillers.

The economic feasibility of absorption chillers is strongly affected by the heat source used. The use of solar collectors increases the investment costs significantly because of the high upfront costs of solar collectors, which also require large areas for their installation. Therefore, regardless of the high solar irradiation available, this alternative is not that attractive for the scenarios studied. Moreover, the use of natural gas (and when available waste heat sources) looks sounder and more attractive to drive absorption systems.

Natural gas has low costs in Colombia and is widely available, and as compared to the use of solar energy requires little area for their installation. Solar collectors require from 40 to 70% of the available area to support a share of the cooling demand, depending on solar irradiation. Furthermore, the use of solar energy to activate absorption chillers results in 1.1–1.7 higher investments contrasted to hybrid systems, and from 2.6 to 8 times as compared to natural gas systems.

The development of policies to promote the use of absorption chillers should focus on the use of natural gas and waste heat. The use of solar energy as the only energy input is not recommended to power absorption systems for air-conditioning in shopping malls in Barranquilla under current conditions.

5. Conclusions

In the present investigation, a technical, environmental, and economic study about the use of H_2O/LiBr absorption chillers driven by solar energy and/or natural gas was carried out to prove their feasibility in the Caribbean region of Colombia. A thermodynamic model was developed and validated to simulate the performance of a Thermax absorption cooling system considering the operating conditions reported by the manufacturers. The model was then used to evaluate the performance of the absorption chillers for 3 shopping malls in the city of Barranquilla.

- The results demonstrated that the absorption chiller could reach a maximum COP and SCOP of 0.77 and 0.52, respectively, at the studied conditions, whereas crystallization was not an issue.
- Absorption chillers powered by solar energy, while showing a potential to significantly reduce the emission of GHGs, are economically unfeasible, mainly because of the high upfront costs of solar collectors and limited operation at low solar irradiations. Also, the use of plate solar collectors significantly increased the costs of the solar system in comparison to the use of evacuated solar collectors. Furthermore, absorption chillers powered by solar energy under the studied conditions could reduce GHG emissions by 60% in C.C.1, 57% in C.C.2, and 17% in C.C.3 as compared to the current use of vapour compression chillers in the shopping malls assessed.
- The implementation of solar collectors is constrained by the available area for their installation in shopping malls. Moreover, the use of absorption chillers powered by a combination of natural gas and solar energy results in a significantly more attractive alternative. However, this scenario still requires large areas to install solar collectors, while could potentially reduce GHGs by 66% in C.C.1, 76% in C.C.2, and 34% in C.C.3. Furthermore, the use of absorption chillers powered by natural gas could potentially reduce GHGs by 71% in C.C.1, 53% in C.C.2, and 60% in C.C.3.
- The economic results indicated that the best scenario is the use of natural gas-driven absorption chillers with IRR varying from 40% to 54.6% depending on the mall characteristics. The solar/gas (hybrid) driven chillers accounted for IRR values from 12% to 16.9% for the studied scenarios, whereas the solar-driven chillers provided IIR values up to 5.6%. These results are strongly influenced by the costs of natural gas in Colombia.
- These results show the need to promote the exploitation of absorption chillers activated by natural gas or solar/natural gas energy in Colombia, mainly in the Caribbean region of Colombia, as an alternative to mechanical compression chillers, and as a climate change mitigation strategy.

Credit author statement

- Andrés Rodríguez Toscano: Investigation, Formal analysis, modelling, Writing - Original Draft, Visualization.
- Carlos Amaris: Methodology, Conceptualization, Investigation, Formal analysis, modelling, Writing - review & editing,
- Alexis Sagastume Gutiérrez: Conceptualization, Formal analysis, Methodology, Visualization, Writing - review & editing.
- Mahmoud Bourouis: software, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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