

Sustainable Energy Industry Systems in the United States and Canada Demonstrating the Value of Solar-to-X

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Abstract—The transition to highly sustainable energy industry systems is being driven by significant growth in solar photovoltaics (PV). Despite targets to reach net-zero emissions by 2050, fossil fuels still dominate the energy industry systems in the USA and Canada. Transition pathways are developed and analyzed comparing a complete defossilization of both energy and nonenergy demands with business-as-usual conditions based on government projections. The results demonstrate the benefits of transitioning to 100% renewable energy for all sectors, as excess low-cost electricity from solar PV can be used for power-to-X solutions to produce electricity-based fuels, chemicals, and materials. By 2050, the power sector will only consume 20% of generated electricity, with the remaining used to electrify the heat, transport, and industry sectors. Thus, 86% of all primary energy in the system comes from renewable electricity, as total electricity generation increases from 4394 TWh in 2020 to 20 795 TWh in 2050. Solar PV reaches 78% of all electricity generation, leading to 10.6 TW of installed capacity. The full energy industry sector transition leads to reductions in both levelized cost of electricity (LCOE) and levelized cost of final energy (LCOFE). The LCOE sees massive reductions from 72 €/MWh in 2020 to 25 €/MWh in 2050, and the LCOFE decreases from the current 50 to 41 €/MWh in 2050. The strong operational synergies between solar PV and flexible electrolysis enable a transition pathway that demonstrates the viability of a Power-to-X Economy in achieving climate targets of net-zero emissions. The high share of solar PV indicates a Solar-to-X Economy characteristic.

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

I. INTRODUCTION

CLIMATE change currently presents a major societal challenge with the risk of substantial sea rise and major disruptions in ecosystems if tipping points are passed. To mitigate such risks, the defossilization of energy systems is required. In the USA and Canada, however, fossil fuels still dominate the respective energy systems at 90% and 80%. While the USA and Canada have abundant renewable energy (RE) resources, RE

Received 7 June 2024; revised 29 October 2024 and 17 December 2024; accepted 1 January 2025. This work was supported in part by the Green Deal Research and Innovation Programme under Grant 101036457 (EU-SCORES), in part by the Academy of Finland for the ‘Industrial Emissions & CDR’ Project under Grant 329313, and in part by the LUT University Research Platform ‘GreenRenew’. (Corresponding author: Gabriel Lopez.)

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Digital Object Identifier 10.1109/JPHOTOV.2025.3531043

penetration has remained limited, with hydropower having the highest combined share of primary energy (PE) at 2.5% across the countries. Despite this limited penetration, both the Canadian and U.S. governments have set legally binding targets for net-zero emissions by 2050 [1], [2]. Existing 100% RE studies for the USA and Canada consider defossilization of all energy sectors [3], [4], [5], [6], [7]; however, none consider an energy transition for the integrated USA and Canada energy industry systems aiming for a full defossilization of all energy industry sectors, including nonenergy feedstocks. Both the countries are considered an integrated energy market given the long history of energy collaboration.

This article fills this gap for the transition options the USA and Canada by identifying the lowest cost pathway reaching full defossilization of all energy and feedstock demands by 2050 in the context of a larger Americas energy transition. The central scenario presented focuses on a 100% RE supply by 2050 compared with a business-as-usual case projected by the respective governments.

II. METHODOLOGY

The energy industry system transition is analyzed using the LUT Energy System Transition Model (LUT-ESTM) [8], [9]. The LUT-ESTM is technology rich, is hourly resolved, and can be operated in multinode and multisenario applications for an entire energy industry system transition from 2020 to 2050 in five-year time steps. Weather data from 2005 from NASA [10] that had been reprocessed by the German Aerospace Center [11] were used as a representative year for solar irradiation and wind speed data. The LUT-ESTM was applied to the USA and Canada in 16 regions including two for Canada and 14 for the USA. The approach of Bogdanov et al. [12] was applied in this research with first simulations applied for four macroregions (shown in Fig. 1) before the 16-region simulations, with electricity and e-fuel trade between macroregions as exogenous model inputs. Importantly, 70% of each macroregion’s e-Fischer–Tropsch liquid (e-FTL) demand must be satisfied within the macroregion, with the remaining 30% able to be freely traded or imported from other Americas regions, i.e., Central or South America. e-Methanol may also be freely traded within macroregions, whereas e-hydrogen cannot be traded and must be used in the producing region. The regions are interconnected with the

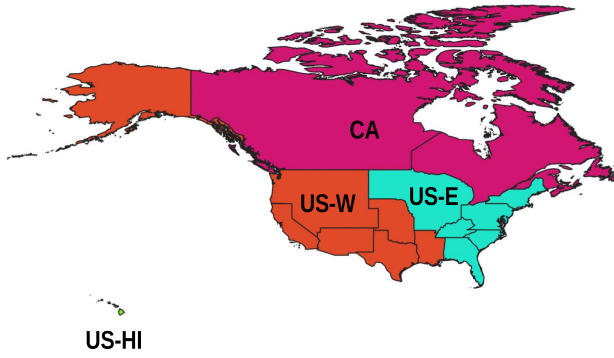


Fig. 1. Regional structure for the USA and Canada applied in hierarchical modeling, with microregions colored based on their corresponding macroregion. Abbreviations: CA: Canada; US-E: U.S. East; US-W: U.S. West; and US-HI: U.S. Hawai'i.

existing high-voltage ac and dc transmission lines and allowed a doubling of transmission capacity from 2030 onwards. Electricity transmission and distribution within each region are modeled as losses applying the methodology of Sadovskaia et al. [13].

The LUT-ESTM covers the power, heat, transport, industry, and desalination sectors. The power sector includes direct electricity demands in the residential, commercial, and industrial segments excluding electricity for heat, transportation, or energy-intensive industry. The heat sector includes domestic hot water demand, industrial process heat, and biomass for cooking, developed according to Keiner et al. [14]. The transport sector covers the transport modes of road, rail, marine, and aviation for passenger and freight transportation, developed according to Khalili et al. [15]. Transport sector demands can be satisfied by electricity, fossil fuels, and e-fuels, including e-FTL, e-methanol, and e-ammonia. The industry sector includes cement, steel, chemical, aluminum, and pulp and paper industries plus all other industries. For the steel and chemical industries, available defossilized processes include hydrogen direct reduction and electrowinning for primary steel and electricity-based methanol and electricity-based ammonia for the chemical industry. More information about these processes can be found in [16], [17]. Techno-economic parameters for key components can be found in Table I.

Demand assumptions for the different energy and industry sectors have been derived from various sources and are presented in Table II. RE resource potentials follow the standard setting of the LUT-ESTM [9], which implies 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 using waste, residues, and by-products. A notable exception is Hawai'i, where 1% and 2% of land area is available for solar PV and wind power, respectively. Furthermore, the e-fuel demands in Hawai'i, except for direct e-hydrogen, are produced in the U.S. West region. In 2025, renewable capacities installed up to 2023 according to IRENA [19] are set as lower limits, with additional capacities allowed in 2024 based on the compound annual growth rate from 2019 to 2023.

The scenarios are denoted as follows:

- 1) best policy scenario (BPS) reaching 100% RE by 2050 in all energy industry sectors for the USA and Canada with no new nuclear;

TABLE I
TECHNO-ECONOMIC PARAMETERS FOR KEY SYSTEM COMPONENTS

Tech	Parameter	2020	2030	2040	2050
PV fixed tilted	Capex ¹	475	306	207	166
	Opex _{fix} ²	7.76	5.66	4.47	3.7
	Opex _{var} ³	0	0	0	0
	Lifetime ⁴	30	35	40	40
PV single-axis tracking	Capex ¹	523	337	228	183
	Opex _{fix} ²	8.54	6.23	4.92	4.07
	Opex _{var} ³	0	0	0	0
	Lifetime ⁴	30	35	40	40
Wind onshore	Capex ¹	1150	1000	940	900
	Opex _{fix} ²	23	20	18.8	18
	Opex _{var} ³	0	0	0	0
	Lifetime ⁴	25	25	25	25
Battery utility scale	Capex ³	234	110	76	61
	Opex _{fix} ²	3.28	2.2	1.9	1.71
	Opex _{var} ³	0	0	0	0
	Lifetime ⁴	20	20	20	20
Water electrolyzer	Capex ¹	803	446	347	291
	Opex _{fix} ²	28.1	15.6	12.1	10.2
	Opex _{var} ³	0.001	0.001	0.001	0.001
	Lifetime ⁴	30	30	30	30
	Efficiency ⁵	0.701	0.701	0.701	0.701
Methanol synthesis	Capex ¹	835	835	835	835
	Opex _{fix} ²	33.4	33.4	33.4	33.4
	Opex _{var} ³	0	0	0	0
	Lifetime ⁴	30	30	30	30
	Efficiency ⁶	0.819	0.819	0.819	0.819
Ammonia synthesis	Capex ¹	1285	1285	1285	1285
	Opex _{fix} ²	64.3	64.3	64.3	64.3
	Opex _{var} ³	0	0	0	0
	Lifetime ⁴	30	30	30	30
	Efficiency ⁶	0.859	0.859	0.859	0.859
e-FTL synthesis	Capex ¹	1017	1017	915	915
	Opex _{fix} ²	30.5	30.5	27.5	27.5
	Opex _{var} ³	0	0	0	0
	Lifetime ⁴	30	30	30	30
	Efficiency ⁶	0.692	0.692	0.692	0.692

A full list of techno-economic assumptions applied in the LUT-ESTM can be found in [9] and [18]. Note that hydrogen-to-X processes have additional process energy and material demands, including electricity, heat, or CO₂, and its energy demand to obtain all supplies, which are included in the modeling.

¹ in €/kW.

² in €/kW·a.

³ in €/kWh.

⁴ in years.

⁵ in kW_{H₂,LHV}/kW_{el}.

⁶ in kW_{th,LHV}/kW_{H₂,LHV}.

- 2) current policy scenario (CPS) following central references from the 2023 EIA Annual Energy Outlook [26] and Canada's Energy Future 2021 [21].

III. RESULTS

The final energy and PE demands for the BPS and the CPS are shown in Fig. 2. While the energy demand remains largely stable during the transition, a reduction in demand can be noticed in 2030 in the BPS, as direct electrification increases before

TABLE II
ENERGY AND INDUSTRY DEMANDS FOR THE USA AND CANADA FROM 2020 TO 2050 [20], [21], [22], [23], [24], [25]

		2020	2030	2040	2050
Population	mil	364.7	385.6	405.0	419.8
Power sector	TWh _{el}	3463	3709	3972	4254
Heat industrial ¹	TWh _{th}	1519	1799	1843	1905
Heat domestic	TWh _{th}	3036	3298	3538	3751
Road passenger	bil p-km	9741	11681	13637	15509
Road freight	bil p-km	2888	3256	3669	4125
Rail passenger	bil t-km	76.02	82.29	85.07	83.37
Rail freight	bil p-km	3278	3689	4156	4654
Marine passenger	bil p-km	4.25	7.70	10.30	12.13
Marine freight	bil t-km	19187	22867	25959	29254
Aviation passenger	bil p-km	2164	3006	4253	5951
Aviation freight	bil t-km	48.85	74.77	108.78	147.17
Cement	kt	122234	112682	114122	119299
Primary steel	kt	49461	49998	44717	29052
Secondary steel	kt	34257	42490	54409	77941
Chemical feedstock ²	TWh	1907	2163	2388	2575
Ammonia share	%	17.6	18.6	19.6	20.9
Alumina	kt	3431	3911	4356	5358
Primary aluminum	kt	7666	8698	9176	10272
Secondary aluminum	kt	3691	5196	7008	7845
Pulp and paper	kt	53709	54688	55566	56284

p-km: passenger kilometers; t-km: ton kilometers.

¹ Industrial heating demand excludes heat for energy-intensive industries.

² Chemical feedstock demands are met by fossil feedstocks, e-methanol, or e-ammonia, depending on scenario. e-FTL naphtha may also substitute e-methanol.

significant growth in indirect electrification through power-to-X technologies. Power-to-X is especially important for the defossilization of key industrial processes, including e-steel and e-chemicals. Feedstocks for these industries in the USA and Canada composed around 7% of the total primary energy demand (TPED) in 2020. The final energy demand of industry in the BPS becomes more significant during the transition, as it is 22% of the total final energy demand in 2020 and increases to 35% in 2050, as hydrocarbons are still required for high-temperature heating and e-chemical synthesis. In the CPS, electrification remains limited, only reaching 19% of the TPED in 2050. Furthermore, the growth in industrial energy demands only slightly increases as fossil-to-X processes remain dominant, with industry reaching 23% of total final energy demand in 2050.

With the growing role of electricity in the TPED in the BPS, the electricity capacity and electricity generation, shown in Fig. 3, significantly increase from 1309 GW and 4394 TWh in 2020 to 12 628 GW and 20 795 TWh in 2050, respectively. The most significant growth in electricity generation in the BPS is projected to come from solar PV, as it composes 84% of all installed capacity and 78% of all generated electricity in 2050. Onshore wind power plays a complementary role, contributing 18% of electricity generation in 2050. The growth of onshore

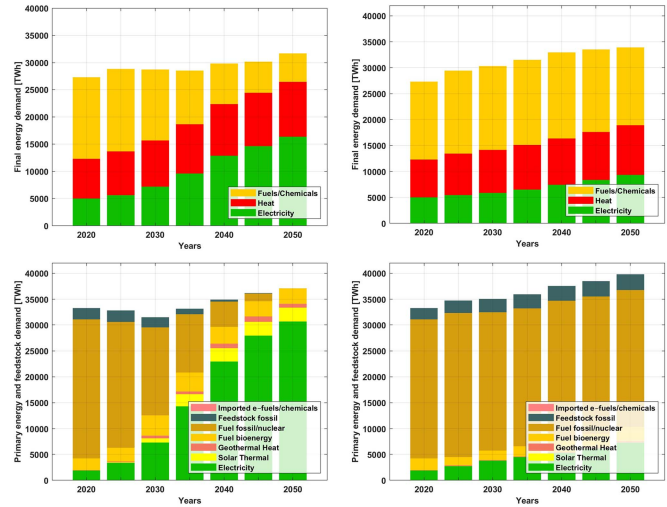


Fig. 2. Final (top) and primary (bottom) energy demand in the BPS (left) and CPS (right) for the USA and Canada.

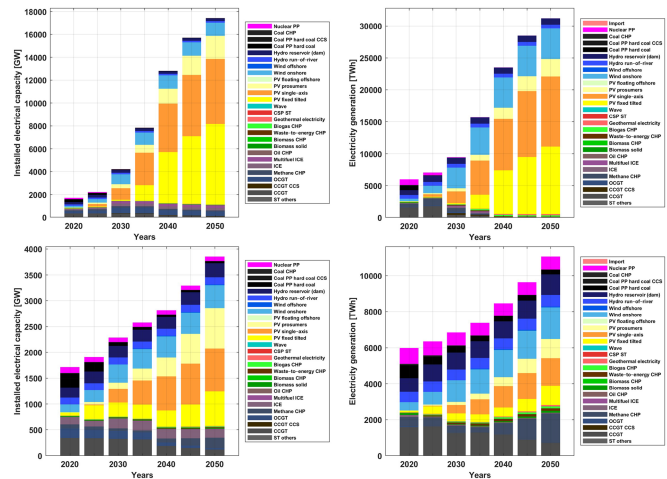


Fig. 3. Installed electricity capacity (left) and electricity generation (right) for the BPS (top) and the CPS (bottom). Note that axes are not aligned.

wind power is most significant in 2025 and 2030 when the cost structure of onshore wind power is the most competitive. In the 2030s and 2040s, however, low-cost solar PV dominates new investments. By 2050, all onshore PV technologies, including prosumers (1359 GW), fixed tilted (6792 GW), and single axis (2447 GW), have significant roles in the American and Canadian energy systems. Large hydropower installations remain within the electricity generation mix but are not significantly expanded as most of the sustainable potential has been used. The growth in solar PV strongly correlates with the growth in power-to-X technologies, as low-cost electricity is required to enable cost-competitive power-to-X products, including e-fuels, e-chemicals, and e-materials.

The CPS, however, does not see such expansions in renewable electricity as electricity generation only reaches 7093 TWh in 2050. Of this electricity generation, solar PV and wind power contribute 2839 and 1356 TWh, respectively. Interestingly,

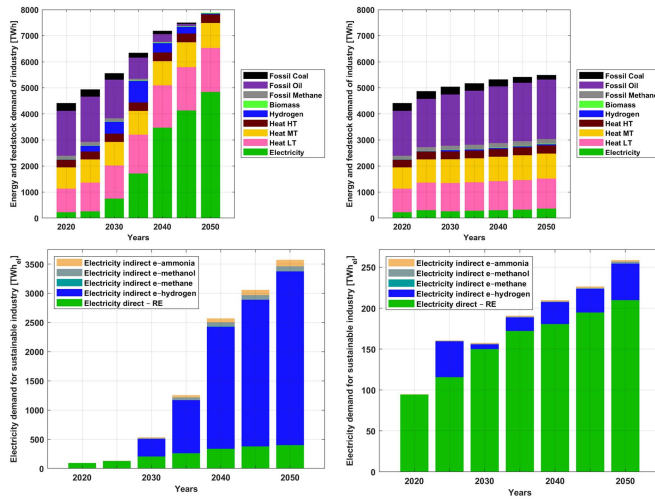


Fig. 4. Final energy demand for industry (top) and electricity demand for sustainable industry (bottom) for the BPS (left) and the CPS (right). Note that axes are not aligned.

while government projections find similar shares of solar PV and wind power, the cost-optimal conditions of the BPS find a solar-dominated structure. Although the CPS projects a total renewable electricity generation share of 70% in 2050, high shares of fossil fuels in the TPED indicate that there is limited penetration of power-to-X technologies.

The solar-dominated structure found in the BPS can further be reflected in the structure of industry demand, as shown in Fig. 4. Electricity remains limited in the final industry energy demand in the 2020s and 2030 but grows significantly starting in 2035, which correlates heavily with the growth in solar PV. The total electricity demand for sustainable energy-intensive industry increases from 220 TWh in 2020 to 4602 TWh in 2050, corresponding to 23% of generated electricity. The electricity demand for sustainable industry is dominated primarily by electricity for e-hydrogen production through electrolysis, followed by direct electricity and electricity for e-chemical synthesis units, which are required to defossilize chemical feedstock demands. The electrolyzer electricity demand for sustainable energy intensive industry in 2050, at 2973 TWh, corresponds to 29% of all electricity for e-hydrogen. Conversely, in the CPS, the electricity demand for industry only increases to 360 TWh in 2050, only 7% of the total industry final energy demand. Fossil feedstocks especially remain prominent, at 47% of all final industry demand. Furthermore, power-to-heat penetration remains limited at all temperature levels corresponding to existing government projections.

Given the renewable electricity-dominated nature of the energy industry system described in the BPS, storage becomes essential in managing the variability and seasonality of the PE supply. Electricity storage is essential in balancing the renewable electricity supply with inflexible demands in the power sector, industry sector, and power-to-X processes. The capacity and throughput for electricity storage, shown in Fig. 5, play an increasing role in the 2030s as renewable electricity begins to dominate the electricity supply. By 2035,

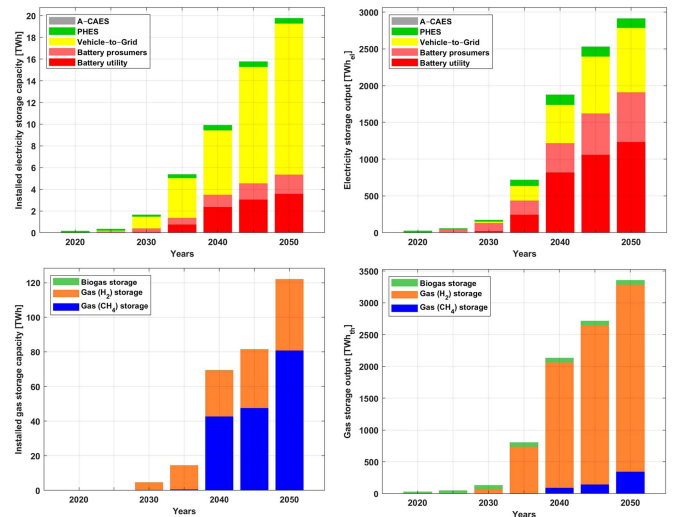


Fig. 5. Installed electricity storage capacity and throughput (top) and installed heat and gaseous storage capacity and throughput (bottom) for the BPS.

total electricity throughput reaches 719 TWh and reaches 2915 TWh by 2050. However, compared with the total electricity demand, electricity storage appears to play a less important role, as electricity storage throughput only corresponds to 12% of the total electricity demand. A similar role can be observed for low- and medium-temperature heat storage, as heat storage throughput of 1452 TWh in 2050 corresponds to 22% of the total heat demand. Nevertheless, heat storage is fundamental to manage electricity-based heat through direct electric heating and heat pumps, solar thermal heating, and waste heat from electrolysis and other power-to-X processes. Gaseous storage, particularly that of hydrogen, plays a comparatively more important role, as hydrogen supply provided by flexible electrolysis requires intermediate storage for inflexible power-to-X processes. Indeed, 41% of the total hydrogen production of 7181 TWh_{H₂,LHV} passes through intermediate storage.

Although the high growth power-to-X technologies in the 2030s and 2040s lead to significant growth in electricity generation and storage of all kinds, there is not a respective increase in the demand for fuels and chemicals. Indeed, the total supply for fuels of chemicals decreases by 61.1% from 21 409 TWh in 2020 to 8334 TWh in 2050 (see Fig. 6). By the end of the transition, e-hydrogen and e-hydrocarbons are primarily required for marine, aviation transport, and industrial feedstocks, as the other energy segments have largely been electrified. Furthermore, free trading of 30% of the e-FTL fuel demand allows for the USA and Canada to use low-cost e-fuel production in lowest cost-producing regions in the Americas. In total, 486 TWh of e-FTL fuels are imported, largely from South American countries, such as Chile.

Coal is the first fuel to be phased out, followed by gas and oil. Due to its importance as a fuel for transport and chemical feedstock, oil may be the most challenging fossil fuel to fully phase out of the energy industry system. Bioenergy has a relatively constant supply, ranging from 1915 to 2656 TWh, indicating that the majority of the sustainable bioenergy potential is being

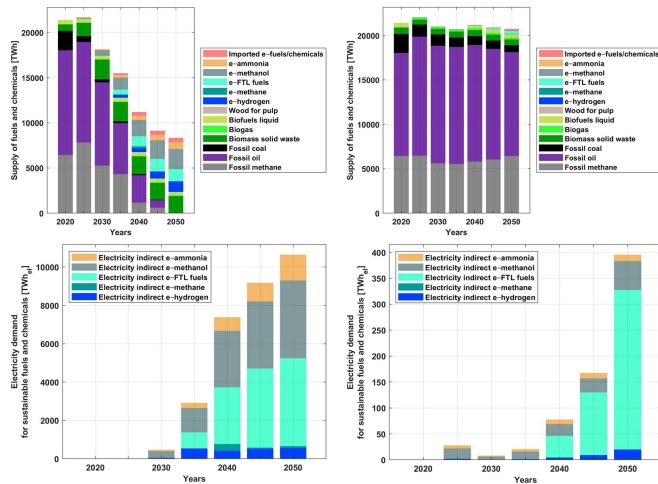


Fig. 6. Supply of fuels and chemicals (top) and electricity demand for sustainable fuels and chemicals (bottom) for the BPS (left) and CPS (right). Note that axes are not aligned.

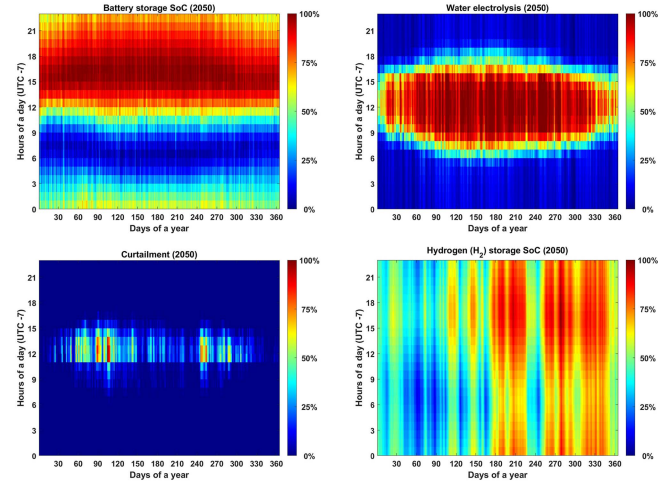


Fig. 7. Hourly utility-scale battery state of charge (top left), operation of electrolyzers (top right), curtailment (bottom left), and hydrogen buffer storage state of charge (bottom right) for the BPS in 2050.

used. Thus, a significant quantity of electricity is required to defossilize the remaining fuel demand. By 2050, this electricity demand reaches 10 645 TWh, corresponding to 51% of all electricity generation

The operational dynamics of key system components, shown in Fig. 7, highlight the role of solar PV in enabling a cost-competitive e-fuel and e-chemical supply. Utility-scale batteries and water electrolyzers show operational characteristics largely aligned to when excess solar PV electricity is available. The seasonality of solar resources is also reflected in the operation of these components, as the operational window for water electrolyzers and hours of high state of charge for batteries increases during the summer months. Interestingly, higher solar PV availability does not correspond to higher curtailment, as curtailment peaks during the spring and fall seasons. With a highly sector-coupled system, flexible demands such as water electrolysis and the availability of electricity and heat storage

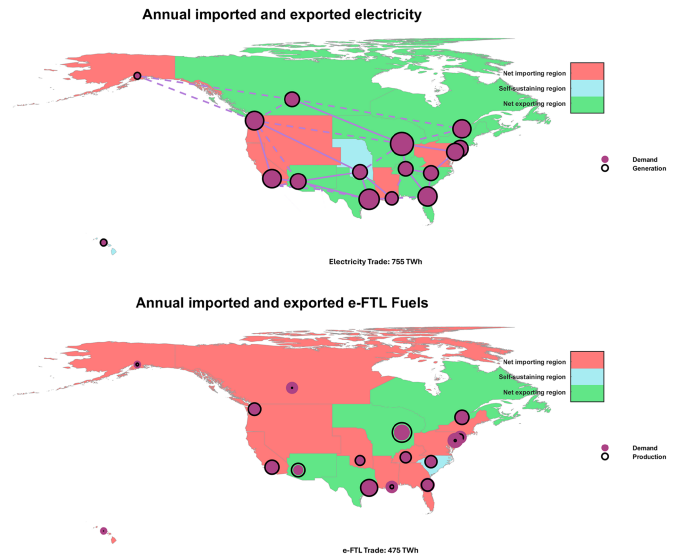


Fig. 8. Annual electricity trade (top) and e-FTL trade (bottom) between microregions in the BPS in 2050. Solid lines represent transmission capacities at or above 1 GW, and dashed lines represent capacities below 1 GW. Self-sufficiency for e-FTL trade is defined as supplying 95–105% of a region’s e-FTL demand.

keep curtailment low, at 0.5% of electricity generation in 2050. Hydrogen storage, as shown in Fig. 4, plays an essential buffer role, largely following the seasonality of solar resources.

Electricity transmission and e-fuel trade within the U.S. and Canada regions become increasingly important to most effectively use the strongest RE resources in the two countries. In Canada, the results indicate that significant grid expansion between East and West Canada is not required, with both regions exporting electricity to the USA (see Fig. 8). Rather, interconnection between the two Canada regions may manifest itself through e-fuel trade, as the strong wind resources in East Canada result in e-fuel exports to West Canada. e-Fuel trade of e-FTL fuels and e-methanol in the U.S. East region is essential to supply the fuel and feedstock demand in regions with low land availability, particularly in the U.S. New York and New England and U.S. Mid-Atlantic regions as the U.S. Midwest becomes a major exporter. In addition, the land constraints in the U.S. Mid-Atlantic region result in net electricity imports of 435 TWh in 2050. The higher land availability in U.S. West, conversely, indicates that significant electricity and e-fuel trade may not be required, with net electricity transmission within U.S. West reaching 78 TWh in 2050. The results additionally indicate that U.S. Southwest and U.S. Texas become e-FTL suppliers to the U.S. Gulf, U.S. Alaska, and U.S. Hawai’i regions.

In the BPS, the levelized cost of electricity (LCOE) and levelized cost of final energy (LCOFE) and nonenergy use see significant reductions as fossil fuels are phased out (see Fig. 9), suggesting that a 100% RE industry system can be achieved at final energy costs similar to today’s fossil-fuel-dominated structure. Widespread electrification through direct solutions and power-to-X allows for significant usage of solar PV and wind electricity with no storage requirements, e.g., through electrolysis and electric heating supply. Thus, the LCOE can be reduced from 72 €/MWh (86.4 US\$/MWh) in 2020 to

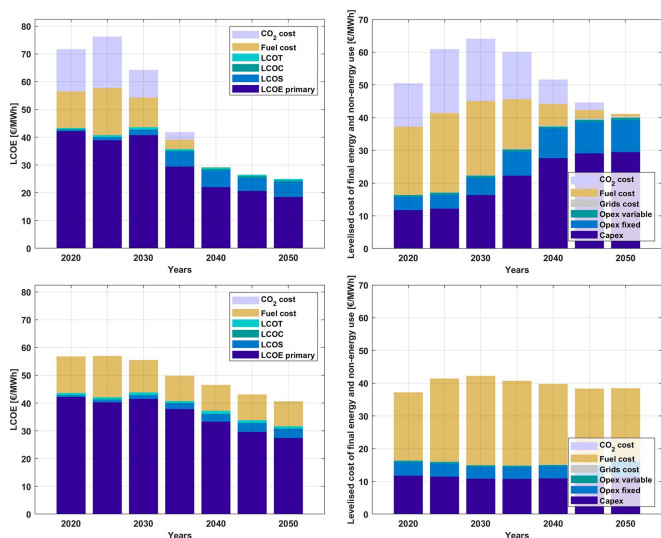


Fig. 9. LCOE (left) and LCOFE and nonenergy use (right) for the BPS (top) and the CPS (bottom). LCOS: levelized cost of storage; LCOC: levelized cost of curtailment; and LCOT: levelized cost of transmission.

25 €/MWh (30 US\$/MWh) in 2050. The CPS sees reductions in the LCOE; however, the limited penetration of renewables and power-to-X across the energy industry system results in an LCOE of 40 €/MWh (48 US\$/MWh) in 2050, where fuel costs compose 21% of total costs compared with <1% in the BPS. The LCOFE in the BPS sees significant reductions, particularly when considering CO₂ emission costs, as the LCOFE decreases from 50.5 €/MWh (60.6 US\$/MWh) in 2020 to 41.1 €/MWh in 2050. The LCOFE in the CPS, conversely, remains stable throughout the transition, reaching 38.5 €/MWh (46.5 US\$/MWh) in 2050. These results suggest that, even without emissions pricing mechanisms, a 100% RE industry system leads to levelized costs competitive with business-as-usual conditions.

IV. DISCUSSION

As the entire energy industry system in the USA and Canada trends toward complete defossilization in the BPS, low-cost electricity will be required, and, as a consequence, solar PV is massively ramped from 2040 onwards. Such rapid expansion of electricity generation, at 7.7%/a, may be feasible. While this growth has not been observed in recent years in the USA and Canada, such growth rates have been observed in large emerging economies [27], [28]. Even with significant solar PV growth, the total utility-scale solar PV required only corresponds to 9% of the total 6% area limit applied for onshore solar PV. Even in the northern regions of Canada, solar PV may still play an important role in a wind-dominated system, as results indicate a 26% share of solar PV in 2050 (see Fig. 10). Bennet et al. [29] investigate the potential of defossilizing energy demands in Canada with solar PV suggesting that solar-PV-based e-fuel exports may be an option to retain energy exports, although the results of this research find that Canada becomes a net importer of e-fuels. The operational profiles for electrolyzers largely indicate that

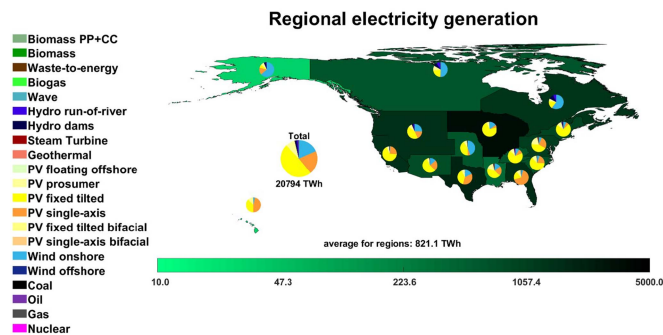


Fig. 10. Electricity generation in 2050 in the BPS.

e-hydrogen production will be based on the availability of low-cost solar PV with additional flexibility provided by wind power. Furthermore, the role of power-to-X in the defossilization of the transport and energy intensive industry sectors can be observed in the high shares of electricity for e-hydrogen production, at 49% in 2050. Notably, fuel and chemical requirements are significantly reduced in the BPS, with 39% of the 2020 fuel and chemical requirement needed by 2050. This finding is consistent with [30], which project that future refinery throughput would be around 54% of the 2020 throughput.

Compared with business-as-usual conditions in the CPS, the total system annualized costs are 13.2% higher in the BPS, suggesting that the transition to 100% RE can lead to a cost-competitive future energy industry system. The strong interaction of power-to-X results in increased sector coupling and synergies, as excess renewable electricity can be used for flexible e-hydrogen production without the need for electricity storage. e-Hydrogen can then be supplied to less flexible e-fuel, e-chemical, and e-material processes through inexpensive hydrogen storage in salt and rock caverns, which are abundant in the USA and Canada [31]. The CPS benefits less from this system flexibility and the limited penetration of renewable electricity and power-to-X. With continued fossil fuel usage, total tank-to-wheel emissions remain high, only decreasing from 5185 MtCO₂ in 2020 to 4704 MtCO₂ in 2050. With this emissions level and the 2050 greenhouse gas (GHG) emission cost in the BPS, there would be an added 44 €/MWh (52.8 US\$/MWh) to the LCOFE. Thus, GHG emission pricing mechanisms are essential in promoting the viability of a net-zero emission energy industry system in the USA and Canada. Additional economic incentives, such as carbon credits for sustainable CO₂ used for power-to-X products [32], may aid in facilitating a transition to systems dominated by primary renewable electricity.

The presented results and the energy flow diagram of the BPS (see Fig. 11) demonstrate the technical feasibility of future energy systems of the USA and Canada based on renewable electricity and dominated by power-to-X solutions. Direct electrification should be prioritized wherever possible. For energy demands that cannot be directly electrified, hydrogen is essential; however, its role is primarily as an intermediate for power-to-X processes. The final use of hydrogen is limited

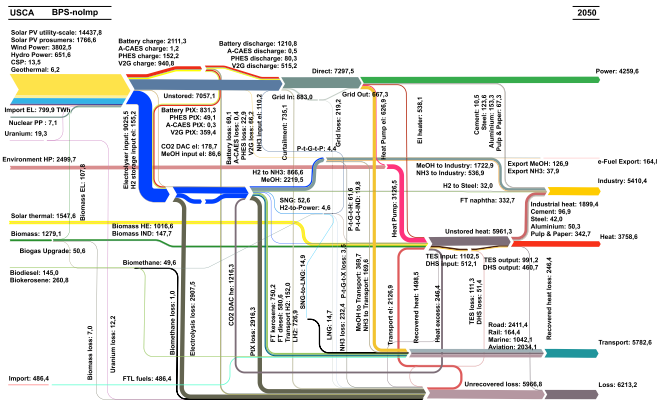


Fig. 11. Energy flow for the USA and Canada in the BPS for 2050.

primarily as a feedstock for e-steel production and as a fuel for high-temperature heating and some transport applications. The energy flows of the BPS, thus, demonstrate that the future energy systems for the USA and Canada can be described as a Power-to-X Economy [33], as electricity composes 85% of all PE. In the context of a full energy industry system defossilization, the term Solar-to-X Economy may best describe such a system given the operational characteristics of key power-to-X processes and the high share of solar PV in electricity generation at 78%.

This study has several limitations that can be addressed in future research. The rapid transition of the electricity supply indicates that a faster transition of the whole energy industry system may be viable; thus, future research should investigate the effects of varying transition speeds. An additional limitation is the use of one weather year throughout the transition, as resource variability may affect system resiliency. Thus, interannual storage requirements from resource variation, especially in the context of climate-change-induced variations [34], should be further investigated. Industrial capacities are assumed to remain within the same regions throughout the transition; future research can investigate the effects of a solar-dominated North America on new industry investments, especially for the steel and chemical industries [35], [36]. Researchers increasingly find that value chain reallocations seem to be beneficial via trade of intermediate energy carriers and materials [37]. In addition, the results of this research indicate nearly an 80% electricity supply from solar PV. Future research should investigate the effects of increased supply diversity [38].

V. CONCLUSION

This research demonstrates the opportunities for the USA and Canada to completely defossilize their energy industry systems and reduce total electricity and final energy costs. By developing a Power-to-X Economy dominated by solar PV, at 74% of the PE demand under best policy conditions, current industrial demands can be decoupled from fossil fuels and feedstocks. Indeed, the Solar-to-Hydrogen-to-X route is a fundamental component of future sustainable energy systems for widespread electrification

of all sectors. Compared with business-as-usual conditions, a 100% RE system achieves competitive economic and improved environmental performance, consistent with current government targets.

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