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Transitioning from 100 percent natural gas power to include renewable energy in a hydrocarbon economy

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ABSTRACT

Transitioning from heavy carbon fuels such as coal and oil to lighter carbon fuels and renewable energy is necessary to reduce greenhouse gas emissions to keep global temperatures less than 2 °C above pre-industrial levels. This study considers the transition from full natural gas power generation to include renewables via utility-scale photovoltaic (PV) facilities in the Caribbean small island state of Trinidad and Tobago. By using the EnergyPLAN software and hourly solar radiation and electricity data, the electric power generation and quantities of natural gas avoided for several hundred-megawatt PV facilities were estimated. The direct and opportunity savings that could be derived from the avoided natural gas is substantial for a small island state. Additionally, payback periods, avoided carbon dioxide emissions from the power generation sector and levelized costs of electricity make a strong economic case for utility-scale PV. As solar PV is intermittent, a smart energy system is suggested to provide affordable and efficient electricity generation and to include other renewable energy sources such as wind power and electric vehicles.

1. Introduction

The role of energy is critical for the development of most Small Island Developing States (SIDS). Globally, energy access has promoted social, economic and environmental challenges [1,2]. The United Nations (UN) “Agenda 2030” aims to ensure affordable, reliable, universal access and sustainable energy within developing nations using untapped renewable energy resources [3]. The Caribbean Community and Common Market (CARICOM) region provides a substantial example that there is copious unused renewable potential [4–6] for island states that are all highly dependent on fossil fuels.

The CARICOM is an intergovernmental association making up twenty SIDS nations with objectives promoting sustained economic, social and environmental development all the while accelerating regional trade [7]. The longstanding use of renewable energy can therefore be achieved through these objectives along with the reinforcement of the CARICOM Energy Policy [8]. Transitioning from fossil fuel power generation to renewables in the CARICOM region is important given the islands’ vulnerability to climate change effects such as sea level rise and extreme climate systems [9,10] together with high and unstable fossil fuel prices.

Within developed countries, the increasing global energy demand is an indicator of increased economic growth and the current energy pattern is dependent on diminishing fossil fuels that are contributing to unprecedented levels of greenhouse gases (GHGs) [11]. Therein lies one of the negative effects responsible for the vulnerability of SIDS. Thus, the need to transform and challenge economies has been adopted by several islands within the CARICOM region through the ratification of the Paris Agreement [12]. SIDS face the challenge of fulfilling a growing energy demand and at the same time transitioning to a low carbon energy system. Geographically located within the Caribbean, the CARICOM region possesses many forms of renewable energy such as wind, solar, geothermal and hydroelectric power [13].

Many countries such as Germany [14–16], Russia [17], USA [18] and China [19,20] have transitioned their power generation sector through the increased use of the lower carbon fuel natural gas. In hydrocarbon dominated economies such as the Gulf Cooperation Council (GCC), which include countries such as United Arab Emirates (UAE), Qatar, Bahrain and Oman, natural gas is the primary fuel

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Abbreviations

CARICOM	Caribbean Community and Common Market
CHP	combined heat and power
CO_2	carbon dioxide
EIA	Energy Information Administration
GCC	Gulf Cooperation Council
GHGs	greenhouse gases
GWh	Gigawatt hours
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power producer
IRENA	International Renewable Energy Agency
LCOE	levelized cost of electricity
LNG	liquefied natural gas
MMBtu	million British Thermal Units
MMSCF	million standard cubic feet
MW	megawatt
MWh	megawatt hours
NDC	nationally determined contribution
NREL	National Renewable Energy Laboratory
O + M	Operations and Maintenance
OAS	Organization of American States
PLIE	Point Lisas Industrial Estate
PPA	Power Production Agreement
PV	photovoltaics
SDG-7	Sustainable Goal 7
SIDS	Small Island Developing State
T&TEC	Trinidad and Tobago Electricity Commission
TTMS	Trinidad and Tobago Meteorological Service
UNDESA	United Nations Department of Economic and Social Affairs
UNFCCC	United Nations Framework Climate Change Convention
US$	United States Dollars
WMO	World Meteorological Office

for electricity generation [21,22]. Whilst most countries across the globe are now trying to transition from carbon heavy fuels to natural gas and eventually renewables, Trinidad and Tobago is in the unique position of already having 100% of power generation from natural gas. It is also the only small island developing state with its own active native supply of hydrocarbons that has resulted in a predominantly hydrocarbon economy. During the 1980's, Trinidad and Tobago, a hydrocarbon rich nation within the Caribbean, transitioned from oil to natural gas power generation [23]. Similar to major hydrocarbon producing economies, Trinidad and Tobago's economy is unique in using natural gas as the sole generation fuel. Currently with fluctuating gas supplies to facilitate the downstream petrochemical and the export liquefied natural gas (LNG) sector [24], along with global trends of sustainable energy transitions, the need to deploy renewable energy is critical to achieving transformation for the energy demand in Trinidad and Tobago. The diversification of the energy matrix to include renewable energy will allow the island state to redirect the 'avoided' natural gas to its petrochemical sector for the production of higher value carbon products. Furthermore, the accompanying reduced emissions of carbon dioxide (CO_2) will contribute to the country's nationally determined contributions to the Paris Agreement. To this end, Trinidad and Tobago has started exploring solar PV energy (112 MW) to reduce annual avoided GHGs to 0.15 million tonne per carbon dioxide per year by 2022 [25].

While many CARICOM nations involved with the Paris Agreement have aimed for 100% renewable energy grid power by 2050 [26], Trinidad and Tobago's current renewable energy grid power goal stands at 10% by 2021 [27]. Currently the Caribbean region lacks guidance in understanding the various pathways in achieving full renewable energy transition [28,29].

Therefore, this present study examines the use of multiple scenarios using techno-economic assessments for evaluating transition pathways toward lower carbon emissions. We examine scenarios where 100–700 MW solar PV are increased in 100 MW increments and added into the power generation matrix. For these resulting scenarios, cost of natural gas for power generation, opportunity cost of avoided natural gas, payback times for such facilities, levelized cost of electricity of utility-scale solar PV and avoided carbon emissions are assessed. Additionally, certain characteristics of solar PV generated electricity and natural gas power generation are discussed in the context of smart energy systems. The inclusion of utility-scale solar PV into Trinidad and Tobago's national electricity grid would require a smart energy system as smart energy systems can efficiently and effectively monitor, regulate and optimize electricity generation [30,31]. The results of this study could be useful to policy makers in making decisions to transition from a 100% natural gas economy to a future with renewable energy. The overview of the energy situation in Trinidad and Tobago and the methods used in this study are described in sections 2 and 3, respectively. Results are presented in section 4 and discussed in section 5. Conclusions and recommendations are made in section 6.

2. Country overview

Trinidad and Tobago is a twin island republic and is the southernmost island state in the Caribbean chain of islands with an area of 5130 km^2 and a population of approximately 1.4 million persons [32]. The island state is located just off the coast of north-eastern Venezuela and shares maritime boundaries with Barbados to the northeast, Guyana to the southeast, and Venezuela to the south and the west. The GDP per capita for Trinidad and Tobago in 2017 was reported as US$ 31,300 and the energy use per capita for 2017 was recorded as 6510 kWh [33]. Total carbon dioxide emissions in 2017 was recorded as 17.19 Mt with the electricity generation sector accounting for 4.9 Mt CO_2 or 29% of total CO_2 emissions [33].

Until recently, Trinidad and Tobago was the leading producer of oil in the Caribbean. It has maintained its ranking as the Caribbean's number one producer of natural gas [34]. Trinidad and Tobago is also one of the largest trading partners in the CARICOM trading block which comprises 15 independent states and 5 associate members, all developing countries in the Caribbean region [35].

In Trinidad and Tobago, natural gas is used locally as feedstock to produce downstream petrochemicals including ammonia, urea, and methanol at the Point Lisas Industrial Estate (PLIE) in addition to being sold in the international market as cargoes of liquefied natural gas (LNG). This gas is guaranteed to all independent power producers (IPPs) for their power production requirements and is supplied to the IPPs at no cost [34]. Power generation is the least profitable of its uses as the natural gas supplied to the Trinidad and Tobago Electricity Commission (T&TEC) from the National Gas Company (NGC) is sold for far less than the value it could sell either as feedstock for petrochemical plants at the PLIE or as LNG cargoes [34].

Recent reduction on the production of native natural gas has also led to significant concerns in the energy sector of Trinidad and Tobago [24]. This local shortage of natural gas on the PLIE has led to the shut down or mothballing of some petrochemical plants, including Yara, Methanex and Proman [24] resulting in a reduction of downstream petrochemical products, a loss of taxes collected and a reduction of foreign exchange from a loss of export sales of these commodities. Consequently, it is timely that in this context of accelerating achievement of the United Nations Sustainable Energy Goal of ensuring access to sustainable energy (SDG -7) that consideration can be given to diverting some natural gas from the power generation sector to the downstream sector to secure foreign exchange revenues. This displacement of natural gas would require power generation from renewable energy sources as a replacement modality in line with the 2015 announcement of 10% of power generation from renewable energy by 2021 [36]. Subsequent to this policy, the current administration announced in 2020 the award of a contract for the construction of a 112 MW solar farm at two sites in Trinidad by a consortium including bpTT, Shell and Lightsource bp [25].

Trinidad and Tobago has a strong affiliation to the energy sector with the energy sector accounting for around 34.9% of the country's GDP [37]. The Atlantic LNG facility in Point Fortin in the south-western peninsula of Trinidad houses one of the largest natural gas processing facilities in the Western Hemisphere. Additionally, Phoenix Park Gas Processors Limited (PPGPL) natural gas liquids (NGL) complex which is located in the Port of Savonetta has a processing capacity of almost 2 billion cubic feet (Bcf) per day and an output capacity of 70,000 barrels per day (bbl/d) of NGL [38]. After processing, the gas is then transferred to the various power generators (POWERGEN, Trinidad Generation Unlimited or Trinity power) for generation of electricity and to the petrochemical plants for use as a feedstock [38].

The Trinidad Generation Unlimited (TGU) power plant, formerly known as the Union Estate Power Station, located in La Brea is the second combined cycle plant in the country with a generating capacity of 720 MW [38] and was opened on October 31, 2013 [38]. The other power plants, spread throughout both islands, are also natural gas powered: Powergen Penal (236 MW), Powergen Point Lisas (818 MW), Trinity (225 MW) and Cove in Tobago (16 MW) [38]. Thus, the total installed capacity is 2062 MW [39]. Total installed capacity in 2017 was 2094 MW with a base load of 1064 MW and system peak of 1355 MW [36]. The total electricity generated in 2017 was 9,318,244,000 GWh [39].

For Trinidad and Tobago, with an installed active capacity of 2062 MW [39] and a daily peak demand of 1355 MW [36], both from natural gas generation, it is envisaged that surplus available capacity from gas powered turbines could buffer the intermittency and availability issues of solar PV. However even at the smaller size of 100 MW and moving to 700 MW solar PV, a smart energy system would be needed to regulate gas combustion against solar peaking. An analysis of the implementation of a smart energy system to obtain efficient and affordable solutions using the five power generation stations and the proposed utility-scale PV facilities is an area that needs to be interrogated in greater detail as in past studies [30,40]. Such a study would require information on the five power generation facilities which are not publicly available. For the current study, we use the EnergyPLAN software to model the integration of solar PV into the energy mix for the power generation sector as it was designed to apply the smart energy system concept and it is capable of simulating the entire islands' energy system as more information becomes available.

3. Methods

The methods and subsequent analyses have four main components:

(1) The energy production of seven PV plants starting at 100 MW and increasing at 100 MW increments to 700 MW PV in Trinidad and Tobago. Section 3.1 introduces the EnergyPLAN software which was used to analyse the electrical and insolation input, and estimate the production of solar PV into the national energy matrix (Section 3.1.1). In addition, the input data are described (Section 3.1.2) and the monthly variance between the actual values and modelled output is determined (Section 3.1.3).
(2) The estimation of the natural gas avoided by using this quantum of PV electricity in replacement of natural gas, the associated cost at which this avoided natural gas could be sold in-country (avoided cost) as well as exported (opportunity price) and the payback time as a result of the avoided and opportunity costs of natural gas and the installation costs of each size of PV plant (Section 3.2) are calculated.
(3) The estimation of an LCOE for each size of PV plant (Section 3.3).
(4) The projected reductions in CO_2 emissions for each of these PV plants (Section 3.4).

A summary of all methods as a four-step process map is shown below as Fig. 1. This is a simplified version of a process map introduced by Rashawn et al. [41] which looked at the inclusion of a small solar PV facility in Saudi Arabia. The process map and model has been modified for this study which involves the use of the EnergyPLAN software and a different cost analysis and payback time methodology.

3.1. Estimates of solar PV plant energy production

3.1.1. EnergyPLAN software

EnergyPLAN was used in this study to analyse the current and proposed energy transition scenarios. EnergyPLAN is an energy modelling and forecasting software that is used to assist in the design of national energy planning strategies. The outputs of the software include various energy demands (orange boxes in Fig. 2); this study focuses on electricity demand.

3.1.2. Input and output data for technical analysis

EnergyPLAN requires four sets of input for technical analyses:

1. The annual heating consumption of the district, the annual consumption of electricity, the total electrical hourly demand from power production facilities (in MWh), and flexible demand and electricity consumption from the transport sector, if any.
2. The capacity of photovoltaic power including hourly demand insolation data and wind speeds at various altitudes as well as heat production inputs to district heating.
3. Capacities and operation efficiencies of combined heat and power (CHP) units, power stations, boilers, and heating pumps.
4. Values for some technical limitations, namely, the minimum CHP and power facility percentage of the load to continue grid stability [30].

As Trinidad and Tobago does not have district heating or CHP facilities nor a significant number of electric vehicles, the only variables required were the local hourly electricity demand and the hourly solar insolation.

The hourly demand electricity data were obtained from the national electricity utility, Trinidad and Tobago Electricity Commission (T&TEC) for 2015. This year was used as it was the only recent year for which verified hourly demand power values were

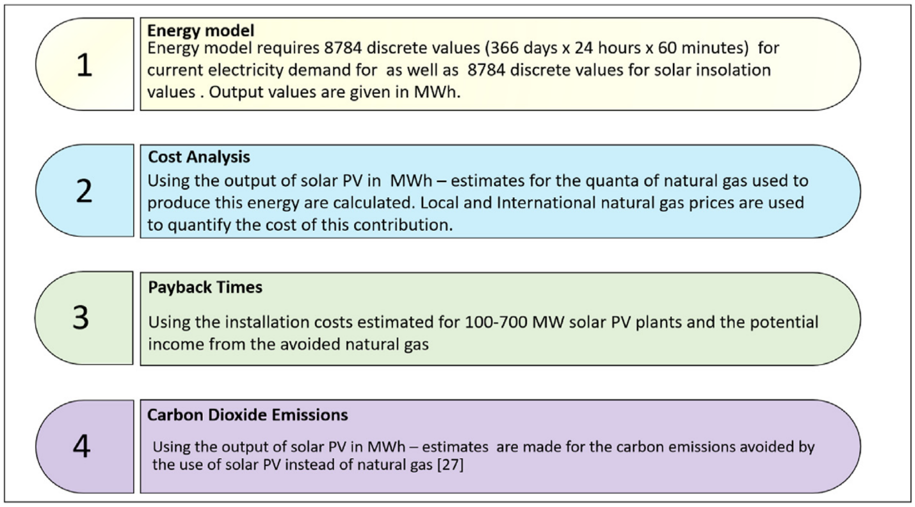

Fig. 1. A process map outlining the methods used (adapted from Rashawn et al. [41]).

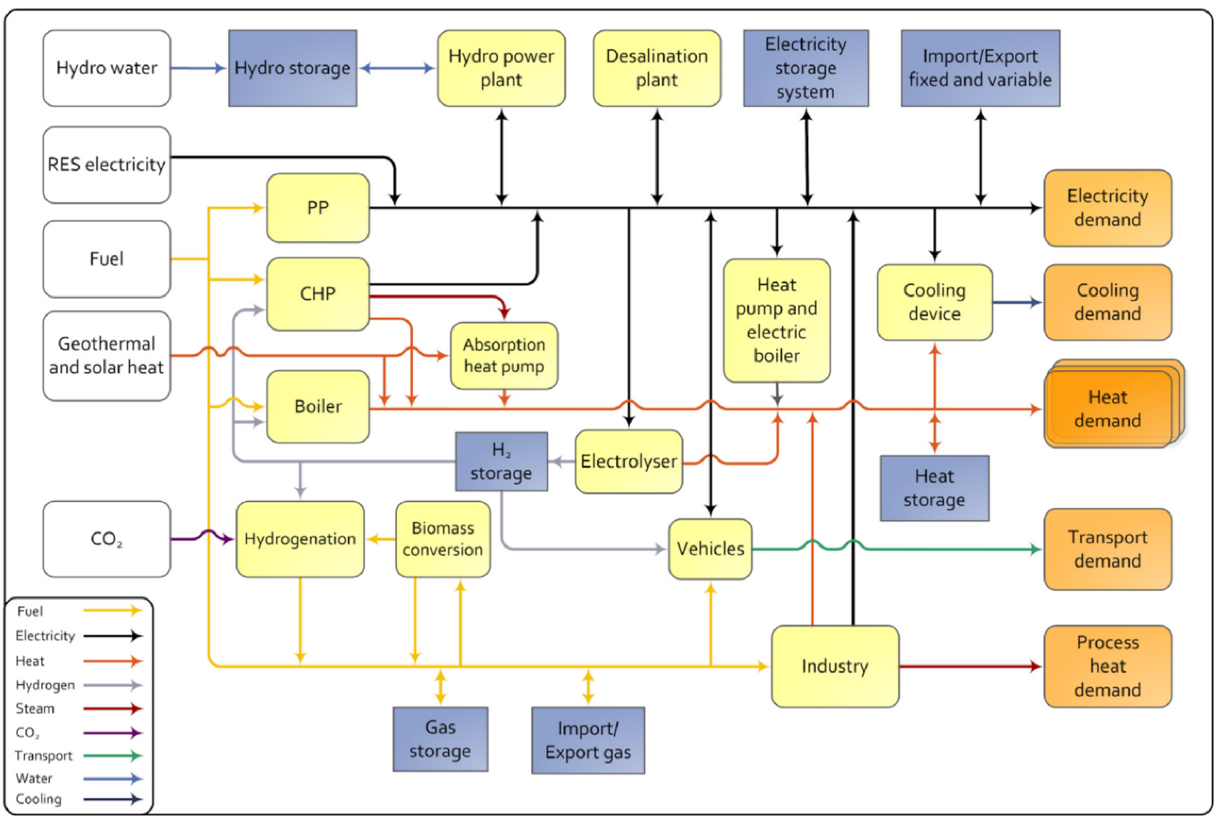

Fig. 2. Schematic of EnergyPLAN pathways [40].

available from the T&TEC [42]. The total installed power generation capacity for Trinidad and Tobago was set at 1800 MW which represents the sum of all natural gas power generation facilities in 2015 [42]. A default grid stabilization of 0.7 was used and the other values were also left at default settings [40].

The hourly demand values of electrical power generation for 2015 were used as input into EnergyPLAN for 366 days - the value for February 28 was repeated as 2015 was not a leap year. An optimised electricity generation profile for Trinidad and Tobago for 2015 is produced and referred to as the EnergyPLAN reference model. Solar PV is chosen for this study in line with the current administration's announcement of 10% power generation from renewable sources by 2021 [25] and subsequently, the announcement in 2020 of the award of a contract for the construction of a 112 MW solar farm across two sites in Trinidad by a consortium comprised bpTT, Shell and Lightsource bp.

In order to calculate the energy production from solar PV, hourly solar insolation data were obtained from the Trinidad and Tobago Meteorological Service (TTMS). The TTMS is tasked with monitoring weather conditions according to World Meteorological

Organization (WMO) standards [43]. Their measurements are taken at two national airports: The Piarco International Airport in Trinidad and the A.N.R. Robinson International airport in Tobago. Hourly demand solar PV insolation data for the TTMS station at Piarco were used for the analysis. Energy production for solar PV was estimated using an assumed capacity factor of 28% [44]. Accordingly, a reference model was established and validated (section 3.1.3).

3.1.3. Validation of an EnergyPLAN reference model for Trinidad and Tobago

To ensure that the EnergyPLAN software models the electricity generation profile of Trinidad and Tobago accurately, it is important to establish that the input values from T&TEC's hourly demand data, when processed, would be replicated accurately, thereby validating the model. The reference model is validated by comparing the actual electricity demand input data values, from T&TEC against the output values of EnergyPLAN [45]. These results are given in section 4.0.

3.2. Natural gas avoided, avoided cost, export opportunity price and payback times for solar PV

The capacity of PV to be included in the power generation scenario was varied from 100 MW to 700 MW in increments of 100 MW. Seven (7) simulations were considered using EnergyPLAN to estimate the electrical demand from the hourly insolation values for solar PV.

3.2.1. Natural gas avoided

The quantity of natural gas that is used to produce 1 MWh of electricity is required and was determined using the following for Trinidad and Tobago: (1) The electrical demand for Trinidad and Tobago for the year 2015 was 9,689,987 MWh [42] and (2) this electrical demand was produced from 107,675 MMSCF natural gas [46]. Accordingly, the natural gas required to generate 1 MWh of electrical power is 9,689,987 MWh/107,675 MMSCF x 1.037 = 11.52 MWh/MMBtu, using a conversion factor of one thousand cubic feet of natural gas being equivalent to 1.037 MMBtu of natural gas [47]. Therefore, the generation 1 MWh of electricity requires 11.52 MMBtu of natural gas.

Thus, the avoided natural gas for each PV scenario is determined via:

$$\textit{Avoided natural gas}\ (mmBtu) = \textit{solar electric demand}\ (\textit{in MWh}) \times 11.52 \frac{MMBtu}{MWh}. \tag{1}$$

3.2.2. Avoided cost and export opportunity price

Avoided gas refers to the amount of natural gas no longer required in the power generation scenario when solar PV is supplying some of the national electrical demand. The cost of this gas would have been US $1.31/MMBtu [34].

Thus, the avoided natural gas cost is given by:

$$\textit{Avoided natural gas cost}\ (US\$) = \textit{Avoided natural gas}\ (mmBtu) \times \frac{US\$\ 1.31}{MMBtu}. \tag{2}$$

The opportunity gas price is calculated by considering that if the local electrical utility no longer needs to supply this gas for power generation, then the avoided gas quanta can be sold at the Henry Hub Price of US$ 3.04 per MMBtu [34]. Thus, the opportunity price is determined from:

$$\textit{Opportunity price}\ (US\$) = \textit{Avoided natural gas}\ (mmBtu) \times \frac{US\$\ 3.04}{MMBtu}. \tag{3}$$

3.2.3. Simple payback periods

The simple payback period is typically taken as the number of years by which time the initial investment is recovered. The simple payback period is the time required to recover the cost of the investment into solar PV and is often considered a breakeven point where the cumulative annual income equals the installation cost or as the ratio of the investment cost to the annual cash inflow [48]:

$$\textit{Simple Payback}\ (\textit{Years}) = \frac{\textit{Total Installation Costs}\ (\$)}{\textit{Annual Cash Flows}\ \left(\frac{\$}{Year}\right)}. \tag{4}$$

The annual income from the sale of natural gas is determined from the avoided cost and opportunity price of natural gas. In this study, the annual income is determined solely from (i) the annual avoided natural gas cost, which is no longer payable as a result of the solar PV inclusion, (ii) the opportunity gas price which the natural gas can now be sold for and the (iii) total of both.

As there was no local information available on the installation costs for utility-scale solar PV, recent installation costs of solar PV and their nameplate capacity facilities in various countries (Fig. 3) [49,50] were used to estimate the cost for solar PV facilities (100–700 MW) to be commissioned in Trinidad and Tobago. Dobrotkova et al. (2018) compiled a range of investment costs for utility scale solar PV plants around the world, from 11 MW to 800 MW with solar PV capacity factors ranging from 17% to 34% [50]. The line of best fit for the data points was used to estimate costs of the 100–700 MW size facilities (Table 1). For reference EnergyPLAN uses a capacity factor for solar PV of 28% [44].

3.3. Levelized cost of electricity from solar PV

The levelized cost of electricity (LCOE) of solar PV is a fundamental tool to assess the financial viability of solar PV against other forms of power [51]. LCOE is calculated using the total investment costs, maintenance and total generation output of a facility distributed over its lifetime. LCOE is recorded as the price of electricity per kWh and provides a simple metric to compare the price of electricity production between different modalities using costs which are distributed over the lifetime of a power production facility. A low LCOE generally makes a project more attractive to potential developers or potential investors. Reducing the LCOE via reductions in cost over the lifetime of the facility is extremely important for project developers to gauge the economic profitability of a power production project [52] and assess the potential need for financial incentives to make electricity generation projects more attractive [53,54].

The LCOE is given by Ref. [51]:

$$LCOE = \frac{\textit{Lifecycle cost of solar project}}{\textit{Lifetime energy production of solar project}} \tag{5}$$

where the lifecycle cost of a solar project is given by

$$\textit{Life cycle cost} = \sum_{t=1}^{n} \frac{(I + O\&M)}{(1+r)^t} \tag{6}$$

and the lifetime energy production of a solar project is given by

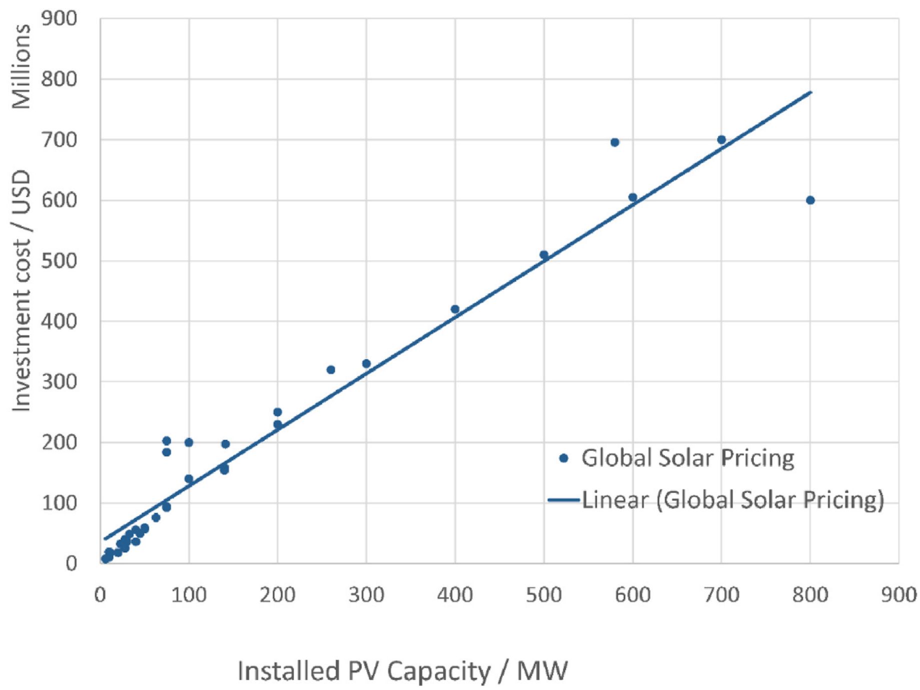

Fig. 3. Solar PV facility costs using costs of solar PV installed globally and associated nameplate capacity (Adapted from Refs. [49,50]).

Table 1
Estimated Investment cost (US$) for various solar PV plant sizes.

PV size (MW)	100	200	300	400	500	600	700
Installation cost (Million US$)	142	225	310	400	485	575	660

$$\text{Lifetime energy production} = \frac{\text{Annual output}}{\sum (1+r)^t}. \tag{7}$$

In estimating the LCOE, the investment or capital costs (denoted by I) are determined using the method in section 3.2.3 and that for a 100 MW facility was US$ 142,000,000. The expected lifetime of solar PV facilities (n) is taken as 25 years and an operations and maintenance (O + M) value of US$ 9.50/KW per year or US$ 710,000 for a 100 MW facility was assumed in accordance with IRENA's statistics for non-OECD countries in 2019 [51].

The discount rate (r) for Trinidad and Tobago is initially taken as 10% as in Dookie et al. [54]. However, discount rates of 5%, 10% and 15% are used for a sensitivity analysis. The parameter t (year) takes values from 0 to 25 years in one-year increments. The annual energy output is determined from EnergyPlan using the sum of monthly demand of generated solar power.

3.4. Reduction of carbon dioxide emissions

The quantum of CO_2 emissions potentially avoided in each of the 100–700 MW scenarios was estimated by using the amount of electricity generated by solar PV panels and a conversion factor from the IPCC. The conversion factor for natural gas power generation is that for each 1 MWh of power generated, 201.96 kg CO_2 is emitted [55].

4. Results

4.1. Validation of the energy plan reference model

The outputs of EnergyPLAN are hourly, daily, weekly, monthly and annual profiles as well as a cumulative sum of power generation for that year. These are matched to the original inputs and the variances calculated. As there are no solar PV facilities installed in the country, the solar PV model cannot be validated using installed PV facilities. The percentage differences in the model's output from the actual monthly electricity demands varied from −3.9% to −11.4% (Table 2). According to the T&TEC hourly demand data for 2015, the total national electricity demand for 2015 was 9,688,855 MWh [42]. EnergyPLAN's estimate of the total electricity demand is 7.1% lower than the actual demand (Table 2).

Whilst there appears to be good agreement between the estimate of and the actual electricity demand, there have been concerns that natural gas generated power shows wide variations across different countries. This may be due to a lack of reliable data as well as the configuration of the facilities themselves. Some studies have shown differences in the actual values and model values of up to 17% [45,56–59]. A 7% percent is acceptable for the purposes of this study due to the system optimization and EnergyPLAN's inability to decouple hourly demand data. Consequently, the reference model for Trinidad and Tobago can be considered reasonable and may be used for simulations that include utility-scale solar PV facilities.

4.2. Solar PV electricity demand for a 100 MW solar PV facility

The annual output for a 100 MW solar PV facility was calculated to be 250,450 MWh. The total electrical output (MWh) from the natural gas powered plants and the generated electrical output for a 100 MW solar PV facility for one month are shown in Fig. 4.

The Trinidad and Tobago electricity demand profile for the month of June is illustrated in Fig. 4. Natural gas-powered electricity varies between a minimum of approximately 750–850 MW

Table 2
Validation of the reference model using actual and model monthly demand for electricity generation for 2015.

Month	Reported Monthly Demand (T&TEC)/ MWh	EnergyPLAN Reference Model Monthly Demand/ MWh	Difference between reported demand and model's demand/ %
January	796,999	738,369	−7.4
February	742,027	709,100	−4.4
March	796,776	765,589	−3.9
April	783,245	727,687	−7.1
May	836,165	774,611	−7.4
June	799,480	742,352	−7.1
July	837,683	774,831	−7.5
August	854,041	797,676	−6.6
September	837,616	775,768	−7.4
October	845,685	780,371	−7.7
November	770,095	714,644	−7.2
December	789,044	698,969	−11.4
Annual	**9,688,855**	**8,999,967**	**- 7.1**

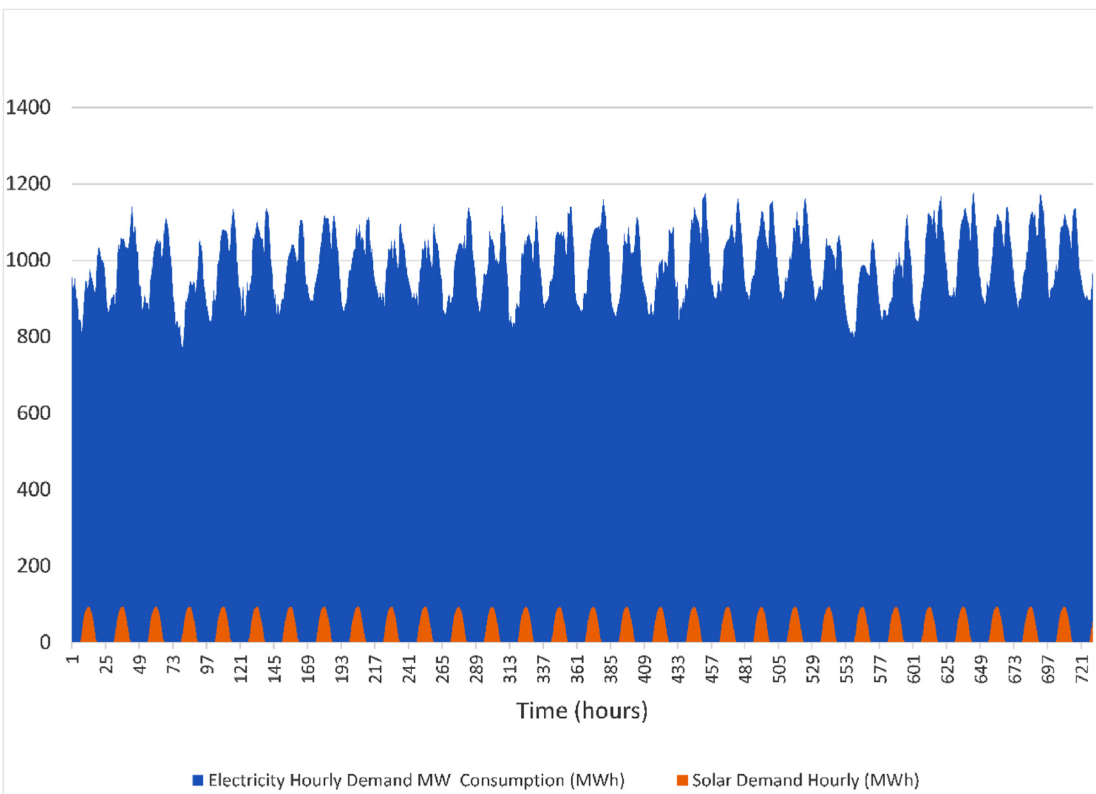

Fig. 4. Hourly natural gas electricity demand and modelled solar PV electricity demand for 1 month (June) in Trinidad and Tobago.

at around 10 a.m. and gradually rises to a peak demand of 1000−1190 MW at 7−8 p.m. After the peak, the demand gradually declines to the minima values and the cycle repeats throughout the month with small changes in the demand values but with the same general daily temporal demand profile. In contrast, the average diurnal solar PV contribution for a 100 MW facility (Fig. 5) shows that the highest solar output value occurs at approximately 1 p.m. when the sun is at its zenith for Trinidad and Tobago. The bell-shaped curve is typical of the output for a solar PV panel at 10° off the equator under typical weather and temperature conditions [18]. The difference in timing in peak demand for electricity (from natural gas) and the highest solar power output indicate the need for a smart energy system to optimize electricity generation and use.

Fig. 6 shows the estimated monthly output of a 100 MW solar farm in operation (orange bars) that has an annual output of 250,450 MWh with the 2015 national electricity demand from natural gas power (blue bars) and the reduced electricity demand from natural gas when natural gas is used together with PV for electricity generation (green bars). The maximum output of the solar PV facility was 3.1% in March and the lowest was 2.5% in June. The 100 MW solar PV facility would represent 2.6% of the total national power generation.

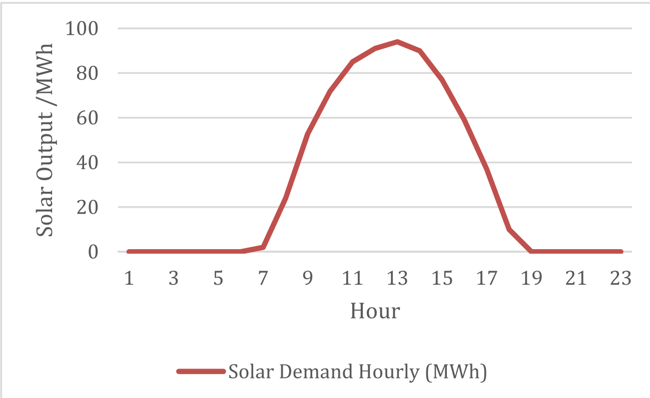

Fig. 5. Diurnal plot of solar PV electricity hourly output in Trinidad and Tobago.

4.3. Avoided and opportunity natural gas as a result of a 100 MW solar facility

The solar PV contribution to electricity would replace that quantum of electricity which would have otherwise been generated from the combustion of a certain volume of natural gas. As this gas is for power generation, it would have been sold at a price of US$ 1.31/MMBtu [34]. The annual avoided cost, opportunity price and thus total savings (avoided cost + opportunity price) for a 100 MW solar PV facility were determined from the corresponding monthly values (Fig. 7). The natural gas that is avoided if a 100 MW solar PV facility is integrated into the electricity mix amounts to 2,885,184 MMBtu resulting in an avoided cost of US$ 3,779,591 and an opportunity price of US$ 8,770,959. Thus, the total saving of avoided natural gas is US$ 12,550,550.

4.4. Simple payback periods

In this study, the simple payback period was determined for three situations where the annual income is determined solely from (i) the annual avoided natural gas cost, (ii) the opportunity gas price and (iii) the total of both. These results are illustrated in Fig. 8. In the first case, the simple payback period is estimated at approximately 39 years. This is reduced to 18 years when the second case of opportunity price is considered and 13 years when both the avoided natural gas cost and opportunity price are considered. These estimates for the payback period do not consider revenue

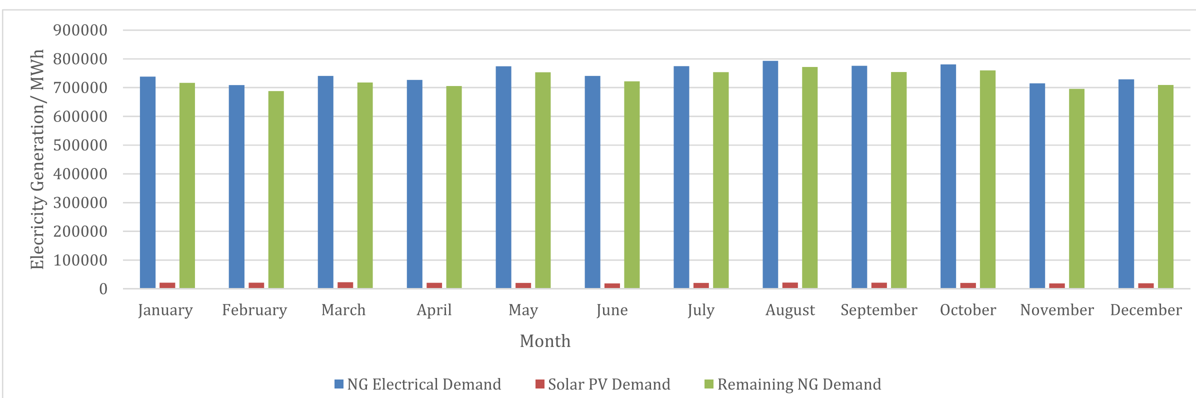

Fig. 6. 2015 National annual electricity generation in Trinidad and Tobago (blue bars) with 100 MW solar PV demand (orange bars) and natural gas demand after solar generated electricity is dispatched (green bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

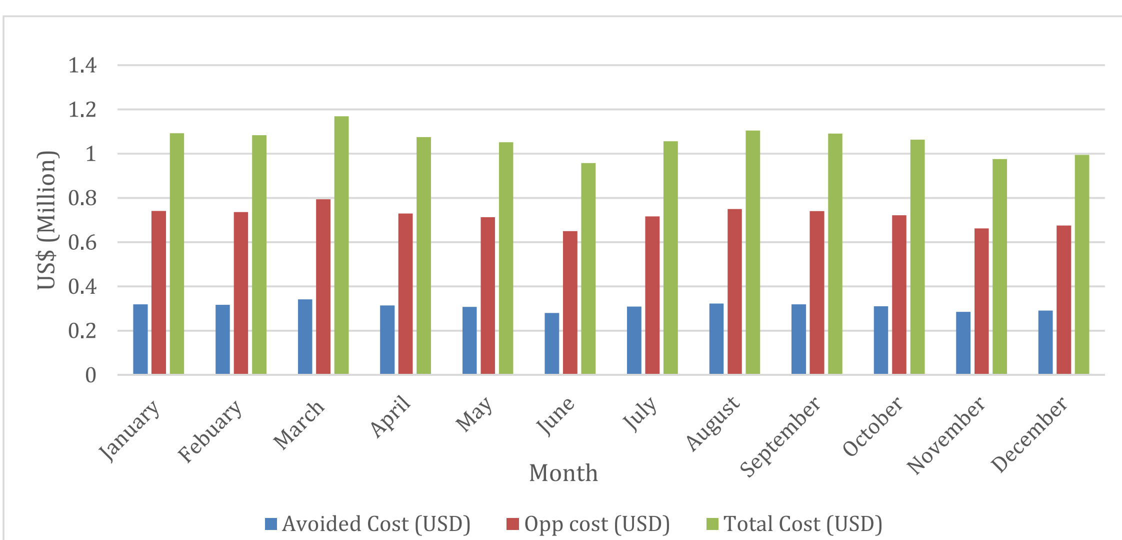

Fig. 7. Avoided cost, opportunity price and total savings associated with a 100 MW PV plant integrated into the natural gas generation system.

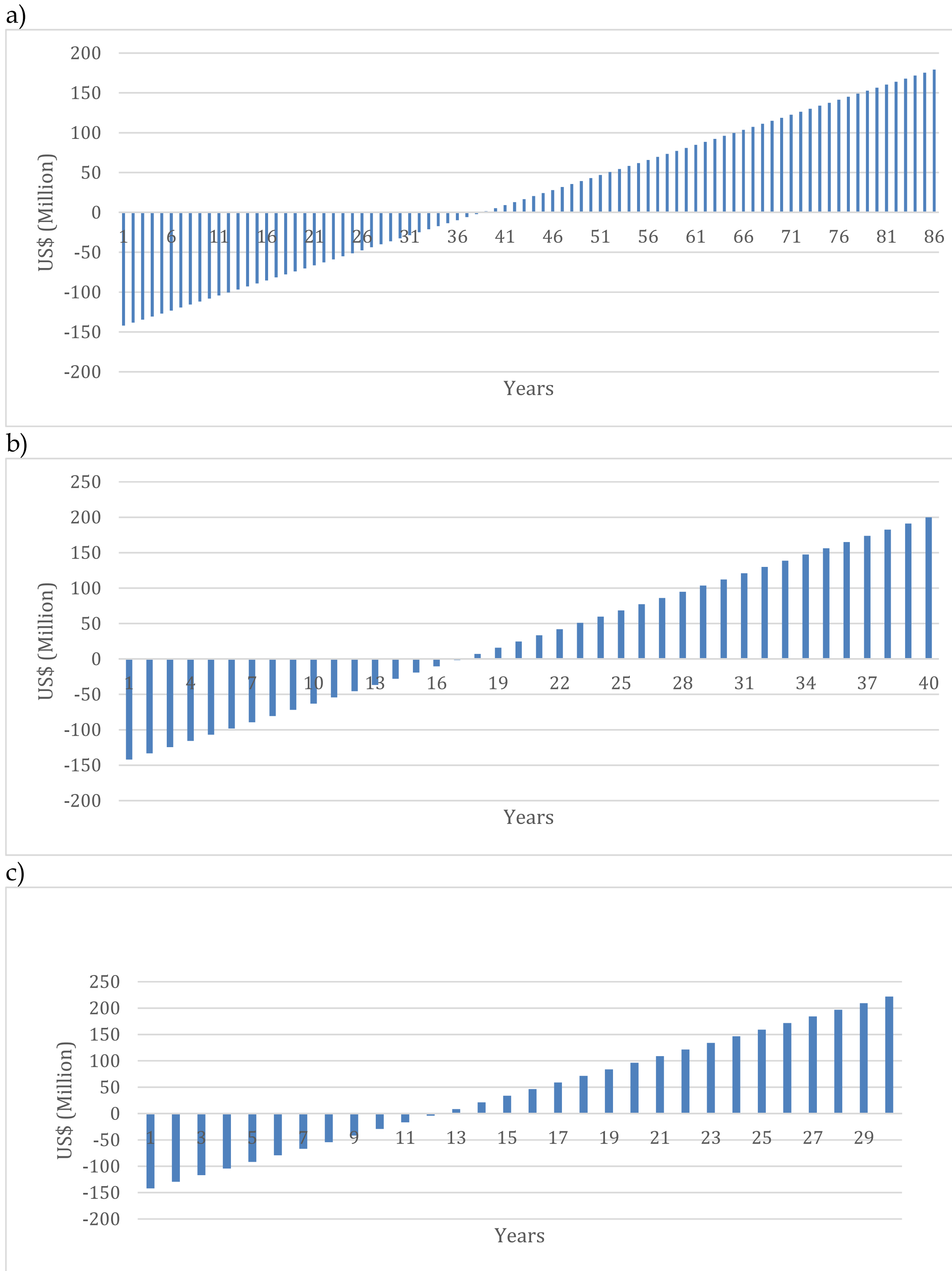

Fig. 8. Payback times for a 100 MW Solar Facility-a) avoided cost b) opportunity price c) total income.

obtained from the actual sale of the PV generated power but represents solely the cost-benefit of not paying for the use of the avoided natural gas in electricity generation and routing that quantum to exports.

4.5. *Levelised cost of electricity (LCOE) for a 100 MW solar PV plant*

The LCOE value calculated for a 100 MW PV facility was US$ 0.06/kWh at a 10% discount rate as recommended by IRENA for developing countries [51]. We also looked at the effect of a 5% discount rate and a 15% discount rate for a sensitivity analysis. At 5% discount rate, the LCOE is US$ 0.04/kWh while at 15% discount rate it is US$ 0.08/kWh. The 5%–10% range produces LCOE values that are comparable with the current residential electricity tariff of US$ 0.045–0.060/kWh [42].

4.6. Reduction in carbon dioxide emissions

The carbon dioxide emissions evaded by using the electricity output of the proposed 100 MW solar PV facility during January to December are shown in Fig. 9 (orange line; right axis). Also shown in Fig. 9 is the estimated monthly carbon dioxide emissions in 2015 (blue line; left axis) from the power generation sector. The cumulative annual carbon dioxide emissions avoided by a 100 MW solar PV is 50,581 tonnes with the most carbon dioxide avoided in March (4650 tonnes) and the lowest in June (3810 tonnes) In total, this avoided CO_2 emissions is 2.6% of CO_2 emissions from the power generation sector.

4.7. Estimates for 200–700 MW PV scenarios

The annual electricity demand, payback periods, LCOEs and carbon dioxide emissions were presented for a 100 MW PV plant as a base scenario in Sections 4.1-4.5 as current developments in PV in Trinidad and Tobago are at this scale. In this section, we consider similar scenarios for 200–700 MW PV with increments of 100 MW.

Table 3 provides results for the following for the inclusion of 6 sizes of solar PV facilities:

(i) Estimates of annual electricity generation from solar PV and percentage of these compared to electricity generation from natural gas
(ii) Installation costs for the solar PV utility facilities
(iii) The volume of natural gas saved by the inclusion of these PV facilities
(iv) The avoided cost of this volume of natural gas
(v) The opportunity price for this volume of natural gas
(vi) Total (avoided + opportunity) income for this volume of natural gas
(vii) The simple payback times for this volume of natural gas
(viii) The reduction in carbon dioxide emissions.

Of note is the percentage contribution solar PV could make to the national electricity generation mix based on 2015 electrical demand data. Solar PV facilities of 200 MW could contribute to 5% of electrical demand, 400 MW to 10%, and 600 MW to 15%, with corresponding reduction in CO_2 emissions from the power generation sector. Solar PV facilities of 700 MW could potentially provide up to about 18% of the current electricity demand and thus, also 18% reduction in CO_2 emissions up to approximately 354.2 kt. This would represent a significant contribution to achieving the target of the Paris Agreement of 2015 where Trinidad and Tobago committed to a 30% reduction in GHG emissions by 2030 [60]. The reduction in GHG emissions, coupled with a short payback period of 7.5–11.3 years based on both avoided cost and opportunity price makes utility-scale PV of this magnitude attractive for electricity generation. These sizes could be used to revise targets to diversify the power generation sector.

The LCOEs for 200 MW, 400 MW and 600 MW facilities lie in the range US$ 0.03–0.06 per kWh for discount rates varying from 5% to 15% (Table 4). This LCOE range is smaller than that for a 100 MW solar PV facility US$ 0.04–0.08 per kWh (Table 4). The LCOE range for a 700 MW plant has a slightly smaller range than the 600 MW plant at US$ 0.03–0.05 per kWh. In addition, for solar PV facilities greater than 300 MW, the LCOE at 10% discount rate is less than those for 100 MW and 200 MW facilities.

From the calculations, we conclude that the discount rate is critical to the investment decision as the discount rate must be 10% or less and larger than 300 MW for any discernible profit to be realised. At a discount rate of 5%, any size of facility would be

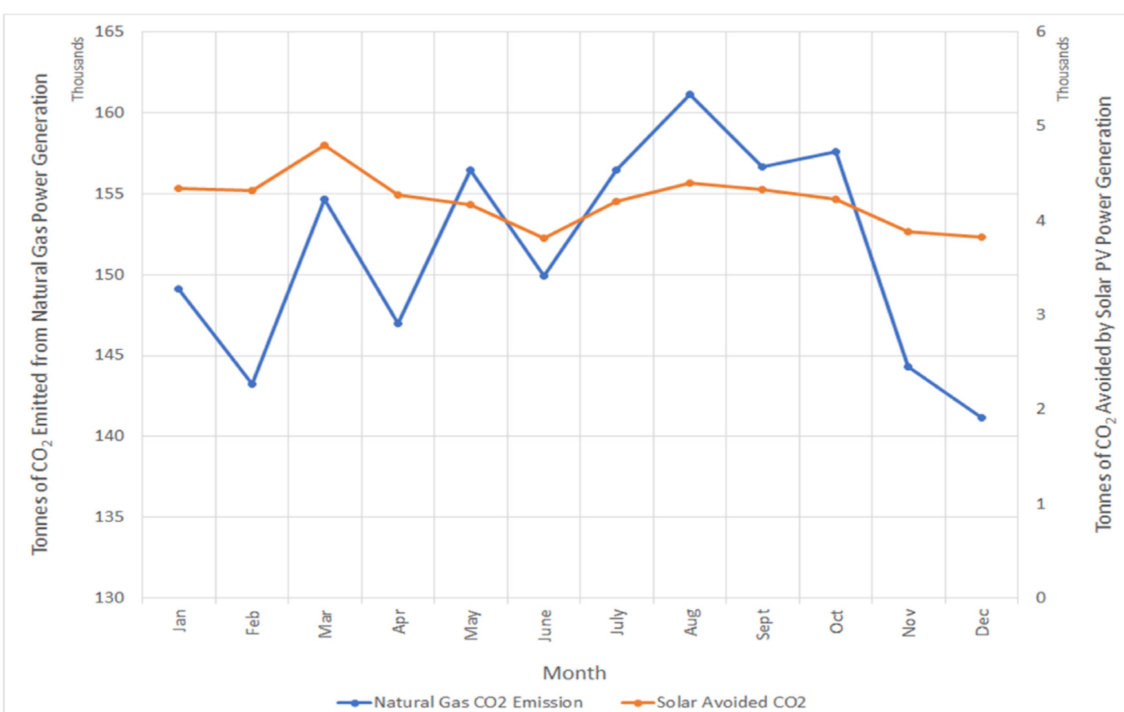

Fig. 9. Carbon dioxide emissions from natural gas power generation (blue line and left axis) and reduction due to inclusion of a 100 MW solar PV facility for 1 year (orange line and right axis). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Summary of Results for the inclusion of 100–700 MW Solar PV facilities.

	(Units)	100 MW	200 MW	300 MW	400 MW	500 MW	600 MW	700 MW
Total Annual PV generation (% national power generation in 2015)	(MWh)	250,450 (2.6%)	501,093 (5.2%)	751,483 (7.8%)	1,001,888 (10.3%)	1,252,493 (12.9%)	1,503,121 (15.5%)	1,753,582 (18.1%)
Installation cost of Solar PV Facility	(Million US$)	142	225	310	400	485	575	660
Natural Gas Avoided	(MMBtu)	2,885,184	5,772,591	865,704	11,541,749	14,428,719	17,315,953	20,201,264
Cost of Avoided Gas	(US$)	3,779,591	7,562,094	11,340,780	15,119,692	18,901,622	22,683,899	26,463,656
Price of Opportunity Gas	(US$)	8,770,959	17,548,677	26,317,535	35,086,919	43,863,306	52,640,499	61,411,844
Total = Avoided Cost + Opportunity Price	(US$)	12,550,550	25,110,772	37,658,316	50,206,611	62,764,921	75,324,399	87,875,501
Simple Payback Period (Avoided cost)	(Years)	37.57	29.75	27.33	26.46	25.65	25.34	24.93
Simple Payback Period (Opportunity Cost)	(Years)	16.19	12.82	11.78	11.40	11.06	10.92	10.75
Simple Payback Period (Total = Avoided Cost + Opportunity Price)	(Years)	11.31	8.90	8.20	7.97	7.73	7.63	7.51
CO_2 Avoided (% Total CO_2 lowered from national power generation)	(Tonnes)	50,581 (2.6%)	101,201 (5.2%)	151,770 (7.8%)	202,341 (10.3%)	252,953 (12.9%)	303,570 (15.5%)	354,153 (18.1%)

Table 4
LCOE (US$/kWh) for 100–700 MW PV nameplate capacity at 5%, 10% and 15% discount rates.

Discount Rate	LCOE (US$/kWh) for PV Nameplate Facility						
	100 MW	200 MW	300 MW	400 MW	500 MW	600 MW	700 MW
5%	0.04	0.03	0.03	0.03	0.03	0.03	0.03
10%	0.06	0.05	0.05	0.04	0.04	0.04	0.04
15%	0.08	0.06	0.06	0.06	0.06	0.06	0.05

expected to turn a profit, but it is recommended for the facility to be of at least 200 MW capacity.

5. Discussion

One of the main results is that LCOE at 5% discount rate for a 100 MW facility matches the current utility tariff in Trinidad and Tobago of US$ 0.045–0.060 per kWh [42]. At the highest discount rate of 15%, the prospect of turning a profit does not appear feasible even with the 700 MW facility. Whether it makes economic sense to purchase electricity at these rates is a larger issue that must be answered in the context of the potential income to the state from the avoided natural gas, the cost of installation and the commitments to international policies and protocols. All stakeholders in electricity generation would need to have discussions with potential investors. Tax incentives and credits may form a part of any new PPA for IPPs who may wish to include solar PV as part of their electricity generation portfolio upon expiry of their current contracts. Corporate entities interested in investing in PV projects may negotiate a tariff that is higher than the cost of electricity generation which was found to be as high as US$ 0.08/kWh and as low as US$ 0.03/kWh depending on facility size and discount rate. The country would still enjoy the benefits of lowered national carbon dioxide emissions as well as a native guaranteed supply of electricity. We note that a 700 MW solar PV facility could potentially provide up to about 18% of the current electricity demand and thus, also 18% reduction in CO_2 emissions in the power generation sector.

Drivers to energy transition worldwide include issues of energy security, native sustainable energy, and carbon dioxide abatement. In the case of natural gas hydrocarbon economies such as the Caribbean small island developing state of Trinidad and Tobago, an opportunity to redirect natural gas as a power generation fuel and sell it as a profitable commodity could be another driver to transition from a hydrocarbon economy to a future with renewable energy. Global case studies by Fattouh et al. [61] and Fouquet et al. [62] show that it is possible to transition between major energy sources within a few decades if governments recognise energy transition as a priority issue for the stability of energy supplies, thereby marshalling resources in a sustained way.

Studies have shown that transitioning to renewables with an integrated smart energy system is essential for the transition to be effective. Lund et al. [30] concluded that smart energy systems would be effective in enabling efficient and affordable solutions in any energy transition from fossil fuels to renewables including storage and allied infrastructure [40]. Cabrera et al. [63] showed that using a smart energy system to integrate renewables into a water-energy island system could result in approximately a five-fold increase in the contribution of renewables to the national electricity demand [30]. Mathiesen et al. [31] investigated smart energy systems to monitor and regulate gas supply and demand balances with fluctuating renewable energy in an hour-by-hour approach. Their results concluded that the application of a smart energy system would be both cost effective and fuel efficient in an energy transition scenario from fossil fuel power to renewables [31].

Groppi et al. (2019) proposed that island energy systems that are dependent on imported fossil fuels for power generation, (Smart Energy Systems) SESs are indispensable for transitioning to an autonomous and low-carbon energy system [64]. Whilst Trinidad and Tobago is not yet dependent on imported fossil fuels for power generation, this point is valid as natural gas is a non-renewable resource and electricity power diversification strategies need to be contemplated in a holistic and well-planned manner for future electricity demand. An important and timely study from Russia, in anticipation of a recurrent COVID-19 scenario concluded that an increased decentralisation of electricity generation should be supported as it lowers the grid load and capital expenditures for equipment upgrade and maintenance. In advocating for a smart energy monitoring system, they conclude that a robust and flexible energy foresight and monitoring system, which includes SES will allow for timely identification of these unexpected events and planning for their effective use, or mitigation of their effects [65].

These studies suggest that Trinidad and Tobago with 100% natural gas power and distributed generation can make use of smart energy systems in its transition to include renewables into its national power matrix. A smart energy system can coordinate the production of electricity from the five geographically separate facilities in the island state. Each facility will have different thermal efficiencies and contributions to national electricity demand. The individual demand contributions and efficiencies of these five plants are currently not available to the public. Additionally, the hourly national electricity demand peak (currently supplied by natural gas) is out of sync with solar PV demand. Furthermore, with the announcement of electric vehicle incentives in September 2021 in Trinidad and Tobago], the proliferation of electric vehicles may change the timing of peak electric demand [66]. Other renewable energy sources may be required to help satisfy this demand such as wind power [67]. Thus, the seamless integration of the various renewable energy sources as well as storage and end-user electric technologies may be possible by incorporating smart energy systems early in the transition from natural gas to renewables to provide for optimal grid stability and efficient power distribution whilst minimising natural gas use.

Estermann et al. (2021) found that smart energy systems including smart meters were valuable to encourage the integration of higher shares of renewable energies into the power supply [68]. Studies of other hydrocarbon rich economies have already shown the importance of modelling future power scenarios to include renewable energy integration into the power generation sector which can be used as policy tools for policymakers [69].

Other countries could also use the approach presented here to determine the benefit of incorporating large-scale PV into their electricity mix. Such analyses will advise on choosing between installing more fossil fuel electricity generation or investing in solar PV which could make economic sense with competitive LCOEs possible in addition to energy independence from imported fossil fuels, native energy security and reduced carbon dioxide emissions.

This study can also be helpful to any country dependent on fossil fuel for power generation who may be considering a shift towards renewables as it uses empirical data to make a case for moving away from fossil fuel based electricity where the recurring fuel costs are subject to global availability and price volatility even when the fuel source is native in origin.

They could use the approach and calculate for their situation and proposed scenarios. This study makes a case for the sale of native fossil fuels fuel when the export price is higher than a subsidised cost for power generation to the economic advantage of the state and where the LCOEs are attractive at the higher solar PV facility sizes.

This study may be important to emerging economies such as Guyana and Suriname where natural gas contributes to power generation. However, because of recently uncovered massive sources of natural gas, these two countries may be tempted to implement and subsidise natural gas-powered electricity instead of incorporating renewables. They will have to make decisions on a case-by-case basis and in tandem with other environmental and social concerns.

This study makes a clear case for the acceleration of deployment of utility-scale solar photovoltaic plants for electricity generation in a natural gas economy seeking to transition from a 100% fossil fuel electricity scenario as the transition may be a profitable, sustainable and carbon friendly power generation modality.

For Trinidad and Tobago, where a 112 MW facility is already being developed, it is recommended that policymakers consider a multi-agency approach involving all stakeholders to accelerate the policies, physical, technical, and fiscal terms to rapidly deploy even more utility-scale renewable energy facilities to provide electricity to the national grid. This can be further extended on a case-by-case basis for the inclusion of feed-in-tariffs for small-scale PV facilities and other renewables such as wind energy [29]. These measures may be considered a few years ahead of the expiration of the current PPAs supporting natural gas power production to enable future PPAs with IPPs to integrate utility-scale PV facilities as part of the electricity demand forecast in a phased approach. The phased approach may thus enable the transition from natural gas to operational renewable energy power production.

The United Nation's SDG-7 specifically refers to universal access to clean energy sources including solar. In this context, transitioning from a fossil fuel-based power generation scenario to the inclusion of clean energy source, lowered carbon dioxide emissions and with a clear prospect of economic advantages to the country, utility-scale solar PV facilities should have a guaranteed place in the country's power generation future. The 112 MW solar PV facility in Trinidad and Tobago under development is already the largest such project in the CARICOM.

There were some limitations associated with the study. Firstly, the national electrical demand data used to run the model was from 2015, the latest validated data. It would have been interesting to use more recent annual electrical demands to observe any changes in the scenarios presented but these figures were not available. Secondly, the installation costs of turnkey PV utility facilities also had to be estimated using recent studies. There is also a paucity of information on the installation, fixed and variable costs of a solar PV utility scale facility in the wider Caribbean region. Such information for current installations in the Caribbean is proprietary as PPAs are confidential in nature. Estimates had to be made on published installation costs from global prices relevant to the facility sizes. Also, while electricity tariff prices are readily available, they may not necessarily reflect the LCOE. Thus, an accurate levelized cost of energy could not be compared.

6. Conclusion

In this study, the benefits of including 100–700 MW solar PV into the electricity grid of the island state of Trinidad and Tobago was explored with the aid of EnergyPLAN. The inclusion of utility-scale solar PV facilities into the national grid could offset the use of natural gas for power generation. The cost of avoided gas and the opportunity it presents as an export product open the path for Trinidad and Tobago to transition from a 100% natural gas economy to include renewable energy whilst maintaining critical income to the country's economy for national development.

The potential income, payback times and carbon dioxide reductions increase significantly with an increase in installed capacity of utility-scale PV. The inclusion of a 100 MW utility-scale solar facility could result in potential income of approximately US$ 13.5 million per annum with a payback time of 13 years. The power generation sector would also benefit from a reduction in carbon dioxide emissions of approximately 50.58 tonnes. The potential annual income to the economy for a 700 MW solar PV facility would be approximately US$ 87.9 Million, which represents 1.2% of the total annual budget of Trinidad and Tobago for 2021 with a payback period of 8 years and a reduction in carbon dioxide emissions of 354.15 Tonnes.

The discount rate is critical to investment decisions for solar PV in Trinidad and Tobago. For a discount rate less than 10% as recommended by IRENA [53] and larger than 300 MW or at a discount rate of 5% with utility sizes of 200 MW and greater, PV should be profitable as LCOEs could be as low as US$0.03–0.04 per kWh.

Overall, our findings suggest that solar PV, once considered prohibitively expensive, can serve as a driver for Trinidad and Tobago's transition to a low carbon future whilst supporting the demands of the downstream gas sector, which is critical to the country's economy. In addition, a case is made for integrating smart energy systems early in the transition from natural gas to include solar PV for electricity generation. This will enable the future integration of other renewable energy sources such as wind power and end-user technologies such as electric vehicles to provide for optimal grid stability and efficient power distribution whilst minimising natural gas use.

The results of our analyses justifies the present development of a 112 MW solar farm in Trinidad and Tobago and additionally make a strong case for the immediate integration of more utility-scale PV facilities in Trinidad and Tobago, which can provide viable solutions to the current issues of native natural gas shortages and reducing carbon dioxide emissions. Whilst this is a simple study, the analyses could be used by other countries such as Oman and Kuwait which may be considering such a transition, especially in terms of reducing their carbon dioxide footprint and diversifying their current energy matrix. Closer to home, emerging hydrocarbon economies such as Guyana and Suriname may find these analyses to be useful in planning for a power projection scenario which integrates renewables and natural gas power into the electricity grid as demand increases.

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Ethics in publishing

The authors have no conflicts to declare.

CReDiT statement

Randy Ramadhar Singh: Conceptualization, Methodology, Investigation Software**,** Data curation, Writing- Original draft preparation.
Ricardo Clarke: Writing, Supervision, Reviewing, Visualization, Investigation.
Xsitaaz Chadee: Writing, Supervision, Reviewing, Editing.

Declaration of competing interest

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

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