Role of Solar Photovoltaics for a Sustainable Energy System in Puerto Rico in the Context of the Entire Caribbean Featuring the Value of Offshore Floating Systems

Christian Breyer, Ayobami Solomon Oyewo, Alejandro Kunkar, and Rasul Satymov

***Abstract*—The Caribbean and Puerto Rico are lagging in ramping renewable energy (RE) capacities. Energy system transition pathways reaching 100% RE by 2050 for Puerto Rico and the Caribbean are analyzed for all energy supplies. Islands are often limited in available land; therefore, scenario variations are considered, including offshore floating photovoltaics (PV). The results for Puerto Rico clearly indicate the enormous benefits of reaching 100% RE, as the levelized cost of electricity (LCOE) can be reduced from more than 100 €/MWh in 2020 to 47.4 €/MWh in 2050, and the levelized cost of energy, including all energy sectors, declines from 79 to 53 €/MWh, respectively. PV reaches 81% of all electricity supply, leading to 33.4 GW installed capacity, thereof 17.5 GW offshore floating PV due to area limitation. Without area limitation, the total system cost would be about 2.7% lower. The key metrics for the Caribbean development from 2020 to 2050 are as follows: electricity generation from 110 to 677 TWh, PV supply share from 2% to 92%, PV capacity from 1 to 332 GW, thereof 19% prosumer, 81% utility-scale with up to 38% offshore floating PV, and LCOE from above 100 to 31.9 €/MWh. The prosperity of Puerto Rico and the Caribbean is closely related to solar PV, the dominating source of energy in their Solar-to-X Economy.**

***Index Terms*—Energy storage, energy management, offshore installations, photovoltaic systems, renewable energy sources, wind power generation.**

I. Introduction

TRANSITIONING to renewable energy (RE) is at the inner core of climate change mitigation, sustainable development, and fighting multiple energy crises [1]. This transition implies phasing out fossil fuels to eliminate CO_2 emissions and to avoid health impacts and fatalities associated with air pollution [2]. RE-based solutions have become low cost and thus they reduce levelized cost of electricity (LCOE) and overall cost of energy supply [3]. Islands are in focus of the energy transition, since climate-change-induced rising sea levels threaten many islands in general, and the risk of climate and weather extremes has increased [1]. Energy crises lead to higher energy expenditures for energy correlating with energy poverty and reducing economic prosperity. Islands especially benefit from higher shares in RE, as higher cost of energy supply is a general challenge on islands in the world.

The energy transition options for the Caribbean have not been well researched yet [4] as only a limited number of studies are available, which are largely limited to the power sector and do not cover the entire energy system. However, research has demonstrated that increasing the share of RE, and in particular of solar photovoltaics (PV), reduces the energy system cost [5]. The first 100% RE system analysis for any Caribbean island was published in 2017 for Montserrat [6], 13 years after the first respective study for an island as identified by Meschede et al. [4], whereas the high value of renewables in the regions had been known for many years. Almost all Caribbean island countries had grid-parity of solar PV for all rooftop applications, from residential to industrial systems, between 2010 and 2013, indicating self-sustained and profitable business cases [7]. Jamaica was studied for the first time in 2020 for the highest share of renewables [8]. A smaller region in Cuba was studied in 2021 [9], [10]. The Caribbean is the island region in the world with the lowest coverage of studies. The largest overview on 100% RE system studies covered 550 journal publications [11] while with the same method in the meantime, more than 900 articles are known, whereas the published articles for the entire Caribbean are still the five articles as references in this study. The studies on Jamaica and Montserrat cover only the power sector, and the studies on Cuba covered a region of less than 100 000 inhabitants. It is of high importance for the Caribbean that more 100% RE studies are published in general and using latest available methods covering entire islands and countries for all energy sectors, in particular to avoid policy failures due to lack of awareness.

Wallsgrove et al. [12] discuss implications for microgrids on Puerto Rico in the transition toward 100% RE, though concrete energy system analyses were not presented. The Puerto Rico Office of Budget and Management published the Puerto Rico Energy Public Policy Act in 2019 [13] with the dedicated aim for 100% renewable electricity supply by 2050 and intermediate targets of 40% (2025) and 60% (2040). A comprehensive research

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study is being conducted by major US research institutions on 100% RE for Puerto Rico [14], called PR100; however, a preliminary report published in January 2023 does not yet contain results for energy system analyses. No research article is known for highly RE system analyses neither for Puerto Rico nor the entire Caribbean.

This article fills this research gap for transition options in Puerto Rico and the entire Caribbean, providing contextualized results for Puerto Rico. The research setup focuses on a 100% RE supply by 2050 with allowed electricity-based e-fuels imports for liquefied natural gas (e-LNG) and Fischer–Tropsch liquids (e-FTL), and local electricity and e-hydrogen supply. Four scenarios are investigated to address the onshore area limitation that can be overcome with offshore floating PV systems, both for Puerto Rico and the entire Caribbean.

II. Methodology

The energy system transition is analyzed using the LUT Energy System Transition Model (LUT-ESTM) [15]. LUT-ESTM is a technology-rich, hourly-resolved model that can be operated in multinode and multiscenario applications for a complete transition from 2020 to 2050 in five-year increments. LUT-ESTM was applied for the Caribbean, structured in nine regions, thereof one region for Puerto Rico (see Fig. 9), which also includes, for practical reasons, the British Virgin Islands and United States Virgin Islands. Puerto Rico, however, accounts for 96% of the energy demand in this region.

LUT-ESTM covers the sectors of power, heat, and transport. The heat sector includes domestic hot water demand, industrial process heat, and biomass for cooking, according to Keiner et al. [16]. The transport sector covers the transport modes of road, rail, marine, and aviation for passenger and freight transportation. The road transport mode is composed of light-duty vehicles (LDV), 2/3-wheelers (2,3W), buses, medium-duty vehicles (MDV), and heavy-duty vehicles (HDV). The applied powertrains are internal combustion engines, battery-electric vehicles (BEV), plug-in hybrids, and fuel cell electric vehicles. More details and assumptions for the transport sector can be found in Bogdanov et al. [15] and Khalili et al. [17].

The demand assumptions for Puerto Rico for the different energy sectors are derived from Inter-American Development Bank and International Renewable Energy Agency [18], [19] for the power sector, Keiner et al. [16] for the heat sector and Khalili et al. [17] for the transport sector and are projected, as summarized in Table I.

The techno-economic assumptions, as listed in Table II, are aligned to previous publications [15], [20] and detailed for the core components: solar PV (residential prosumer, single-axis tracking, offshore floating), onshore wind power, utility-scale batteries, and electrolyzers.

The existing PV options are residential, commercial, and industrial PV prosumers, fixed-tilted ground-mounted, and single-axis tracking utility-scale PV systems. These five different PV system options are complemented for the first time in LUT-ESTM with offshore floating PV following the assumptions of Keiner et al. [20]. Solar PV installations are assumed to follow best practice standards [21] and special consideration for severe weather standards [22].

TABLE I
Demand for Energy Services for Puerto Rico From 2020 to 2050

		2020	2030	2040	2050
Population	mil	3.07	3.04	2.82	2.56
Power sector	TWh_{el}	18.7	23.4	30.7	41.4
Heat industrial	TWh_{th}	15.9	14.0	11.3	8.6
Heat domestic	TWh_{th}	0.79	0.90	0.93	0.93
Road LDV	mil p-km	5283	5474	6686	9106
Road 2,3W	mil p-km	10 870	10 253	11 450	14 491
Road BUS	mil p-km	1330	1103	1057	1145
Road MDV	mil t-km	5775	5563	6359	8479
Road HDV	mil t-km	610	588	661	837
Rail	mil p-km	20.0	19.0	22.0	29.0
Marine passenger	mil p-km	182	171	155	141
Marine freight	mil t-km	92 583	100 512	127 333	173 955
Aviation passenger	mil p-km	4136	4985	6887	9994
Aviation freight	mil t-km	238	332	539	884

Note: Abbreviations: Passenger Kilometers–P-Km, Ton Kilometers–T-Km.

TABLE II
Techno-Economic Assumptions for the Core Energy System Components

	capex [€/kW; €/kWh]	opex [€/(kW·a)]	lifetime (a)	efficiency (%)
PV residential	715 / 453	6.7 / 4.4	35 / 40	
PV single-axis utility	306 / 183	6.2 / 4.1	35 / 40	
PV floating offshore	695 / 332	13.9 / 6.6	30	
Wind power onshore	1000 / 900	20 / 18	25	
Batteries utility-scale (energy, interface)	110 / 61 55 / 30	2.2 / 1.7 1.1 / 0.8	20 20	93% / 95%
Electrolyzers	313 / 204	11.0 / 7.1	30	70%

Note: Assumptions are aligned to previous publications [15], [20] and applied for every period. The values for 2030 and 2050 are listed. Lower heating values and capex per input power are applied for electrolyzers. Abbreviations: Capital Expenditures–Capex; Operational Expenditures–Opex.

RE resource potentials follow the standard setting of LUT-ESTM [15], which assumes 4% of the region's area for wind power and 6% for solar PV, and bioenergy according to its sustainable potentials avoiding energy crops, thus, utilizing wastes, residues, and by-products. The standard assumption of 6% maximum area availability was reduced to 1% in this research as default to investigate the realistic case of limited area and the application of offshore floating PV as a solution.

The scenarios are denoted as follows.

1) *BPS-PRV-1:* Best policy scenario reaching 100% RE by 2050 in all energy sectors for Puerto Rico, British Virgin Islands, and United States Virgin Islands with 1% area availability for ground-mounted PV.
2) *BPS-PRV-6:* As BPS-PRV-1 but with 6% area availability for ground-mounted PV.
3) *BPS-CAR-1:* As BPS-PRV-1 but for the entire Caribbean.
4) *BPS-CAR-6:* As BPS-PRV-6 but for the entire Caribbean.

The BPS-PRV-1 and BPS-CAR-1 are applied as default in this research.

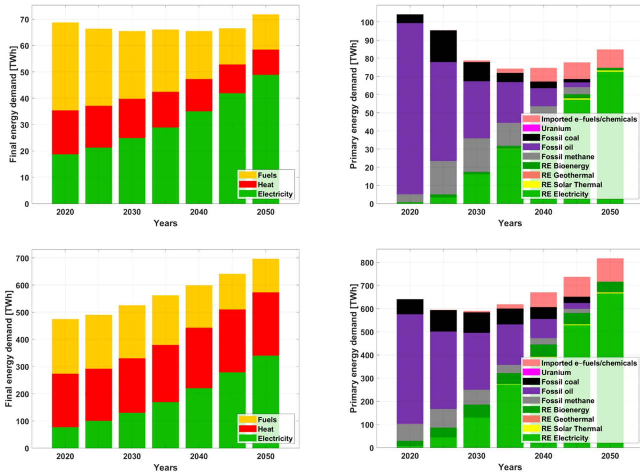

Fig. 1. Final (left) and primary (right) energy demands for Puerto Rico (top) and the Caribbean (bottom).

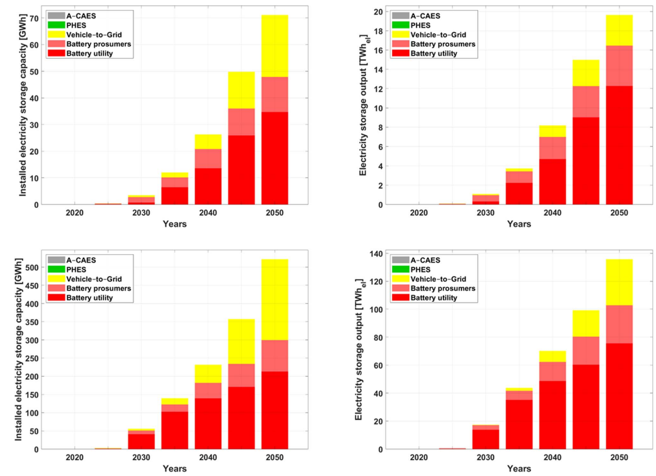

Fig. 3. Installed electricity storage capacity (left) and electricity storage output (right) for Puerto Rico (top) and the Caribbean (bottom).

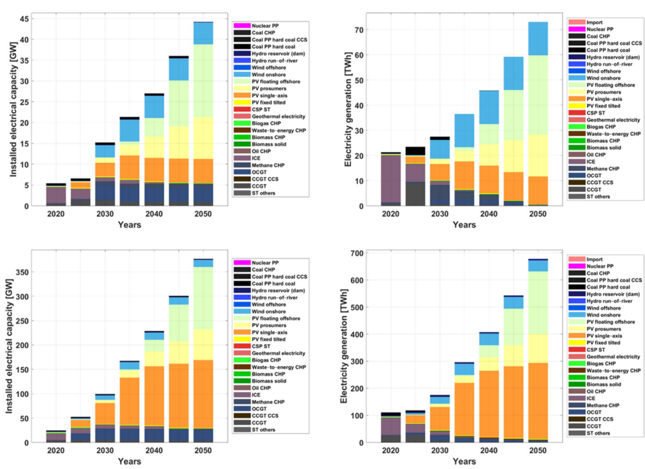

Fig. 2. Installed electricity capacity (left) and electricity generation (right) for Puerto Rico (top) and the Caribbean (bottom).

III. Results

The final and primary energy demands for the BPS-PRV-1 and BPS-CAR-1 are shown in Fig. 1. The final energy demand for Puerto Rico is stable, as most final energy fuels and heat demand are substituted by electricity where possible. While the present primary energy demand is dominated by fossil oil without relevant electricity contribution, the energy transition leads primary energy demand reductions driven by much higher efficiencies of direct electric solutions and some imported e-fuels, mainly e-FTL for aviation, marine, and some remaining road demand and smaller shares of e-LNG (see Fig. 5). Trends for the entire Caribbean are similar but with an increase in final and primary energy demands due to rising standards of living across the Caribbean.

Electricity generation in Puerto Rico increases substantially from 21.2 TWh in 2020 to 73.0 TWh in 2050, as shown in Fig. 2. While phasing out fossil oil and gas-based generation, the potential of PV prosumers and the respective zero impact rooftop space, single-axis tracking PV is fully utilized and, from 2040 onward, substantial offshore floating PV capacities are installed. Onshore wind power complements the electricity generation in the 2030s, still benefiting from an attractive cost structure, which is challenged by offshore floating PV from the late 2030s onward. Offshore floating PV is built in the BPS-PRV-1 due to the area limitation, as no offshore floating PV is built in the BPS-PRV-6, where about 4.7% of all onshore area of Puerto Rico is required. The results for the entire Caribbean are similar (see Fig. 2) but, compared to Puerto Rico, there is less wind power (6% versus 18%), less prosumer PV (16% versus 23%), less offshore floating PV (34% versus 43%), and more single-axis tracking PV (41% versus 16%). The electricity generation in the Caribbean and Puerto Rico is dominated by solar PV with 92% and 81%, respectively. The capacity breakdown is even more dominated by solar PV with a total of 332 GW (63.9 GW for prosumers, 1.0 GW for fixed-tiled, 139.2 GW for single-axis tracking, and 127.4 GW for offshore floating) in the Caribbean and 33.4 GW (10.1 GW for prosumers, 5.8 GW for single-axis tracking, and 17.5 GW for offshore floating) in Puerto Rico. Generation and capacity shares differ due to higher full-load hours of wind power compared to solar PV. Other sources of RE supply are negligible.

Systems dominated by variable RE require flexibility measures, including supply complementarity, grid balancing, demand response, storage, and curtailment [2]. In this study, supply complementarity comprises solar PV and wind power, as well as sustainable bioenergy and reservoir hydropower where available. Grid balancing is not investigated for Puerto Rico. Demand response is considered for smart BEV charging using the battery flexibility in road vehicles and electrolyzers using their flexibility in combination with hydrogen buffer storage. Electricity storage plays a substantial role for the diurnal storage of solar PV utilizing batteries for prosumers as well as utility-scale and vehicle-to-grid (V2G) storage, as shown in Fig. 3. Storage demand starts in the 2020s, is rolled out in the 2030s, and scaled in the 2040s. By 2035, 10% of electricity generation is stored directly, which increases to 27% by 2050. Storage throughput is enabled by utility-scale batteries, prosumer batteries, and V2G storage by 62%, 22%, and 16%, respectively. The

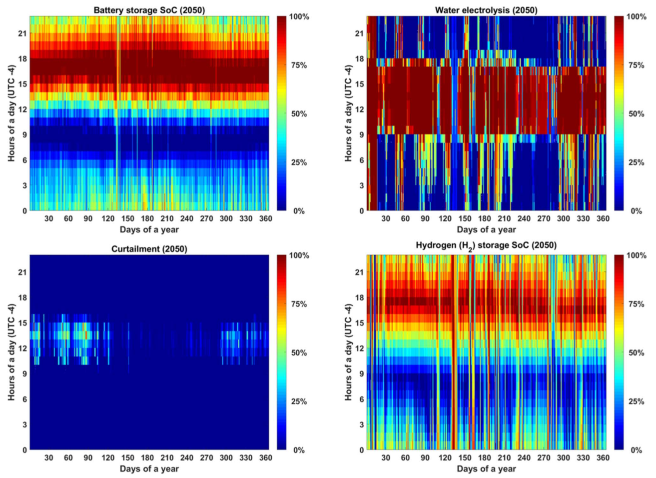

Fig. 4. Hourly state-of-charge for utility-scale battery (top left), operation of electrolyzers (top right), state-of-charge for hydrogen buffer storage (bottom right), and curtailment (bottom left) for Puerto Rico in 2050.

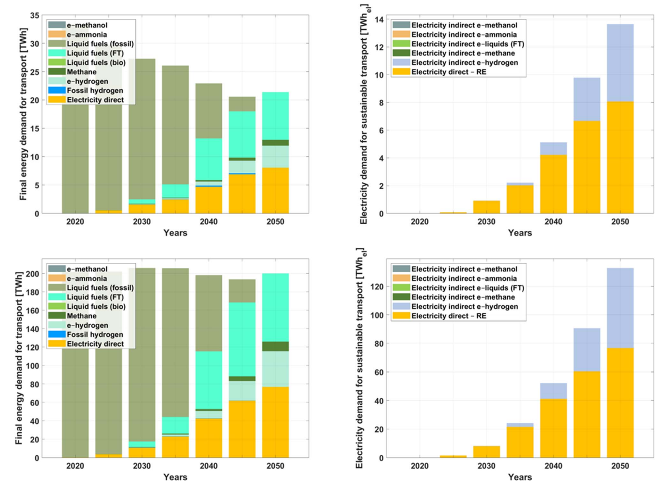

Fig. 5. Final energy demand per fuel (left) and electricity demand for direct use and e-hydrogen (right) for the transport sector for Puerto Rico (top) and the Caribbean (bottom).

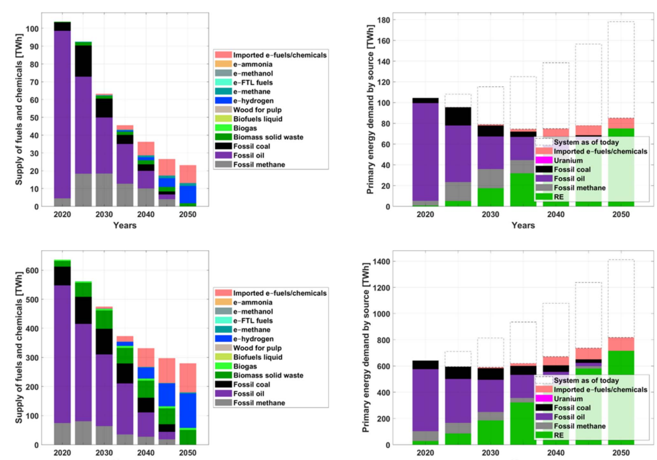

Fig. 6. Supply of fuels (left) and primary energy supply with actual and not improved system efficiency (right) for Puerto Rico (top) and the Caribbean (bottom).

energy-to-power ratio of batteries is 6.6 and 5.1 h for prosumers and utility-scale batteries in 2050 and does not change much compared to the previous periods. The role of direct electricity storage is very similar for the entire Caribbean, with a bit higher V2G share of 24% on average. The flexible operation of the battery storage capacity is depicted in Fig. 4, showing its strong diurnal characteristic with charging from morning to afternoon hours, and then discharging until the next morning. The solar resource is quite stable over the entire year, as only small variations over the year can be observed in the battery storage operation.

The influence of weather pattern is more noticeable in the operation of electrolyzers with default operation during daytime hours with PV electricity (see Fig. 4) and some nighttime operation when wind is available, primarily in some periods across the mid and end of year. The hydrogen storage operates as diurnal buffer for the more baseload hydrogen demand; however, it occasionally operates as longer term buffering, in contrast to battery storage. Batteries are partly discharged in morning hours via electrolyzer operation to avoid solar PV curtailment in the following day, in total for 2.6 TWh_{el} (see Fig. 10), which represents about 16% of all battery discharge. The purpose of this discharging is not to maximize electrolyzer utilization, but rather, to ensure that battery capacity is available to avoid curtailment of solar PV. This effect is described in more detail in [23].

The effective sector coupling and high flexibility in the energy system across sectors reduce curtailment to 3.4% for the 100% RE system in 2050. This overall characteristic is almost identical for the entire Caribbean, with 3.5% curtailment in 2050. Curtailment in Puerto Rico is noticed during the daytime and limited to the months from November to April (see Fig. 4). Longer term storage is not needed much; however, 2.4 TWh_{el} are contributed by gas turbines in hours when direct electricity supply and battery discharge are not sufficient, representing 4.3% of the direct electricity demand (see Fig. 10). The transport sector represents 28% of the final energy demand in Puerto Rico. Due to cost scaling, fuels other than electricity and hydrogen are assumed to be imported, most likely from mainland Americas, which mainly affects e-FTL for aviation and marine fuels (see Fig. 5). Electricity and e-hydrogen used for transportation are supplied from local sources, for which 19% of total electricity generation is required, thereof 59% directly and 41% for e-hydrogen production.

The ratios of fuels and electricity share for direct use and hydrogen do not differ much for the Caribbean; however, the overall fuel demand remains roughly stable for the Caribbean. That is, the high efficiency gain in electrification of road transportation is compensated by the demand increase for marine and aviation transportation, which is already at high levels in Puerto Rico, leading to lower overall growth in Puerto Rico compared to the entire Caribbean.

The overall fuels demand sharply declines for Puerto Rico and the Caribbean (see Fig. 6), with a local supply of e-hydrogen and some sustainable bioenergy. Conversely, marine and aviation fuels other than electricity and e-hydrogen are assumed to be

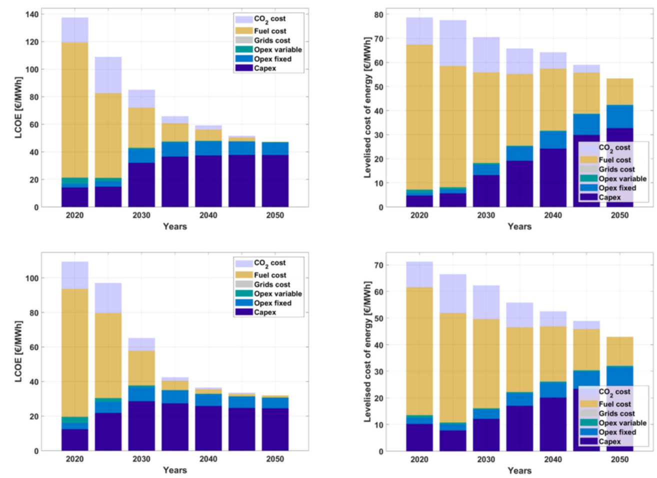

Fig. 7. LCOE (left) and levelized cost of energy (right) for Puerto Rico (top) and the Caribbean (bottom).

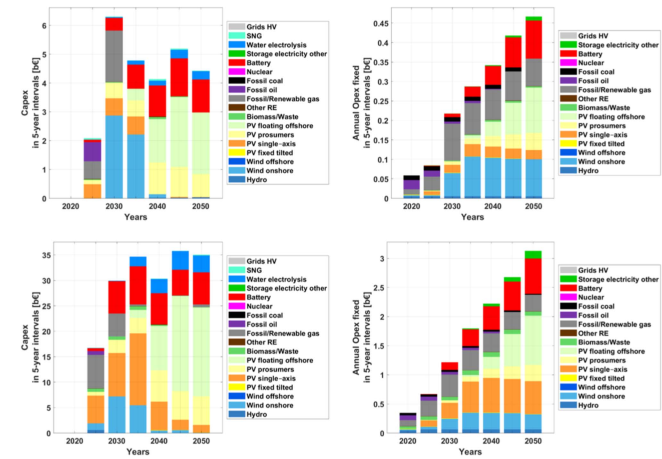

Fig. 8. Capital expenditures (left) and operational expenditures (right) for Puerto Rico (top) and the Caribbean (bottom). Abbreviations: capital expenditures—capex; operational expenditures—opex.

imported from mainland Americas. The dominating fuels for Puerto Rico and the Caribbean are oil products, with smaller shares of fossil gas and coal. The overall energy system can realize a substantial increase in efficiency, as shown in Fig. 6. Both the phase-out of inefficient fuel use and the massive electrification across the energy system, such as BEV, make this efficiency gain possible, as described in the literature [2], [15], [24]. The LCOE and levelized cost of energy strongly benefit from phasing out fossil fuels and using low-cost renewable electricity (see Fig. 7) in as many direct electrification applications as possible, and indirect power-to-X solutions otherwise, such as for heat supply and e-hydrogen. The LCOE drastically declines from above 100 €/MWh in 2020 to 47.4 €/MWh in Puerto Rico and 31.9 €/MWh in the Caribbean in 2050. Levelized cost of energy, defined as the ratio of total annualized system cost divided by total final energy demand, declines from 79 and 53 €/MWh in 2020 to 71 and 43 €/MWh in 2050 for Puerto Rico and the Caribbean, respectively, even excluding costs for CO_2 emissions and air pollution. The enormous levelized cost reductions for electricity and overall energy supply require substantial investments.

The current dominating cost share is fuel cost in LCOE and levelized cost of energy (see Fig. 7), whereas the remaining fuel costs in 2050 are for imported marine and aviation fuels. Different technologies require higher capex shares across the transition period with wind power in the next 10–15 years and solar PV from now onward with dominating shares from 2040 onward. Batteries are required on a large scale from 2030 onward with significant electrolyzer capacities from 2035 onward. Operational expenditures (opex) continue to grow in LCOE and levelized cost of energy (see Fig. 7) and across technologies (see Fig. 8). These opex also indicate the creation of jobs needed for the operation of the energy system, which is a structural feature of highly RE systems [25].

IV. Discussion

The electricity generation mix is a clear consequence of the available onshore area for solar PV, since a 6% maximum onshore solar PV area potential does not lead to any offshore floating PV installations, whereas a 1% limit for the land availability strongly forces offshore floating PV. In the relative merit order of least cost options, ground-mounted PV is applied first, in parallel to prosumer PV on zero impact land, i.e., rooftops. While wind power is competitive in some regions of the Caribbean, such as Puerto Rico, in the 2030s, it is no longer competitive in the 2040s, when the cost of offshore floating PV is further reduced. The requirement for offshore floating PV decreases as the available area to meet the demand increases, as observed in Cuba in the BPS-CAR-1 (see Fig. 9). Conversely, Haiti and the Venezuelan islands have the highest proportions, accounting for over 50% of their total electricity generation. Third in this regard is Puerto Rico.

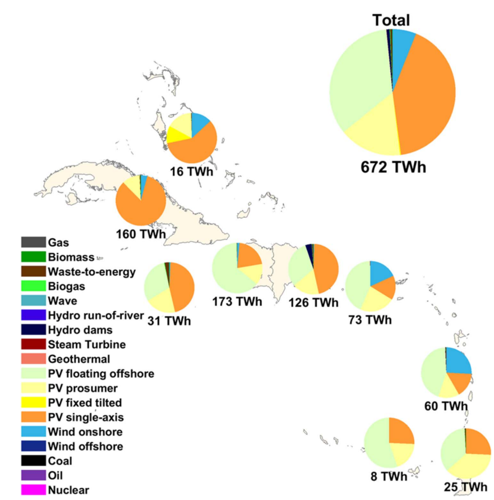

Fig. 9. Electricity generation in 2050 in the BPS-CAR-1.

The cumulative costs of the BPS-PRV-1 and BPS-PRV-6 pathways vary by 2.7%, due to the substantial phase-in of offshore floating PV; however, the total cumulative pathway costs are only marginally shifted. Compared to the BPS-PRV-6, the BPS-PRV-1 annualized system cost is 4.7% higher in 2050.

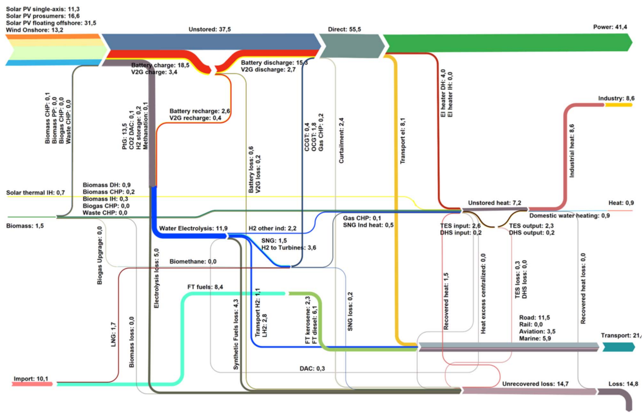

Fig. 10. Energy flow for Puerto Rico in the BPS-PRV-1 for 2050.

Similarly, results for the Caribbean find respective cost increases of 3.0% and 9.0% for the entire pathway and 2050.

The energy flow diagram of the BPS-PRV-1 (see Fig. 10) reveals that the arising energy system in Puerto Rico is primarily electricity-based and largely domestic with only limited imports of e-FTL and e-LNG for aviation and marine fuels and various power-to-X solutions across the energy system. Batteries play a major role in stationary, smart BEV charging, and V2G applications. Hydrogen is relevant, though not for seasonal balancing, as only 3.6 TWh_{H2} are used for reconversion to electricity (and total electricity generation of 73.0 TWh). 3.9 TWh_{H2} are used for transport, mainly marine and aviation, and the remaining hydrogen is used for industrial demands.

The energy flows of Puerto Rico in the BPS-PRV-1 can be described best as a power-to-X economy, and since 81% of all electricity is provided by solar PV, the term Solar-to-X Economy may be suited best [26], [27], even more for the Caribbean with a share of solar PV of 92%. The implementation of optimized techno-economic pathways in Puerto Rico and the Caribbean could be hindered by existing policies and societal constraints [5]. Analyzing the effectivity of different policy measures revealed that net-metering and net-billing programs are strongly and positively correlated with increases in installed capacity of RE, particularly solar PV [28]. These findings suggest that the RE transition in the Caribbean can be advanced through policies targeting the adoption of small-scale and distributed solutions. The findings of this research are critical, and may be representative for islands across the sunbelt [4], [5], including Pacific Island states, islands in the Indian Ocean, or islands disconnected from their mainland of archipelago countries, such as Indonesia and the Philippines.

This study is limited in some aspects, which may be overcome in follow-up research. The main limitations are in the diversity of ocean energy technology, as offshore wind power [29], wave power [30], and ocean thermal energy conversion [31] are not included in this research. These options may help to mitigate limited onshore land availability. Further diversification in PV systems may improve the optimal system configuration. Vertically erected bifacial PV systems could further reduce the need for battery storage due to higher yields in the morning and afternoon hours [32], [33], [34], whereas the yield profiles are close to the used single-axis tracking PV systems [35]. The impact on system costs may be negligible when land availability is unrestricted, whereas the impact on system costs and design can be significant when land constraints are more stringent, as vertical bifacial PV systems can be used in agrivoltaic systems with small footprints. Bifacial PV systems may improve the energy system cost in general, since the yield is improved [36], whereas the PV system costs are expected to remain rather unchanged. The interannual variability of RE resources may be a challenge for Puerto Rico. Solar resources were found to fluctuate by about 5% over the years [37], which is slightly higher than the corresponding analyses for Hawaii at a comparable latitude [38]. The variability within one year and across the island can be higher, whereas such variabilities can be balanced in a sector-coupled and interconnected energy system. The overall impact of interannual variability on the system design and configuration may be rather low. The principal options are some higher capacities, interannual storage, or load restriction in resource limited years, whereas some higher capacities of about 5% may be least cost solution. Sensitivity analyses for interannual variability are needed to further validate the findings of this study. Broader sensitivities for techno-economic assumptions may be helpful for analyzing the robustness of the findings. Desalination as a demand sector [39] was not modeled in this research while freshwater limited islands in the Caribbean may benefit from a respective detailing. In addition, grid connection of Puerto Rico to nearby islands, in particular to Dominican Republic, is not considered, which could create additional value in reducing costs.

V. Conclusion

This research highlights the enormous opportunities for Puerto Rico and the entire Caribbean in transitioning toward 100% RE supply, as the LCOE drastically declines and the levelized cost of energy comprising the entire energy system also declines. Maintaining and increasing standards of living in Puerto Rico and the Caribbean strongly correlate with an ambitious energy transition. The dominating source of energy for electricity supply and the entire energy system is found to be solar PV with 80% and 91% of supply share in Puerto Rico and the Caribbean, respectively. When limited onshore land availability is applied, a substantial share of all PV generation can be provided by offshore floating PV for minimal extra costs. Only marine and aviation fuels need to be imported, and all other energy demand, electricity or hydrogen, can be provided locally. The arising energy system of Puerto Rico and the Caribbean can be described best as a Solar-to-X Economy.

References

[1] Intergovernmental Panel on Climate Change, *Synthesis Report of the IPCC Sixth Assessment Report (AR6)*. Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2023.

[2] C. Breyer et al., "On the history and future of 100% renewable energy systems research," *IEEE Access*, vol. 10, pp. 78176–78218, 2022, doi: 10.1109/ACCESS.2022.3193402.

[3] International Renewable Energy Agency, *Renewable Power Generation Costs in 2020*. Abu Dhabi, United Arab Emirates: Int. Renewable Energy Agency, 2021.

[4] H. Meschede et al., "A review of 100% renewable energy scenarios on islands," *WIREs Energy Environ.*, vol. 11, 2022, Art. no. e450, doi: 10.1002/wene.450.

[5] P. Blechinger et al., "Global analysis of the techno-economic potential of renewable energy hybrid systems on small islands," *Energy Policy*, vol. 98, pp. 674–687, 2016, doi: 10.1016/j.enpol.2016.03.043.

[6] B. Römer, K. Aldonza, Y. Julliard, and O. Lewis, "Planning 100% renewable energy islands: The case of the Caribbean island of Montserrat," *CIRED Open Access Proc. J.*, vol. 2017, no. 1, pp. 2488–2492, 2017, doi: 10.1049/oap-cired.2017.0728.

[7] C. Breyer and A. Gerlach, "Global overview on grid-parity," *Prog. Photovolt.: Res. Appl.*, vol. 21, pp. 121–136, 2012, doi: 10.1002/pip.1254.

[8] A. A. Chen, A. J. Stephens, R. Koon, M. Ashtine, and K. M.-K. Koon, "Pathways to climate change mitigation and stable energy by 100% renewable for a small island: Jamaica as an example," *Renewable Sustain. Energy Rev.*, vol. 121, 2020, Art. no. 109671, doi: 10.1016/j.rser.2019.109671.

[9] M. Korkeakoski, "Towards 100% renewables by 2030: Transition alternatives for a sustainable electricity sector in Isla de la Juventud, Cuba," *Energies*, vol. 14, 2021, Art. no. 2862, doi: 10.3390/en14102862.

[10] E. A. Alvarez et al., "Long-range integrated development analysis: The Cuban Isla de la Juventud study case," *Energies*, vol. 14, 2021, Art. no. 2865, doi: 10.3390/en14102865.

[11] S. Khalili and C. Breyer, "Review on 100% renewable energy system analyses—A bibliometric perspective," *IEEE Access*, vol. 10, pp. 125792–125834, 2022, doi: 10.1109/ACCESS.2022.3221155.

[12] R. Wallsgrove, J. Woo, J.-H. Lee, and L. Akiba, "The emerging potential of microgrids in the transition to 100% renewable energy systems," *Energies*, vol. 14, no. 6, Mar. 2021, Art. no. 1687, doi: 10.3390/en14061687.

[13] Puerto Rico Office of Management and Budget, *Puerto Rico Energy Public Policy Act – Act. No. 17*. San Juan, Puerto Rico: Puerto Rico Office Manage. Budget, 2019.

[14] N. Blair et al., *PR100 One-Year Progress Summary Report*. Golden, CO, USA: Nat. Renewable Energy Lab., 2023.

[15] D. Bogdanov et al., "Low-cost renewable electricity as the key driver of the global energy transition towards sustainability," *Energy*, vol. 227, 2021, Art. no. 120467, doi: 10.1016/j.energy.2021.120467.

[16] D. Keiner et al., "Global-local heat demand development for the energy transition time frame up to 2050," *Energies*, vol. 14, 2021, Art. no. 3814, doi: 10.3390/en14133814.

[17] S. Khalili et al., "Global transportation demand development with impacts on the energy demand and greenhouse gas emissions in a climate-constrained world," *Energies*, vol. 12, 2019, Art. no. 3870, doi: 10.3390/en12203870.

[18] Inter-American Development Bank, *The Energy Path of Latin America and the Caribbean*. Washington, DC, USA: Inter-Amer. Develop. Bank, 2018.

[19] International Renewable Energy Agency, *Global Renewable Outlook: Energy transformation 2050 – Latin America and the Caribbean*. Abu Dhabi, United Arab Emirates: Int. Renewable Energy Agency, 2020.

[20] D. Keiner et al., "Powering an island energy system by offshore floating technologies towards 100% renewables: A case for the Maldives," *Appl. Energy*, vol. 308, 2022, Art. no. 118360, doi: 10.1016/j.apenergy.2021.118360.

[21] C. Doyle et al., "Best practices in commercial and industrial (C&I) PV systems installation," Nat. Renewable Energy Lab., Golden, CO, USA, Tech. Rep. NREL/SR-6A20-65286, 2015.

[22] J. Elsworth and O. Van Geet, "Solar photovoltaics in severe weather: Cost considerations for storm hardening PV systems for resilience," Nat. Renewable Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-7A40-75804, 2020.

[23] A. Gulagi, D. Bogdanov, and C. Breyer, "The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India," *J. Energy Storage*, vol. 17, pp. 525–539, Jun. 2018, doi: 10.1016/j.est.2017.11.012.

[24] N. Eyre, "From using heat to using work: Reconceptualising the zero carbon energy transition," *Energy Efficiency*, vol. 14, no. 7, pp. 1–20, Oct. 2021, doi: 10.1007/s12053-021-09982-9.

[25] M. Ram et al., "Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050," *Energy*, vol. 238, Jan. 2022, Art. no. 121690, doi: 10.1016/j.energy.2021.121690.

[26] C. Breyer et al., "Reflecting the energy transition from a European perspective and in the global context—Relevance of solar photovoltaics benchmarking two ambitious scenarios," *Prog. Photovolt.*, vol. 9, pp. 1–27, 2022, doi: 10.1002/PIP.3659.

[27] C. Breyer, G. Lopez, D. Bogdanov, and P. Laaksonen, "The role of electricity-based hydrogen in the emerging power-to-X economy," *Int. J. Hydrogen Energy*, vol. 31, 2023, Art. no. 210254, doi: 10.1016/j.ijhydene.2023.08.170.

[28] J. Kersey, P. Blechinger, and R. Shirley, "A panel data analysis of policy effectiveness for renewable energy expansion on Caribbean islands," *Energy Policy*, vol. 155, 2021, Art. no. 112340, doi: 10.1016/j.enpol.2021.112340.

[29] International Energy Agency, *Offshore Wind Outlook 2019*. Paris, France: Int. Energy Agency, 2019.

[30] R. Satymov et al., "Techno-economic assessment of global and local wave resources potentials for energy harvesting by a reanalysis dataset with high temporal resolution," 2023.

[31] J. Langer, J. Quist, and K. Blok, "Recent progress in the economics of ocean thermal energy conversion: Critical review and research agenda," *Renewable Sustain. Energy Rev.*, vol. 130, 2020, Art. no. 109960, doi: 10.1016/j.rser.2020.109960.

[32] S. Reker, J. Schneider, and C. Gerhards, "Integration of vertical solar power plants into a future German," *Smart Energy*, vol. 7, 2022, Art. no. 100083, doi: 10.1016/j.segy.2022.100083.

[33] S. Guo, T. M. Walsh, and M. Peters, "Vertically mounted bifacial photovoltaic modules: A global analysis," *Energy*, vol. 61, pp. 447–454, 2013, doi: 10.1016/j.energy.2013.08.0.

[34] D. Chudinzow, S. Nagel, J. Güsewell, and L. Eltrop, "Vertical bifacial photovoltaics—A complementary technology for the European electricity supply?," *Appl. Energy*, vol. 264, 2020, Art. no. 114782, doi: 10.1016/j.apenergy.2020.114782.

[35] S. Afanasyeva, D. Bogdanov, and C. Breyer, "Relevance of PV with single-axis tracking for energy scenarios," *Sol. Energy*, vol. 173, pp. 173–191, 2018, doi: 10.1016/j.solener.2018.07.029.

[36] C. D. Rodriguez-Gallegos et al., "Global techno-economic performance of bifacial and tracking photovoltaic systems," *Joule*, vol. 4, pp. 1–28, 2020, doi: 10.1016/j.joule.2020.05.005.

[37] N. Grue et al., "Quantifying the solar energy resource for Puerto Rico," Nat. Renewable Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-5D00-75524, 2021.

[38] R. Bryce et al., "Consequences of neglecting the interannual variability of the solar resource: A case study of photovoltaic power among the Hawaiian islands," *Sol. Energy*, vol. 167, pp. 61–75, 2018, doi: 10.1016/j.solener.2018.03.085.

[39] J. C. Osorio-Aravena et al., "Synergies of electrical and sectoral integration: Analysing geographical multi-node scenarios with sector coupling variations for a transition towards a fully renewables-based energy system," *Energy*, vol. 279, 2023, Art. no. 128038, doi: 10.1016/j.energy.2023.128038.