# Floating Offshore Solar Photovoltaics for Land-Constrained and Diverse Renewable Supply Conditions in the United States and Canada

Gabriel Lopez, Dmitrii Bogdanov, Rasul Satymov, and Christian Breyer

***Abstract*—Energy transition pathways for large continental areas are largely understood to be achievable using a diverse set of onshore renewable energy technologies. Previous research for the integrated United States and Canada energy–industry system indicated that solar photovoltaics (PVs) may dominate the primary energy structure, complemented by onshore wind power. However, societal constraints may require increased supply diversity, and onshore renewable energy may not be sufficient for densely populated regions, especially on the east coast of the United States. The LUT Energy System Transition Model was applied to investigate the role of floating offshore solar PV coupled with offshore wind and wave power when onshore solar PV is limited. The results indicate that, when onshore solar PV is limited to 60% of electricity generation, 434 GW of floating offshore solar PV may be installed by 2050 as part of a hybrid power plant sharing the same grid connection as offshore wind power, which reaches 414 GW of installed capacity, contributing 607 and 1576 TWh to the electricity supply, respectively. In total, 7.4 TW of solar PV capacity is installed by 2050, complemented by 1.4 TW of onshore wind power. Increased supply diversity still leads to a 42% reduction in the levelized cost of electricity, reaching 32.7 €/MWh in 2050. Compared with cost-optimal conditions, the levelized cost of final energy and nonenergy use in 2050 increases by 28% to 52.7 €/MWh. Nevertheless, such increased costs may be justifiable to meet societal constraints, and a diverse power-to-X economy structure for the United States and Canada may still be technoeconomically viable.**

***Index Terms*—Energy management, energy storage, net zero, photovoltaic systems, renewable energy sources, wave power, wind energy.**

## I. INTRODUCTION

CLIMATE change continues to present major societal challenges, threatening sensitive ecosystems throughout the United States (US) and Canada. Existing targets for net-zero emissions [1], [2] will require system-wide defossilization to reach climate targets; however, the specific technology mix that would provide a technoeconomically and socially acceptable transition pathway remains uncertain. Previous work [3] identified a dominating role for solar photovoltaics (PVs), which were found to supply 78% of all generated electricity, corresponding to 0.5% of available land area. Onshore wind power in several regions, especially on the US East coast, reached the upper potential limit, corresponding to 4% of available area. Offshore energy resources may, therefore, be relevant for the defossilization of coastal states with limited area if a transition dominated by onshore solar PV is not chosen. Indeed, Williams et al. [4] find a role for offshore wind power that upwards of 1.0 TW of offshore wind power may be required to defossilize all energy demands in the US, especially for northeastern states. Jacobson et al. [5] estimate that 855 GW of offshore wind power may be required across the US, supporting 1.1 TW of onshore wind power and 3.8 TW of solar PV. In addition, 9.8 GW of wave power is installed and plays a minor role.

Interest in ocean energy resources for continental energy systems has increased as concerns have grown over the societal acceptance of large utility-scale onshore renewable energy (RE) systems [6], [7], particularly in regions with limited land availability. In Europe, the role of offshore wind power is increasingly being investigated as a supply for direct use and hydrogen production [8], [9], [10]. Offshore wind power has also been shown to have a role in the decarbonization of New York state's power and space heating demands [11].

Research in ocean energy solutions at the continental system level tends to focus on offshore wind power. As such, offshore resources across the US and Canada have been extensively researched [12], [13], [14]. Results from [15], however, indicate that wave power may have similar technoeconomics to offshore wind power as early as 2040, as also found for the case of the United Kingdom [16], and may have higher social acceptance. Wave power may also have a role in the Iberian Peninsula [17]. Furthermore, while research has found a role for wave power and floating offshore solar PV in Hawaii [18], a role for floating offshore solar PV coupled with offshore wind power and wave power has not been investigated for the continental systems in the US and Canada. Such systems have increasingly viable technoeconomics [19] and may lead to possible co-benefits on marine environments [20], [21]. Indeed, a role for floating

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offshore solar PV has been found for regions in the Sun Belt [22], [23], [24] and may have a role in north Atlantic waters [20], [25]. Thus, this research serves to fill the research gap by examining the potential for floating offshore solar PV and other ocean energy technologies to contribute to the defossilization of energy–industry systems in the US and Canada through a near cost-optimal scenario [26].

## II. METHODOLOGY

This research uses the LUT Energy System Transition Model (LUT-ESTM) applied in [3] and [27] to model four macroregions across the contiguous US, Canada, and Hawaii, which were then disaggregated to 16 regions using the hierarchical modeling approach described in [28]. Similarly, all simulation input data and regional structure can be found in [3] for the power, heat, transport, industry, and desalination sectors. Within the continuous US, the regions are largely aligned to North American Electric Reliability Corporation Reliability Assessment Areas [29]. For variable RE resources in a representative year, 2005 weather data from NASA reprocessed by the German Aerospace Center were used for solar irradiation and wind speed data. Solar PV module efficiency is assumed to increase from 18% in 2020 [30], [31] to 30% in 2050, with installation density correspondingly projected to increase from 90 to 134.9 MW/km$^2$ [32]. Offshore wind and wave power are projected to have constant power densities at 10 and 14.8 MW/km$^2$ [15], [33].

Hourly resource profiles for floating offshore solar PV assume a fixed-titled profile, with 15% of the exclusive economic zone (EEZ) for each region assumed to be available for floating offshore solar PV. Similar limits were applied for offshore wind and wave power due to potential EEZ usage conflicts between offshore energy plants and maritime uses [15]. Offshore wind power resource modeling applies a weighted average approach to the levelized cost of electricity (LCOE) of EEZ grid zones, applying bottom-fixed turbines for depths below 100 m and floating foundations for depths up to 1000 m [13]. By region, individual capital (capex) and operational (opex) expenditure factors were applied to each region considering the depth and distance from the shore. Similar to offshore wind power, wave power profiles were calculated considering all wave power sites that could provide electricity under 100 €/MWh, but sorted by full-load hour (FLH) rather than the LCOE [15]. The upper limits of onshore and offshore variable RE technologies by macroregion are shown in Table I.

TABLE I
RE LIMITS BY REGION

| Region | **Onshore solar PV** | **Onshore wind power** | **Floating offshore solar PV** | **Offshore wind power** | **Wave power** |
|---|---|---|---|---|---|
| Canada-West | 44 997 | 1677 | 52 167 | 52.2 | 1349 |
| Canada-East | 14 428 | 538 | 34 498 | 34.5 | 107 |
| US-New York and New England | 635 | 24 | 4058 | 184 | 260 |
| US-Mid Atlantic | 638 | 24 | 2176 | 77.3 | 47.6 |
| US-Carolinas | 434 | 16 | 5076 | 142 | 211 |
| US-Southern | 1038 | 39 | 7871 | 303 | 154 |
| US-TVA[1] | 490 | 18 | 0 | 0 | 0 |
| US-Midwest | 4039 | 151 | 0 | 0 | 0 |
| US-Central | 2616 | 97 | 0 | 0 | 0 |
| US-Texas | 4493 | 167 | 1926 | 1.93 | 0 |
| US-Southwest | 4419 | 165 | 0 | 0 | 0 |
| US-Northwest | 12 397 | 462 | 3716 | 3.72 | 50.8 |
| US-California | 2606 | 97 | 8654 | 8.65 | 52.2 |
| US-Gulf | 747 | 28 | 3286 | 3.29 | 0 |
| US-Alaska | 11 470 | 427 | 55 371 | 55.4 | 1657 |
| US-Hawaii | 24.1 | 2.69 | 37 121 | 37.1 | 25.9 |

All numbers are in GW. [1]TVA: Tennessee Valley Authority.

The results from [3] indicate that solar PV may have a dominating role under cost-optimal conditions; however, near cost-optimal solutions may provide insights regarding the consequences of incorporating additional societal constraints. In this regard, the Best Policy Scenario with 60% onshore solar PV electricity supply limit (BPS-60) was developed to incorporate societal constraints of supply diversity and land use for large-scale onshore RE. Importantly, similar to the BPS of [3], the BPS-60 targets net-zero CO$_2$ emissions for all energy and nonenergy demands, including industrial feedstocks and desalinated water demands. In addition, short-term RE capacity growth is limited according to the International Renewable Energy Agency [34], with capacities installed through 2023 as the lower capacity limit, and additional capacities allowed in 2024 based on the compound annual growth rate from 2019 to 2023. The 60% onshore solar PV limit was applied for the entire macroregion, allowing some regions to exceed the 60% share as long as the 60% share for the whole macroregion is maintained. This assumption allows for an optimization of RE resource use within the macroregion, which can then enable electricity transmission and trading of electricity-based Fischer Tropsch liquid (e-FTL) fuels and electricity-based methanol (e-methanol) between regions. Important to note is that each macroregion was required to supply 70% of e-FTL fuels and all e-methanol locally, with free trading within the macroregion. Electricity transmission between regions is done via high-voltage ac and dc transmission lines, with capacities allowed to be doubled in five-year time steps from 2030 onwards. Transmission and distribution grid losses are modeled as losses within each region based on [35]. A list of key technoeconomic parameters for technologies considered in this research is provided in Table II.

TABLE II
TECHNOECONOMIC PARAMETERS FOR KEY OCEAN ENERGY COMPONENTS BY YEAR OF INSTALLATION

| Tech | Parameter | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Floating offshore solar PV | Capex[1] | 1425 | 765 | 414 | 322 |
| | Opex$_{fix}$[2] | 28.5 | 15.3 | 8.28 | 6.64 |
| | Lifetime[3] | 20 | 25 | 30 | 30 |
| Wind offshore | Capex[1] | 2976 | 2287 | 2168 | 2130 |
| | Opex$_{fix}$[2] | 85.0 | 65.9 | 62.0 | 60.7 |
| | Lifetime[3] | 25 | 25 | 25 | 25 |
| Wave power | Capex[1] | 21420 | 2777 | 2012 | 1731 |
| | Opex$_{fix}$[2] | 1050 | 75 | 48 | 42 |
| | Lifetime[3] | 20 | 25 | 30 | 30 |

[1] in €/kW.
[2] in €/ kW·a.
[3] in years.

A full list of technoeconomic assumptions applied in LUT-ESTM can be found in [36] and [37]. Note that the variable operational expenditures (opex$_{var}$) for all technologies are zero.

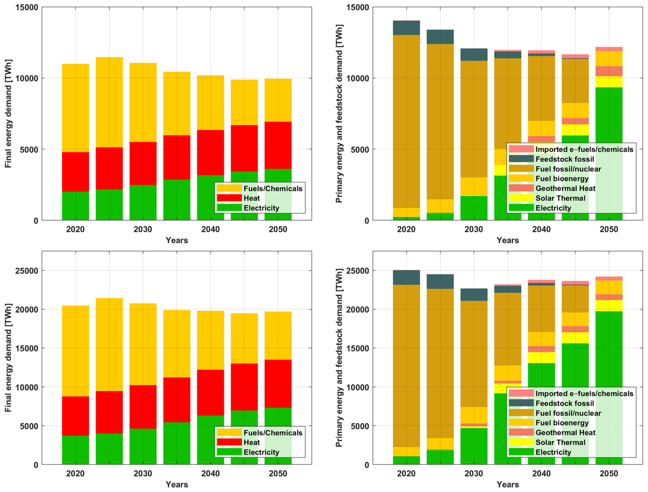

Fig. 1. Final (left) and primary (right) energy demands in the US-East (top) and US and Canada (bottom).

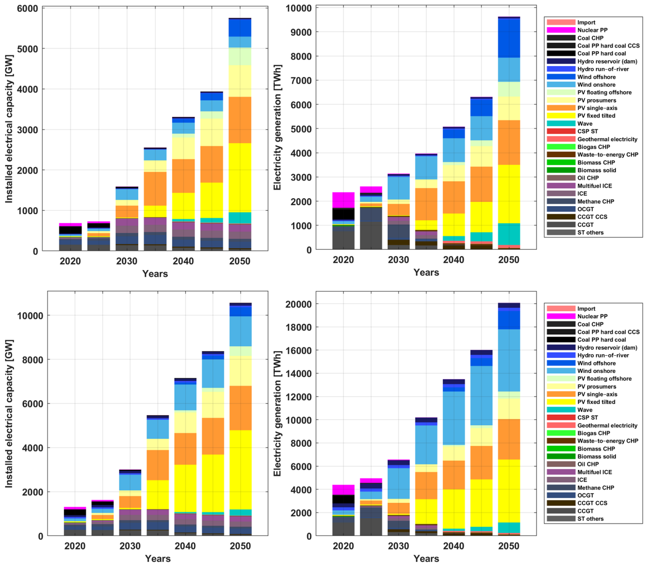

Fig. 2. Installed electricity capacity (left) and electricity generation (right) for the US-East (top) and the US and Canada (bottom). Note that axes are not aligned.

Research on sea and ocean applications for floating solar PV structures has increased significantly in recent years, with methodologies being introduced to develop stable designs that can withstand high wind and wave loads [38]. Co-location of offshore wind power and floating offshore solar PV has been suggested to increase the energy density of ocean energy installations [19], [39], [40], as the complimentary profiles allow for both capacities to use the same grid infrastructure [41]. Given public concern surrounding the visual impact, noise, and potential impact on economic and recreational ocean activities of ocean energy, particularly offshore wind power [42], [43], hybrid plants may increase public acceptance. Multienergy source parks co-locating offshore wind power, wave power, and floating offshore solar PV can additionally be developed to reduce LCOEs from ocean energy parks more rapidly than independent installations [44]. Furthermore, the structural integrity of floating offshore solar PV structures has been found to increase when applying a breakwater around the edges of floating PV [45]. Huang et al. [38] suggest that this breakwater could be attached to a wave energy converter, supporting the idea of co-location. To reflect this view of ocean energy co-location, the expansion of ocean energy technologies was interlinked, such that, if installed, wave power capacity was set to be at least 67% of the installed offshore wind power capacity, and floating offshore solar PV was set to 95–105% of the wind power capacity.

## III. RESULTS

The final and primary energy demand structure in the BPS, shown in Fig. 1, shows a roughly stable final energy demand throughout the transition, as growth in energy service and industrial product demand is compensated by increased efficiency through electrification. In the US-East macroregion, an increase in total primary energy demand (TPED) can be observed from 2045 to 2050. This growth is largely driven by increases in primary renewable electricity needed to completely defossilize all energy and feedstock demands. Indeed, the share of primary renewable electricity in the TPED in US-East increases from 51% in 2045 to 78% in 2050. The structure of final energy demand and primary energy suggests that RE is still able to defossilize the power, heat, and industry sectors. The fuel demand in the transport sector becomes the most challenging demand segment to defossilize, as fossil-fuel-based hydrogen remains a more cost-competitive option for e-FTL production than electricity-based hydrogen (e-hydrogen). Thus, the observed growth in renewable electricity seems to be driven by power-to-X (PtX) processes in the transport sector. For the greater US and Canada energy transition, primary renewable electricity becomes the key primary energy source more gradually, reaching 19 821 TWh, or 82.2% of the TPED.

In the US-East, renewable electricity growth first occurs with onshore RE, primarily through wind power (see Fig. 2). By 2035, onshore solar PV and wind power generate 2085 and

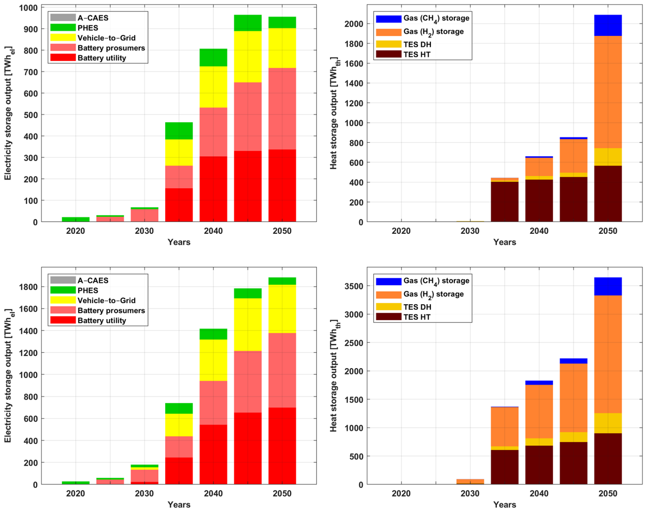

Fig. 3. Electricity storage throughput (left) and heat and gaseous storage throughput (right) for the US-East (top) and US and Canada (bottom).

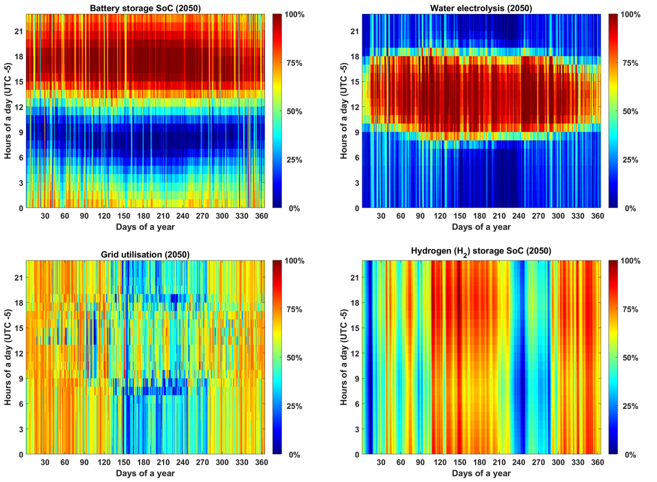

Fig. 4. Hourly utility-scale battery state of charge (top left), operation of electrolyzers (top right), grid utilization (bottom left), and hydrogen buffer storage state of charge (bottom right) for the BPS-60 in US-East in 2050.

958 TWh, respectively, corresponding to 77% of all generated electricity. However, in 2040, the onshore solar PV limit begins to be reached, and the onshore wind power upper limit of 271 GW is reached. Thus, 95, 91, and 61 GW of floating offshore solar PV, offshore wind power, and wave power are, respectively, installed to increase the renewable electrification of the system. Collectively, these sources contribute 13% of all generated electricity in 2040, increasing to 32% in 2050, with 434, 413, and 277 GW of floating offshore solar PV, offshore wind power, and wave power, respectively. As observed in the electricity supply structure (see Fig. 2), the growth of electricity from 2045 to 2050 includes significant investments in ocean energy technologies.

All solar PV technologies including prosumers (1359 GW), fixed-tilted (3595 GW), single-axis (2010 GW), and floating offshore (434 GW) in the BPS-60 significantly contribute to system-wide defossilization in the US and Canada, The 11 285 TWh of generated electricity from solar PV corresponds to 56% of electricity supply, followed by onshore and offshore wind power at 6936 TWh (35% ), and wave power at 901 TWh (4.5% ). Notably, outside of the US-East macroregion, offshore energy technologies are not required, as onshore wind resource potentials are sufficiently large to supply the remaining electricity demands in the system.

A consequence of increased supply diversity is the reduction of storage requirements compared with a system dominated by solar PV [3]. Indeed, the total installed storage capacity for centralized storage (excluding vehicle-to-grid) across the US and Canada in 2050 decreases by 27% to 4.3 TWh$_{\mathrm{cap}}$. Even more noticeable is the difference in storage throughput, which decreases by 35% to 1883 TWh (see Fig. 4) compared with [3]. The US-East region contributes 51% of the total throughput of the US and Canada in 2050, at 956 TWh. The increased supply complementarity, particularly as the solar PV generation share limit is reached, leads to electricity storage throughput leveling off. By 2050, the total electricity storage throughput across the US and Canada corresponds to 9.4% of all generated electricity, and storage throughput in the US-East corresponds to 9.9% of electricity generated in the region.

The thermal and gaseous storage throughput demonstrates an interesting growth pattern, as hydrogen storage throughput grows significantly in the final time step, indicating that growth in electricity during that time step is primarily used for PtX processes, as hydrogen buffer storage is required between flexible electrolysis and inflexible PtX processes. Before the system is forced to fully defossilize in US-East, blue hydrogen remains the main source of hydrogen as a precursor for FTL liquids, which both operate at high FLH. In 2045, the hydrogen storage throughput, at 338 TWh, only corresponds to 11% of hydrogen production, whereas, in 2050, the 1132 TWh of throughput corresponds to 33% . For the entire US and Canada system, total hydrogen storage throughput reaches 2073 TWh in 2050, 29% of all hydrogen production. Furthermore, the large growth of hydrogen storage throughput in the final time step is reduced when examining the entire system throughput, indicating that the US-West and Canada regions achieve sufficiently low electricity costs for e-hydrogen to compete with blue hydrogen for e-FTL production.

Thermal energy storage for heating demands across the US and Canada is first introduced to the system in 2035 (671 TWh), largely to balance medium temperature solar thermal and direct electric heat, and is nearly doubled by 2050, reaching 1256 TWh. Low-temperature thermal energy storage (TES DH in Fig. 3) is primarily used to balance renewable electricity supply and low-temperature electric heat and heat pumps; however, its role is reduced similar to electricity storage compared with [3], with a 23% reduced TES DH throughput (331 TWh in BPS-60).

The effects of supply diversity and offshore energy technologies are similarly observed in the operational dynamics of key system components in the US-East, shown in Fig. 4. While utility-scale batteries and water electrolyzers largely operate when excess solar PV electricity is available, influence from excess onshore and offshore wind power and wave power can be observed, particularly in winter months. However, the significant

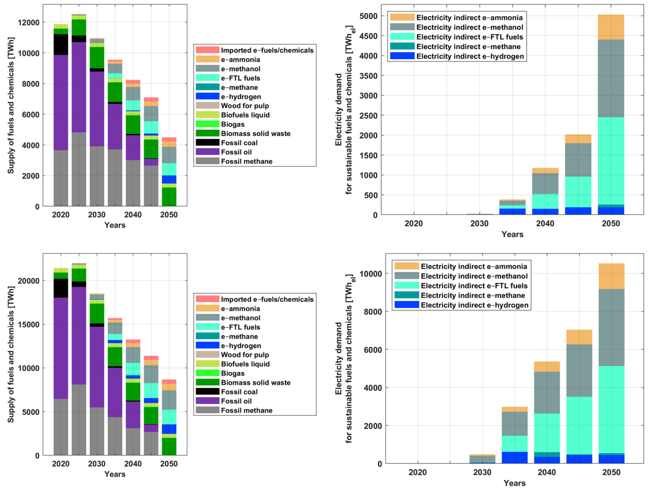

Fig. 5. Supply of fuels and chemicals (left) and electricity demand for sustainable fuels and chemicals (right) for US-East (top) and the US and Canada (bottom).

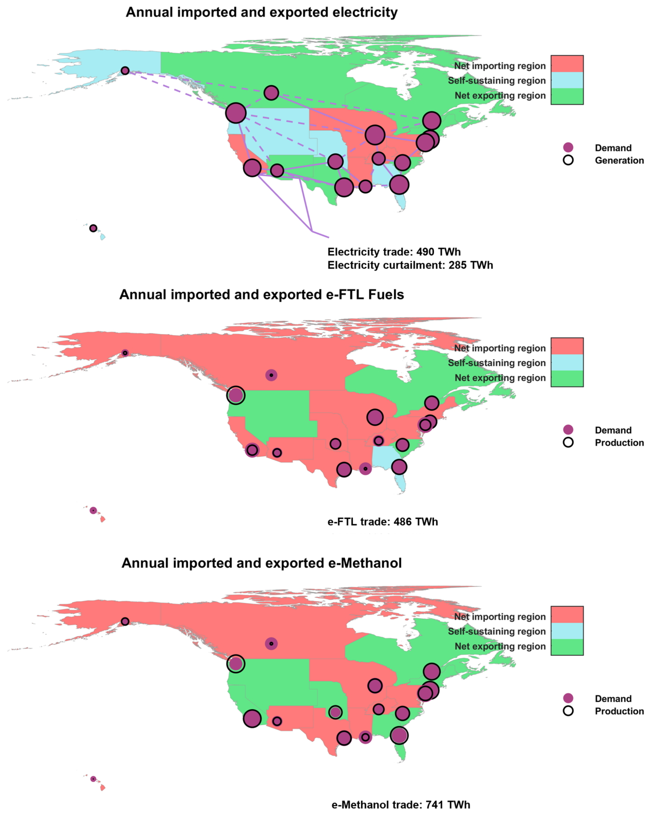

Fig. 6. Annual electricity trade (top), e-FTL trade (center), and e-methanol trade (bottom) between regions in 2050. Solid lines represent transmission capacities at or above 1 GW, and dashed lines represent capacities below 1 GW. Self-sufficiency for e-FTL trade and e-methanol trade is defined as supplying 95–105% of a region's e-FTL or e-methanol demand.

supply from all solar PV technologies indicates that low-cost solar PV electricity is still prioritized when balancing electricity through storage or operating electrolyzers. The effect of wind and wave power on the US-East system can be observed through the grid use profile, as the grid capacities are most used in the winter months when wind and wave power are available, and less in the summer, as all regions have access to solar PV electricity.

High transmission usage along wind and wave profiles does not appear to correlate strongly with storage or electrolysis patterns, which indicates that under diverse supply conditions in the BPS-60, wind and wave power are primarily used to satisfy direct electricity demands in all sectors, whereas solar PV is used as an inexpensive electricity source driving PtX in the system. Nevertheless, electrolyzer FLH for the integrated US and Canada system increases by 22% compared with [3] in 2050, at 4117 FLH. Hydrogen storage, similar to [3], shows a largely seasonal characteristic with some shorter term buffering on top. The system reaches a high state of charge earlier in the year due to the increased, but still relatively limited, usage of wind and wave power to operate electrolyzers.

The reliance of the system on low-cost electricity for indirect electrification of fuel and chemical demands can be observed. Fossil fuels, particularly natural gas for blue hydrogen and oil for the transport sector, are significant components of the supply of fuels and chemicals to the system until the net-zero emissions year. Indeed, as shown in Fig. 5, natural gas composes 37% (2651 TWh) of the fuel and chemical supply in 2045 in US-East. Natural gas usage across the US and Canada by 2045 is predominantly limited to the US-East macroregion, as total natural gas supply is 2675 TWh (24% of fuel and chemical supply). By 2050, the fuel and chemical demand is completely met by bioenergy, e-fuels, and e-chemicals, with 8470 TWh across the US and Canada. Compared with [3], the total fuel and chemical supply is 4% (336 TWh) higher in 2050, largely due to a slightly larger role of bioenergy.

The delayed transition to PtX leads to significant growth in indirect electricity demands in the US-East, increasing from 2017 TWh in 2045 to 5027 TWh in 2050. For the integrated US and Canada system, total indirect electricity demands reach 10 522 TWh in 2050, 52% of all generated electricity. Thus, a strong PtX aspect to the energy–industry system is maintained, although delayed due to diversity and land use constraints.

These constraints similarly affect the energy trading between regions, as shown in Fig. 6. With abundant wind resources and less reliance on solar PV, Canada maintains its role as an exporter to the US, with both West and East Canada being exporters, primarily to the US-East. Within the US-East, most regions, except for US-New England and New York and US-Carolinas, are either net importers of electricity, or self-sufficient. The US-Southwest region is an exporter to US-California, and US-Texas becomes an exporter to the US-Gulf region. Net electricity trade between regions reaches 481 TWh in 2050, corresponding to 2.4% of generated electricity.

Trading of e-FTL remains a significant component of a defossilized energy–industry system as part of a PtX economy [46]. Similar to [3], East Canada remains an exporter of e-FTL fuels to West Canada due to East Canada's strong wind resources; however, in the US, the dynamics of exporters and importers varies. With its large area, US-Northwest becomes an exporter to the rest of the US-West macroregion and US-Hawaii, but most regions are near self-sufficiency, with US-Gulf being an exception. Regions within the US-East macroregion similarly

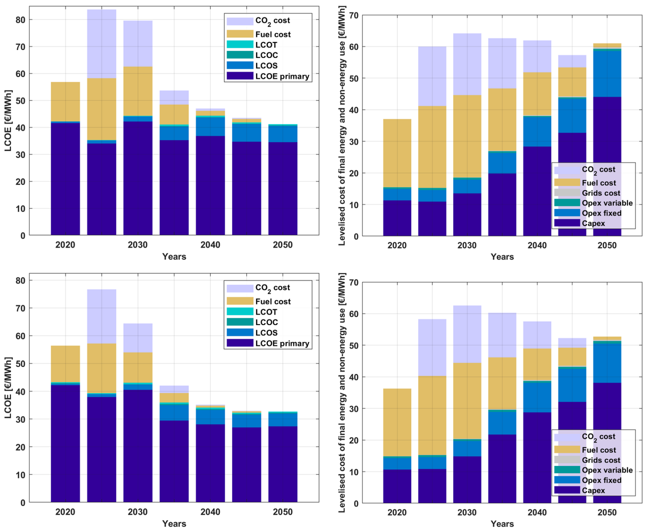

Fig. 7. LCOE (left) and LCOFE (right) for the US-East (top) and the US and Canada (bottom). Abbreviations: LCOS: Levelized cost of storage; LCOC: Levelized cost of curtailment; LCOT: Levelized cost of transmission.

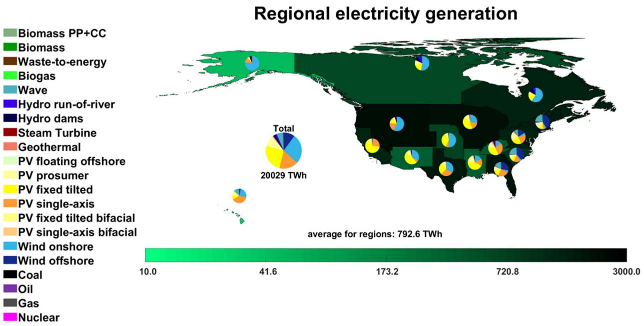

Fig. 8. Electricity generation in 2050 in the BPS-60.

largely remain self-sufficient, with US-Southern being a minor exporter. A key difference between cost-optimal conditions in the US-East is that the diversity constraint limits the potential of the US-Midwest region, with the largest area in the macroregion, to be a major e-FTL exporter. Conversely, the use of ocean energy in coastal regions allows them to supply much of their demands. e-Methanol trading appears to show similar characteristics to the e-FTL trade, with many regions that are e-FTL exporters also being e-methanol exporters. US-California, US-Central, US-Southern, and US-Northeast and New England are exceptions, as they are importers of e-FTL but exporters of e-methanol. US-New England and New York being e-methanol exporters are rather significant, as this result suggests that ocean energy supplies can drive large-scale PtX production. While the trends between regions remain somewhat consistent, the quantities of e-methanol trade increase significantly, reaching 752 TWh, partly driven by e-methanol exports to US-Hawaii and the Caribbean, at 127 TWh from the US-West macroregion. The quantities of traded e-methanol correspond to 34% of all production, indicating that, for most regions, e-methanol production can provide an important source of flexibility [47].

Across the US and Canada, transitions to high shares of renewable electricity lead to reductions in the LCOE, as shown in Fig. 7. In the US-East, the LCOE declines from 56.8 €/MWh in 2020 to 41.2 €/MWh in 2050 and becomes dominated by capex, particularly of offshore wind power and solar PV, which each compose 26% of the total LCOE and wave power (17% ). The levelized cost of storage (LCOS) in the LCOE is limited with increased supply diversity, at 15% for US-East, and 14% for the US and Canada (total LCOE of 32.7 €/MWh in 2050). By comparison, the LCOS under cost-optimal conditions [3] composed 21% of the LCOE. The large self-sufficiency of regions in the US and Canada keeps the levelized cost of transmission low, at 1.1% for US-East, and 1.2% for the integrated US and Canada system.

Comparatively, the levelized cost of final energy and nonenergy use (LCOFE) sees noticeable increases as the LCOE cannot achieve similar cost reductions as the BPS in [3]. Thus, the LCOFE for the US-East and US and Canada increases from 37.0 and 36.3 €/MWh in 2020 to 61.0 and 52.7 €/MWh in 2050, respectively. For the integrated US and Canada system, the LCOFE in 2050 is 28% higher than the BPS of [3], and 37% higher than the current policy scenario, which applies no $CO_2$ emission costs. While the energy supply can be greatly diversified, particularly with investment in onshore wind power, hybrid floating offshore solar PV and wind power plants, and wave power, doing so comes at a noticeable cost increase, especially if high energy, self-sufficiency, and security of supply are societal goals.

## IV. DISCUSSION

While affordable renewable electricity can rapidly defossilize direct electricity demands across energy and industry sectors, increased supply diversity conditions may lead to a delay to system-wide defossilization and lead to a 28% increase in total LCOFE compared with BPS conditions [3]. Especially in the US-East, the limited land availability for onshore wind power when onshore solar PV is limited leads to large-scale implementation of floating offshore solar PV, offshore wind power, and wave power, particularly for indirect PtX electricity demands. Thus, ocean energy resources can contribute 32% of generated electricity in US-East and 15% for the integrated US and Canada system (see Fig. 8), which can be seen in the operational profiles for batteries, electrolyzers, and interregional grids.

The PtX in the defossilized system of the BPS-60, as part of a larger PtX economy [46], remains largely driven by e-hydrogen as an intermediate energy carrier to fuels and chemical feedstocks, as well as limited direct usage in transport and for high-temperature heating. Indeed, the fundamental power flows of the system, shown in Fig. 9, remain similar to those of the BPS, although with higher shares of wind power, floating offshore solar PV, and wave power as key primary electricity sources. The reduced role of storage under increased supply diversity can also be observed in balancing electricity, heat, and e-hydrogen demands. Increasing supply diversity and integrating ocean energy for continental systems may require dedicated solar PV for PtX processes, as the cost increase for electricity from a diversified supply may be manageable for direct electricity demands.

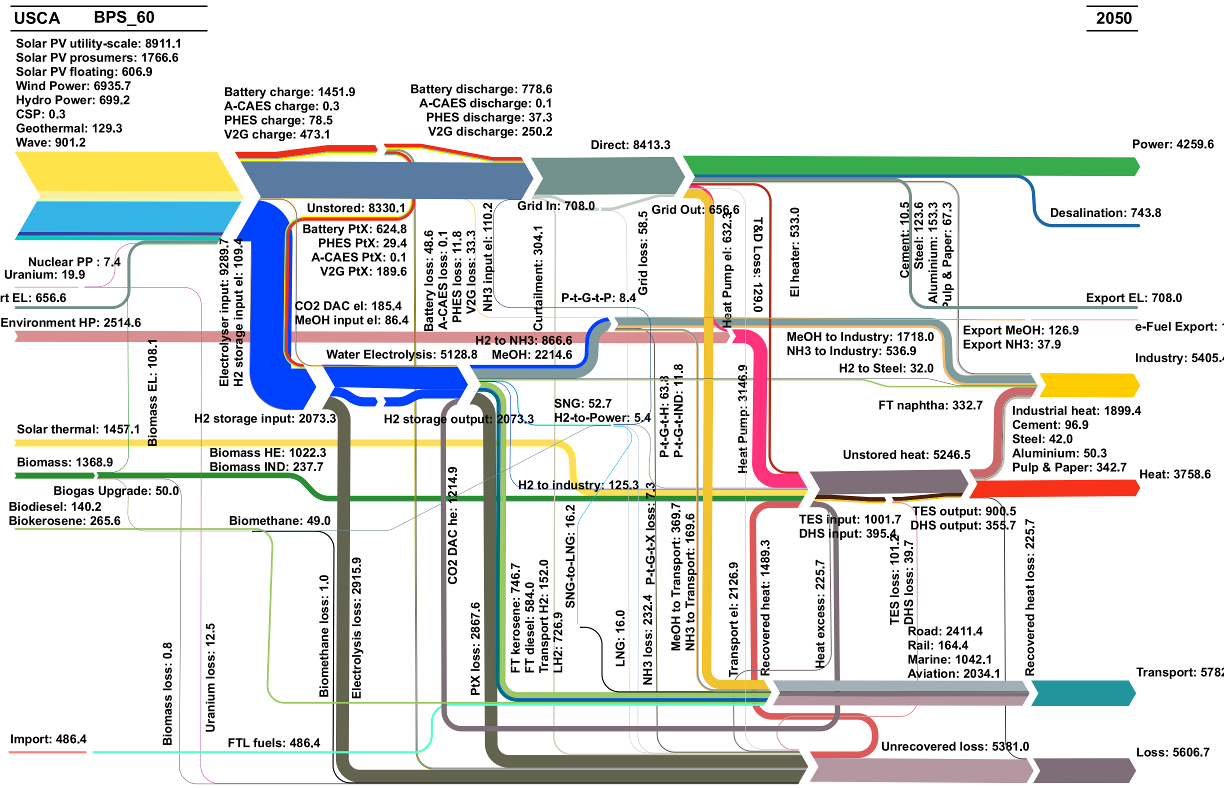

Fig. 9. Energy flow for the US and Canada in the BPS-60 for 2050. All numbers are in TWh.

These results represent a near-cost optimal solution [26] for the US and Canada energy transition incorporating higher system supply diversity [48]. Such supply diversity may be needed, particularly in the US East, where results from [3] indicate that the onshore solar PV potential is completely used by 2050 in all regions except for US-Southern. However, the same limits are reached for wind power. The combination of societal constraints of high regional supply diversity and self-sufficiency necessitates the installation of large-scale ocean energy, to which floating offshore solar PV may contribute, as the LCOE by 2050 ranges from 21.7 to 25.4 €/MWh. Co-locating floating offshore solar PV with offshore wind power and wave power may increase the economic viability of these technologies, which have LCOEs of 60.2–69.8 €/MWh and 64.9–86.4 €/MWh across the US-East, respectively. Assuming financial parameters in Table II and considering the generation of offshore renewable capacities in 2050, the resulting weighted average LCOE from a co-located power point would be approximately 58.7 €/MWh with 2737 FLH per year. Such LCOE may be economically viable, particularly to satisfy direct electricity demands across the power, heat, transport, and industry sectors. The value of offshore energy supplies as a source of direct electricity to onshore markets has also been found by Gea-Bermúdez et al. [9], although only for the offshore wind power system.

Using this hybrid power plant configuration across the east coast of the US could free up limited but low-cost solar PV and wind power resources across the US-East region to operate electrolyzers for economically viable e-fuel, e-chemical, and e-material supplies. Indeed, recent analysis from [49] finds that off-grid e-ammonia and e-steel production in regions of the US with strong RE resources, access to low-cost hydrogen storage, and proximity to process feedstocks are all critical for e-hydrogen supplies to PtX processes to be economically competitive with gray and blue hydrogen. The results from the BPS-60 indicate that 1.6 $\mathrm{TW}_p$ of onshore solar PV potential is available, representing 37% of the 4.4-$\mathrm{TW}_p$ potential. Future work could, therefore, investigate the effects of off-grid e-fuel, e-chemical, and e-material production on the US and Canada transitions under diverse supply conditions.

The results further indicate large-scale e-FTL and e-methanol trading between regions. Other PtX products, including e-ammonia, e-steel, and e-aluminum, could be traded, but trading was blocked as the required infrastructure is not modeled in LUT-ESTM. Furthermore, PtX product trading could be expanded in future work to allow free trading within all US regions, as well as increased trading with Canada. Since the US-West region does not require ocean energy even when onshore solar PV is limited, demands for e-FTL and e-methanol in US-East could be supplied by US-West, which was not allowed due to scenario constraints. Continental industrial relocation should, therefore, be investigated under a wide array of supply conditions to analyze the effect of the RE supply mix on industrial and PtX supply chains, particularly in the context of increased reshoring of manufacturing capacities.

Increased spatial resolution may identify additional bottlenecks that may exist within the US and Canada energy system where hybrid ocean energy supplies may contribute. Notably, the Canada-West, Canada-East, and US-California are found to have wave power LCOEs of 45.3, 43.1, and 46.0 €/MWh in 2050, respectively, although wave power is not chosen as these regions have high land availability. Integration of wave power in California may supplement existing plans to develop offshore wind farms [50], [51]. Hybrid floating offshore solar PV and wave power in these regions may have a niche within the near-cost optimal solution space. The yield effects of detailed degradation modeling on solar PV systems may also be investigated, although this impact is expected to be minor.

## V. CONCLUSION

This research shows the potential for diversified energy supplies to reach net-zero emissions in the US and Canada across all energy and industry sectors. Despite increases in electricity and final energy and nonenergy costs, the system maintains a PtX economy structure dominated by renewable electricity. The limited onshore RE potential in the US-East region leads to significant contribution from floating offshore solar PVs as well as offshore wind and wave power. Coupling ocean energy technologies with complementary resource profiles may facilitate the integration of these technologies, if high supply diversity becomes a societal constraint.

Offshore hybrid power plants can provide more consistent power profiles throughout the year compared with individual capacities, thereby reducing energy storage needed to balance a variable renewable electricity supply and allowing onshore renewable electricity to be installed where the lowest cost electricity is needed, particularly to operate flexible electrolyzers for economically viable e-FTLs and e-methanol. As such, trading of these fuels and chemicals becomes essential, as 12% of e-FTL supply and 33% of all e-methanol supply are traded among US and Canada regions. Nevertheless, under particularly strict regional supply conditions, hybrid ocean energy capacities may be used to drive PtX processes with marginal increases in total system costs. Therefore, additional research should investigate the different roles that ocean energy, especially floating offshore solar PVs, can have on continental energy systems, whether as a high-capacity-factor grid-connected supply or as a source for off-grid ocean energy-driven PtX.

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