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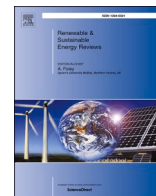
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# Renewable and Sustainable Energy Reviews

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## Strategies toward an effective and sustainable energy transition for Cuba

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### ABSTRACT

This study evaluated the possibilities of energy transition in Cuba 2030. Cuba is currently in a vulnerable energy situation since it strongly depends on the importation of fossil energy. Strategies based on intermittent RES (solar and wind) can reduce this vulnerability, but the introduction of this type of source impacts the energy system's characteristics and aspects at a country/regional scale. Most of the studies about energy transition strategies focus on the evaluation of a few specific arbitrary scenarios or the classic economic optimization approach. This research relies on existing methods to evaluate energy scenarios. However, some aspects of our approach are original: differently to the comparison of arbitrary scenarios we evaluate a fairly large number of scenarios, and differently to the classic optimization we consider many different indicators (e.g., energy security, carbon footprint, air quality, and economic). This allows the description of the trends of the changes in the energy system and the evaluation of the benefits linked to a progressive introduction of intermittent sources. Scenarios for Cuba correspond to a progressive introduction of intermittent sources to reduce fossil fuel importation. These scenarios were compared with the official projection of the Cuban government for 2030 showing that the introduction of solar and wind improve the situation of the island by reducing CO<sub>2</sub> emissions, improving air quality, and generating economic benefits. Monetizing the CO<sub>2</sub> emissions results in greater economic benefits through carbon compensation. Furthermore, replacing Internal Combustion Vehicles (ICVs) with Electric Vehicles (EVs) could offer additional benefits across all these aspects.

### 1. Introduction

Human activities in our modern society require more and more energy which is mainly supplied by fossil fuels (~80%). This type of energy source is responsible for the acceleration of global warming and premature mortality due to poor air quality worldwide [1–4]. To face these problems, it is urgent to substitute fossil fuels with other energy sources. There are several possible options for implementing this substitution. The choice of the best option depends on the availability of technologies and the energy resources they require. But this choice is not only dictated by technological constraints but also by economic, social, and political considerations so it must be adapted to the different local situations [5].

A large number of studies are regularly published to analyze energy supply systems as a whole (from production to energy demand) in order to help choose the best options [6]. Some of these studies simply assess the current state of an energy system [7], but the majority are concerned

with developing scenarios for the future [8–17]. Since a very large number of options can be considered, the methods used for these studies must be able to handle many different scenarios.

Some methods are based on optimization algorithms that automatically generate a very large number of scenarios and select a single one by minimizing a very few characteristics (usually economic costs) [18–20]. This approach has the advantage of generating scenarios systematically but suffers from the disadvantage of not being able to consider enough characteristics to select the most appropriate scenario for decision-makers. Indeed, the search for minimum costs is perhaps not the only important criterion for a decision-maker, who must also consider many other characteristics linked to social, political, or even geopolitical issues.

Other methods consist of choosing arbitrary scenarios based on the expertise of the study's authors [8–13]. Compared with optimization-based methods, it can use a larger number of diverse criteria to compare the different scenarios. In general, such methods do not result in the choice of a single scenario, but seek to describe as best as

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Nomenclature. Abbreviations	
RES	Renewable energy sources
SIDS	Small island developing states
GHG	Green house gases
TAC	Total annual costs
CCGT	Combined cycle gas turbine
PV	Photovoltaic
API	American petroleum institute
GDP	Gross domestic product
AQM	Air quality modeling
CTM	Chemical transport model
WRF	Weather research and forecasting
EI	Emissions inventory
SNAP	Sectoral classification for reporting on environmental protection expenditure and revenue
GLCF	Global land cover facility
MS	Macro sectors
VOC	Volatile organic compounds
NOx	Nitrogen oxides
SO <sub>x</sub>	Sulfur oxides
PM <sub>2.5</sub>	Particulate matter of 2.5 μm diameter
NH <sub>3</sub>	Ammonia
CO <sub>2</sub>	Carbon dioxide
US	United States of America
BL	Baseline scenario
BC	Basecase scenario
CCTAC	Carbon compensated total annual costs
CUPE	Cuban oil union
EEZ	Cuban economic exclusion zone
MAED	Model for analysis of energy demand
Int-a, Int-b	Scenarios of intermittent introduction for 30% and 60% respectively
ΔTAC	Differences in TAC between the scenarios Int-a, Int-b, and the reference scenario BL
ΔCCTAC	Differences in TAC between the scenarios Int-a, Int-b, and the reference scenario BL
ICVs	Internal combustion engine vehicles
EVs	Electric vehicles
<i>Notations/Symbols and Units</i>	
$Ex_{PM2.5}$	Personal exposure to PM <sub>2.5</sub> ( $\frac{\mu}{m^3}$ )
$C_i^{PM2.5}$	Annual average of PM <sub>2.5</sub> concentration at a region “i” ( $\frac{\mu}{m^3}$ )
$Pop_i$	Population in region “i”
$I_s$	Indicator value of scenario “s”
$C_{BL}$	Value of characteristic “C” for the baseline scenario
$C_s$	Value of characteristic “C” for scenario “s”
$C_0$	Value of characteristic “C” for an ideal desired situation
$TAC_t^{(SC)}$	Total annual cost of technology “t” and for the scenario “SC” (\$/yr)
$IC_t^{(SC)}$	Installed capacity of technology “t” and for the scenario “SC” (MW)
$AC_t$	Annual cost of technology “t” (\$/yr)
$FC_t$	Fixed cost of technology “t” (\$/MW)
$EP_t^{(SC)}$	Energy production of technology “t” and for the scenario “SC” (MWh/yr)
$VC_t$	Variable cost of technology “t” (\$/MWh)
$FUC_t$	Fuel cost of technology “t” (\$/MWh)
$\eta_t$	Efficiency of technology “t”
$CC_t$	Capital cost of technology “t” (\$/MW)
$r$	Return rate
$l$	Life time (yr)
$Cf_t^*$	Capacity factor of technology “t”
$CAC$	Carbon costs (\$/tCO <sub>2</sub> /yr)
$E_{CO2Eq}^{(BC)}$	Greenhouse gas emissions of the scenario “BC” (tCO <sub>2</sub> /yr)
$E_{CO2Eq}^{(SC)}$	Greenhouse gas emissions of the scenario “SC” (tCO <sub>2</sub> /yr)
$CCTAC^{(SC)}$	Carbon compensated total annual costs of the scenario” SC” (\$/yr)
$TAC^{(SC)}$	Total annual costs of the scenario” SC” (\$/yr)
$CO_2C^{(SC)}$	Carbon compensation of scenario “SC” (\$/yr)
$\Delta TAC^{(SC-BL)}$	Difference of total annual costs between the scenarios “SC” and “BL” (\$/yr)
$\Delta IC_{solar}^{(SC-BL)}$	Difference of solar installed capacity between the scenarios “SC” and “BL” (MW)
$AC_{solar}$	Annual costs of solar (\$/MW/yr)
$FC_{solar}$	Fix costs of solar (\$/MW/yr)
$\Delta IC_{wind}^{(SC-BL)}$	Difference of installed capacity between the scenarios “SC” and “BL” (MW)
$AC_{wind}$	Annual costs of wind (\$/MW/yr)
$FC_{wind}$	Fix costs of wind (\$/MW/yr)
$\Delta EP_{tc}^{(SC-BL)}$	Difference of energy production between the scenarios “SC” and “BL” for the controllable technology “tc” (MWh/yr)
$VC_{tc}$	Variable cost of the controllable technology “tc” (\$/MWh/yr)
$FUC_{tc}$	Fuel cost of the controllable technology “tc” (\$/MWh)
$\eta_{tc}$	Efficiency of the controllable technology “tc”
$\Delta CO_2C^{(SC-BL)}$	Difference of carbon compensation between the scenarios “SC” and “BL” (\$/yr)
$e_{CO_2}^{tc}$	CO <sub>2</sub> emission factors for the technology “tc” (tCO <sub>2</sub> /MWh)
$\Delta EP_{tc}^{(BC-SC)}$	Difference of energy production between the scenarios “BC” and “SC” for the controllable technology “tc” (MWh)

possible the many characteristics of the scenarios evaluated. Their weakness is that they can only handle a limited number of scenarios that have not been systematically generated, so there is a risk of missing scenarios that could be of interest to a decision-maker. Improvements can be achieved by using statistical classification methods, which can help to describe a larger number of scenarios by grouping them into clusters [14,15]. Designing scenarios based on progressive trends in their characteristics (such as an increasing percentage of wind power in the energy mix) is also a way of describing a larger number of scenarios more easily [16,17,21].

In this work, we decided to rely on the existing methods mentioned previously to generate and compare different scenarios. However, some aspects of our approach are original: Primary energy sources are divided between intermittent and controllable sources. Intermittent sources

(solar and wind) can only provide energy when available in nature while controllable sources can potentially produce energy at any time. The scenarios to be analyzed are designed by gradually increasing the percentage of energy produced by intermittent sources. The remaining energy to be supplied by controllable sources is then hourly evaluated to meet the energy demand. For each percentage of intermittent energy considered, an optimization calculation is carried out to find the least expensive repartition between solar and wind for the intermittent production. A series of indicators (such as economic costs, climate and health benefits and/or necessary energy imports, etc) are estimated for each scenario. This method aims to compare a fairly large number of scenarios using a fairly large number of criteria easily chosen according to the local context.

The local context chosen for this study is the case of Cuba since this

country is in a very critical energy situation that requires rapid change. The country is both under embargo and is highly dependent on imports of fossil fuel resources [22]. Moreover, the Cuban energy transition is especially interesting to investigate due to several characteristics of the country: i) because of the embargo the Cuban population is already showing great sobriety to reduce its energy consumption, therefore, there is no need to consider scenarios dedicated to the energy demand reduction scenarios, ii) the country is an island whose interest is to move towards energy autonomy by limiting its exchanges with neighboring countries/regions, which simplifies the analysis of possible scenarios, and iii) due to its location (tropical country) it has a large potential of renewable energy sources (RES), especially solar.

This research aims to analyze the Cuban energy system and a set of scenarios for a reliable energy transition. A base case that corresponds to the year 2015 is used to describe the current situation of the Cuban energy system in terms of resources, technologies, and services. 2015 has been selected as the reference year because data were easily available for this year. 2015 also has the advantage of being well representative of a situation where the country is not affected by the effects of the COVID-19 pandemic. The official projection of 2030 is chosen as the baseline scenario from which several alternative scenarios are derived by introducing solar and wind energy into the energy mix and electric vehicles for transportation. The different scenarios are analyzed and compared using indicators quantifying energy security (i.e. dependence on energy imports), carbon footprint (i.e. CO<sub>2</sub> emissions), air quality (i.e. concentration of harmful air pollutants), and economic cost (i.e. total annualized costs -TAC- and carbon compensation).

## 2. The energy system of Cuba

During the 1990s, after the collapse of the Soviet Union, energy dependency on foreign resources led to a major setback for the Cuban economy. The state was forced to slash its energy imports which affected its energy security. The government responded by implementing reforms that led to a change in society concerning energy use. Such reforms included: increasing the production of domestic crude oil and associated gas, reduction of energy demand, reduction of electricity losses, and improving energy infrastructure. Between 1992 and 2003, domestic oil production grew annually by 7% [23], but this fuel showed to be far from optimal due to its high sulfur content. This condition caused damage to the power plants in terms of corrosion, as a consequence, many power plants had to shut down. This situation triggered a crisis in 2005, the government replied with the policy called the “Energy Revolution”. This decision instituted measures to reduce electricity demand and increase energy efficiency with investments in distributed electricity generation systems. Around 2000 small diesel generators were scattered around the island, covering 70% of the municipalities [24]. The energy system continued to be highly dependent on imported resources.

During the 2000s preferential trading agreements with Venezuela allowed the importation of oil from this country. This dependency led to a new crisis that caused the Cuban energy sector to once again enter a period of uncertainty due to the political instability of the Venezuelan economy since 2010.

In July 2016, the Cuban government announced new goals to reduce electricity and fuel consumption by 6% and 28% respectively intending to reduce oil imports [25,26]. Currently, the country is still exploring ways of fostering energy efficiency: the necessity caused by the aforementioned economic crises enforced moving toward a less-demanding energy system, but it has been and still is heavily reliant on fossil fuels [27]. The country still largely uses fossil fuels and remains dependent on external sources compromising energy sustainability and security despite the large potential of RES available in Cuba.

### 2.1. Situation in 2015

#### 2.1.1. Energy demand

Energy consumption is the consequence of human activities which are connected with all the aspects of daily life through the vast use of energy, from households to industries. In Cuba, industrial processes encompass major consumers (41%), followed by the residential sector (37%) and then transport (11%)(Table 1). The various other sectors (i.e., water supply, construction, and agriculture) use 12% of the total energy consumed. The demand of the island is fulfilled with two different branches of energy resources: Oil sub-product (63%) and electricity (37%).

#### 2.1.2. Electricity production

The largest part of electricity (59%) is produced by seven thermo-electric power plants that consume large amounts of crude oil as well as, in smaller quantities, fuel oil, and diesel [28]. 22% of electricity is produced by a set of distributed generators (so-called “generator set”) reliant on fuel oil and diesel, 15% comes from natural gas by a combined-cycle gas turbine (CCGT) generating plants, 3.5% from biomass plants from bagasse (i.e. the dry pulp residue left over after sugar extraction from sugar cane), and around 0.5% from other renewables resources such as water, sunlight, and wind (Table 2).

Thermoelectric power plants have an installed capacity of 2.59 GW. Currently, the obsolescence of these technologies joined with the use of low-quality crude oil leads to high rates of failure and inefficiencies. Most of the power plants run at only 60–65% of their potential [29].

Generator-sets account for 2.52 GW, this technology is a singular aspect of the Cuban grid, it offers benefits against centralized schemes since it helps when facing natural disasters, such as hurricanes, as each generator set contributes to a sector of the grid with its capacity [25,30]. Generator-sets also reduce electricity losses as they do not rely on transmission networks extensively and they can be brought back online faster than centralized generation plants [31]. One important disadvantage is that the generator sets require high-quality oil subproducts, which leads to a costly option to match daily load profiles [32]. Previous studies show that they are not a viable solution in the long run and may only serve as a supplementary power source to the major thermoelectric power plants [29].

The installed capacity of natural gas power plants is mostly of the type CCGT which currently accounts for 580 MW. This infrastructure is operated by the foreign company Energas (i.e. a joint venture between Canada’s Sherritt and Cuba’s Cupet and Unión Eléctrica). The largest facilities are located near the country’s capital city (i.e. Havana) [25].

Biomass power plants account for 470 MW spread among 40 sugar factories. The sugar industry is the sector that uses most of the biomass to cogenerate heat and electricity. But currently, only small amounts of electricity are exported to the grid (i.e., 3.5% of the energy produced) [22,33–36]. In addition, biomass-based energy is used only for 3 600 h per year (~150 days).

The RES capacity is composed of 62.8 MW of hydropower, 11.7 MW of onshore wind turbines, 24.4 MW of utility-scale photovoltaic (PV) panels, and 0.66 MW of biomass-based power plants from the gasification of forest biomass. RES are currently not significantly exploited. They are mainly used in remote locations, inaccessible to the supply of

**Table 1**  
Energy demand of Cuba by demanding sectors in 2015 [27].

Macro Sector	Electricity (GWh/yr)	Oil Sub-products (GWh/yr)	Total (GWh/yr)
Residential	12 440	4 376	16 816
Industry	4 713	13 939	18 651
Transport	0	5 048	5 048
Other	0	5 459	5 459
Total	17 153	28 821	45 974

**Table 2**

Electricity production of Cuba in 2015 sorted by technologies and resources, the energy consumption column corresponds to the primary resources needed to produce the amount of electricity in the column called electricity production with the current Cuban energy system.

Technologies	Resource	Electricity Production (GWh/yr)	Energy consumption (GWh/yr)
PV panels	Sun radiation	15	–
Wind turbines	Wind	35	–
Hydroelectric	Water	48	–
Sugar factory	Bagasse	898	22 450
CCGT	Natural Gas	2 950	7 375
Thermoelectric	Oil & Oil sub-product	11 943	33 175
Generator set	Oil sub-product	4 399	11 576
<b>Total</b>		<b>20 288</b>	<b>74 576</b>

conventional resources [35].

2.1.3. Fuel production

The country uses 106 TWh/yr of primary resources: 42% imported and 58% produced domestically. The domestics (45 TWh/yr) include 3 million tons of crude oil, 1200 million cubic meters of natural gas, and 1.2 million tons of sub-products from oil and gas.

Cuban crude oil is a heavy product (less than 10 °API) extracted from shallow waters just off the coasts with high-sulfur content [37]. Crude natural gas corresponds to the associated light hydrocarbons of the crude oil reservoirs [32].

The primary energy imports (40 TWh/yr) account for 9 TWh/yr of crude oil and 31 TWh/yr of oil sub-products. Due to the low quality of the Cuban crude oil, refined light fuels such as diesel, fuel oil, and gasoline, are obtained from the refining of imported oil, or directly imported as oil subproducts. These imports are mainly from Algeria (which accounts for 80–85% of the total imports), Venezuela (8%–10%), the European Union (6%), Mexico (2%), and Russia (2%), such imports account for 25–30% of total domestic demand of refined products [28].

In terms of gross domestic product (GDP) the country spends more money on energy (mainly imports) than other nations; the total value of the energy consumed in Cuba is 14% of the GDP, whereas the world average is 10% [25].

2.1.4. Overview of the energy fluxes

Fig. 1 shows the Cuban energy system in 2015 through a Sankey diagram [38]. Blocks correspond to production, transformation, or consumption processes. The links between blocks show the energy flow from the left to the right of the diagram linking the production to

the consumption through the transformation of different energy forms. The differences between the size of the left (input) and right (output) links in a block provide information about the losses associated with a transformation process.

Energy is mostly demanded by three macro sectors (right side of diagram Fig. 1): residential, industry, and transport, the industry being the most demanding followed by residential. These three macro sectors need energy from electricity (17 TWh i.e. 37% of the demand) and oil subproducts (29 TWh i.e. 63% of the demand). The residential sector consumes mostly energy as electricity meanwhile the industry consumes mostly oil subproducts. The transport sector currently demands only oil subproducts.

Part of the oil subproducts is directly imported while another part is refined from imported or domestic crude oil. The losses which result from the refining process amount to 10% (Fig. 1).

The electricity production generates more losses than the refining processes used to obtain the oil subproducts. The lost part of primary resources depends strongly on the way the electricity is produced. The losses of the production by generators are 62%, by thermoelectric power plants 64%, by CCGT 60%, and by sugar factories 96%. Solar, wind, and water resources are not comparable to the other primary resources such as fossil fuels or biomass, as they are used to produce electricity directly, without any transformation processes. This is why we have chosen not to associate losses with the production of electricity from solar, wind, and water. However, the power supply is affected in all cases by additional losses due to the transport of electricity through the grid. These losses are estimated at 15.5% in the Cuban situation (shown between electricity generation and electricity demand in Fig. 1).

The energy supply can be affected by very different losses depending on the resources used, with different consequences.

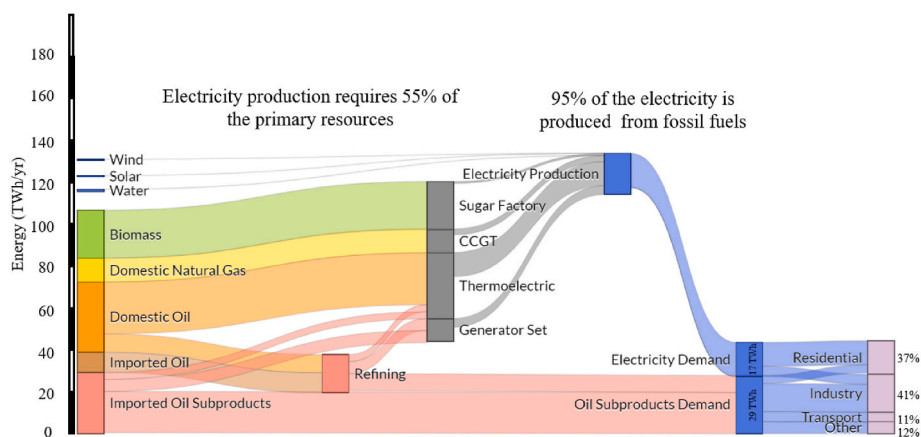
- while electricity production consumes 55% of all primary resources: hydropower, solar, and wind included, it satisfies only 37% of energy demand,
- while the electricity is produced at 95% by fossil fuels and only 5% by biomass.

2.2. Official projection into 2030

2.2.1. Energy demand

The energy generation and consumption in Cuba have been relatively steady during the last decades [27,39]. Fig. 2 shows the energy demand trends in terms of electricity and fuels.

The electricity sector will play an increasingly important role in energy consumption, which prompted the Cuban government to implement several policies to improve the performance of the energy



**Fig. 1.** Sankey diagram of the Cuban energy flows for the year 2015. The energy flows go from the primary energy resources on the left of the diagram to the main sectors of human activity on the right of the diagram.



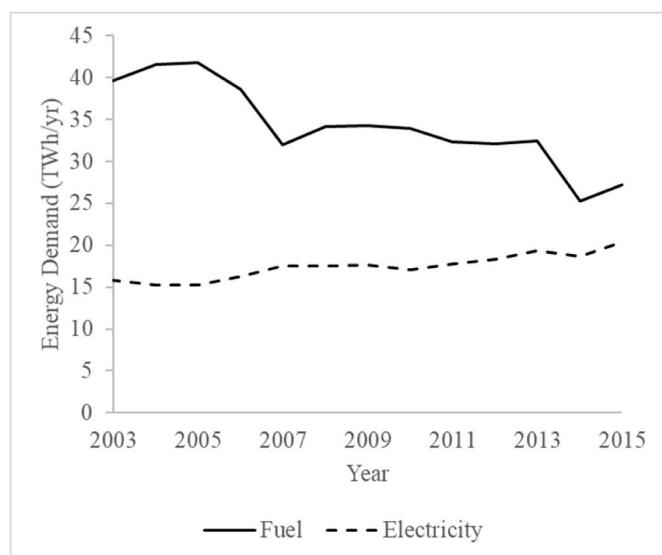


Fig. 2. Trend of Cuban energy demand from 2002 to 2015.

sector. A fundamental part of them was the replacement of household and state entities appliances with more efficient equipment. The policy also introduced a new electricity tariff with a reduction of government subsidies to encourage savings of electricity [23,40]. The industrial sector, although technologically outdated [39], has also implemented policies to improve energy efficiency [41]. Despite the measures taken by the government, the electricity consumption from 2002 to 2015 shows an average increase of 3.6% per year, with 4.8% from 2014 to 2015 alone (Fig. 2). This trend can be explained by the increased demand from the residential sector (around 4.7% per year after 2010). According to Ref. [26], the opening of the private segment of the economy during the 2000s (where Cubans were allowed to set up businesses in their homes and front porches) highly influenced this drift. For all other sectors, the increase is lower (less than 3% per year). Following this trend, Cuban electricity consumption is expected to have a small variation in the future [37]. Official estimations foresee an increase of 3.28% per year reaching around 28 TWh in 2030 [34].

It is important to keep in mind that a significant increase in temperature is expected in the coming years due to climate change that will particularly affect the Caribbean region [42,43]. This should lead to an increase in the use of air conditioning throughout this region. Because of this, the rate of increase of 3.28% per year of the electric demand estimated by the Cuban authorities is optimistic and it is very likely to be higher than 4% per year [22].

The direct consumption of oil sub-products, by services other than electricity, experienced a decreasing trend. At the risk of being too pessimistic about the planning horizon, such demand is assumed to remain constant at 29 TWh. Consequently, the total energy demand will increase from 46 TWh in 2015 to 57 TWh in 2030 with a share of 51% of oil sub-product and 49% of electricity.

### 2.2.2. Electricity production

The Cuban government is aiming to match future energy needs with a more self-reliant supply. Its strategy consists of reducing the importation of energy by producing more domestic resources. Broadly, the 2030 strategy includes i) increasing technological capacity to use domestic fuels (i.e. crude oil and natural gas), ii) increasing efficiency of electricity production, distribution, and consumption with energy-saving measures, iii) and expanding the renewables share; [44], documented by "Cartera de oportunidades Cuba - 2017".

Thermoelectric capacity will increase by 800 MW in 2030 (an additional 13% of the current capacity), this new thermoelectric capacity will produce electricity by burning domestic oil allowing to

initially reduce imported energy needs. CCGT will increase the installed capacity by 12% [24]. The generator set installed capacity is maintained at the same level as in 2015.

Regarding the RES, 74 small hydroelectric plants (375 MW), 13 onshore wind farms (583 MW), and 19 utility-scale PV plants (263 MW) will be added. Most of the hydropower energy will remain produced in isolated areas. Onshore wind farms will be located on the northeast coast where wind speeds at 50 m and 100 m allow an average capacity factor greater than 30%. 720 MW of biomass burning-based powerplants will be added mainly by increasing the efficiency (between 5% and 10%) in nineteen of the existing sugar factories.

Table 3 summarizes the main energy technologies and resources projected for 2030.

### 2.2.3. Fuel production

To fulfill the projected demand in 2030 the country may manage around 120 TWh/yr of primary resources including crude oil and sub-products. Domestic crude oil production is expected to rise to 56 TWh/yr, and natural gas to 1 TWh/yr. The biomass may be set up to 34 TWh/yr. The importation of oil subproducts demanded by the generators sets, and the vehicles fleet will be needed due to the low quality of the domestic crude oil in Cuba. The needs of oil sub-products will be covered by Cuban facilities with refining capacities for 9 TWh/yr of imported oil and subproducts imports of 7 TWh/yr.

### 2.2.4. Overview of the energy fluxes

Fig. 3 shows the Sankey diagram of the Cuban energy system for the year 2030. Final electricity demand reached 28 TWh/year, an increase of 11 TWh/year compared to 2015. The share of electricity generated from fossil fuels will decrease to 75% (from 95% in 2015) in the benefit of RES such as biomass, water, solar, and wind. However, the increase in the share of RES and the use of domestic fuels (to power thermoelectric and CCGT plants) is still insufficient to completely end dependence on imported sources (i.e., imported oil and oil subproducts).

Compared to 2015, the 2030 scenario (Fig. 3) counts on an improvement in the efficiency of the different power generation processes, the loss rate is expected to reach 85% for the sugar factory. Even so, for the other technologies (CCGT, Thermoelectric, and Generator set) the loss rates are expected to be the same as in 2015.

## 2.3. Environmental concerns

Since the energy system of Cuba is dependent on fossil fuels, greenhouse gas (GHG) emissions, and atmospheric pollution turn into important aspects [45]. In addition, most of the power installations are close to urban areas which may have an impact on population health.

To represent the pollution on the island, and its variation with different emission scenarios, an air quality modeling (AQM) was performed. The AQM was developed using the Chemical Transport Model (CTM) called CHIMERE for the aforementioned scenarios of 2015 and 2030 [46]. The meteorology over Cuba needed for the AQM was

Table 3  
Electricity production of Cuba in 2030 sorted by technologies and resources

Technology	Resource	Electricity Production (GWh/yr)	Energy consumption (GWh/yr)
PV panels	Solar radiation	518	–
Wind turbines	Wind	1 535	–
Hydroelectric	Water	985	–
Biomass	Bagasse	5 152	34 347
CCGT	Natural Gas	4 481	11 203
Thermoelectric	Oil & Oil sub-product	15 855	44 042
Generator set	Oil sub-product	4 399	11 576
Total		32 925	101 167

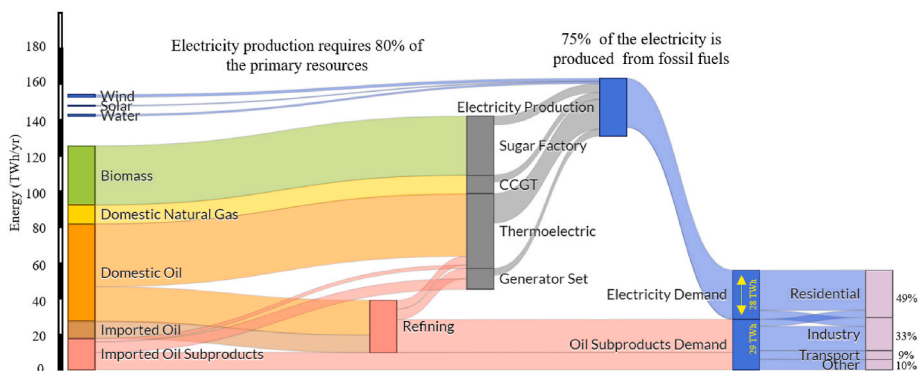


Fig. 3. Energy flow Sankey diagram of Cuba for the year 2030.

simulated with the WRF (Weather Research and Forecasting) model [47, 48].

2.3.1. Emissions inventory (EI)

The emission inventory developed in a preview study for Cuba in 2015 was used to assess their projection into 2030 [49]. Since this projection only acts on electric generation (i.e. other services held steady from 2015), only the emission parameters (i.e. emission factors, activity levels, and allocations) of power units are modified. The developed emissions inventory is based on eleven key macro sectors (MS) according to the SNAP sectors classification. A summary of the yearly emissions of the two baseline scenarios (2015 and 2030) is shown in Table 4 sorted by macro sector and pollutant.

Emissions from MS1 were calculated for each source location by using local activity levels and emission factors either measured [50,51] or set based on “AP42, Compilation of Air Pollutant Emission Factors” [52]. For the MS2, emissions were estimated according to fuel consumptions reported by the energy section of [53] and emission factors from Refs. [54–56].

Emissions of MS7 were computed by using the EMISENS model [57, 58] according to the average activity levels of the Cuban vehicular fleet [59], classified into five vehicle categories (gasoline and diesel passenger, heavy vehicles, buses, and motorcycles) and spared into five road categories (semi-urban, urban, locals, and neighborhood streets) [49,60, 61].

The road network lengths repartition used is based on OpenStreetMap® [62]. Emissions from MS3, MS4, MS6, MS9, and MS10 were compiled from the literature [53].

The geographical location of stationary sources was taken from the Cuban State Registration of Companies and Budgeted Units in Ref. [63].

Table 4

Emissions of Cuba (Ton/yr) for 2015 and 2030 baseline scenarios considering the sectors: Combustion in energy and transformation industries (MS1), Non-Industrial combustion plans and residential (MS2), Combustion in manufacturing industry (MS3), Production processes (MS4), Extraction and distribution of fossil fuels and geothermal energy (MS5), Solvent and other product use (MS6), Road transport (MS7), Other mobile sources and machinery (MS8), Waste treatment and disposal (MS9), Agriculture (MS10), and Other sources and sinks (MS11).

Sector	2015						2030					
	PM <sub>2.5</sub>	NO <sub>x</sub>	SO <sub>x</sub>	VOC	NH <sub>3</sub>	CO <sub>2</sub>	PM <sub>2.5</sub>	NO <sub>x</sub>	SO <sub>x</sub>	VOC	NH <sub>3</sub>	CO <sub>2</sub>
MS1	6 195	45 975	376 858	738	555	13 433 900	26 661	54 814	512 134	865	1 076	13 735 078
MS2	5 077	753 063	1 771	38 631	–	8 475 087	5 077	753 063	1 771	38 631	–	12 233 951
MS3	–	2	1 644	9 446	–	–	–	2	1 644	9 446	–	–
MS4	–	8	5 956	34 214	–	–	–	8	5 956	34 214	–	–
MS5	–	–	–	–	–	–	–	–	–	–	–	–
MS6	–	–	–	32 490	–	–	–	–	–	32 490	–	–
MS7	463	90 753	3 173	16 014	246	1 261 883	463	90 753	3 173	16 014	246	1 261 883
MS8	–	–	–	–	–	–	–	–	–	–	–	–
MS9	–	589	–	–	–	–	–	589	–	–	–	–
MS10	–	7 098	–	–	–	–	–	7 098	–	–	–	–
MS11	–	–	–	–	–	–	–	–	–	–	–	–
Total	11 735	897 488	389 402	131 533	801	23 170 870	32 201	906 327	524 678	131 660	1 322	27 230 911

For agriculture, the spatial distribution is based on the Global Land Cover Facility GLCF-Cropland database (Sexton et al., 2013), which supplies an extensive agricultural land classification from remotely sensed satellite data including built-up, water, snow, forest, savannas, and shrub, grass, and croplands [64–66].

CO<sub>2</sub> emissions have been computed using the emission factors in Table 7.

Changes in the pollutants’ emissions are driven by the differences between the use of the primary energy sources. These differences are mainly characterized by the increase in biomass, domestic oil, and imported oil primary resources use in Cuba as explained in the sections above.

The differences in the emissions due to changes in the energy consumption between 2015 and 2030 are represented as changes in sector MS1. MS1 is taken as the key sector since it is the most energy-demanding one and it is directly related to the electricity production on the island, changes in the vehicles fleet are not considered between the scenarios 2015 and 2030.

The increase in the NO<sub>x</sub>, SO<sub>x</sub>, and VOC emissions is mainly linked to an augmentation of primary resources consumed by the thermoelectric power plants, CCGT; and oil subproducts production, storage, and transportation. While the increase in PM<sub>2.5</sub> and NH<sub>3</sub> emissions is due to the operation of new biomass-based power plants and the increase in biomass use as a primary resource.

As result by 2030, the emissions due to electricity generation will increase in comparison to 2015. The percentages of increase by pollutant are NO<sub>x</sub> (19%), SO<sub>x</sub> (36%), VOC (17%), PM<sub>2.5</sub> (330%), and NH<sub>3</sub> (94%).

The implementation of the official plan for the energy mix in 2030 will lead to an 18% increase in total CO<sub>2</sub> emissions. MS2 has an increase

of 44% and MS1 has a small increase of 2% in the CO<sub>2</sub> emissions in 2030 with respect to 2015. The MS7 remained unchanged in terms of CO<sub>2</sub> emissions in 2030 compared to 2015.

### 2.3.2. Air quality modeling

Fig. 4 shows the AQM results regarding the PM<sub>2.5</sub> yearly average concentrations over Cuba for the current situation (2015), and the difference in the concentrations between 2030 and 2015.

Fig. 4-a shows that the most polluted areas of Cuba are located in the northwest around Havana. Pollution is dispersed in the west of Havana, it is also evidenced in the north of Matanzas where the city of Matanzas and the touristic areas of Varadero are located.

Fig. 4-b shows the difference between the pollution levels in 2030 and 2015, the color scale shows that the pollution in 2015 is relatively greater than the pollution levels in 2030 since an important number of cells are blue-colored on the map (i.e. the concentration of PM<sub>2.5</sub> is greater in 2015 than in 2030 for this cells).

The most important reductions are observed in the west of the island (i.e. the region of Pinar del Rio), and the east (i.e. region of Guantánamo). In the sea, the northern coasts have more reductions than the southern coasts except for the Guantánamo region near Santiago de Cuba. Two maritime areas present important reductions in the northwest of the simulation domain: one near Florida's coasts and the other

on the west on the parallel 24°N and left of the meridian 84°W.

Air quality impact is evaluated based on the population exposure and is considered as a population-weighted mean level ( $EX_{PM_{2.5}}$ ) of PM<sub>2.5</sub>, it is calculated with equation (1) where  $C_{PM_{2.5}}$  is the annual average of PM<sub>2.5</sub> concentration at a region "i"; and  $Pop$  the population in the same region "i".

$$EX_{PM_{2.5}} = \frac{\sum_i C_{PM_{2.5}} \cdot Pop_i}{\sum_i Pop_i} \quad (1)$$

### 2.4. Costs estimation

Evaluation and comparison of different energy transition strategies should consider the different components of the economical constraints. The first component is the total annualized cost (TAC) of the all energy system which is based on the investment and fixed costs as well as, the value of money over time, fuel costs, variable costs, and replacement linked to the use-life of the energy production infrastructure. The second component corresponds to the environmental gains, which are characterized as both local and global benefits. The local environmental benefits are linked to the reduction of the population's exposure to air pollutants, which is limited to the Cuban population and only affects the

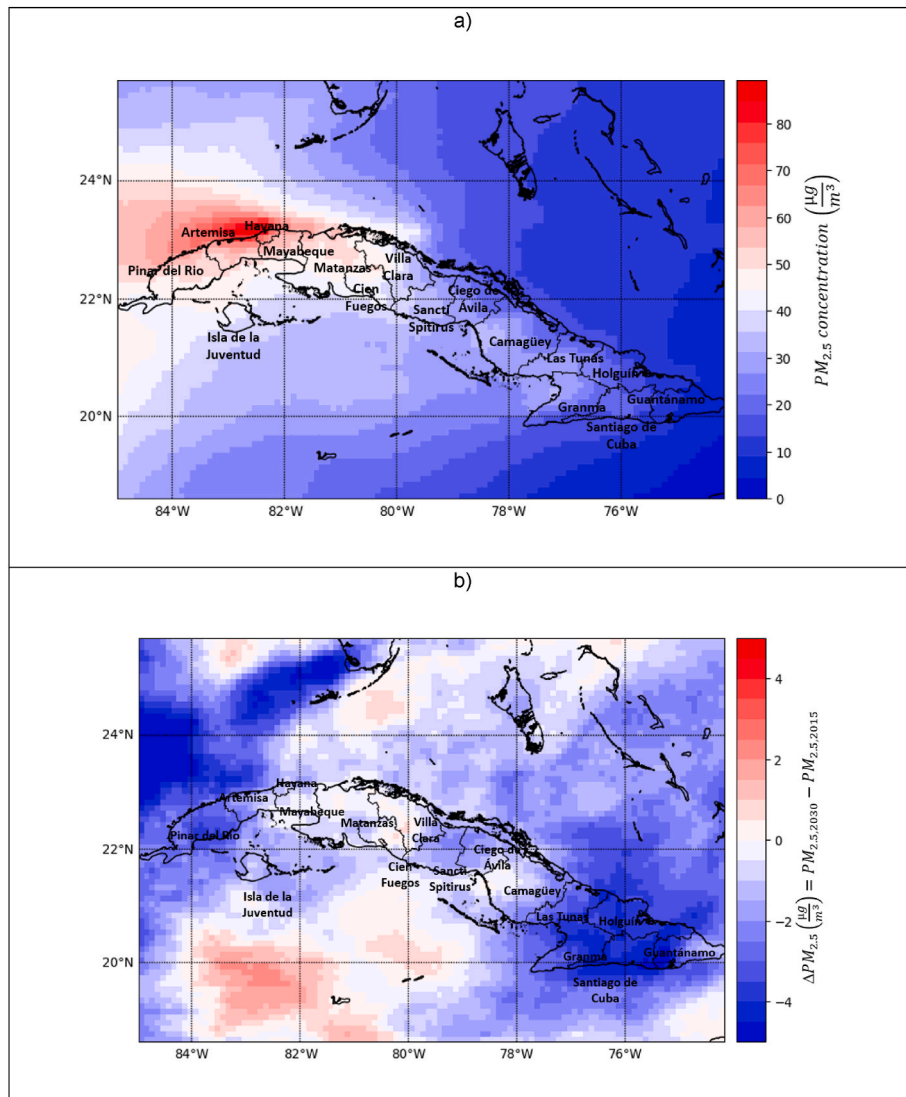


Fig. 4. PM<sub>2.5</sub> yearly average concentration maps for Cuba: a) 2015, and b) difference of PM<sub>2.5</sub> concentrations between 2015 and 2030 ( $PM_{2.5,2030} - PM_{2.5,2015}$ ).



country's internal economy. Conversely, the reduction of GHG gas emissions provides global environmental benefits as it affects the entire world by helping to mitigate global warming. Local environmental benefits cannot be directly capitalized to obtain the foreign currency needed by the Cuban authorities to purchase equipment and fuel, while global environmental benefits can be used to raise funds through carbon compensation [67–73].

The economic indicators used in this study are based on the TAC and the carbon compensation. The carbon compensation uses the basecase 2015 as a reference to evaluate the reduction of GHG gas emissions in ton of CO<sub>2</sub> equivalent resulting from the introduction of solar and wind resources into the energy mix. It is then computed by taking a carbon price of 50 \$/ton which is a projected price of CO<sub>2</sub> credits in 2030 [74]. The carbon compensation is added to the TAC to compute a carbon compensated total annual costs (CCTAC) of each scenario.

## 2.5. Cost calculation

### 2.5.1. Total annualized costs (TAC)

The total annualized costs of a technology “t” and scenario “SC” ( $TAC_t^{(SC)}$ ) derives from two parts, the first part of the cost is variable and depends on the quantity of energy produced while the second part is fixed. For the scenario “SC”  $TAC_t^{(SC)}$  is computed as the sum of a term proportional to the annual energy production in MWh/yr ( $EP_t^{(SC)}$ ) and a term proportional to the installed capacity in MW ( $IC_t^{(SC)}$ ). The  $TAC_t^{(SC)}$  is calculated using equation (2), where,  $FC_t$  is the annual fixed costs in \$/MW/yr, which corresponds to the costs of operating the system over a year and includes staff costs, insurance, taxes, repair, or spare parts.  $AC_t$  is the annualized capital cost in \$/MW/yr, it is calculated based on the overnight capital costs of the technology “t” ( $CC_t$ ) in the energy mix in \$/MW, the lifetime ( $I$ ) in years, and the discount rate ( $r$ ) (equation (3)). That is,  $AC_t$  is the value of the initial investment of the infrastructure amortized over its estimated lifetime. As a consequence, the  $AC_t$  has a value different from just dividing the capital investment costs by the lifetime in years due to the value of the money change in time according to  $r$ .

$$TAC_t^{(SC)} = IC_t^{(SC)} \times (AC_t + FC_t) + EP_t^{(SC)} \times \left( VC_t + \frac{FUC_t}{\eta_t} \right) \quad (2)$$

To consider the change of money value over time, the  $AC_t$  is calculated using a  $r$  value of 5.77% for the analysis of energy strategies based on the values reported in published studies (equation (3)) [69,75–78].

$$AC_t = CC_t \times \frac{r \times (1 + r)^I}{(1 + r)^I - 1} \quad (3)$$

$VC_t$  is the annual variable costs in \$/MWh/yr, which includes expenses related to the variation of the mean capacity factor of the system, e.g. contracted personnel, consumed materials, and costs for disposal of operational waste per year, excluding fuel costs.  $FUC_t$  is the cost of fuels consumed for electricity production in \$/MWh/yr, it is used with the fuel usage efficiency ( $\eta_t$ ) to compute the ratio  $\frac{FUC_t}{\eta_t}$  which corresponds to the cost of consumed fuel. With these parameters, and using equation (4) the  $TAC_t^{(SC)}$  can be computed for the technology “t”. Then, adding all the technologies in scenario “SC” the  $TAC^{(SC)}$  is calculated with equation (5).

$$TAC_t^{(SC)} = EP_t^{(SC)} \times \left( \frac{AC_t + FC_t}{C_f^*} + VC_t + \frac{FUC_t}{\eta_t} \right) \quad (4)$$

$$TAC^{(SC)} = \sum_t TAC_t^{(SC)} \quad (5)$$

The parameters used for the cost analysis of Cuba's energy strategies in this research are presented in Table 5. These values are taken from the year of reference 2020 and are expressed as US dollars, assuming the

**Table 5**

Parameters for the calculation of costs for the case of Cuba's energy strategies.

Technology	Capital cost (\$/MW)	Variable Cost (\$/MWh)	Fixed cost (\$/MW/yr)	lifetime (yr)	Efficiency
PV panels	1 500 000	0	20 000	25	–
Wind turbines	1 800 000	0	26 000	25	–
Hydroelectric	Not available estimation in Cuba	0	0	50	–
Biomass	2 050 000	10	74 000	30	0.15
Gas Turbine (CCGT)	850 000	7	20 000	25	0.4
Thermoelectric	1 500 000	10	74 000	25	0.36
Generation set	500 000	50	30 000	20	0.38

currency value in 2020 [67,68,79]. The fuel costs of reference are shown in Table 6 [80].

### 2.5.2. Carbon compensation and carbon compensated TAC (CCTAC)

The carbon compensation of any scenarios (BL2030, Int-a, or Int-b) is computed using the difference of carbon footprint between the scenario “SC” and the basecase scenario (BC) (equation (6)).

$$CO_2C^{(SC)} = CAC \times \max \left[ 0 ; \left( E_{CO_2Eq}^{(BC)} - E_{CO_2Eq}^{(SC)} \right) \right] \quad (6)$$

where  $CO_2C^{(SC)}$  is the carbon compensation of scenario “SC”,  $CAC$  is the carbon cost. For the case of Cuba a carbon credit value is projected in 2030 (50 \$/ton) [74].

$E_{CO_2Eq}^{(BC)}$  and  $E_{CO_2Eq}^{(SC)}$  are the greenhouse gas (GHG) emissions of the BC and of the scenario “SC” in tons of CO<sub>2</sub> equivalent.

The carbon compensation and carbon compensated TAC (CCTAC) are calculated by equation (7).

$$CCTAC^{(SC)} = TAC^{(SC)} - CO_2C^{(SC)} \quad (7)$$

### 2.5.3. Cost difference between the scenarios

The difference between scenarios is denoted by  $\Delta$ , e.g., the term  $\Delta TAC_t^{(SC-BL)}$  denotes the difference of TAC between scenarios “SC” and BL, where “t” is one technology for electricity production (e.g., thermoelectric, solar, wind, etc ...), and “SC” is the scenario (e.g., 30% of the demand meet by intermittents or 60%, etc.) (equation (8)). The difference of TAC can be computed with equation (9).

$$\Delta CCTAC^{(SC-BL)} = \Delta TAC^{(SC-BL)} - \Delta CO_2C^{(SC-BL)} \quad (8)$$

$$\Delta TAC^{(SC-BL)} = \sum_t \left[ \Delta IC^{(SC-BL)} \times (AC_t + FC_t) + \Delta EP^{(SC-BL)} \times \left( VC_t + \frac{FUC_t}{\eta_t} \right) \right] \quad (9)$$

For the scenarios Int-a and Int-b a large number of terms can be simplified since the installed capacity of the technologies that

**Table 6**

Fuel costs estimated for Cuba.

Primary resource	Fuel Cost (\$/MWh)
Coal	Not used in Cuba
Gas	31.9
Imported Oil	47.6
Domestic Oil	17.8
Biomass	Not data available for Cuba
Diesel	149.7
Fuel Oil	107.1
Refined motor gasoline, with local Oil	97.6
Refined motor gasoline, with imported Oil	98.9
Imported Gasoline	144.6

correspond to controllable sources keep their installed capacity “tc” and the variable and fuel cost of solar and wind are zero (equation (10)).

$$\Delta TAC^{(SC-BL)} = \Delta IC_{solar}^{(SC-BL)} \times (AC_{solar} + FC_{solar}) + \Delta IC_{wind}^{(SC-BL)} \times (AC_{wind} + FC_{wind}) + \sum_{tc} \left[ \Delta EP_{tc}^{(SC-BL)} \times \left( VC_{tc} + \frac{FUC_{tc}}{\eta_{tc}} \right) \right] \tag{10}$$

The difference of carbon compensation can be computed with equation (11).

$$\Delta CO_2 C^{(SC-BL)} = CAC \times \left\{ \max \left[ 0; \left( E_{CO_2Eq}^{(BC)} - E_{CO_2Eq}^{(SC)} \right) \right] - \max \left[ 0; \left( E_{CO_2Eq}^{(BC)} - E_{CO_2Eq}^{(BL)} \right) \right] \right\} \tag{11}$$

The difference of carbon footprint ( $\Delta CO_2 C$ ) for the BL2030 is negative so that its carbon compensation is zero then equation (11) can be written as equation (12).

$$\Delta CO_2 C^{(SC-BL)} = CAC \times \max \left[ 0; \left( E_{CO_2Eq}^{(BC)} - E_{CO_2Eq}^{(SC)} \right) \right] \tag{12}$$

Then, the difference of GHG emissions results from differences of fuel consumption of the technologies that use controllable sources “tc” (see equation (13)).

$$E_{CO_2Eq}^{(BC)} - E_{CO_2Eq}^{(SC)} = \sum_{tc} \left[ \frac{\Delta EP_{tc}^{(BC-SC)}}{\eta_{tc}} e_{CO_2}^{tc} \right] \tag{13}$$

where the factor  $e_{CO_2}^{tc}$  are the CO<sub>2</sub> emission factors for the technology “tc”(Table 7) [81].

### 2.6. Comparison between the scenarios

The historic dependency on imported fuels has made Cuba vulnerable to geopolitics and oil market variations, so that, energy security is a key issue in the economic development of the country. In addition, the availability of fossil fuels is finite, hence, the energy strategies based on fossil fuels are not a sustainable solution for the country’s energy system and lead to the release CO<sub>2</sub> into the atmosphere. The current energy systems are using technologies based on combustion, the atmospheric emissions, and therefore, the concentrations of pollutant play an important role in the strategies to consider [39,82].

Since the energy transition requires the introduction of RES-based technologies to produce energy there are costs associated with the investment and operation of the system of the old and new technologies. These costs change depending on the technologies characteristics, and energy mix (i.e. shares of different technologies within the system). These aspects make important to consider the financial aspects of the different assessed energy transition scenarios.

To evaluate the different possible energy strategies of Cuba a set of indicators was designed based on the country’s specific interests: energy security, carbon footprint, air quality, and economic (CCTAC). These indicators may allow the comparison between the baseline scenario

**Table 7**  
Greenhouse gas (GHG) emission factors for the use of primary resources in the Cuban energy system.

Source/Technology	GHG (tCO <sub>2</sub> /MWh primary resources consumed)
Solar	0
Wind	0
Biomass <sup>a</sup>	0
Gas turbine	0.18
Thermoelectric	0.31
Generation set	0.27
Fuel/gasoline	0.25

<sup>a</sup> The biomass is assumed to be a carbon-neutral primary energy source.

2030 and other scenarios of the energy transition.

The indicators are expressed as ratios (equation (14)) where the baseline scenario for 2030 (BL) is considered as a reference. In equation (14),  $I_s$  denotes the indicator value of scenario “s” for the different characteristics  $C$  used to compare the different scenarios.  $C$  can be the amount of imported fuels (energy security), the amount of emitted CO<sub>2</sub> (carbon footprint and global environmental benefit), the population exposure to air pollutants (local environmental benefit), or the economic cost of energy computed as the CCTAC.  $C_s$ ,  $C_{BL}$  and  $C_0$  are three values of the characteristic  $C$ :  $C_s$  is the value for scenario “s”,  $C_{BL}$  is the value for the Baseline scenario “BL” and  $C_0$  is the value for an ideal desired situation (i.e. zero fuel importations, zero CO<sub>2</sub> and other air pollutants emissions in Cuba, a TAC entirely compensated by the CO<sub>2</sub> compensation).

$I_s$  can take different values relative to BL to compare the different scenarios. When  $I_s = 1$  the scenario corresponds to a maximum possible improvement, i.e. it reaches the ideal desired situation, while it does not improve the BL situation when  $I_s$  takes a value greater or equal to 0.

$$I_s = \frac{C_{BL} - C_s}{C_{BL} - C_0} \tag{14}$$

These indicators offer intuitive formulations that compare the needs of primary resources and the consequences on air quality of their use, using the 2030 official plan as a base. In short, when an indicator is equal to 1, there is no change in comparison to the baseline scenario for Cuba 2030. When the indicators are less than 1 there is an improvement over time, and likewise, when the indicators are larger than 1 there is deterioration over time. The ideal situation arises when these indicators have a value of zero.

### 3. Alternative strategies for the energy mix: introduction of additional solar and wind energy

The first set of alternative scenarios is designed to exploit more intensively the resources available in Cuba to supply the 28 TWh/yr of electricity demand anticipated in 2030 by the Cuban authorities.

#### 3.1. Potential resources

##### 3.1.1. Fossil fuels

The known quantity that would be extracted with the available Cuban technologies was estimated by the Cuba oil union (CUPE) as 98 million toe. Nevertheless, the recent discovery of crude oil and natural gas reserves in the so-called “Cuban economic exclusion zone (EEZ)” of the Gulf of Mexico is expected [83]. The Cuban government has estimated that at least 2.7 billion tons can be found deep in the sea, while the United States Geological Survey’s estimates a more modest 630 million tons, which is still a significant number [84]. Based on historical extraction rates for crude oil and gas (5 million tons), and considering hypothetically that all the reserves can be extracted, estimated onshore reserves will last approximately 22 years and offshore reserves approximately 155 years [85].

##### 3.1.2. Biomass

Sugar cane and marabu (marabu is a type of tree that has invaded vast swathes of agricultural land in Cuba) are expected to be the most important biomass sources in Cuba during the following years. The country has around 6.2 million ha of agricultural surface. During the last ten years, more than 0.4 million ha of sugar cane have been cultivated (Fig. 5) for an average annual production of 14 610 million tons, with a harvest yield of 36 tons/ha.

In 2015, sugar cane was harvested across 436 600 ha (7% of the agricultural surface), with the total production increasing up to 19.3 million tons [53,86]. One ton of sugar cane processed in a sugar factory yields on average around 240 kg of bagasse. Their cogeneration potential is documented in ranges of 20–25 kWh/ton-of-cane [87], 580

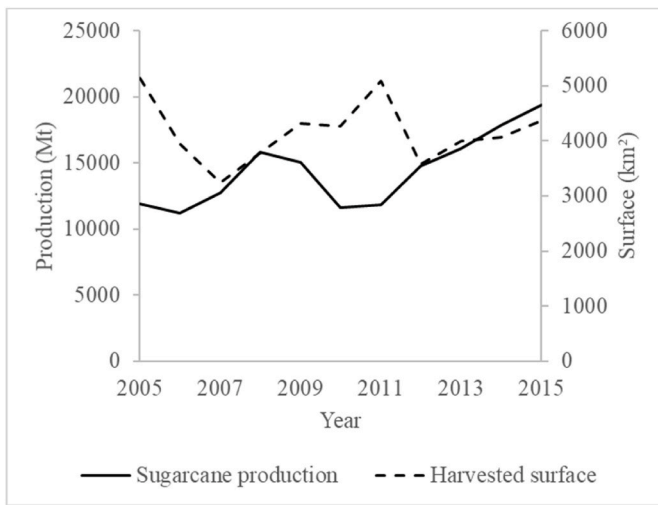


Fig. 5. Trend of sugarcane production from 2005 to 2015 in Cuba.

kWh/ton-of-bagasse [39] or 35–40 kWh/ton-milled-sugarcane [36,39,87], based on different sugar factory generation pressures (18–23 bar) and efficiencies. Opportunities exist to increase the rates of production from bagasse, which include enhancements in harvest yields (90 ton/ha) and electricity production efficiency (140 kWh/ton-milled-sugarcane). Considering an average harvest of 47.5 million tons of sugarcane (i.e. following the trend 2010–2015 which increases production by 2 million ton/yr), the 2030 production of bagasse is estimated at 8.4 million tons. The potential cogeneration ranges between 1700 and 6 500 GWh depending on current and optimal efficiencies.

The marabu covers over 1.7 million ha (i.e. 15% of the Cuban territory) [33,37,39]. The shrub expands quickly at an average occupancy of 37 tons/ha and a natural renewability period of three years. Currently, about 63 million tons of marabu are available all over the country. This resource could either be progressively eradicated to release agricultural surface for other applications or be re-used. The heating value of this biomass is 120–1 268 kWh/ton [34,39]. Considering the capability of harvesting 21 million tons (1/3 of availability) every year [33], the potential electric generation ranges between 2 520 and 26 628 GWh/yr.

### 3.1.3. Water, wind, and solar

The average annual precipitation in Cuba is 1 400 mm. There are about 900 runoff water streams, though they are not extensive owing to the long and narrow shape of the country (with an average width of 97 km). The estimated hydropower potential is 1 300 GWh/yr [85]; however, it cannot be completely exploited because of environmental protection constraints. This research considers that the hydropower potential that can be effectively used is 985 GWh (75% of the official projection).

Estimations of the wind potential for the Caribbean derived a considerably large potential with good to exceptional power densities: 200–300 W/m<sup>2</sup> [88] and 500–1 000 W/m<sup>2</sup> [89]. However, investigations carried out with assistance from Cuban meteorological stations identified a limited number of twenty suitable sites with potential for around 2 GW [37] and a utilization factor of 23% (4.03 TWh/yr). Other Cuban estimations from climate modeling identified 448 km<sup>2</sup> of land with good wind conditions and merely 63 km<sup>2</sup> having excellent wind conditions for electricity generation; these led to an estimated potential of 2.55 GMW [25]. The lowest values of the annual potential are around 1 200 MW (2.42 TWh) [85] while the highest goes from 5 to 14 GW [90].

Due to its geographical location in the tropical latitude, the country is extremely well endowed with solar energy. Studies on climate conditions provide confirmatory evidence of around 2 800 sunshine hours

(32% of utilization factor) annually. The daily average solar energy that reaches Cuban land throughout the year is 5 kWh/m<sup>2</sup> [25]. This value is relatively uniform across the country and shows little variation (0.5 kWh/m<sup>2</sup>) from winter to summer seasons [34]. [5] estimated a possible PV panels' installed capacity of 8.73 TW, only considering suitable rural land areas (i.e. rural land areas receiving a minimum acceptable solar insolation and being appropriated for PV panel installation). This huge potential represents an amount of energy of around 24.4 TWh/yr.

Table 9 shows the resource potentials estimated for Cuba. The reduction of energy dependence in Cuba entails more intensive exploitation of local renewable energy resources: biomass, wind, or solar radiation. However, the exploitation of these resources depends on the area that is dedicated to them, such that solar panels, wind turbines, and biomass crops must compete to occupy land surfaces across the country.

Fig. 6 provides a comparison of the physical land surface needed for the use of each renewable resource assuming that it will provide 100% of the Cuban electricity demand by 2030. The physical land surface includes the spacing between devices avoiding, for example, the partial shadowing of the energy yield of PV systems or the interference due to the wake of a wind turbine with others downwind. Utility-scale PV has an installed spacing density of 100–300 MW/km<sup>2</sup>, which is assumed based on estimations performed by Ref. [91] for different types of PV modules with efficiencies of 0.12–0.20 and areas of 1.3–1.7 m<sup>2</sup>.

For wind turbines, the range 7.1–13.6 MW/km<sup>2</sup> is used for the estimations [5,92]. For biomass, the occupied surface area is based on the harvesting area needed to generate electricity during 150 days from bagasse and 225 days from marabu. This estimation also combines minimal and maximum expected generation rates in terms of harvesting yields, technological efficiencies, and biomass properties.

The comparison between the physical land surfaces needed by the different kinds of renewable energies shows that widespread use of solar or wind energy should account for 0.1–1.9% of Cuba's land, respectively. The estimation for biomass is between 14.6% and 128%.

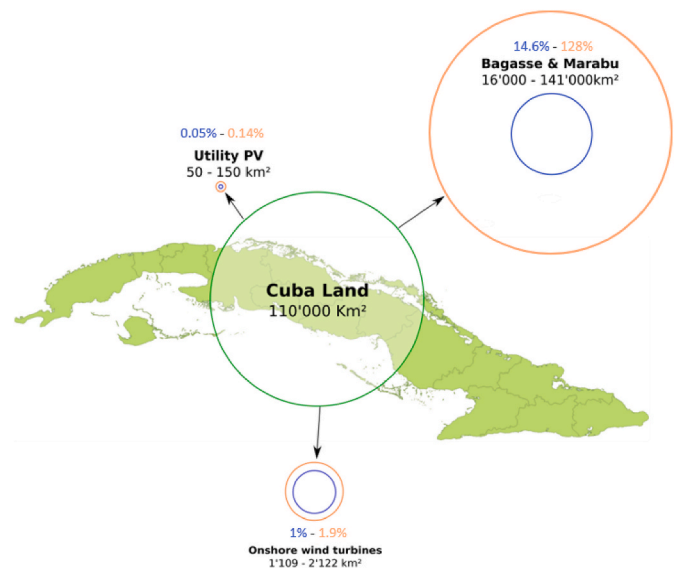


Fig. 6. Land surface required to meet Cuban electricity demand from solar, wind, and biomass resources. The central green circle corresponds to the surface of the country. The other circles represent the surface required to install intermittent energy production infrastructure with the capacity to generate 100% of the country's electricity demand. The larger red circles correspond to the critical case in which the maximum surface is needed and the smaller blue circles correspond to the cases of minimum surface required. The central green circle corresponds to the surface of the country.

### 3.2. Design of the scenarios

Since solar radiation and wind are intermittent energy sources, the energy produced by PV panels and wind turbines will depend on the local atmospheric conditions and their fluctuations over time. To consider how much of these intermittent sources of energy can be effectively introduced into the energy mix of the island an analysis of the solar and wind potential hourly fluctuations and the hourly electricity demand of Cuba was performed. The one-year-long hourly profiles of the intermittent potentials in terms of their capacity factors were obtained from climate simulations results from the weather research and forecasting (WRF) model ran over Cuba [47,48,93]. The hourly data of wind speed and solar radiation was used to estimate the average capacity factors profiles of typical utility-scale solar PV panels and wind turbines [92]. The energy demand hourly profile was obtained from the model for analysis of energy demand (MAED) [94].

Hourly energy analysis was performed considering the following three components of the system: the electricity demand, the intermittent sources, and the controllable sources. The electricity demand of the country is hourly fulfilled by intermittent sources that cannot produce energy permanently (i.e., solar PV panels and wind turbines) and by controllable sources whose energy production can follow the variations of the demand and satisfy it every hour. Several calculations have been performed by introducing into the electricity mix different amounts of energy produced from intermittent sources (expressed as percentages of the electricity production ranging from 0% to 100%). In each of these calculations, the hourly electricity demand is first met by the intermittent sources, then the remaining electricity to be supplied is produced by controllable sources. Many technologies, such as gas power plants, can modulate their energy production to follow fluctuations in electricity demand, but cannot shut down completely. For these reasons, it was assumed that controllable energy sources could not fall below a minimum threshold equal to 20% of its maximum possible energy production [95].

The scenarios considered in this work do not involve electrical energy storage. Indeed, there are different storage technologies with different costs, which multiplies the possible options and makes the

analysis of strategies more complicated. In the first step, it has been decided to publish only the analysis of the scenarios without electrical energy storage. The results obtained with storage will be the subject of a second publication.

For each percentage of intermittent sources introduced into the mix, the distribution between solar and wind sources is chosen to minimize the TAC.

The losses generated along the grid between the energy sources and the demand were considered as 15.5% assuming they will remain the same as in the current situation.

The results of this analysis are summarized in Fig. 7. They show three important points: Controllable sources cannot be completely removed, and their full installed capacity must be maintained regardless of the amount of intermittent sources of energy introduced into the mix (Fig. 7-a). The energy produced by the intermittent sources entirely substitutes the energy produced by the controllable sources as long as it does not exceed 40% of the electricity demand. Beyond 40%, the system is saturated, intermittent sources only partially replace controllable energy so solar and wind cannot satisfy the demand without the help of controllable sources and overproduce energy (Fig. 7-b). The most economical share between solar and wind energy changes with the percentage of the electrical production it supplies. When this percentage is less than 20%, it is more cost-effective to use only solar and no wind. Beyond 20%, the best profitability is obtained by increasing progressively the percentages of wind compared to solar.

Three specific scenarios have been analyzed. The baseline scenario (BL) is based on the official projection for 2030 and corresponds to 6% of the electricity supplied by wind and solar sources. Two scenarios (Int-a and Int-b) for which the intermittent sources reach respectively 30% and 60% of the electricity production. The scenario Int-a corresponds to the scenario in which GHG emissions are reduced to levels equal to those of the 2015 BCE baseline scenario. The reduction in GHG emissions due to the introduction of solar and wind sources compensates the increase resulting from projected energy growth during 2015–2030. Therefore, carbon offsetting begins to have a net effect on the economic balance of the Cuban electricity generation system. The scenario Int-b corresponds to the maximum economic benefit (see Fig. 11).

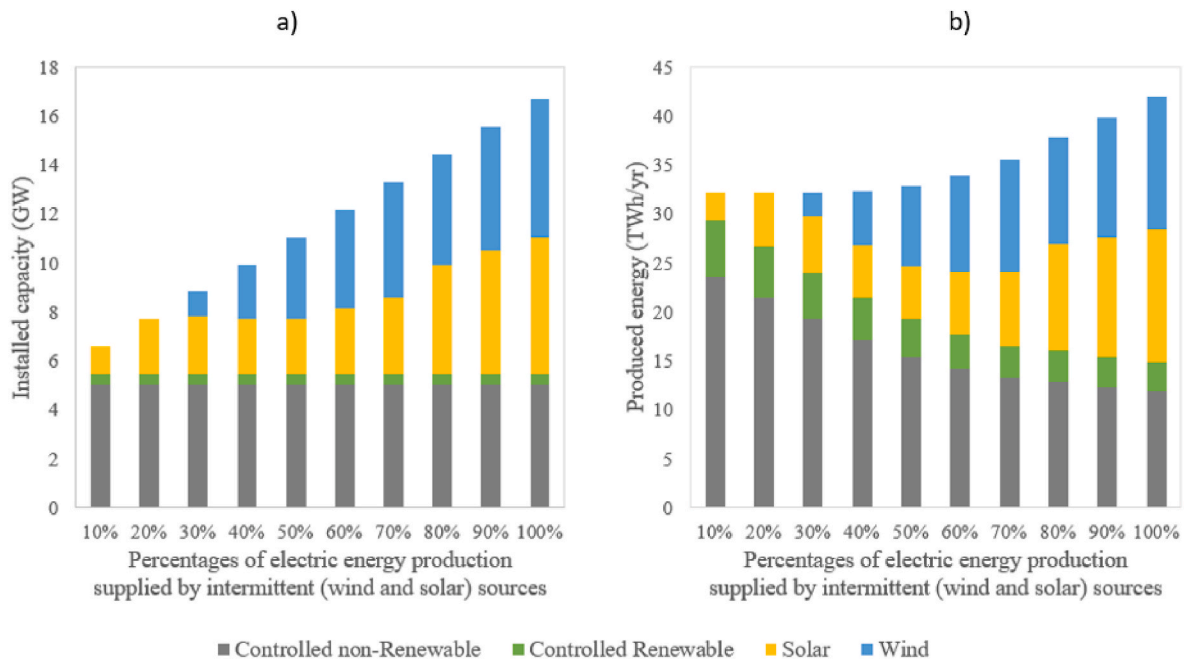


Fig. 7. Installed capacity (a) and produced energy (b) for different percentages of the electricity production supplied by solar energy source without energy storage. The energy sources shown correspond to solar, wind, controllable renewable (hydropower and biomass), and controllable non-renewable (CCGT, thermoelectric, and generator set). The repartition between the solar and wind sources is chosen as the proportion that bring the greatest economic benefit.



In the scenarios considered, the energy produced by controllable sources decreases as they are replaced by solar and wind energy. For each scenario, the reduction in energy from controllable sources was determined to affect each technology by the same percentage. This is to account for the constraints highlighted by our analysis based on hourly variations in resources and electricity demand: the capacity of controllable sources must be maintained despite the addition of solar and wind power (Fig. 7), and controllable sources, such as gas or oil thermoelectric plants, cannot be completely shut down and must always produce a minimum amount of energy (20%).

The importation of primary energy sources (i.e. imported oil and imported oil subproducts) is progressively reduced with scenarios Int-a and Int-b (Fig. 8). Even so, a small amount of imported primary resources is maintained. The main reason for this is the low quality of the Cuban oil since it can only be partially refined to obtain low-quality oil subproducts. Thus the importation of fully refined oil subproducts or crude oil of better quality remains necessary to supply the fuels demanded by the industry and transport macrosectors.

### 3.3. Comparison of the different scenarios

Compared to the situation in 2015, the BL scenario for 2030 aims to use domestic primary resources and RES as much as possible. The BL scenario foresees that primary biomass resources increase strongly (from 6 to 34 TWh/yr) while solar, wind, and hydroelectric production increases too but remains low (from 0.02 TWh/yr to 0.52 TWh/yr for the solar, from 0.04 TWh/yr to 1.53 TWh/yr for the wind, and 0.05 TWh/yr to 0.99 TWh/yr for the hydroelectric). Domestic gas and oil production increases slightly (from 7 to 11 TWh/yr for gas and from 41 TWh/yr to

56 TWh/yr for oil). Oil importations (9 TWh/yr) are maintained constant while oil subproducts importations are reduced (from 31 TWh/yr to 18 TWh/yr). By reducing imports of oil subproducts, the country's energy security and resource sustainability are improved.

Fig. 9 shows the primary resources used in scenarios BL, Int-a, and Int-b. The production of electricity by intermittent sources (solar and wind) is lower in the BL scenario (2 TWh/yr) than in the scenarios Int-a (8.5 TWh/yr) and Int-b (17 TWh/yr). The amount of biomass, water, domestic gas, domestic oil, imported oil, and imported oil sub products is progressively reduced with the introduction of solar and wind.

Fig. 10 shows the differences in CCTAC between the scenarios Int-a, Int-b, and the reference scenario BL (i.e.  $\Delta$ CCTAC). It distinguishes the different economic consequences of implementing the scenarios Int-a and Int-b in terms of costs to be paid (negative part of the bars) and benefits from savings and carbon compensation (positive part of the bars). The  $\Delta$ CCTAC without the carbon compensation is equal to the  $\Delta$ TAC.

The necessary costs for the implementation of the scenarios are attributable to the investments and fixed costs related to the solar installation which do not require any variable or fuel costs. Since the installed capacity of the different powerplants and generator sets supplying the controllable sources must be preserved, savings are achieved only by reducing their variable and fuel costs.

Fig. 10 shows that for scenarios Int-a and Int-b, the benefits exceed the costs. The Int-a scenario requires 377 million \$/year of investment in solar panels and wind turbines to finance their operating costs (i.e., capital and fixed costs). On the other hand, this scenario can save 702 million \$/year by reducing fuel and variable costs of the different powerplants and generator sets, and provides 4.2 million \$/yr of carbon

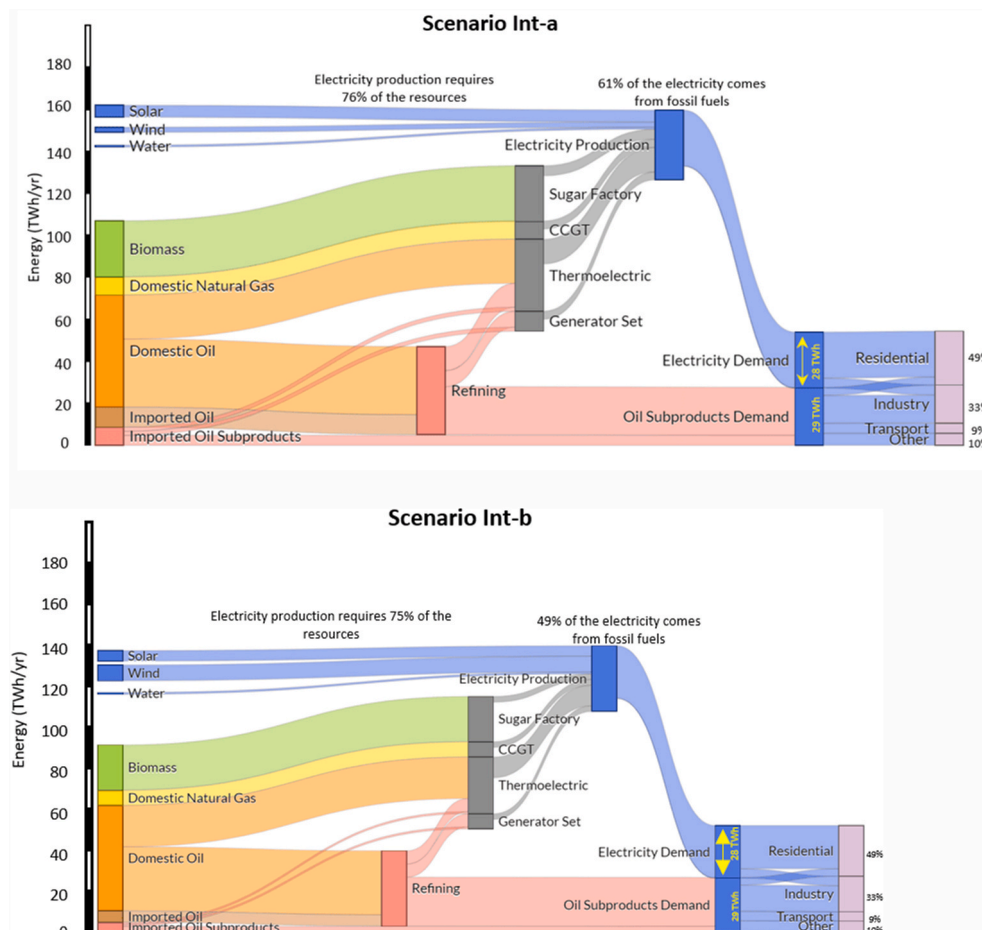


Fig. 8. Sankey energy flow diagrams for Cuba's energy scenarios: Int-a (30% of intermittent) and Int-b (60% of intermittent).



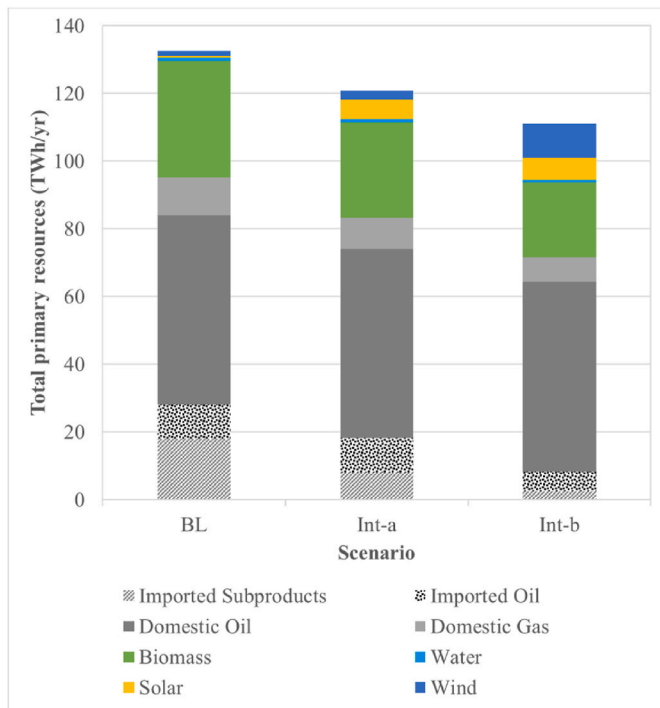


Fig. 9. Primary resources estimated for the energy transition scenarios of Cuba: BL, Int-a, and Int-b.

compensation, so the net benefit of the scenario can reach 329 million \$/yr. The scenario Int-b shows a cost of 917 million \$/year to fund the solar and wind farms and benefit shares between 1 389 million \$/year saved from fuel and variable costs due to the usage reduction in the controllable sources and 197 million \$/year of carbon compensation which provides 669 million \$/year of net benefit.

It is interesting to note that the cost (i.e. investment in solar and wind) of scenario Int-b is two times the cost of scenario Int-a. Similarly,

the benefit (i.e. the fuel and variable costs savings, and the carbon compensation) of scenario Int-b is two times the benefit of scenario Int-a. As a result, the net benefit of scenario Int-b is twice the net benefit of scenario Int-a.

Fig. 11 shows the economic benefits evaluated for scenarios with percentages of intermittent between 0% and 100% of the electricity production of Cuba in 2030. These are plotted in terms of the difference in the total annual costs difference between the BL scenario and the scenarios Int-a and Int-b including the carbon compensation ( $\Delta$ CCTAC) and without carbon compensation ( $\Delta$ TAC).

The repartition between solar and wind shown in the boxes of Fig. 11 corresponds to the one that gives the greatest benefit in terms of  $\Delta$ TAC for each percentage of intermittent.

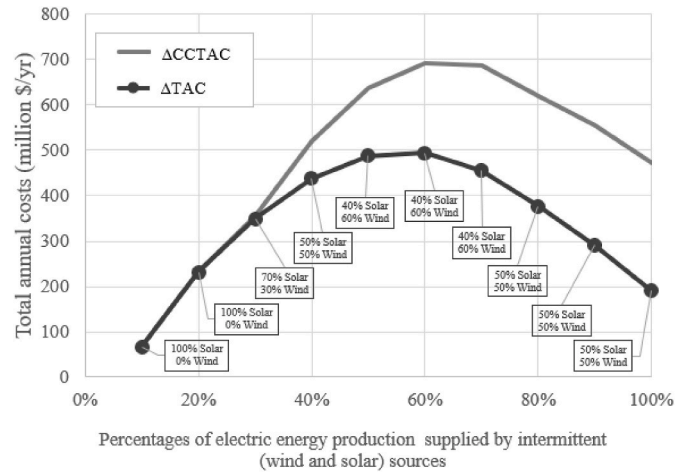


Fig. 11. Total annual costs difference between the scenarios Int-a and Int-b, and the BL including carbon compensation ( $\Delta$ CCTAC) and without carbon compensation ( $\Delta$ TAC). The percentages in the boxes correspond to the repartition between solar and wind sources that makes the greatest benefit (maximum  $\Delta$ CCTAC and maximum  $\Delta$ TAC) for each scenario.

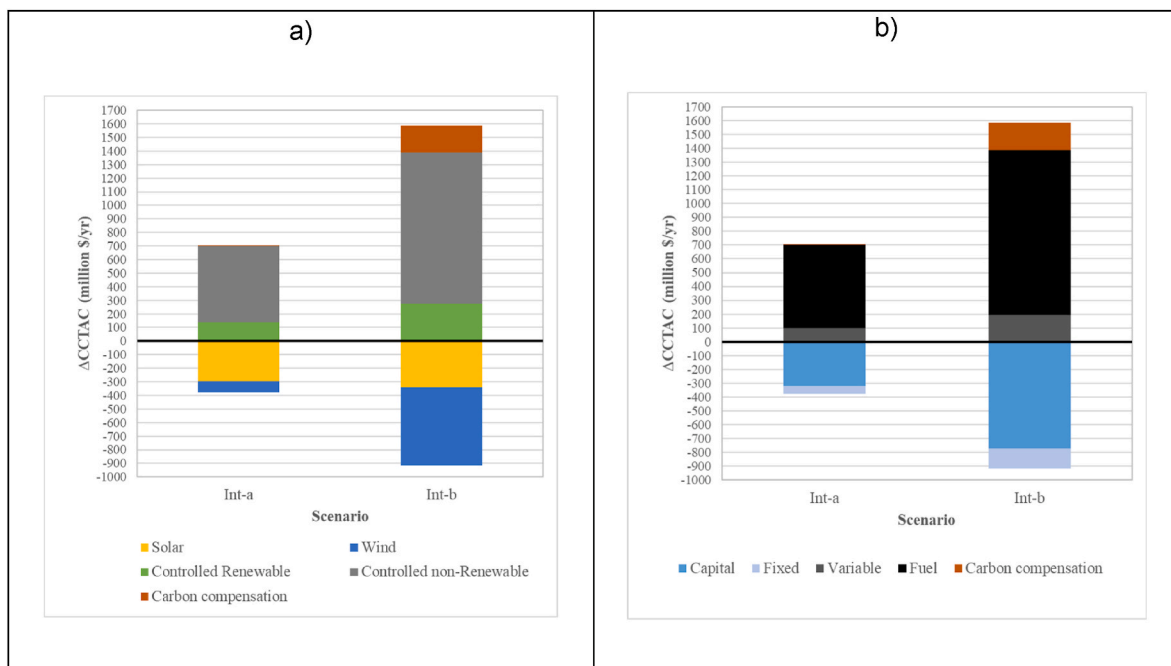


Fig. 10. Components of the total annual costs difference between the scenarios Int-a and Int-b and the BL including carbon compensation ( $\Delta$ CCTAC): a) energy production technologies (solar and thermoelectric, and b) types of costs components (capital, fixed, variable, and fuel). The carbon compensation is included in both parts of the figure (a and b).

The maximum benefit is achieved in the scenario where 60% of electricity is generated from intermittent sources, and where the intermittence share is 40% for solar and 60% for wind. In this scenario the economic benefit without carbon compensation ( $\Delta$ TAC) achieves nearly 500 million\$/yr, and with carbon compensation ( $\Delta$ CCTAC) nearly 700 million \$/yr.

The different indicators mentioned in Table 8 are computed for scenarios Int-a and Int-b using Equation (2). The introduction of 30% and 60% of intermittent sources (solar and wind) in the energy system decreases oil consumption (Fig. 9) which has a positive impact on the different indicators: energy security, carbon footprint, air quality, and economic savings (Fig. 1). The reduction of fuel imports leads to improve the energy security indicator (35.4% for Int-a and 70.3 for Int-b) which is an important result considering the strategic goals of the Cuban government of reducing energy dependency from abroad. Replacing expensive imported fossil fuels with less expensive intermittent sources, such as solar and wind power, leads to an increase in economic indicator. Air quality indicator is also improved with the introduction of intermittent energy sources in the energy strategy of Cuba (Fig. 12). Even so, this improvement is relatively small, it improves 5.6% and 7.5% in the Int-a and Int-b scenarios respectively. These differences are linked with the reduction of the primary energy needed by the non-renewable controllable sources.

The economic indicator (CCTAC) also shows an improvement with the introduction of intermittent energy sources. This indicator improves with respect to BL scenario by 8.2% and 16.6% for the scenarios Int-a and Int-b respectively (Fig. 12).

The second largest improvement is related to the carbon footprint, 21.3% and 42.1% for the scenarios Int-a and Int-b respectively.

#### 4. Alternative strategies for the energy demand: introduction of electric vehicles

In the Int-a and Int-b scenarios, Cuba still needs to import refined fuels which are mainly required by the industrial and transport sectors. Therefore, energy security can be improved by reducing the oil sub-products demanded by these activity macro sectors (i.e. MS1 and MS7). Currently, the Cuban vehicle fleet is based only on internal combustion vehicles (ICVs), most of them being very old and using outdated technologies. Although there are relatively few vehicles in Cuba (38 cars per 1 000 inhabitants), the 362 000 vehicles of the entire fleet still require around 336 400 tons of oil subproducts (diesel and gasoline) per year [96]. Consequently, the shift from ICVs to electric vehicles (EVs) may reduce the consumption of oil subproducts and improve simultaneously the energy security and carbon fingerprint indicators.

Calculations show that refined fuel consumption should decrease from 336 400 tons/year to 82 600 tons/year which reduces the energy security indicator to the value of 0.82 (i.e. an improvement of 18%). But if the consumption of refined fuel by the ICVs is reduced, the electricity demand will increase due to the new EVs. Thus, the total electricity consumption will increase by 8.5% to reach 30.2 TWh/yr. This increase is compensated by additional solar and wind electricity production which reaches 11 TWh/yr in scenario Int-a, and 28 TWh/yr in scenario Int-b.

To estimate the air quality impact of switching from ICVs to EVs, two additional scenarios (called Int-aEV and Int-bEV) were designed by

**Table 8**

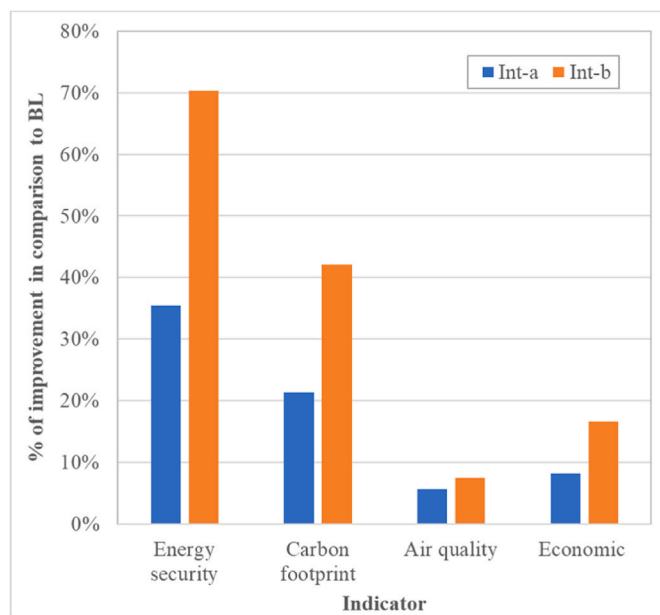
Characteristics used for the calculation of the indicators of the scenarios of energy transition in Cuba

Indicator (I)	Characteristic (C)
Energy security	Energy imports (TWh/yr)
Carbon footprint	CO <sub>2</sub> emissions (Ton/yr)
Air quality	Population exposure to PM <sub>2.5</sub> concentrations (µg/m <sup>3</sup> )
Economic	CCTAC of the energy system (million \$/yr)

**Table 9**

Potential of energy resources and oil and gas reserves of Cuba

Resources	Potential (million tons/yr)	Potential (GWh/yr)	Reserves (yr)
Solar energy	–	24 433 161	–
Wind energy	–	2 418–28 207	–
Marabu biomass	21	2 500–26 628	–
Crude oil and associated gas	5	15 110–20 870	155
Bagasse biomass	4.8	1 700–6 500	–
Water energy	–	985	–



**Fig. 12.** Percentage of improvement of scenarios Int-a and Int-b compared to the 2030 baseline scenario (BL) for the Cuban energy transition.

replacing all ICVs with EVs in the Int-a and Int-b scenarios. The total emissions of different pollutants (NO<sub>x</sub>, SO<sub>x</sub>, PM<sub>2.5</sub>, VOC, and CO<sub>2</sub>) were evaluated for each of these scenarios. Fig. 13 shows the normalized difference in the emissions ( $\Delta$ ) between the BL scenario and the scenarios Int-a, Int-b, Int-aEV, and Int-bEV for the pollutants NO<sub>x</sub>, SO<sub>x</sub>, PM<sub>2.5</sub>, VOC, and CO<sub>2</sub>. Only sectors of energy and transformation industries (MS1) and road transport (MS7) are presented since they are the only sectors with changes in the emissions associated to fleet replacement.

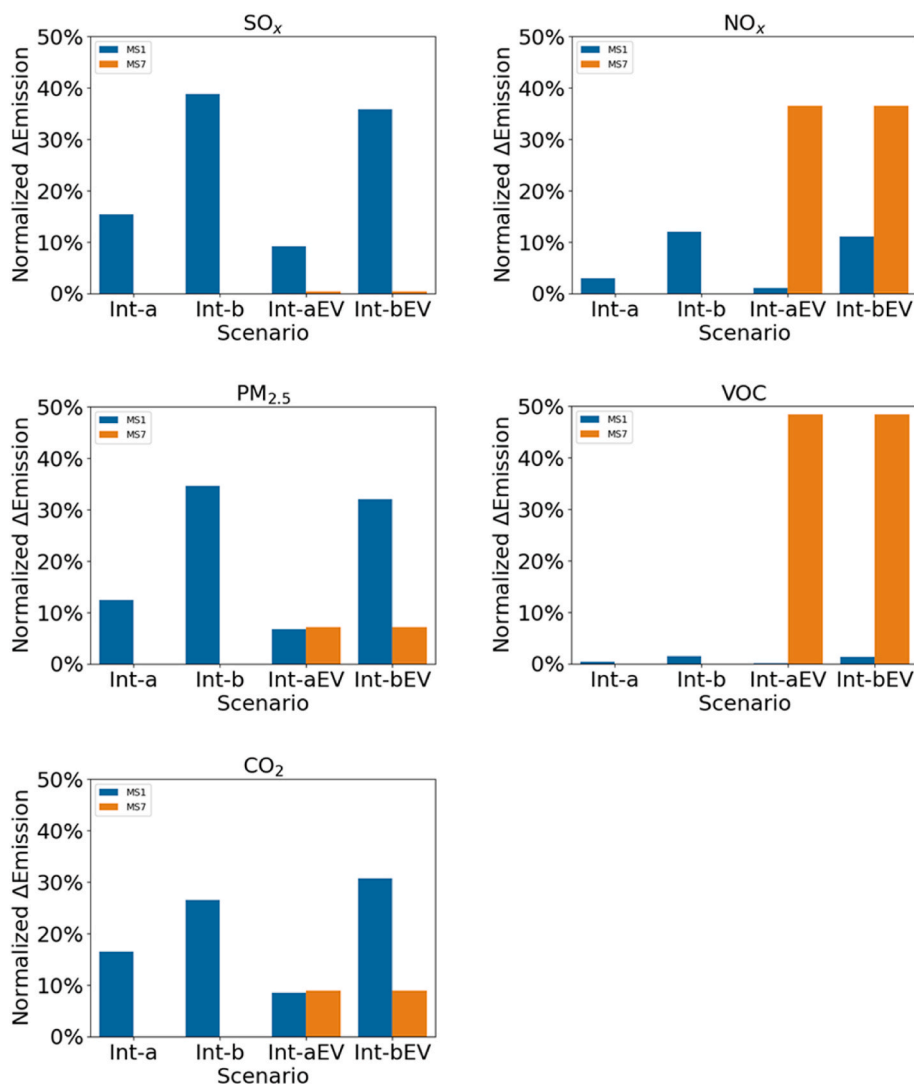
The emissions of the pollutants NO<sub>x</sub>, SO<sub>x</sub>, PM<sub>2.5</sub>, VOC, and CO<sub>2</sub> vary by the introduction of intermittent energy sources in the Cuban mix, differently, the NH<sub>3</sub> is invariant since it is not linked to sectors MS1 or MS7, for this reason, this pollutant is not plotted.

PM<sub>2.5</sub> and SO<sub>x</sub> emissions reductions are linked to MS1, meanwhile, NO<sub>x</sub> and VOC are pollutants for which their emissions reductions are mainly related to MS7.

Reductions of NO<sub>x</sub> and VOC emissions are considered for all the evaluated scenarios, being the scenarios with the introduction of EV (Int-aEV and Int-bEV) the ones with the largest emission reductions of these pollutants mainly driven by the electrification of the MS7 macrosector.

The reductions of CO<sub>2</sub> emissions are observed in all scenarios (Int-a, Int-b, Int-aEV, and Int-bEV).

For MS1, larger reductions of CO<sub>2</sub> are achieved with the current ICVs (scenarios Int-a and Int-b) than with the EVs (scenarios Int-aEV and Int-bEV). This is explained by how the electricity demanded by the EVs introduced is produced. In Cuba, this electricity is supplied mainly by



**Fig. 13.** Normalized differences between the emissions in the baseline scenario for 2030 (BL), and Cuba's energy scenarios analyzed (Int-a, Int-b, Int-aEV, and Int-bEV) in 2030 for the pollutants: NO<sub>x</sub>, SO<sub>x</sub>, PM<sub>2.5</sub>, VOC, and CO<sub>2</sub>. The energy-demanding sectors in the plot are MS1 (combustion in energy and transformation industries) and MS7 (road transport).

thermoelectric plants that must use a greater amount of fuel to increase their production, which leads to higher CO<sub>2</sub> emissions.

Both scenarios, Int-aEV and Int-bEV, have the same CO<sub>2</sub> emission reductions associated with MS7, since the ICV base fleet is the same and is considered to be completely replaced by EV. That is, the amount of fuel used in the ICVs is no longer necessary when the EVs are introduced, which leads to a reduction of CO<sub>2</sub> in the same proportion in the Int-aEV and Int-bEV scenarios.

## 5. Discussion

The discussion addresses the various uncertainties and limitations of the analysis developed in this article. As has already been mentioned, one of the limitations of this study is that it does not consider energy storage. The integration of storage solutions, which typically incur substantial expenses, is expected to elevate the overall costs associated with intermittent energy sources. On the other hand, storage should reduce the capacity of controllable sources by providing energy in their place during peak demand. This should only have a noticeable effect when the share of intermittent sources is high (>60%). We have therefore planned a future study to address this subject.

Another limitation comes from the uncertainties in the parameters

necessary for the estimation of the indicators characterizing the different scenarios. Some of these parameters, such as capacity factors of solar and wind resources, energy demand, and pollutant emissions, are likely to vary from one year to the next. However, the most important source of uncertainty comes from costs, in particular, the cost of fossil fuels and the investment costs of the various technologies used to generate electricity. In fact, almost all of the technologies used in Cuba are very old, especially those using fossil fuels to produce controllable energy, e.g., old thermoelectric power plants. These technologies have already been used well beyond their useful life. Moreover, we are not supposed to know the intentions of the Cuban authorities regarding the renewal of this old infrastructure. It is therefore difficult to predict the depreciation of the capital cost of technologies used for controllable sources even in the near future. To overcome this difficulty our analysis is based on the calculation of the cost differences between the baseline scenario (official projection of the Cuban government for 2030) and the different alternative scenarios designed also for the year 2030. Using these differences, the scenario cost comparison depends only on the variable and fossil fuel costs of technologies used for controllable sources and of the capital costs of technologies used for intermittent sources (Fig. 10). Uncertainties related to the investment costs of technologies used for intermittent sources (wind turbines and solar panels)

are relatively easy to anticipate because these costs have continuously decreased over time during the past decades. We can expect this trend to continue until 2030 and probably beyond. In contrast, fossil fuel prices are difficult to predict because they vary erratically. However, despite the uncertainties surrounding the evolution of fossil fuel costs, we do not foresee a strong and long-lasting decline in these costs in the near future. It is therefore certain that the savings generated by reducing fossil fuel consumption will easily compensate for the investment costs of intermittent energies.

Other limitations are related to the geopolitical situation of Cuba. While wind and solar use free energy once installed, they require a significant and immediate investment. However, due to the embargo affecting the country, the Cuban authorities have difficulty accessing the banking system to borrow the money necessary for investments. The embargo also limits Cuba's access to international markets, making the purchase of solar panels, wind turbines, and electric vehicles limited.

## 6. Conclusions

The current situation of Cuban energy system is vulnerable since the country strongly depends of energy imports. This vulnerability is evidenced through the study of different aspects such as energy security, carbon footprint, air quality, and economic. The introduction of renewable intermittent sources (solar and wind) should improve all these aspects by reducing fossil fuel imports and CO<sub>2</sub> emissions, improving air quality, and generating economic benefits. These positive effects result from the replacement of fossil fuel consumption with solar and wind energy.

Despite Cuba's enormous solar energy potential, the best option is to use combined solar and wind energy. However, in the absence of energy storage, solar and wind resources cannot fully meet energy demand due to their intermittency, so the full capacity of controllable sources must be maintained.

The introduction of intermittent sources causes the reduction of fossil fuel consumption used for electricity production but does not lead to an important reduction of refined fuels which are used mainly in the transportation sector. The reduction in refined fuels can be achieved through the introduction of EVs to replace current ICVs, which will bring further positive benefits.

Because of its geopolitical situation, Cuba has more difficulty than other countries in accessing international markets, which could make the implementation of the energy transition in this country difficult. Nevertheless, the Cuban authorities can be advised to invest progressively in solar and wind energy. Every time solar and wind capacity is progressively increased, Cuban authorities will save on fuel costs and achieve environmental improvements and energy security. The money saved could be gradually reinvested in new solar and wind power installations. As long as intermittent sources provide less than 60% of the electricity demand, the economic benefits will be increasingly significant. Beyond 60% they will still be positive but will start to decrease.

At this stage, it will be time to refine the study already carried out to help Cuban authorities choose between investing in the renewal of obsolete technologies for the production of controllable energy or reducing the capacity of these sources by investing in storage technologies.

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## Authors contributions

MG wrote part of the manuscript (50%), performed the costs calculations, analysis of scenarios, and consolidated the manuscript. JM wrote part of the manuscript (20%), performed the energy calculations, and air quality modeling. EM verified the data and parameters used for the evaluation of the different scenarios, and also contributed to the validation of the latest versions of the manuscript. HM supplied the data and parameters used for the evaluation of the different scenarios, and also contributed to the validation of the latest versions of the manuscript. AC wrote part of the manuscript (30%), contributed to the scenarios design and evaluation, is the main designer of the indicators approach, and managed the research project.

## 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.

## Data availability

Data will be made available on request.

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