The Potential of Wind and Solar Power in Small Island Developing States

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Abstract

This paper provides an order of magnitude assessment of the potential of renewable energy from solar photovoltaic (SPV) and offshore wind in the capital cities of two Small Island Developing States (SIDS) and compares these results to New York City, which serves as a reference for future electricity demand. This investigation illustrates the theoretical superiority of SPV over offshore wind and the greater feasibility with which SIDS can undertake a full renewable transition. However, further investigation is necessary to clarify discrepancies between theory and empirical results. In addition, considerations with regard to the availability of land and local energy storage are needed to determine the best technology for a particular location.

1 Introduction

Small Island Developing States (SIDS) are among the most vulnerable nations to sea level rise driven by anthropogenic climate change. Consequently, there is significant political support within SIDS to reduce carbon dioxide emissions by investing in renewable energy technologies [1]. At the same time, the integration of intermittent renewables, such as solar photovoltaics (SPV) and offshore wind, into existing island electric grids faces exceptional challenges. The remoteness and small size of island states result in extra sensitivity to local weather conditions and fluctuations in power generation cannot be averaged out over a large scale [2]. This makes the integration of renewables in SIDS more technically challenging but smaller in scale than in continental megacities. For this reason, SIDS provide a good pilot study for the global renewable energy transition. This paper aims to offer an order of magnitude assessment of the solar photovoltaic and offshore wind generation capacity available to SIDS and the extent of land cover necessary to facilitate a complete renewable energy transition.

The capital cities of two SIDS – Port Louis (PL) in Mauritius and Port of Spain (PS) in Trinidad and Tobago – will serve as case studies for this report. Mauritius and Trinidad and Tobago were selected because both states are fully electrified and have similar overall population sizes (~1.3 million) but have different electricity mixes [2, 3]. New York City (NYC) in the United States will serve as a reference for the energy demands of a continental megacity and as an estimate of future energy demands in SIDS. The locations of these cities are given in Fig. 1.

Figure 1: Geographic Locations of Case Studies

Figure 1: New York City lies at (40° 42′ 46″ N, 74° 0′ 22″ W), Port Louis lies at (20° 9′ 52″ S, 57° 30′ 15″ E) and Port of Spain lies at (10° 40′ 0″ N, 61° 31′ 0″ W).

This paper considers three “power levels” representing different characteristic electricity demands: (1) average household power usage; (2) current city power usage; and (3) hypothetical “megacity” power usage. This third “power level” is meant to illustrate future power demands in SIDS based on rapid urbanization and global population growth. These “power levels” are used in conjunction with order of magnitude estimates of SPV and offshore wind areal power densities to estimate the size of renewable energy installations necessary to meet these characteristic energy demands. These estimates are intended to provide insight regarding the feasibility of a transition to a fully renewable electric grid in each of these cities and identify the most effective renewable energy technologies to pursue.

2 Methods

2.1 Power Levels

The estimates of the three "power levels" considered in this paper for each location are given in Table 1. The electricity demands of an average household are obtained either from secondary sources or calculated based on residential electricity usage statistics and city population (See Appendix A) [4, 5, 6]. The electricity demands of existing and hypothetical megacities are calculated by multiplying the average electricity usage per capita and the current or hypothetical urban population [7, 8, 9, 10]. It is important to note that the estimates for hypothetical megacities assume that PL and PS will harbor populations comparable to NYC but that per capita electricity usage will remain the same. While this approach serves for an order of magnitude approximation, it is not necessarily an accurate assumption. Electricity use per capita generally increases with GDP. If GDP were to increase due to further industrialization in these cities, both Mauritius and Trinidad and Tobago should experience an increase in electricity use per capita and thus have higher megacity power requirements than estimated here.

Per capita electricity consumption is a better metric for estimating city power consumption than household electricity consumption because per capita electricity consumption does not distinguish between residential and industrial energy uses. For example, in Trinidad and Tobago residential electricity consumption only accounts for 28% of electricity usage [6]. Consequently, using household demand to estimate city demand would severely underestimate the electricity consumption of the city. It is interesting to note that per capita electricity consumption in the United States and Trinidad and Tobago exceeds the electricity usage per household. This indicates significant non-residential electricity usage (e.g. heavy industrialization and manufacturing).

Table 1: Power Levels

Location	**Electricity Use Per Capita** (kWh/month)	**Current City Population** (People)	**Household** (kWh/month)	**Existing City** (GWh/month)	**Megacity** (TWh/month)
New York City (NYC)	1043.8	8,804,190	602	9200	N/A
Port Louis (PL)	180.4	147,066	403	26.5	1.6
Port of Spain (PS)	525.9	81,142	442	42.7	4.6

Table 1: Note the units above. Household, existing city and megacity power requirements occupy different orders of magnitude.

2.2 Solar and Wind Power Data

The appropriate metric for estimating the output of SPV installations is Global Horizontal Irradiance (GHI) [11]. GHI is defined as the light intensity (power per unit area) incident upon a surface parallel to the surface of the Earth. This setup captures both direct and diffuse radiation. In contrast, Direct Normal Irradiance (DNI) is defined as the light intensity incident upon a surface held normal to incoming solar radiation. This captures more direct radiation but less diffuse radiation. Although DNI is used for solar thermal plants, where solar tracking is an operational requirement, it is not suitable for SPV installations because most (especially rooftop SPV) lack solar tracking capabilities.

The GHI data used in this paper is obtained from the Global Solar Atlas by assuming optimal positioning of a solar array within a 100 km (62 mi) radius of each city [12]. This choice of radius was made to capture the likely construction sites for utility scale solar projects. Utility scale solar, as demonstrated in this paper and others, requires significant tracks of land that generally are not available within urban limits, making cities reliant on the surrounding countryside [13]. To make a fair comparison, this paper assumes that solar installations are installed at the sites with the highest solar insolation within each radius (See Table 2).

For a known wind speed, the available power in the wind, P_{wind}, is given by Equation (1) where ρ represents air density and v represents wind speed [11]. However, wind speed is extremely variable. This leads to Equation (2) where ‹v^3› is the average of the cube of wind speed. It is important to recognize that ‹v^3› is not necessarily the same as ‹v›^{3}. In fact, ‹v^3› is always greater than or equal to ‹v›^{3}. Consequently, this paper uses the mean power density given by the Global Wind Atlas, P_{Atlas}, which is defined based on Equation (2) (See Table 2) [14].

$$(1)\ P_{Wind} = \frac{1}{2}\, \rho\, v^3$$

$$(2)\ P_{Atlas} = P_{Wind} = \frac{1}{2}\, \rho\, \langle v^3 \rangle$$

Table 2: Power Densities by Location

Location	**Global Horizontal Irradiance (GHI)** (kWh/m^2/day)	**Mean Wind Power Density (100 m)** (W/m^2)	**Thermal** (W/m^2)
New York City (NYC)	4.031	856 (9.21 m/s)	500-10,000
Port Louis (PL)	5.701	495 (8.37 m/s)	
Port of Spain (PS)	5.842	307 (7.51 m/s)	

***Table 2**: Wind speeds are provided underneath mean wind power densities in the Mean Wind Power Density column in parentheticals. Estimates of thermal power density are adapted from "Power Density" by Vaclav Smil [15].*

2.1 Photovoltaic Solar Calculations

The areal power density of a photovoltaic solar farm is calculated using Equation (3). I_{GHI} represents GHI estimates from the Global Solar Atlas [12]; f represents the packing factor – the fraction of land area covered by solar panels (panels are often spaced out to avoid shading); and η represents the solar panel efficiency. The area that a solar installation would need to cover in order to supply power P is given by Equation (4).

$$(3)\ I_{PV} = f\, \eta\, I_{GHI}$$

$$(4)\ A = \frac{P}{I_{PV}}$$

This paper assumes a standard packing factor of 0.5 and a solar panel efficiency of 15.3% based on the findings of Rughoo et al. at a utility scale solar plant in Mauritius [16].

2.4 Offshore Wind Calculations

The areal power density of an offshore wind farm is calculated using Equation (5). P_{Atlas} represents mean wind power density estimates from the Global Wind Atlas [14]; η represents the combined efficiency of the turbine and generator accounting for electrical, environmental, design and wake effect losses; c_f represents the capacity factor – which can be understood as the fraction of time for which the wind speed is within the operational range of the turbine; c_{betz} represents the maximum fraction of power (0.593) that can be extracted from the wind without losses due to other design factors; and d represents the diameter of the turbine. Note that the areal power density is independent of the diameter of the turbine due to the choice of turbine spacing as $40d^2$. The area that an offshore wind farm would need to cover in order to supply power P is given by Equation (6).

$$(5)\ \ I_{Turbine} = \frac{\eta\ c_f\, c_{betz}\, P_{Atlas}\, \pi \left(\frac{d}{2}\right)^2}{40d^2} = \frac{\pi\, \eta\ c_f\, c_{betz}\, P_{Atlas}}{160}$$

$$(6)\ A = \frac{P}{I_{Turbine}}$$

This paper assumes that offshore wind farms will use Alstom Haliade 150-6-MW wind turbines which are currently used in an offshore wind project in Block Island, Rhode Island [16]. These turbines have a 100 m hub height, a rotor diameter of 150 m and an IEC-3 wind class rating. The appropriate capacity factors, c_f, are listed in Table 3 [14].

Table 3: Capacity Factors

Location	**New York City**	**Port Louis**	**Port of Spain**
Capacity Factor	0.62	0.60	0.51

Table 3: IEC-3 wind class capacity factors are obtained from the Global Wind Atlas [14].

The National Renewable Energy Laboratory estimates that wind turbines experience ~17% net efficiency losses due to electrical losses, environmental losses, turbine design and wake effects [18]. This yields an efficiency η of 0.83.

2.5 Thermal Power Plants

Estimates for the areal power densities of thermal power plants – which includes coal, oil and natural gas-fueled turbines – vary over several orders of magnitude from 500 – 10,000 W/m^2 based on the work of Vaclav Smil [15]. This introduces a significant amount of uncertainty into the estimate for the amount of land that a thermal power plant would need to cover in order to supply power P. This land area is calculated using Equation (7).

$$(7)\ A = \frac{P}{I_{Thermal}}$$

3 Results

3.1 Solar Photovoltaic

Table 4: SPV Areal Power Density and Land Coverage

Location	**Areal Power Density** ($kWh/m^2/month$)	**Household Land Coverage** (m^2)	**Existing City Land Coverage** (m^2)	**Megacity Land Coverage** (m^2)
New York City (NYC)	9.379	64.182	979,280,211 (~0.7%)	N/A
Port Louis (PL)	13.266	30.380	2,000,341 (~0.1%)	119,694,536 (~5.9%)
Port of Spain (PS)	13.594	32.500	3,139,025 (<0.1%)	340,433,164 (~6.6%)

Table 4: The percentage of land area (of Mauritius for PL, of Trinidad and Tobago for PS and of New York State for NYC) is given in parentheticals below the total amount of land when applicable.

The results of the order of magnitude calculations for SPV areal power density and land coverage are summarized in Table 4. NYC has the lowest areal power density of 9.379 $kWh/m^2/month$. This is ~30% lower than the areal power densities of PL and PS. The dominant driver of this is latitude as annual insolation is ~20% lower at 40˚ N than 20˚ S or 10˚ N [11].

In terms of household land coverage, all cities share the same order of magnitude; however, households in NYC require twice the amount of land to power as PL and PS. This discrepancy is due to the aforementioned 30% lower areal power density of SPV and the 50% higher electricity consumption per household (See Table 1). It is also relevant to note that this assumes solar is being used to satisfy all household electricity demands. In reality, many residential rooftop solar installations are only intended to meet half of the daily electricity requirement as evening and night power needs are met by the grid.

The estimate of land area required to meet existing city power needs within city limits varies significantly between the study locations. NYC requires over two orders of magnitude more land to power than PL and PS. This is primarily driven by the high population in NYC which is also two orders of magnitude greater than the SIDS cities. However, since New York

State is larger than Mauritius and Trinidad and Tobago, the percentage of land coverage is within one order of magnitude of the land coverage for PL and PS (See Table 4). It is interesting to note that PS requires over 50% more electricity than PL despite having a population that is 45% smaller. This is due to much higher electricity use per capita in Trinidad and Tobago – a natural consequence of cheap electricity prices born of plentiful fossil fuel reserves [3]. This illustrates opportunities for significant energy savings and emission reductions in Trinidad and Tobago through demand-side management and efficiency upgrades [3].

Finally, the land area required by SIDS megacities are of the same order of magnitude as for NYC currently. The unusually high land coverage requirements of PS for existing city power needs also translate into the megacity model. In addition, the percentage of land coverage required by the SIDS cities increases by over an order of magnitude. Consequently, PL and PS transition from requiring the conversion of a smaller fraction of land to SPV than NYC in the existing cities model to requiring the conversion of a larger fraction of land to SPV in the megacities model.

Overall, exclusive reliance on utility-scale SPV farms is more feasible in PL and PS than in NYC for existing city sizes given the smaller fraction of land required. However, future megacities may prove significantly more challenging to power in SIDS given the limited amount of available land in these island states and the much larger fraction of land needed to sufficiently power a megacity. New York State is significantly larger and can better support the implementation of utility-scale SPV farms to power NYC in the megacities model. Thus if city populations rapidly increase in Mauritius and Trinidad and Tobago, it would be worthwhile to examine floating solar installations. This nascent technology has been successfully implemented in Singapore and has the added benefit of enhancing cooling, improving panel performance [19].

3.2 Offshore Wind

Table 5: Offshore Wind Power Density and Land Coverage

Location	**Areal Power Density** (kWh/m^2/month)	**Household Land Coverage** (m^2)	**Existing City Land Coverage** (m^2)	**Megacity Land Coverage** (m^2)
New York City (NYC)	3.744	160.785	2,453,250,184 (<0.1%)	N/A
Port Louis (PL)	2.095	192.337	12,664,441 (<0.1%)	757,803,198 (~0.06%)
Port of Spain (PS)	1.126	392.226	37,888,049 (~0.05%)	4,109,029,057 (~5.5%)

Table 5: The percentage of each nation's exclusive economic zone is given in parentheticals below the total amount of ocean surface area when applicable [19].

Ironically, offshore wind underperformed significantly in the SIDS. The areal power density of offshore wind is 1.7 times higher in NYC than in PL and 2.7 times higher than in PS. This is due to low mean wind speeds and mean power densities near the equator which increase significantly closer to the north and south poles (See Fig. 2).

Figure 2: Global Wind Atlas Mean Power Densities

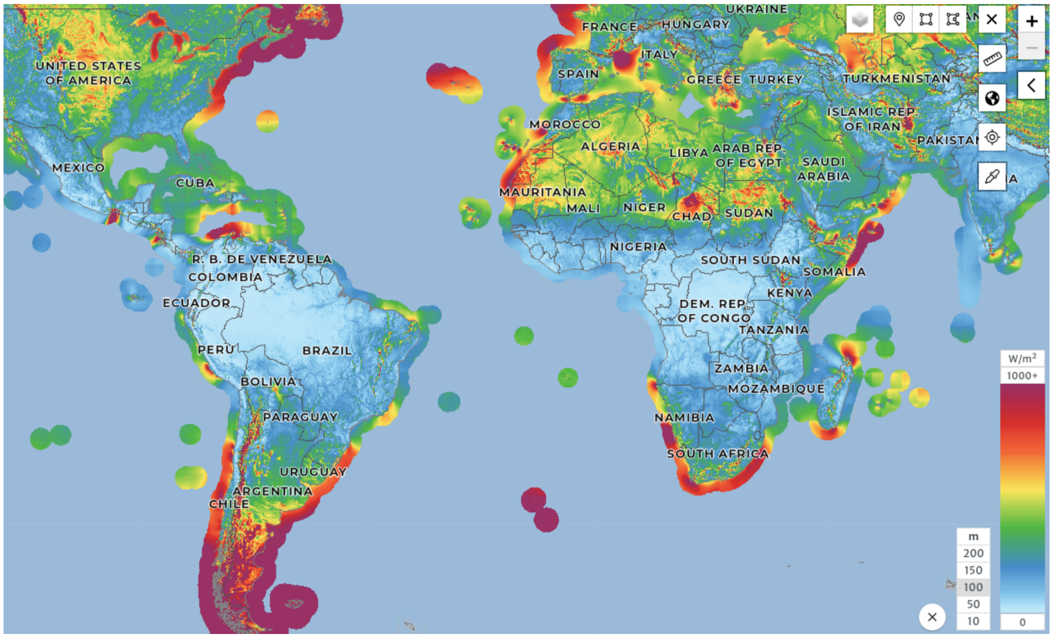

Figure 2: The mean wind speed and wind power density and are generally low close to the equator. Further north and south the mean wind speed and wind power density are significantly higher.

However, a recent paper discussing the potential of onshore wind power in Trinidad and Tobago claims that onshore wind would be economically competitive in wind speeds of 5.8-6.9 m/s [3]. This is less than the mean offshore wind speed of 7.5 m/s reported in Trinidad and Tobago (See Table 1). Consequently, even if there is less harvestable wind energy offshore in PL and PS than NYC, it still remains economically viable to pursue offshore wind.

The land coverage needed to power a household with offshore wind power is on the same order of magnitude for all cities and constitutes a fraction of the space needed for a single turbine (<0.1% for all cities) (See Table 5). Thus, in operational conditions, a single wind turbine can power over 1,000 households in any of these locations.

Similar to estimates for SPV, the total amount of land needed to supply existing cities and megacities diverges significantly. Once again, PS has a greater land requirement than PL in both models; an issue which is exacerbated by an areal power density 45% lower than PL. This low areal power density and high energy use per capita result in megacity land needs over 1.5 times that of NYC. With regard to the percentage of land used to power cities, PL performs significantly better than PS because Mauritius has one of the largest exclusive economic zones in the world [20]. However, it is important to recognize that not all of this ocean territory is currently viable for wind turbines. Most existing offshore wind installations are constrained to within 15 km of the shore because they require foundations on the sea floor. Efforts are currently underway to develop floating wind turbines which could allow for the construction of turbines further offshore –maximizing the potential of available ocean space [21].

Compared to the areal power density and land requirements of SPV installations, offshore wind is underperforming significantly. However, the maximum areal power density of offshore wind does coincide with the minimum areal power density of SPV. Thus, while it is indisputable that SPV is the technology of choice for SIDS located reasonably close to the equator, it is worth investigating if there are inhabited regions closer to the North and South poles where wind power is unambiguously preferable to SPV. In addition, offshore wind may be useful to SIDS if existing cities grow into megacities because it would enable power generation from otherwise unused ocean territory. This would allow for the conservation of land resources, which are arguably more precious to SIDS.

3.3 Thermal Power Plants

Table 6: Thermal Power Density and Land Coverage

Location	**Areal Power Density** ($kWh/m^2/month$)	**Household Land Coverage** (m^2)	**Existing City Land Coverage** (m^2)	**Megacity Land Coverage** (m^2)
New York City (NYC)	365 – 7,300	0.082 – 1.649	1,258,259 - 25,165,175 (<0.01-0.02%)	N/A
Port Louis (PL)		0.055 – 1.104	3,635 – 72,700 (<0.01%)	217,508 – 4,350,163 (0.01-0.21%)
Port of Spain (PS)		0.061 – 1.210	5,845 - 116,906 (<0.01%)	633,933 – 12,678,667 (0.01-0.25%)

Table 6: The percentage of land area is given in parentheticals below the total amount of land when applicable as in Table 4. Note that the range in areal power densities results in estimates ranging over an order of magnitude.

Traditional thermal power plant areal power densities are much higher than the power densities of renewable resources. In some cases, household energy needs can be met with a fraction of a square meter. As a result, entire cities (and even megacities) can be powered by a small number of generation facilities spanning a few square kilometers. The percentage of land coverage that this would require is marginal in all models. Although SPV proved more efficient than offshore wind, it is still orders of magnitude lower than the high power densities achieved by conventional fossil fuel facilities.

4 Discussion

Order of magnitude calculations are useful tools for capturing the behavior of a system with minimal computation, simple models and assumptions. However, it is important to verify that the assumptions imposed on the model reflect reality – otherwise these calculations can diverge significantly. To verify the calculations of areal power density in this paper, the annual output of several wind and solar installations are used as case studies for comparison. It is important to note that these case studies do not offer a one to one comparison. Neither Mauritius nor Trinidad and Tobago currently have offshore wind installations and the renewable sector in Trinidad and Tobago, as a whole, is critically underdeveloped [2, 3].

4.1 SPV Case Study near Port Louis

The Skytron Energy Bambous SPV plant serves as a case study of an operational SPV installation in Mauritius. The utility scale solar installation produces 22,162 MWh/year over a land area of 34 hectares [16]. This translates into an areal power density of 5.43 kWh/m^2/month, which is 41% of the order of magnitude calculation. Thus the calculation for the SPV output is on the correct order of magnitude, however certain parameters could be adjusted in future research to fine tune this approximation. In particular, the packing factor, which was assumed to be 0.5, may be an overestimate. A packing factor of 0.2 makes the order of magnitude calculation agree with the empirical value. In addition, there could be other non-idealities that have not been considered in this paper. For instance, shading of individual solar panels due to variations in cloud cover or debris can have significant impacts on the overall output of a utility scale solar installation [11]. If one panel is shaded, then every other panel connected in series is current limited by the underperforming panel. Factors such as these may explain the discrepancy between the order of magnitude calculations and empirical data.

4.2 Offshore Wind Case Study near New York City

The Block Island Wind Farm, constructed by the offshore wind company Deepwater Wind, was the first offshore wind farm in the United States [17]. The project is composed of 5 Alstom Haliade 150-6-MW turbines that provide 125 GWh of energy annually [22]. Assuming a spacing of $40d^2$, this translates into an areal power density of 11.57 kWh/m^2/month. This result is only three times larger than the areal power density for offshore wind obtained in this paper and hence still within an order of magnitude. The discrepancy may be due, in part, to the fact that the Block Island Wind Farm is only composed of 5 turbines in a row and hence experiences minimal wake effects. This could account for ~10% of the difference between theory and observation. Other potential contributors to this discrepancy are differences in capacity factors and mean wind power density at finer spatial resolutions than provided in the Global Wind Atlas.

Overall these case studies confirm that that the order of magnitude calculations for SPV and offshore wind areal power density will arrive at the correct order of magnitude, however, minor discrepancies illustrate the need for more precise modelling and fine tuning of parameters.

4.3 Energy Storage

Unfortunately, wind and solar are intermittent, non-dispatchable power sources. This leads to two problems: over-generation risk and the evening-ramp challenge [23]. During the day, plentiful solar power allows traditional, dispatchable power sources to operate under their rated capacity [23]. However, to ensure grid stability, non-dispatchable energy sources cannot be switched off in order to ensure that electricity supply meets demand. This can result in either renewable curtailment or negative prices. This is when some electricity generated by renewables is either wasted or utilities are forced pay consumers to increase their power usage. In addition, in the evening when solar power ceases to generate electricity, utilities must massively ramp up the use of dispatchable energy sources, such as natural gas, which is a growing technical challenge [23].

The ultimate solution to these issues is energy storage. If the excess energy generated by SPV during the day could be stored for the evening when SPV output diminishes, then there is no threat posed by over-generation and the need for a steep evening ramp-up in dispatchable electricity generation is greatly reduced. Many technologies are currently being investigated for applications in energy storage. Two of the most prominent are Battery Energy Storage (BES) and Pumped Hydroelectric Storage (PHS). Battery Energy Storage has made headlines in recent years as projects like the Hornsdale Power Reserve come online [24]. However, a study of the economics of energy storage in Mauritius found that pumped hydroelectric energy storage is the most economical energy storage option for the nation currently since a fully renewable electric grid would require ~1.5 days' worth of energy storage [25].

In addition to energy storage, there are strategies for ensuring a complementary portfolio of renewable energy and reducing overall energy demand. For example, offshore wind tends to be strongest in the afternoon and evening when SPV output begins to drop [26]. Installing a mixture of SPV and offshore wind would provide more comprehensive coverage of daily energy requirements. In addition, energy demand can be reduced through the use of solar water heaters. Solar water heaters are very common throughout SIDS. These rooftop solar collectors serve to reduce the electricity demand for indoor heating resulting in significant electricity savings. In Mauritius, solar water heaters led to a 5MW drop in peak electricity demand [2]. In summary, the challenges associated with integrating non-dispatchable energy sources into the electric grid must be addressed through energy storage, but there are many other innovative best practices and technologies that can help minimize the amount of energy storage necessary.

5 Conclusion

Renewable energy from SPV and offshore wind are viable alternatives to fossil fuels in SIDS given current population and energy consumption. Powering cities like Port Louis or Port of Spain entirely using SPV or offshore wind would require the conversion of <1% of land or water areas to this purpose, which is a manageable prospect. In addition, the magnitude of the land or water areas required are also significantly less than those required to power New York City. This makes SIDS, as they are currently situated, prime candidates for leading the renewable energy transition. This is especially true if these SIDS focus on SPV rather than wind power since SPV has a much higher power density near the equator than offshore wind.

However, if population trends change and Port Louis or Port of Spain grow into megacities like New York City, the outlook for the renewable energy transition dramatically changes. In this case, it would be more reasonable to expect continental megacities, such as New York City, to lead the renewable energy transition. This is because the power demands of SIDS would now be of the same order of magnitude as New York City but the nations themselves would likely lack the land to convert to renewable energy purposes (converting ~5-6% of land to renewable energy is much more challenging than converting <1%).

Furthermore, investment in SPV and offshore wind alone is not sufficient to guarantee a renewable energy transition. Since solar and wind resources are inherently intermittent these technologies must be paired with an energy storage mechanism, such as Battery Energy Storage or Pumped Hydroelectric Storage, in order to ensure that supply and demand are balanced continuously. While battery storage is gaining traction globally, pumped hydroelectric storage remains the most economical solution in the short term. Overall, the renewable energy transition is feasible but the exact trajectory that it takes depends as much on population and consumption dynamics as it does on technological innovation.

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Appendix A: Power Level Calculations

The calculations for the “power levels” considered in this paper are as follows. Per capita electricity usage is calculated using Equation (a) where E represents average annual electricity usage; and P represents population. This can then be used to calculate the existing and hypothetical megacity power levels by using Equation (b) where P_{city} represents the city population. Average annual electricity usage data is obtained from Our World In Data [7] and population data is obtained from the statistics offices of each individual country [8, 9, 10].

$$\text{(a)}\ E_{pc} = \frac{E}{P}$$

$$\text{(b)}\ E_{city} = E_{pc}\, P_{city}$$

Household electricity usage is more difficult to calculate because it depends on a number of factors such as average family size, lifestyle and income. While average household electricity usage for New York State (and hence NYC) could be obtained from secondary sources [4], the average household electricity usage for PL and PS had to be calculated according to Equation (c) and Equation (d) respectively. E_{res} represents national residential electricity usage, n represents the total number of households, p_{res} represents the percentage of electricity for residential use and s_h represents the size of an average household. The national residential electricity usage and number of households in Mauritius were obtained from Statistics Mauritius [5]. The percentage of electricity used for residential purposes in Trinidad and Tobago was obtained from the National Renewable Energy Laboratory [6] and the average household size was obtained from the Trinidad and Tobago Central Statistics Office [9].

$$\text{(c)}\ E_{ph} = \frac{E_{res}}{n}$$

$$\text{(d)}\ E_{ph} = E_{pc}\, p_{res}\, s_h$$