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Comparative energy consumption and photovoltaic economic analysis for residential buildings in Santiago de Chile and Santo Domingo of the Dominican Republic

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A B S T R A C T

This research compares the building energy consumption and the photovoltaic economic analysis between residential buildings in Santiago de Chile and Santo Domingo of the Dominican Republic. The methodology considered thermal simulation, sizing of a solar PV system, an economic analysis and CO_2 emissions given the solar resources of both countries. A scenario where the constructive systems are switched between the countries was also analyzed. A comparison of the energy performances of the houses exposed to other climate conditions. Results show that housing in Santiago de Chile required less energy than housing in Santo Domingo due to the fact that the thermal transmittance of the enclosures of the Chilean housing has better thermal behavior, compared to the materials of the Dominican housing. Dominican houses need a higher amount of electricity for air cooling due to the high temperatures in the tropic. Meanwhile, Chilean countries requires a higher amount of gas for heating purposes. The Dominican Republic lacks thermal regulation for construction material, and applying Chilean standards in Dominican houses, helped to lower the yearly electricity demand by 19%. Dominican constructions materials improvement could have an important impact in the country's overall goal to lower CO_2 emission and in-house energy savings. The economic analysis showed that the Dominican Republic renewable energies incentives contribute to the development of very attractive PV projects, meanwhile in Chile, the use of net metering instead of net billing could increase by 11 times the net present value of PV projects.

Keywords:
PV system
Thermal simulation
Energy efficiency
Energy consumption
Residential building
Economic analysis

1. Introduction

Worldwide, the energy demand of buildings represents 35% of the final energy use, from which 56% is considered for water and space heating [1]. In terms of CO_2, the building sector is currently responsible for approximately 40% of the global emissions [2], where 85% are caused by heating, cooling and lighting activities [3]. Therefore, as countries seek to reduce their CO_2 emissions per capita and at the same time maintain current comfort conditions, the use of renewable sources becomes critical [4].

The Chilean reality reinforces the global trends as the energy demand of the residential sector accounted for 15.6% of the total in 2017, the third place after industry (38.6%) and transport (36%) [5]. Also, the energy consumed by Chilean houses is mostly used for heating and cooling (53%) and generating domestic hot water (20%) [6]. In terms of CO_2 emissions, all these activities contribute to increase their production, as the used energy sources are biomass (38.9%), electricity (24.0%), liquefied gas (22.5%) and natural gas (11.8%).

In another American country, the Dominican Republic, the residential sector also demands an important amount of the total energy demand. According to its last energy balance report, the residential sector was in the third place at energy consumption with a 23.5%, after transportation (39.7%) and industry (26.0%) [7]. Its energy consumption profile differs from Chile, since its first and second consumptions are due to food cooking (68%) and space cooling (16%), respectively [8]. As the country has tropical weather, with high temperatures, its people tend to use more energy for air conditioners and fans, rather than domestic hot water.

Considering the high energy consumption of the residential sector

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Abbreviations	
AC	Alternating current
DC	Direct current
EPS	Expanded Polystyrene
ES	Electrical Split system
ETICS	External Thermal Insulation Composite System
HVAC	Heating, Ventilating and Air-Conditioning system
IRR	Internal Return Rate
LPG	Liquid Petroleum Gas
NPV	Net Present Value
PV	Photovoltaic
RE	Renewable Energy
S	Santiago de Chile
SD	Santo Domingo
tCO_{2eq}	Tons of CO_2 equivalent

implied by the heating cooling, domestic hot water and other appliances, for Chile and the Dominican Republic, the countries' high dependence on fossil fuels and the CO_2 emissions that the use of these implies, it is attractive to consider renewable energy alternatives for both cases. This statement is reinforced when taking into account the ratification of the Paris Agreement of both countries during 2017, in an attempt to decouple the economic growth of greenhouse gas emissions [9].

Among the renewable alternatives available to supply the demand of a house, this work focused on photovoltaic technology. A methodology was performed to quantify the economic impact of supplying the energy demand of a home using solar energy given the high solar resources of both countries. Specifically, the methodology was applied in the highest populated cities of both countries, which are Santiago de Chile and Santo Domingo, with a 37% [10] and 25,1% [11] of the total population, respectively. Also, it was analyzed a scenario were the constructive systems are switched between the countries. Therefore, the aim of this research is to compare the energy consumption mainly to maintain the comfort conditions and photovoltaic economic impact on residential buildings in Santiago de Chile and Santo Domingo of the Dominican Republic.

2. Methodology and materials

2.1. Study scenarios and cases

This research focuses on the energy loads analysis and comparison between a typical residential building in Santo Domingo (SD) of the Dominican Republic, and one in Santiago de Chile (S), Chile. Also, in the feasibility of using photovoltaic technology to provide its electrical demand. So, before the explanation of the tools and equations used, it is important to set the three main scenarios that were defined to perform the study:

- Scenario N°1: Base scenario. It considers the analysis of each house, with the enclosure materials used by each country, and exposed to the climate conditions of each original country.
- Scenario N°2: Swap the enclosure materials between countries. This means that energy loads of the house in Santiago de Chile will be analyzed considering Dominican sealing materials, and vice versa to the house at Santo Domingo.
- Scenario N°3: Chilean house using an electrical split system (ES) for its heating and cooling. In Chile, the tendency is to use gas heaters for heating [6], so it was of interest to see the effect of using an electrical split system, as in Santo Domingo.

In every case of each scenario, the economic analysis of the corresponding house will take into consideration the electricity billing regulation and renewable energy (RE) incentives existing in each country. Table 1 summarizes all the scenarios and case studies. In addition, it is important to highlight that Chile has been concerned about developing thermal regulations for buildings implementing them since 2006 [12]. To improve their indoor comfort and energy efficiency they have also generated complementary documents published in 2018 [13]. In the Dominican Republic there are regulations focused mainly on structural safety due to its location in vulnerable areas to earthquakes and hurricanes [14]. There are no thermal regulations or standards related to energy efficiency in buildings.

2.2. General climate conditions

The Dominican Republic is located in the Caribbean region, which falls between the northern latitude of Tropic of Cancer, within a tropical weather system. The Dominican Republic shares the island of La Hispaniola with Haiti and it occupies two-thirds of the island territory [15]. In general, in the Dominican Republic the climate changes due to the geographical conditions of the island that is influenced by the mountains. It originates two predominant types of climates: tropical rainforest climate (Af) and tropical savanna climate (Aw). The average annual minimum temperature is 21.0 °C and maximum 30.4 °C, average precipitation at 160 mm, average relative humidity 80% and average wind speed 2.22 m/s [16]. The solar potential is considered as large, with a Global Horizontal Irradiance at 5–7 $kWh/m^2/day$ throughout most of the country and in Santo Domingo (the biggest city), the average daily global horizontal irradiance is 6.4 $kWh/m^2/day$ [17]. The maximum and minimum average daily global horizontal irradiance are 7.4 $kWh/m^2/day$ and 4.9 $kWh/m^2/day$, respectively [17].

Chile is the longest country in the world with approximately 4300 km from north to south. Located in South America, it accounts with a wide variety of weather through its longitude. Santiago de Chile, its capital, is placed in −33.45° N, −70.66° W, within a basin surrounded by the Andes Mountains in the East and a coast mountain cord in the west. It accounts with a semi-arid climate, the average temperature ranges between 5 °C and 27 °C [18], an average precipitation of 320 mm concentrated during winter and a long dry season during the other three seasons [19]. It has an average relative humidity of 58.4% [20] and average wind speed of 1.87 m/s [21]. In terms of solar potential, the north of Chile accounts with the highest irradiances in the world, meanwhile Santiago de Chile accounts with a daily mean of 5.5 kWh/m^2. In winter the minimum is 3.9 $kWh/m^2/day$ and during summer the maximum has a mean of 7.2 $kWh/m^2/day$ [22]. Table 2 summarizes the general climate conditions of both countries.

2.3. House description

For this research, it was selected one dwelling type for both, Chile

Table 1
Scenarios and cases.

Scenario name	Case name	Location	Enclosure Materials	RE incentives and electricity regulation
Scenario 1	S/S/S	Santiago de Chile	Santiago de Chile	Santiago de Chile
	SD/SD/SD	Santo Domingo	Santo Domingo	Santo Domingo
Scenario 2	S/SD/S	Santiago de Chile	Santo Domingo	Santiago de Chile
	SD/S/SD	Santo Domingo	Santiago de Chile	Santo Domingo
Scenario 3	S/S-ES/S	Santiago de Chile	Santiago de Chile with ES	Santiago de Chile
	S/SD-ES/S	Santiago de Chile	Santo Domingo with ES	Santiago de Chile

Table 2
General climate conditions for Santo Domingo and Santiago.

	Santo Domingo, Dominican Republic	Santiago, Chile
Average annual minimum temperature	21.0 °C	5 °C
Average annual maximum temperature	30.4 °C	27 °C
Average precipitation	160 mm	320 mm
Average relative humidity	80%	58.4%
Average wind speed	2.22 m/s	1.87 m/s
Average daily global horizontal irradiance	6.4 kWh/m^2/day	5.5 kWh/m^2/day
Maximum average daily global horizontal irradiance	7.4 kWh/m^2/day	7.2 kWh/m^2/day
Minimum average daily global horizontal irradiance.	4.9 kWh/m^2/day	3.9 kWh/m^2/day

and the Dominican Republic, but with different constructive systems. This house complies with the minimum area (measured in m^2) as established in national standards [23,24]. The surface area for this house is 70.15 m^2 that is generally distributed in two bedrooms, a bathroom, a kitchen and a living/dining room (Fig. 1).

Regarding the orientation of the house, assuming the criterion of having maximum access to the sun during the cold periods of the year, in Chile the best decision is to do it to the north (major east-west axis). From the Dominican Republic, it was assumed the same orientation, although in this case is not so important due to the climate.

2.4. *Sample selection of constructive systems*

From the Dominican Republic - Sample 1 (S1) the constructive system is as follow: Roof 1 (R1) consist in a flat reinforced concrete slab roof (width: 12.6 cm) without insulation, a mortar exterior layer and it also has a cement and sand mortar interior layer. External Walls 1 (EW1) were made of 20 cm concrete blocks, which were filled with concrete and without insulation. These construction elements have a cement and sand mortar layer on both sides. Floor 1 (F1) consists of a concrete floor that is placed directly on the ground and it was finished with a polished cement layer. The exterior doors (D1) were made out of pine wood. The windows (W1) were made out of simple glass (thick: 3 mm) with an aluminum frame. (Table 2).

From Chile - Sample 2 (S2) the typical constructive system is composed by the following elements: Roof 2 (R2) consists of a layer of asphalt tile, moisture barrier, wood structure with glass wool, vapor barrier and gypsum board as interior finished. While External Walls 2 (EW2) were made with External Thermal Insulation Composite System (ETICS) as exterior finished, expanded polystyrene (EPS), brick as structure and a cement and sand mortar as interior finished. Floor 2 (F2) consists of a wooden floating floor as interior finished, reinforced concrete layer as structure and a polyethylene film. Exterior doors (D2) were made with pine wood. Windows (W2) consists of a simple glazing with an aluminum frame (Table 3).

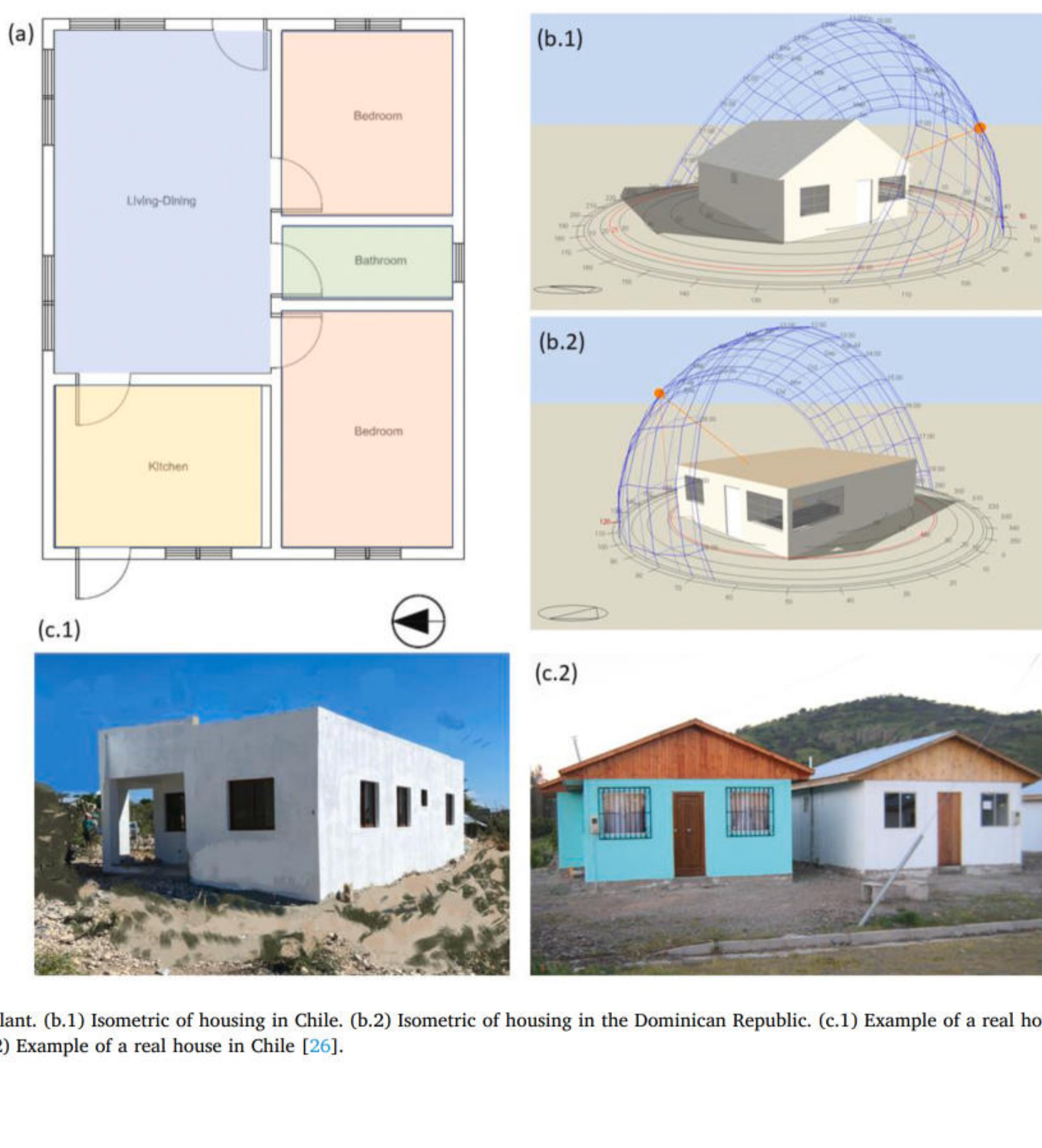

Fig. 1. (a) Floor plant. (b.1) Isometric of housing in Chile. (b.2) Isometric of housing in the Dominican Republic. (c.1) Example of a real house in the Dominican Republic [25]. (c.2) Example of a real house in Chile [26].

Table 3
Constructive systems analyzed for the Dominican Republic [27] (R: roof; EW: exterior walls; F: floor; D: door; W: window.).

		Thickness m	Material	λ Conductivity W/m-K	ρ Density Kg/m^3	Specific heat J/kgK
Sample 1 (S1) – Dominican Republic	R1		Exterior			
		0.015	Mortar	0.800	1600	1.10
		0.126	Reinforced concrete	1.400	2100	1.06
		0.015	Cement and sand mortar	0.700	1600	1.10
			Interior			
		Thermal transmittance (W/m^{2}K): 4.287				
	EW1		Exterior			
		0.015	Cement and sand mortar	0.700	1600	1.10
		0.203	Concrete block 8"	1.040	1841	1.00
		0.015	Cement and sand mortar	0.700	1600	1.10
			Interior			
		Thermal transmittance (W/m^{2}K): 1.637				
	F1	0.05	Reinforced concrete	1.630	2400	1.00
		Thermal transmittance (W/m^{2}K): 4.315				
	D1	0.025	Exterior Door – Pine wood	0.111	400	1.61
	W1	0.006	Single Glazed	1.160	2500	1.00
		0.025	Aluminum Frame	204.000	2700	0.92

Tables 2 and 3 describe the layers that comprise the roof, external walls, floor, doors and windows of the two constructive systems (S1 from the Dominican Republic and S2 from Chile). The values show for their corresponding characteristics: thickness, conductivity, density and specific heat. An important parameter to compare, it is the thermal transmittance. Chilean standards are higher, as their roof, wall and floor thermal transmittance minimums are 92%, 74% and 37% higher than Dominican, respectively. This is due to the fact that Chile has developed thermal and energy efficiency regulations for buildings [12,13], while in the Dominican Republic they still do not have standards that regulate the comfort of buildings. The effect of these differences will be measured with the energy and economic results.

2.5. *Thermal simulation*

The Design Builder v.5.0.2.3 [28] was used to carry out the simulations. The DesignBuilder software package is a well-known tool and widely used in building environmental and energetic simulations. This software package enables the performance of dynamic simulations via the Energy Plus numerical engine [29]. In this study, Design Builder was used to simulate the consumption of lighting, heating, cooling and hot water using the software's weather data of 2002. Also, the indoor temperatures and relative humidity in housing models located in the respective studied cities were obtained.

Fig. 1 (b.1) shows a Chilean housing model and Fig. 1 (b.2) shows a Dominican housing model that has a surface area of 70.15 m^2 and a height of 2.50 m. The construction systems of each house are shown in Tables 3 and 4. It was used the ASHRAE 55–2013 standard [30] to carry out the simulations. The housing model was divided into individual areas called "zones". In total, five thermal zones: (1) dining-living room, (2) kitchen, (3) bathroom, (4) bedroom 1, (5) bedroom 2 were created. These zones were configured according to the following parameters: activity, occupation, consumptions of lighting, heating, cooling and hot water, among others. The thermal zones' configurations were considered according to the literature review [6,8,11,23,27,31,32] and are shown in Table 5. The building materials and its thermal properties of each sample are described in Tables 3 and 4.

Table 4
Constructive systems analyzed for Chile [27] (R: roof; EW: exterior walls; F: floor; D: door; W: window.).

		Thickness m	Material	λ Conductivity W/m-K	ρ Density Kg/m^3	Specific heat J/kgK
Sample 2 (S2) – Chile	R2		Exterior			
		0.002	Asphalt tile	0.190	1100	1.00
		0.000005	Moisture barrier	0.320	920	2.10
		0.05	Wood structure	0.151	600	1.61
		0.1	Glass wool	0.034	80	1.03
		0.000005	Vapor barrier	0.320	920	2.10
		0.0125	Gypsum board	0.180	900	1.05
			Interior			
		Thermal transmittance (W/m^{2}K): 0.328				
	EW2		Exterior			
		0.004	External Thermal Insulation Composite System (ETICS)	0.700	1600	1.10
		0.08	Expanded polystyrene (EPS)	0.047	10	1.20
		0.14	Brick	0.560	1200	1.00
		0.02	Cement and sand mortar	0.700	1600	1.10
			Interior			
		Thermal transmittance (W/m^{2}K): 0.421				
	F2		Interior			
		0.0012	Wooden floating floor	0.090	400	1.70
		0.15	Reinforced concrete	1.630	2400	1.00
		0.001	Polyethylene film	0.320	920	2.10
			Ground			
		Thermal transmittance (W/m^{2}K): 2.722				
	D2	0.025	Exterior Door – Pine wood	0.111	420	1.29
	W2	0.006	Simple Glazing	1.16	2580	0.84
		0.025	Aluminum Frame	204.000	2700	0.92

Table 5
Model configuration.

XZone properties	Santiago de Chile	Santo Domingo
Standard	ASHRAE 55-2013	ASHRAE 55-2013
Zone	3C	1A
Activity	Residential	Residential
Surface	70.15 m^2	70.15 m^2
Occupation	3 people	3 people
Occupational Density	0.043 person/m^2	0.043 person/m^2
Occupation Programming	18:30 to 7:30	18:00 to 7:30
Winter Clothing	1.5 clo	1.5 clo
Summer Clothing	1.0 clo	1.0 clo
Lighting		
Type of Lighting	Fluorescent	Fluorescent
Power Density	5 W/m^2-100 lux	5 W/m^2-100 lux
Minimum Illuminance Level	300 lux	300 lux
HVAC		
Mechanical Ventilation	Minimum outside air (per area)	Minimum outside air (per area)
Heating Fuel	Liquid Petroleum Gas (LPG)	–
Cooling Fuel	Electricity	Electricity
Hot Water Fuel	Liquid Petroleum Gas (LPG)	Electric

2.6. Sizing of solar PV system

Both countries have a high amount of solar radiation, therefore it is interesting to dimension a photovoltaic (PV) system to provide the required demand of electricity of the house for the sunniest day of the year. The model from National Renewable Energies Laboratory (NREL), PVWatts [33], was used for dimensioning the PV system. This model calculates the electric energy generation of a system depending on its size and power. It uses the meteorological variables: radiation, wind speed and ambient temperature. The model starts calculating the temperatures associated to a cell and panel analyzed (equation (1).

$$T_c = T_p + I_{poa}/1000 \cdot \Delta T \quad (1)$$

Where, T_c, T_p, T, and I_{poa} represent the cell temperature (C°), panel temperature (C°), Ambient temperature (C°) and Solar irradiance (W/m^2), respectively. ΔT was considered 3 in this work, using as reference [34]. I_{poa} was obtained from Retscreen [35] and Explorador Solar [22] for Santo Domingo and Santiago de Chile, respectively. The panel temperature was calculated with equation (2).

$$T_p = I_{poa} \cdot e^{a+b \cdot V} \quad (2)$$

Where, V represents the wind speed (m/s). This parameter was obtained from a historic data book of Meteored [21] for both countries. a and b are constants with the values −3.47 and −0.0594, respectively [34]. These coefficients, including the previous ΔT, are for an open rack cell glassback case. This is a form of installing the panels on a structure over the roof when it is needed a different orientation or angle in comparison to the roof of the building. Therefore, the back of the panel is not directly fixed to the roof. On the contrary, in the roof the panel must be mounted in a base in order to fix it in the require angle and orientation.

The model also depends on the capacity of the solar PV system, which was calculated as equation (3):

$$P_{DC0} = A_{panel} \cdot N \cdot \varepsilon_{nom} \cdot 1 \left[kW / m^2 \right] \quad (3)$$

Where P_{DC0}, A_{panel}, N, and ε_{nom} represent the power in direct current, the area of the solar panel, the number of solar panels of the system, and the nominal efficiency of the solar panel, respectively. In this study P_{DC0} was equal to 275 [Wp], a A_{panel} of 1.6 m^2, and ε_{nom} of 16.8% [34]. N was varied from 1 to 40. N is limited to 40 as is the maximum area that the roof of the house can hold. Then, the output power of the solar plant for irradiance greater than 125 W/m^2 was calculated using equation (4).

$$P_{DC} = I_{poa} / I_0 \cdot P_{DC0} \cdot (1 + \gamma (T_c - T_0)) \quad (4)$$

Where T_0 and I_0 are the temperatures and irradiance used as reference for the solar panel. In this case, $T_0 = 25$ (C°) and $I_0 = 1000$ (W/m^2). To calculate the output of energy, it is needed to transform the direct current (DC) to alternating current (AC) because it must be injected to the system. A loss of energy exists during the transformation depending on the efficiency of the electrical inverter. To calculate the real efficiency of the inverter the following equation was used (5):

$$\eta = \eta_{nom} / 0.9637 \cdot (-0.0162 \cdot P_{DC} / P_{DC0} - 0.0059 \cdot P_{DC0} / P_{DC} + 0.9858) \quad (5)$$

Where, η_{nom} is the nominal efficiency of the electric inverter. A value of 96% was used. With the real efficiency was calculated the AC generated with equation (6)

$$P_{AC} = \begin{cases} \eta \cdot P_{DC} & \text{if } P_{DC} < P_{DC0} \\ \eta_{nom} \cdot P_{DC} & \text{if } P_{DC} \geq P_{DC0} \end{cases} \quad (6)$$

There is also a capacity limit of the inverter, it is defined as the system capacity divided by an DC_AC_ratio, which is equal to 1,1.

$$P_{AC} > P_{DC}/DC\_AC\_ratio \quad \Rightarrow P_{AC} = P_{DC}/DC\_AC\_ratio \quad (7)$$

There is also a loss factor to make more real the model and it's calculated based on different factors. See equation (8).

$$TL = 100 \cdot \left(1 - \prod_{i=1}^{n} (1 - Li / 100) \right) \quad (8)$$

Where Li correspond to the different factors of losses and TL are the total losses. The Li factors are mentioned in Ref. [34], and the final TL used is 13.8%. And to obtain the power output with the corrections was used:

$$P_{AC} = P_{AC} \cdot (1 - TL / 100) \quad (9)$$

In order to calculate the total energy produced, it is needed the power of the system in alternating current (P_{AC}) and calculate the energy produced based on the hours of sun from each month:

$$Energy\ produced = P_{AC} \cdot \#Sun\ hours\ within\ a\ month \quad (10)$$

Finally, it is obtained the energy produced in kWh for each month with the PV system. This energy is highly dependent on the capacity or size of the solar plant (P_{DC0}), as well as the available solar radiation.

2.7. Economic analysis

The Net Present Value (NPV) approach was used on each residential building to perform an economic analysis of using a PV system to match the energy demand. Equation (11) was used to calculate it.

$$NPV = \sum_{t=1}^{n} R_t \Big/ (1+i)^t \quad (11)$$

Where R_t, i and t represent the net cash flow in a single period, the discount rate of return and the number of periods, respectively. In all scenarios, the discount rate and the number of periods used are 10% and 20 years, respectively. Each R_t considered the yearly amount paid to the electricity company after deducting the energy produced by the PV system. The electricity bill calculation is different in both countries. In Santiago de Chile, the company charges a fixed fee of 0.9 USD, and then 0.14 USD/kWh when the total monthly consumption is lower than the 230 kWh. If the house required more electricity, all the kWh above the 230 are charged 0.2 USD/kWh [36]. In the case of Santo Domingo, the electricity company charges a fixed fee of 0.72 or 2.59 USD if the monthly consumption is equal or lower to 100 kWh and higher to 100 kWh, respectively. The consumed energy is charged by section according to Table 6. For example, is a house used 400 kWh, the first 200 kWh are charged 0.084 USD/kWh, then the following 100 are charged with 0.132 USD/kWh and the final 100 with 0.205 USD/kWh [37].

The investment of the PV system is considered in R_1. In Chile, the cost of the installed photovoltaic system connected to the grid is 2141 USD/kW and 1913 USD/kW, when the size of the project is smaller than 5 kWp and between 5 and 10 kWp, respectively [38]. In the Dominican Republic, the price of the installed photovoltaic system connected to the grid is 1400 USD/kW according to Ref. [39]. It was considered that each PV project was financed through a personal bank loan in both countries.

Renewable energies incentives for each country were also considered in the analysis. These are classified as: a) Contributions to the capital cost of the project; b) those that act on the energy produced by the technology (project cash flows). The incentives considered for each country are summarized in Table 7.

2.8. CO_2 emissions

The environmental effect of using PV technology instead of grid electricity will be measured by the number of displaced tons of CO_2 equivalent (tCO_{2eq}). According to each country's governmental information, the emission factor of each energy matrix corresponds to 0.42 [44] and 0.37 [45] tCO_{2eq}/MWh for Chile and the Dominican Republic, respectively. Then, for each studied scenario, the total electricity consumed from the solar panels is the total electricity that stops being used from the grid. These totals are multiplied by the corresponding tCO_{2eq} emission factor in order to obtain the total displaced tCO_{2eq}.

3. Results and discussions

3.1. Thermal simulation

3.1.1. Total energy consumption

This section shows the results of the simulations of the four different scenarios: Chilean household with Chilean enclosures, Chilean household with Dominican enclosures, Dominican household with Chilean enclosures and Dominican household with Dominican enclosures.

In Fig. 2 can be seen a summary graph of energy consumption over a year for different housing systems. As can be seen, air-conditioning/heating consumption varies considerably depending on the types of enclosures used. The important proportion of energy consumption for heating water is also highlighted.

In general terms, housing in Santiago de Chile needs less energy than housing in Santo Domingo. In the base case scenarios, Santiago de Chile housing with Chilean enclosures and Santo Domingo housing with Dominican enclosures, the first one has a consumption of 7231 kWh per year, while the second one is 12703 kWh per year, a 76.7% higher. In these scenarios, similar consumption profile and same room occupancy were used for the simulation. Also, the consumption of the refrigerator is not considered. Table 8 shows the detailed consumption per type for both countries in the base case scenario. The type of energy source used can explain the considerable energy consumption difference between countries. SD uses mainly electricity as energy source. In Santiago the tendency is to use gas for heating and hot water production and electricity for cooling, appliances and lighting.

The greatest difference in these consumptions is determined by the cost of energy for air conditioning and/or heating, which is analyzed in detail below.

Table 6
Electricity fee by section in Santo Domingo [37].

Consumption scale	Price (USD/kWh)
0-200 kWh	0.084
201-300 kWh	0.132
301-700 kWh	0.205
>701 kWh	0.209

Table 7
Energy incentives per country.

Country	a) Capital cost incentive	b) Energy production incentive
Chile	• None	• **Net billing**, also known as Distributed Generation Law No. 20,571. Allows both, natural persons, small and medium enterprises with photovoltaic projects of less than 300 kWp, to inject their surpluses of electric generation into the grid (Law No. 21,118). The recovery mechanism will value the solar production at the node price (that is the selling price from generators to distributors), and discount it from the electricity bill each month. This price is about 50% of the buying tariff paid by end customers [40]. Each November, if the sum of energy surpluses is greater than the annual energy consumption of the client, the client will be paid in money for their contribution to the grid.
Dominican Republic	• No import taxes for the equipment. This reduces the price of the whole project and benefits only its users. • Tax reduction from 10% to 5% for projects financed with foreign credits • Return of 40% of the project investment in the next 3 years through the rent tax. Each year is returned a third of the 40% of the total investment.	• **Net Metering,** According to law 57-07 [41,42]. This works making a balance in kWh between the produced and used electricity. If the production is higher than the consumption, the difference is kept for the other month like a credit in kWh. This balance is made monthly. If the balance is positive at the end of the year, the electric distributor pays the client for the surplus at the 75% of the regular rate (first rate BTS1 for the specific time of the year). The law stipulates that electric companies must pay for the surplus one time a year and it cannot be greater than 50% of the energy produced by the PV system. The photovoltaic projects don't have a power limit and everyone is allowed to invest in a PV project. The law considers self-producers to all the plants with installed power lower than 1.5 MW and it must be of an only owner, also the 50% of the energy produced must be self-consumed [43].

3.1.2. Consumption per city

Concerning to energy consumption in Chilean households with its materials, total consumption for air conditioning is 996 kWh in the simulated year, where 971 kWh corresponds to heating and 25 kWh to cooling. On the other hand, regarding Chilean households with Dominican materials, the consumption for heating is 1591 kWh per year, while the cooling system does not work (Fig. 3). The increase in consumption represents approximately 160% of the base scenario.

This is because the thermal transmittance of the enclosures of the Chilean housing (Roof: 0.32 W/m^{2}K, Facades: 0.42 W/m^{2}K) have better thermal behavior, compared to the materials of the Dominican housing (Roof: 4.28 W/m^{2}K, Facades: 1.63 W/m^{2}K).

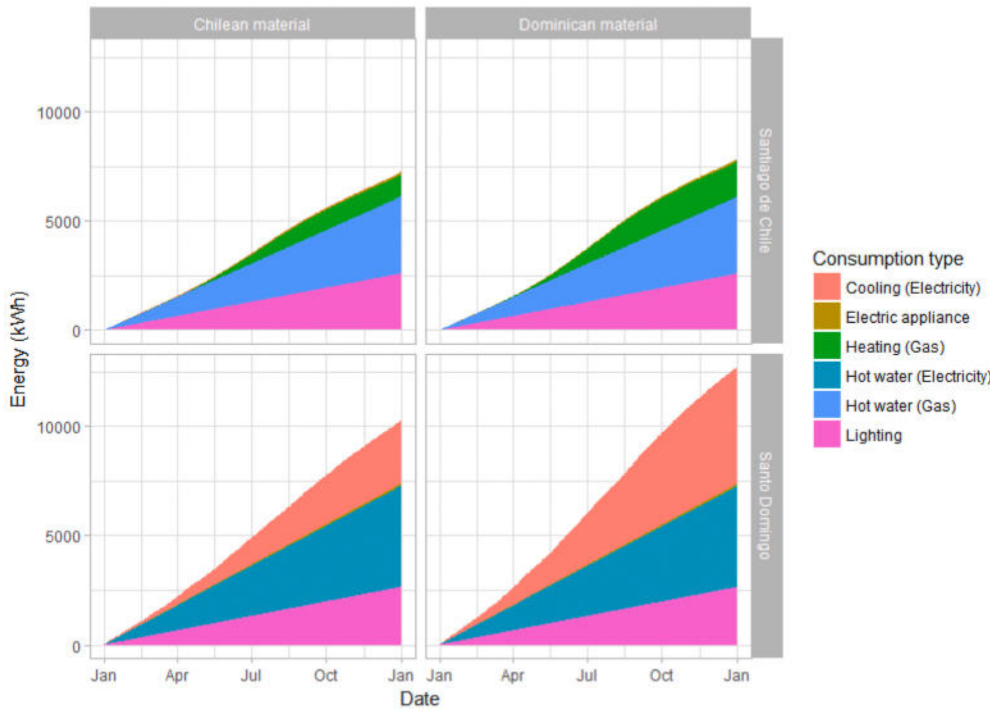

Fig. 2. Total energy consumption per country and construction systems.

Table 8
Detailed energy consumption per type at each base case scenario.

	Santiago de Chile	Santo Domingo
Cooling[a] (kWh)	24.9	5334
Electric appliance (kWh)	106	106
Heating (kWh)[b]	971	0.1
Hot water (kWh)[c]	3534	4611
Lighting (kWh)	2595	2643
Total (kWh)	7230.9	12694.1

[a] The energy source is electricity for both countries.
[b] In Santiago gas is uses as energy source for heating, meanwhile in Santo Domingo almost no heating is used.
[c] The energy source for hot water in Santiago is mainly gas, meanwhile electricity is used in Santo Domingo.

The air conditioning consumption in this scenario is remarkable when Chilean material is used, but not when the material is Dominican (Fig. 3, in red). A careful look at the consumption profile and temperatures shows that, even in summer, the night temperatures in Santiago de Chile are lower. Given that the main energy demand is at night and the Dominican enclosure has a lower thermal mass, the house tends to passively lower its temperature without the need for air conditioning. For the enclosure with a Chilean construction system, the temperature inside does not drop enough, needing energy for air conditioning.

This behavior suggests that the enclosures made with the Dominican construction system can be effective in certain climates, similar to the summer of Santiago de Chile and under similar residential consumption profiles.

Fig. 4 shows that in relation to Dominican household with its traditional construction system, energy consumption for air conditioning is 5534 kWh per year. While, in the case of the use of Chilean enclosures, the consumption is 2860 kWh, a reduction of approximately half of the consumption (48%).

Once again it is evident that this behavior is due to the thermal conductivity of the materials, presenting the Chilean enclosures a better thermal behavior, concerning the Dominican construction system.

3.1.3. Temperature

3.1.3.1. Scenario N°1: base scenario. In Figs. 5 and 6, the base case scenarios are shown. In Scenario No.1 (Fig. 5), the outdoor and indoor temperatures are represented by teal and a red line respectively for Santo Domingo. Regarding this data, the maximum outdoor temperature reached 34.1 °C, the minimum is 18.7 °C and the average is 26.3 °C. The indoor temperature is 29.7 °C, 20.5 °C and 23.9 °C for maximum, minimum and average, respectively.

Santiago de Chile can be seen in Scenario No.1 (Fig. 6), with a wide range of temperature values, from a maximum outdoor temperature of 33.2 °C to a minimum of −5.95 °C. The average outdoor temperature is 14.4 °C. For indoor temperatures, there is a maximum of 24.5 °C, a minimum of 16.1 °C and the average is 20.1 °C.

It should be clarified that the indoor temperatures for both cases (Scenario No1: Bases Scenario) are considering a residential consumption profile, from 6 p.m. to 7 a.m. during weekdays and all day on Saturday and Sunday.

3.1.3.2. Scenario N°2: Swap the enclosure materials between countries. In Fig. 7, it can be seen the indoor temperature behavior for a household in Santo Domingo built with Chilean materials and Dominican materials, represented by a blue line and a red line respectively. As the figure shows, there is a difference between indoor temperatures, which has an average of 0.5 °C. With the Chilean material, the indoor temperature is lower and steady (closer to the indoor temperature setpoint), and the temperature values are achieved with less energy consumption.

Fig. 8 shows a similar behavior but for a household in Santiago de Chile. Two simulations were carried out with Chilean materials and Dominican materials, represented by a red line and a blue line, respectively. The difference between the average temperatures is 0.9 °C. The use of Chilean materials shows a better behavior, maintaining the temperature steady within the comfort range and consuming less energy.

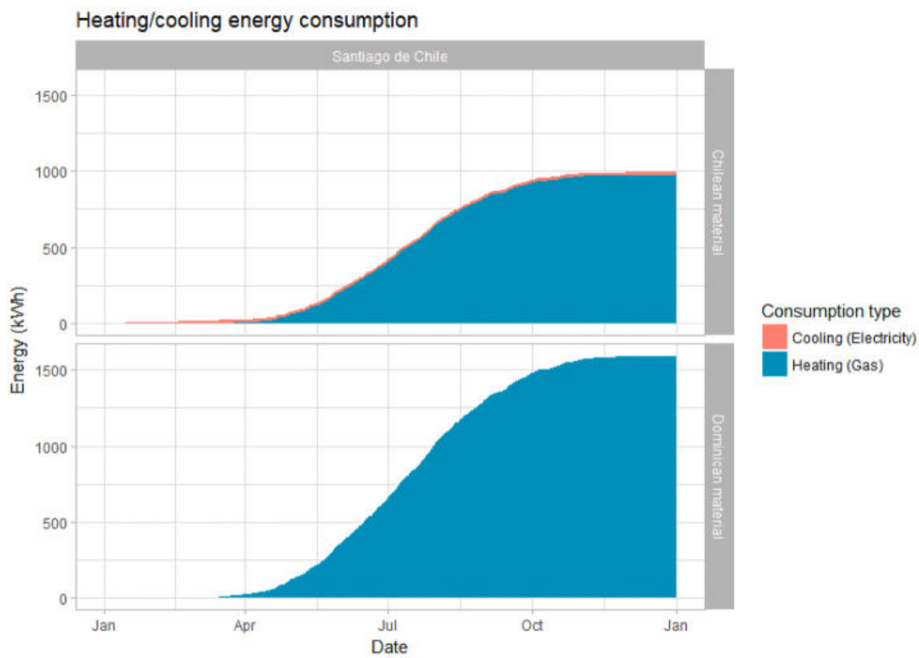

Fig. 3. Energy consumption for air-conditioning/heating system in a Chilean household. In this comparison, two different building materials have been shown. Scenario 1 - Scenario 2.

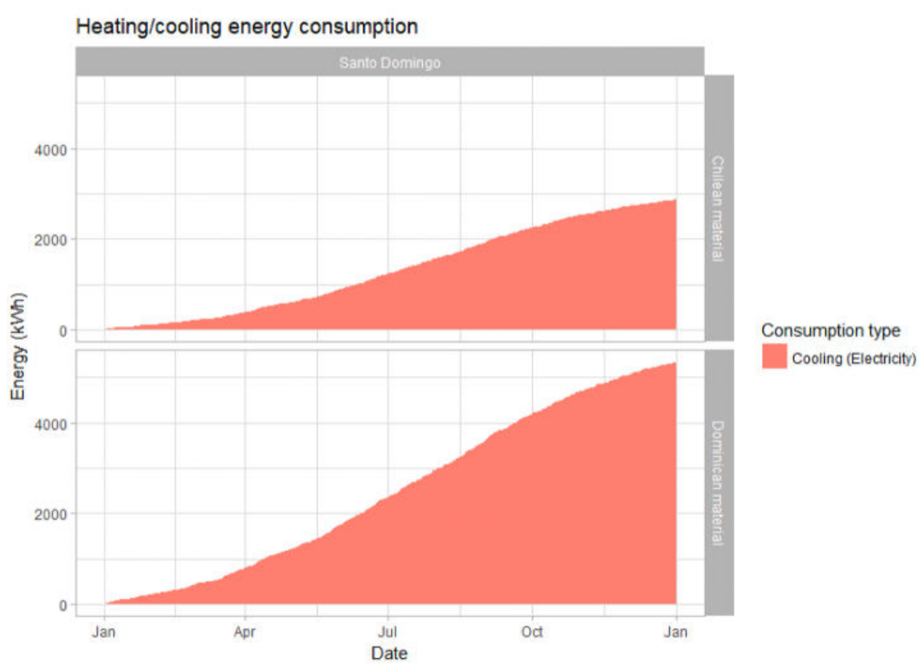

Fig. 4. Energy consumption for air-conditioning/heating system in a Dominican household. In this comparison, two different building materials have been shown. Scenario 1 - Scenario 2.

3.2. PV dimensioning results

Fig. 9 shows the results of the PV dimensioning for each scenario. In each figure, the horizontal lines represent the yearly electrical consumption of each residential building analyzed. The diagonal line shows the electrical production MWh/year per quantity of PV panels. The intersection of the horizontal with the diagonal lines represents the minimum number of panels required to be installed on each house to provide the annual electrical demand. As can be seen, the MWh produced by the panels is rather similar for both countries, nevertheless, the annual electricity demand differs. In scenario 1 (Fig. 9 (a)), Santo Domingo electricity demand is 4.6 times higher than the one from Santiago de Chile (as seen in previous sections), therefore a higher number of PV panels is required (30) than Santiago de Chile (7) to match their electricity demand.

In scenario 2 (Fig. 9 (b)), the annual electricity demand at Santo Domingo accounts with a considerable reduction of 19% in comparison to scenario 1. Also, the minimum amount of PV panels lowers down to 24. This is the effect of considering the Chilean construction standards, which are stricter in terms of insulation level, as mentioned in previous sections. In the case of Santiago de Chile, a house built with Dominican typical construction materials consumes almost the same amount of

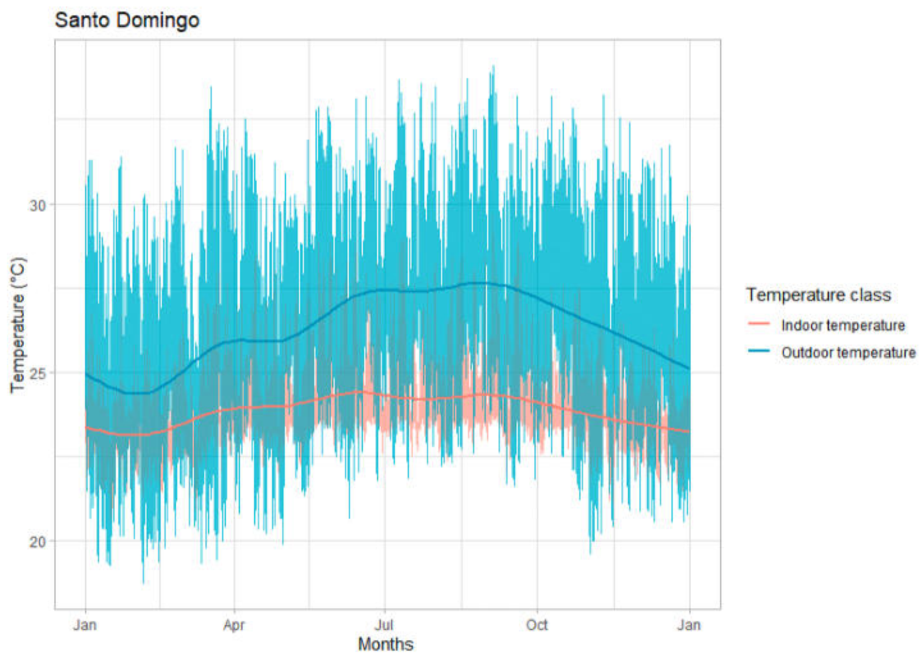

Fig. 5. Temperatures Scenario No1: Base Scenario. The red lines show the indoor temperature and teal lines show the outdoor temperature for Santo Domingo, (Dominican scenario).

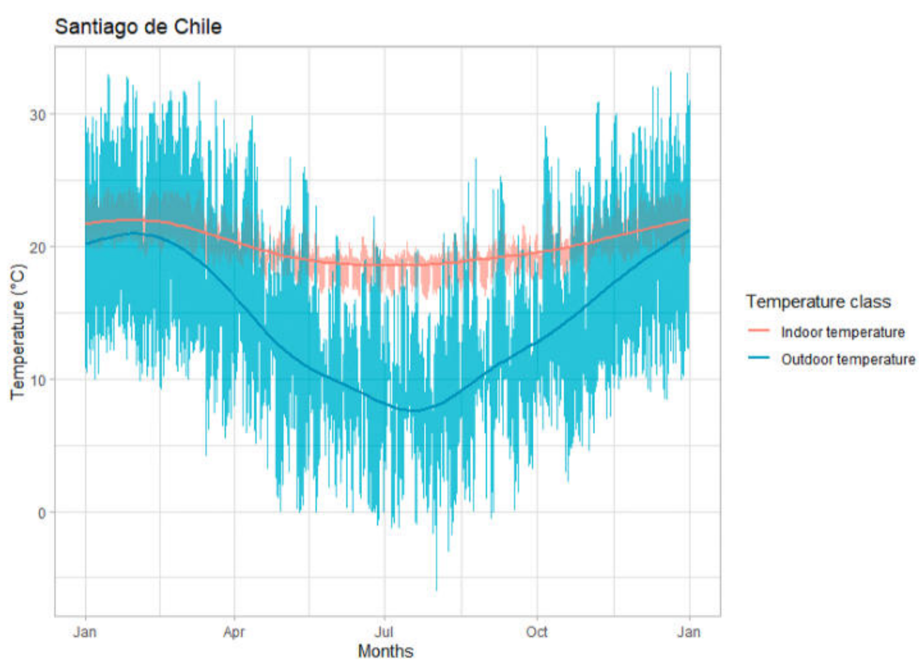

Fig. 6. Temperatures Scenario No2: Base Scenario. The red lines show the indoor temperature and teal lines show the outdoor temperature for Santiago de Chile, (Chilean scenario).

electricity in comparison to scenario 1. This can be attributed to the fact that the electricity is mainly used for appliances and lighting within Chilean houses. The effect of using lower insulating materials is visible in the increase consumption of gas for heating uses, as mentioned in section (3.1).

Scenario 3 (Fig. 9 (c)) compared the effect of heating the Chilean residential building with electricity using a split system. In comparison with the Chilean base case scenario 1, the total consumed electricity increased by 44.5% when using Chilean insulation standards. It increased by 71.7% when considering Dominican sealing. Hence, the minimum quantity of PV panels increased from 7 to 10 and 11, when using Chilean and Dominican sealings, respectively.

Fig. 10 displays the economic results. In each of these figures the left axis has the NPV values in thousands of USD, depending on the quantity of PV panels considered. The right axis values in MWh the total energy that needs to be bought to the electrical company (Comp.) of each country. For scenario 1, Fig. 10 (a), there is a huge difference between Santiago de Chile and Santo Domingo. Meanwhile, in Santiago de Chile the only chance to have a positive NPV is with 1 panel, in Santo Domingo the NPV is only limited due to the roof dimensions. The best NPV for Santiago de Chile is 31 USD, with a payback of 9 years and an internal return rate (IRR) of 11%. The best NPV in Santo Domingo is 14,636 USD,

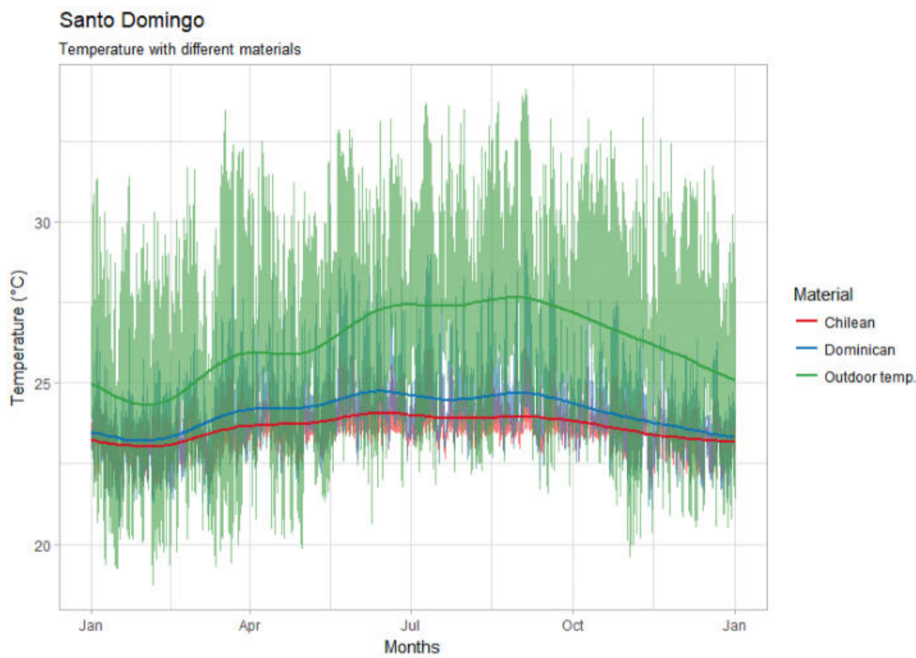

Fig. 7. Temperatures Scenario for Santo Domingo, the Dominican Republic, using different materials. The red line shows the indoor temperature when Chilean materials are used. The blue line refers to the indoor temperature when Dominican materials are used. The outdoor temperatures are shown in green.

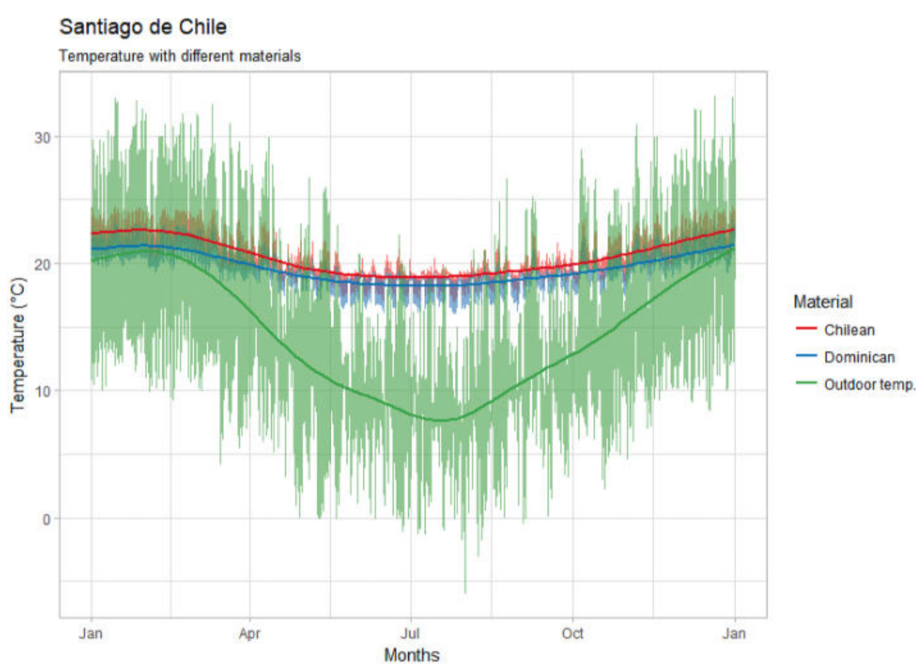

Fig. 8. Temperatures Scenario for Santiago de Chile, using different materials. The red line shows the indoor temperature when Chilean materials are used. The blue line refers to the indoor temperature when Dominican materials are used. The outdoor temperatures are shown in green.

with a payback of 3 years and an IRR of 32%. Another difference is that in Santo Domingo, the residential building can become independent since a minimum of 30 panels installed. On the contrary, Chilean houses will always depend on the electric company because the major energy demand is within hours with less or no solar radiation.

In scenario 2, Fig. 10 (b), the Chilean NPV is even lower when considering Dominican standards, being the best NPV 16.5 USD. The effect of better insulation standards decreases the NPV of the project at Santo Domingo, nevertheless, it still is an attractive project. The best NPV is 11,222 USD (23% lower than best NPV at SD/SD/SD), with a payback of 4 years and IRR of 27%. Also, independency is obtained since panel # 24 due to a reduction in electricity demand.

In scenario 3, Fig. 10 (c), a Chilean house with Chilean insulation standards and heating with electricity still can have a positive NPV, 121 USD, with no more than 1 PV panel. On the contrary, when considering Santo Domingo insulation standards, it does not have a chance to account with a positive NPV. Also, there is no chance to become independent from the electric company because of the net billing.

In Fig. 10 (d), it is shown the differences in the NPV of the Chilean case when considering a net metering regimen. Due to net metering, it is possible to have electrical independence since 10 panels. The best NPV, 347 USD, it is obtained with 6 panels and it is 11 times better than the

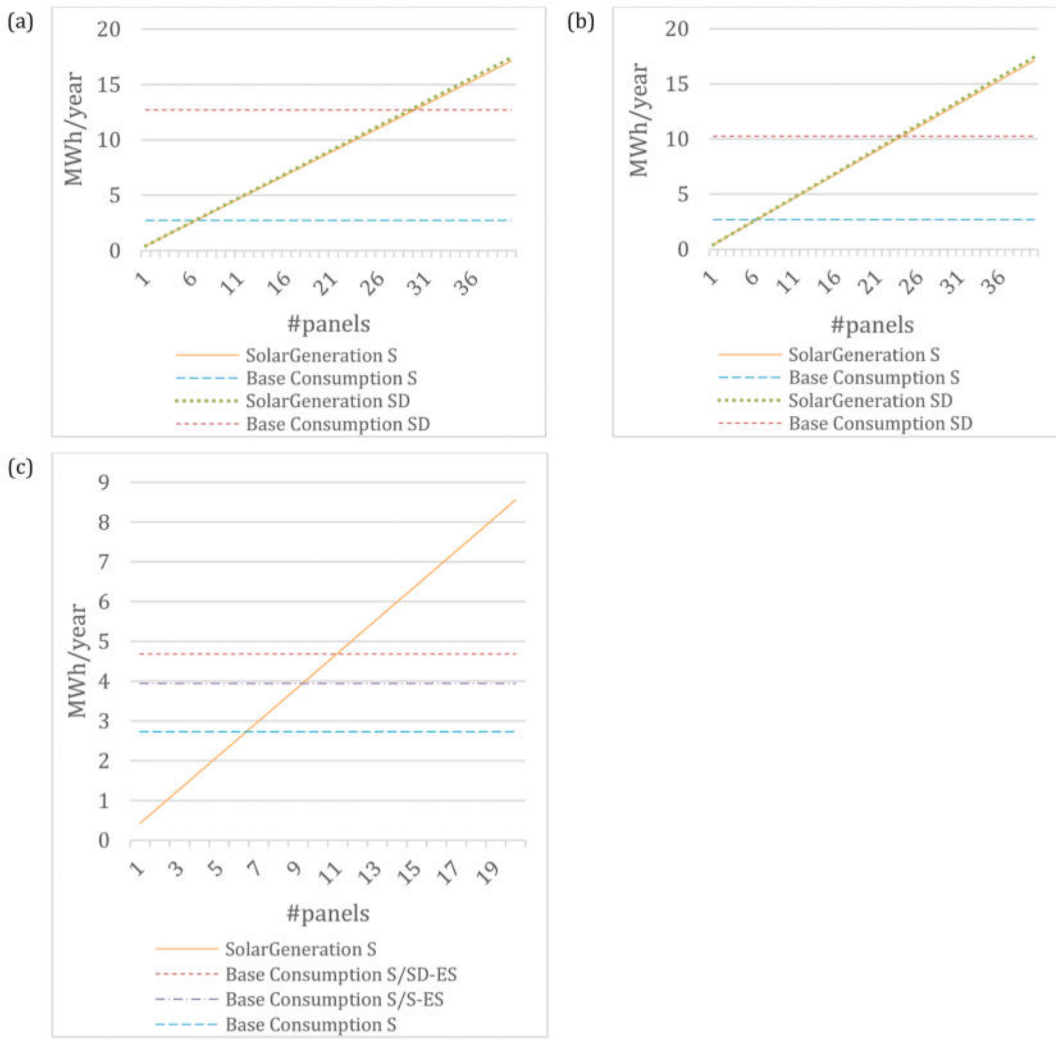

Fig. 9. (a) PV Dimensioning results from Scenario 1. (b) PV Dimensioning results from Scenario 2. (c) Dimensioning results from Scenario 3.

best NPV with net billing, 31 USD. Also, a project with 6 panels accounts for a payback and internal return rate of 8 years and 12%, respectively.

3.3. *Tons of CO_{2eq} analysis*

The chance to decrease the amount of tCO_{2eq}/year produced by a residential building is one of the advantages of using PV technologies in houses, as shown in Fig. 11. In the Chilean house, Fig. 11 (a), a net metering scenario (CO2 S/S/NM) allows to reduce up to 6 times the tCO_{2eq} emissions in comparison to the base case (CO2 S/S/S) and electric air-conditioning case (CO2 S/S-ES/S). In Santo Domingo, Fig. 11 (b), the base case (CO2 SD/SD/SD) allows to remove higher amount of tCO_{2eq} than the case with Chilean insulation standards (CO2 SD/S/SD). However, in Santo Domingo the case with lower savings of tCO_{2eq} represents a more environmentally friendly option, as it represents a scenario with better management of energy resources.

4. Conclusions

This research compared the house's energy demand realities of two American countries: The Dominican Republic and Chile. The performed analysis allowed the following conclusions.

- Dominican houses demand a considerable amount of 12,703 kWh of electricity per year, where 42% goes to air cooling to maintain comfort conditions due to the high temperatures in the tropic. Meanwhile, Chilean central countries demand 2731 kWh per year, 76% lower than Dominican houses.
- Depending on the material, the thermal transmittance of Chilean construction materials are between 37% and 92% stricter than Dominican typical construction materials. Applying Chilean thermal transmittance regulations for construction materials in Dominican houses, could help to lower the yearly electricity demand by 19%. Then, a Dominican insulation construction improvement could have an important impact on their goal to lower CO_2 emission and in-house economies.
- Dominican incentives for PV technologies are very attractive, as they help PV projects to have positive and high NPV in comparison to Chile, only limited by the roof space. On the contrary, PV projects in Chile could be more attractive if using net metering instead of net billing, at least 11 times in the case analyzed in this work. If the country wants to increase PV installations on houses, and lower CO_2 emissions, it would be interesting to check this instrument.
- In terms of tCO_{2eq}, as the energy matrix of both countries are fossil fuel dependent, the usage of PV technologies on houses roof could contribute to decarbonize these countries' grid. The residential house at Santo Domingo could yearly evade to produce up to 4.66 tCO_{2eq}. In Santiago de Chile, the best NPV scenario for the base case could help the house evade 0.16 tCO_{2eq}, meanwhile, it could evade 1.14 tCO_{2eq} if a net metering regimen existed.

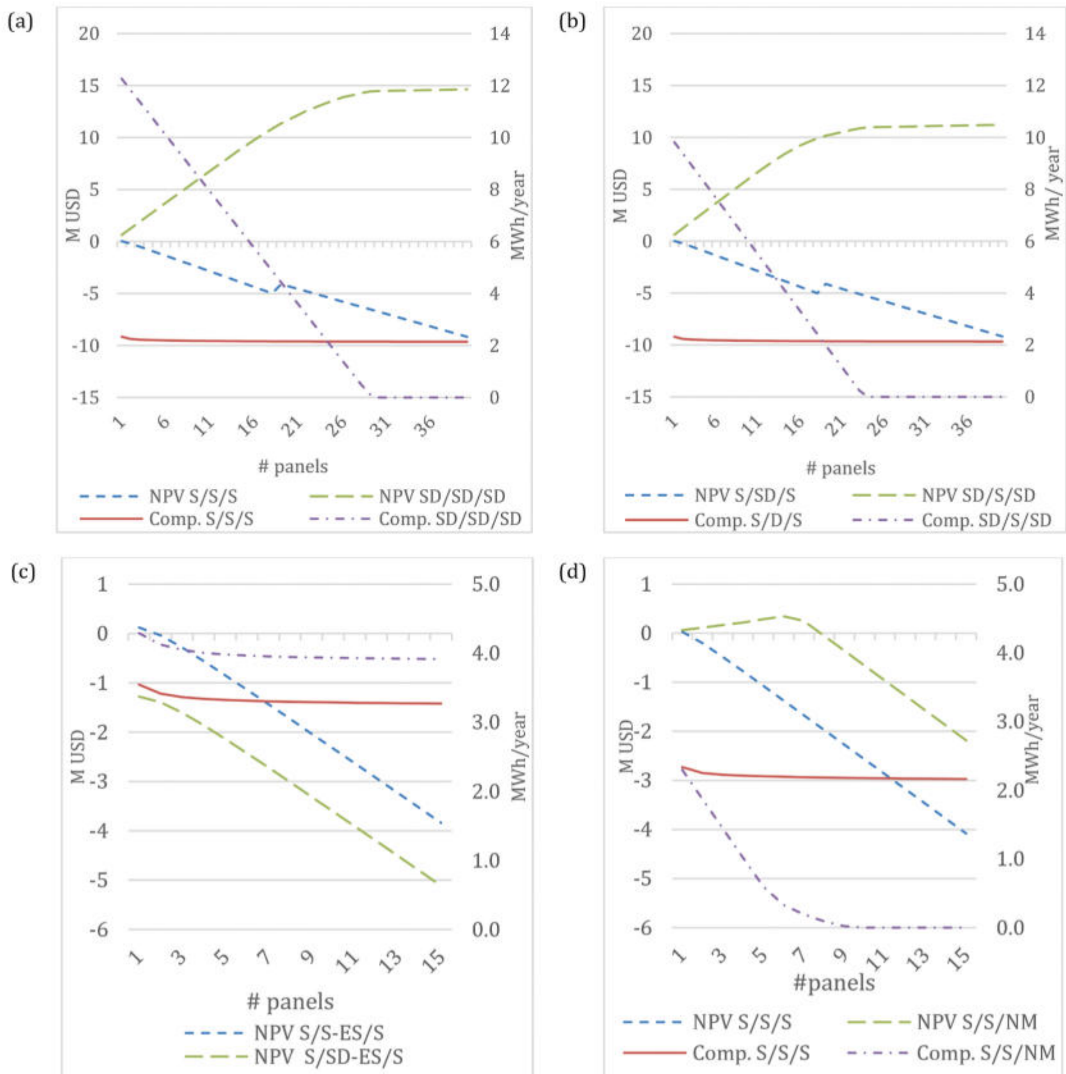

Fig. 10. (a)Economic results Scenario 1. (b)Economic results Scenario 2. (c)Economic results Scenario 3. (d)Economic results, Net Billing v/s net metering.

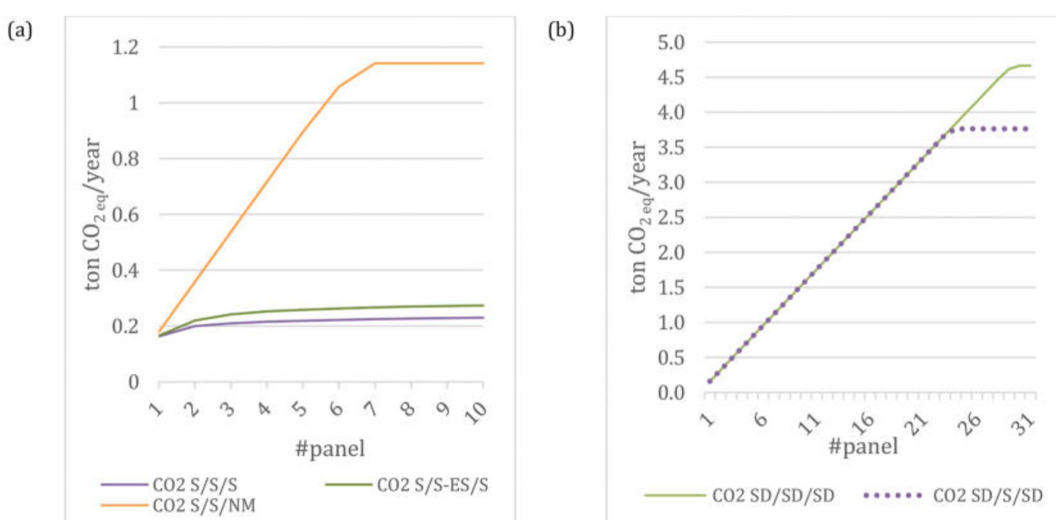

Fig. 11. (a) tCO_{2eq} comparison for Chilean scenarios. (b) tCO_{2eq} comparison for Dominican scenarios.

Credit author statement

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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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