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Projections of when each of 150 countries may eliminate air pollution and carbon emissions from all energy

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Whether the world addresses global warming, air pollution, and energy insecurity in a timely manner depends largely on country transition rates to clean, renewable energy. Yet, no study has examined transition rates by country, especially using recent data. This study estimates when 150 countries can potentially transition to 100% clean, renewable energy across all energy sectors, upon near-electrification of each sector, if the countries add such energy at their most recent rates. Such a transition eliminates air pollution and carbon emissions from energy. Results suggest the world's largest energy consumer and emitter, China, is currently on track to transition fully, thus eliminate 100% of its energy-related health- and climate-damaging pollution, by 2051. China's projected 2025 renewable output increase is 20 times France's fastest (in 1981) nuclear output increase. Further, in 2025, China may already produce ~54% of the clean, renewable energy that the United States will need for supplying 100% of its all-sector demand with clean, renewable energy in 2050. Seven countries could potentially reach 100% renewables faster than China. India and the United States may reach 100% only beyond 2130. Thus, policies focusing on clean, renewable energy alone can effectively speed a transition.

Sustainability spotlight

This paper projects when each of 150 countries can eliminate all energy-related health- and climate-damaging emissions by transitioning to 100% clean, renewable electricity and heat across all energy sectors after near electrification of each sector. It addresses United Nations Sustainable Development Goals 3 (good health and well-being), 7 (affordable and clean energy), 11 (sustainable cities and communities), 12 (responsible consumption and production), and 13 (climate action). The study finds that eight countries, including China, the world's largest energy consumer and CO_2 emitter, can reach 100% by 2051. The U.S. and India may reach 100% only after 2130. China' transition rate is faster than any clean-energy conversion in history. Thus, a focus on clean, renewable energy can speed a transition.

1 Introduction

The world needs to eliminate rapidly atmospheric gases and particles that affect human health and climate. Gas and particle emissions and their atmospheric transformations cause ~7.4 million deaths and billions more illnesses per year[1,2] in addition to an average global warming of ~1.5 °C in 2024 relative to the 1850–1900 period.[3,4] About 90% of anthropogenic air pollutant emissions and 75–80% of anthropogenic climate-damaging emissions originate from energy.[5]

Whereas several studies have discussed country-specific emission-phaseout policies[6,7] and other studies have projected what is needed to transition countries to 100% clean, renewable energy across all energy sectors to eliminate gas and particle emissions from energy,[5,8–14] no study has projected when each country might reach this goal based on existing clean, renewable generation and the growth rate of such generation. Such a study is important for four reasons. First, if some countries can transition quickly, they can serve as good examples for other countries to learn from. Second, comparing the transition speeds among countries can spur competition to encourage countries on a slow timeline to speed up. Third, many countries on a slow timeline may have a false optimistic sense of their progress, so quantifying their real progress may encourage them to speed their transition. Fourth, understanding the timeline of a world transition may help countries better project and prepare for more air pollution and climate damage.

In this study, dates are projected by which each of 150 countries can eliminate all air-quality- and climate-relevant-gas-and-particle emissions from all energy sectors by electrifying or using direct heat for all sectors and providing the electricity and heat from clean, renewable sources. All energy sectors include the residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other sectors.

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Electrifying all sectors means converting technologies (*e.g.*, combustion vehicles; combustion heaters), currently powered by fossil fuels or bioenergy fuels, to those powered by electricity (*e.g.*, electric vehicles; electric heat pumps or electric resistance furnaces). Clean, renewable electricity and heat sources also referred to as wind-water-solar, or WWS, sources, include onshore and offshore wind electricity, solar photovoltaic electricity, concentrated solar electricity, direct solar heat, geothermal electricity and heat, hydroelectricity, and tidal and wave electricity sources.[5,14]

Nuclear is not included as a WWS source because it carries seven major risks: long time-lag between planning and operation (12–23 years worldwide today); carbon and pollution emissions from the background grid due to the long time-lag, reactor construction, and continuous uranium mining and processing; nuclear weapons proliferation risk; reactor core meltdown risk; radioactive waste storage risk; underground uranium mining lung cancer risk from radon; and high cost.[10] Bioenergy is not included because of the air pollution that results from its combustion; the greenhouse gases and pollutants that are emitted during the production of a bioenergy fuel; and the substantial land and water needed to grow many types of bioenergy crops.[10]

Electrifying almost all processes across all energy sectors, using direct heat for the remaining processes, and using WWS to provide all electricity and direct heat eliminates ~100% of fossil-fuel and bioenergy-fuel combustion emissions from energy, but only about 90% of total anthropogenic air pollutant emissions and 75–80% of total anthropogenic climate-damaging emissions.[5] Remaining anthropogenic air pollutant emissions are primarily from open biomass burning, road dust, and construction dust.[5] Remaining anthropogenic climate-damaging emissions are from those sources plus from fertilizers and industry producing nitrous oxide; halogens; agriculture and landfills producing methane; and cement and steel manufacturing chemically producing carbon dioxide. This paper focuses only on the time to eliminate 100% of fossil-fuel plus bioenergy-fuel emissions from all energy by electrifying or using direct heat for such energy and providing all electricity and heat with 100% WWS.

The projected transition-to-100%-WWS dates are determined by combining 2050 estimates for each country of what is needed to achieve 100% WWS across all energy sectors[14] with data quantifying the clean, renewable generators already installed in 2023, 2024, and, in some cases, 2025, along with the rates of change of such installations.[15–20] Data from further back than 2023 were not used given that they are based on older technologies, policies, and costs than from more recent years. Whereas projections based on current installation rates may provide reasonable estimates of transition times that are short (*e.g.*, less than 30 years), they result in more uncertain estimates of longer transition times. The longer the transition time, the more uncertain the estimate because countries may change priorities and technology costs may decrease substantially over time, causing a country to adjust its transition rate over time. However, transition times of up to 325 years are shown here just to compare the relative progress of different countries rather than to give a firm idea of when countries with long transition times will reach 100% WWS.

Whereas this study considers the rates at which generators are being installed, it does not consider rates at which storage and electric machines and appliances (*e.g.*, electric vehicles, electric heat pumps, and electric resistance furnaces) are being adopted. Nevertheless, the Discussion analyzes how fast China is adopting some of these technologies. The study assumes that the adoption of these technologies will accompany the installation of WWS electricity- and heat-generating technologies because such electric appliances and machines reduce end-use energy demand (total final consumption, or TFC) substantially relative to their conventional counterparts (*e.g.*, internal-combustion-engine vehicles, gas heaters, and fossil-fuel furnaces, respectively).[5] Thus, the estimates here are based on how fast WWS electricity and heat generators are being installed relative to how much WWS generation is needed to provide 100% of all-sector electricity and heat across all energy sectors, after electrifying most all non-electric processes, for a country.

2 Experimental section

2.1 Methods

End-use energy demand (TFC) data (GWh per y, or annual GW-demand) from 2022, published by the International Energy Agency,[21] were first projected in a separate study[14] to 2050 in a business-as-usual (BAU) scenario for each of seven fuel types within each of six end-use energy sectors within each of 150 countries. The seven fuel types include oil, fossil gas, coal, electricity, heat for sale, solar and geothermal heat, and wood and waste heat. The end-use energy sectors include the residential, commercial, transportation, industrial, agriculture-forestry-fishing, and military-other sectors. Table S1 lists the 150 countries. Energy use for transportation includes energy for ground, air, and marine transport, including international aviation and shipping. The projections to 2050 assume moderate economic growth, population growth, energy consumption growth, modest energy policy changes that vary by world region, use of some renewable energy, modest energy-efficiency measures, and reductions in energy use.

The 2050 BAU projections of end-use demand (TFC) were then used as a starting point to estimate how much electrical and direct heat energy (GWh per y) might be needed if each BAU fuel type in each end-use sector in each country were switched to electricity, electrolytic hydrogen, low-temperature heat, or high-temperature heat, and if such electricity, hydrogen, and heat were provided by WWS. For example, air and water heating for buildings, originally provided by combustion heaters, was assumed to instead be provided by electric heat pumps. Vehicle transport, originally provided by internal-combustion-engine vehicles, was instead provided by battery-electric vehicles for all but very-long-distance aircraft, ships, trucks, and trains, which were propelled instead with hydrogen-fuel-cell electricity.[22] Industrial heat, originally provided by combustion furnaces and boilers, was instead provided by electric furnaces and firebrick storage. The resulting reductions in end-use energy demand (TFC) were calculated with conversion factors that vary by fuel

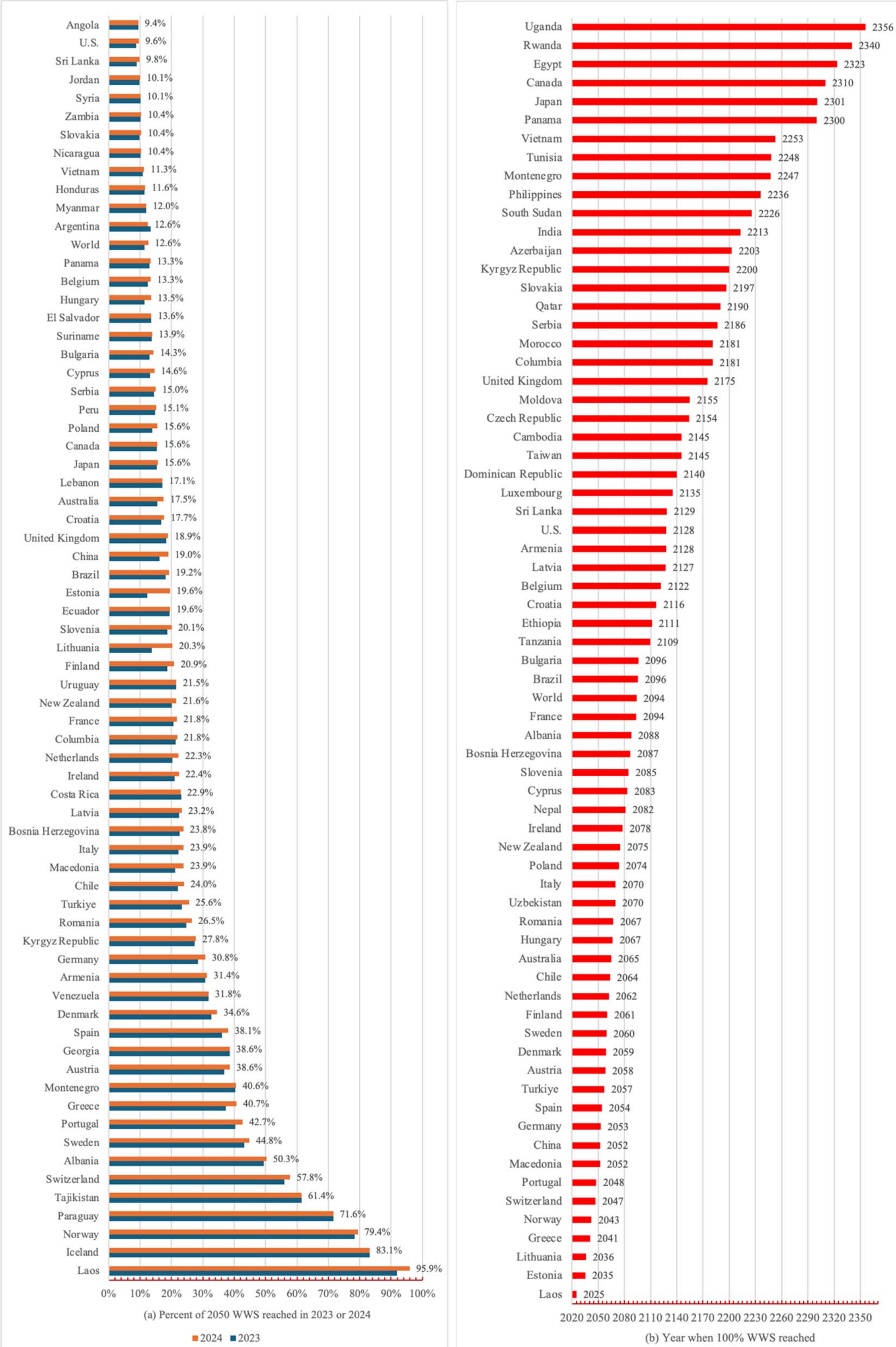

Fig. 1 (a) Percentages of end-use power needed from WWS generators across all energy sectors in 2050 to keep the grid stable actually met by WWS installations in 2023 and 2024. The numbers shown are for 2024. (b) Estimated year that a country is expected to meet 100% of their 2050 end-use demand across all energy sectors after near electrification of all sectors based on the WWS growth rate between 2023 and 2024. Table S1 provides values from both charts for 150 countries.

type within each energy sector.[5,14] For example, transitioning from a gasoline passenger car to a battery-electric passenger car reduces end-use demand (TFC) in 2050 by ~79%.[5,14] A resource analysis was performed for each country to determine which WWS technologies could be developed feasibly, and a mix of WWS technologies was chosen for each country based on this and other factors.[14] The assumption that each country could be converted was not based on policies set in the country but was motivated by the goal that such a transition could address air pollution, climate, and energy security in each country.[14]

Results indicate that such a transition may reduce 2050 annual average end-use power demand (TFC) among the 150 countries by an average of 54.2% (from 19.56 TW-demand to 8.96 TW-demand): 19.75 percentage points due to the efficiency of WWS electricity for transportation, 4.11 percentage points due to the efficiency of WWS electricity for industrial heat, 13.14 percentage points due to the efficiency of WWS for heat pumps instead of combustion heaters, 10.6 percentage points due to eliminating energy for mining, transporting, and refining of fossil fuels and uranium; and 6.57 percentage points due to end-use energy-efficiency improvements and reduced energy use beyond those with BAU.[14]

The end-use demands just calculated are 2050 annual-average electricity and heat targets for each of 150 countries to be met by WWS. However, such targets do not account for the additional generation and storage needed to keep the grid stable or for transmission and distribution losses. The 150 countries were then combined into 29 world regions, and grid stability analyses were performed with the LOADMATCH grid model in each region at a time step of 30 seconds to estimate the nameplate capacities of WWS generators and storage devices needed to meet the demand for three consecutive years (2050–2052) (Table S1). The grid analyses used 30-s wind and solar generation and building heating and cooling-demand data for each country produced by a global weather-prediction model.[14] The grid studies resulted in a 150-country average of ~25% oversizing of generators needed to match continuous demand compared with those needed to match annual-average demand.[14] Some end results of that study were a quantification of the nameplate capacities needed (GW-nameplate) for different WWS generation and storage technologies as well as the WWS generator and storage outputs produced (GWh per y, or annual GW-supplied) before transmission and distribution losses to meet total end-use demand (TFC) after such losses, in each country.[14]

Nameplate capacities of WWS technologies already installed in each of the 150 countries for 2023 and 2024 were then obtained here from IRENA[15] and SEIA.[16] Nameplate capacities were also obtained for China for the first 10 months of 2025,[17] India for the first 9 months of 2025,[18] and the U.S. for the first 7 months of 2025.[19,20] Such partial-year values were extrapolated linearly to all of 2025. The 2023, 2024, and 2025 nameplate capacities (Table S1) were then multiplied by capacity factors (Table S3) and transmission and distribution efficiencies (Table S1, Footnote) to provide annually-averaged power supplied by each generator and by the sum of all generators in a country (Table S1). The difference between the WWS annual-average power needed in 2050 and that already supplied in 2024 or 2025 (in the case of China, India, and the U.S.) was then divided by the rate of WWS power output growth between 2023 and 2024 or between 2024 and 2025 to estimate the number of years beyond 2024 or 2025 needed for the country to reach 100% WWS across all energy sectors assuming WWS growth continued to occur at its 2023-to-2024 or 2024-to-2025 rate.

3 Results

Based on WWS generator installations and corresponding WWS output increases between 2023 and 2024, three countries (Laos, Estonia, and Lithuania) could reach 100% WWS generation (thus eliminate all air pollution and carbon-equivalent emissions from energy) across all energy sectors by 2036 or earlier (Table S1 and Fig. 1b). Four more countries (Greece, Norway, Switzerland, and Portugal) could reach 100% by 2048 or earlier (Table S1 and Fig. 1b). China, which consumes more of the world's end-use energy (23.2% of all end-use energy in 2022) and emits more of the world's anthropogenic carbon dioxide (35.0% in 2023) than any other country,[14] is estimated to achieve a full transition, based on 2023-to-2024 installations, by 2052 (Fig. 2). The U.S., the world's largest economy, and India, the world's most populated country, are estimated to reach 100% WWS only by 2128 and 2212, respectively (Fig. 2 and 4), based on 2023-to-2024 installations. The world, on average, is on track to reach 100% WWS only by 2094 (Fig. 1b).

Whereas by the end of 2024, China, U.S., and India WWS outputs were only 19.03%, 9.60%, and 4.65%, respectively, of the outputs they need for a 100% all-sector WWS energy transition by 2050 (Fig. 1a and Table S1), the estimated growth rates of WWS outputs in these countries between 2024 and 2025 were 2.99% per y, 0.724% per y, and 0.829% per y, respectively (Fig. 3). As such, based on 2024 to 2025 WWS output growth data, China, the U.S., and India may reach the 100% transition

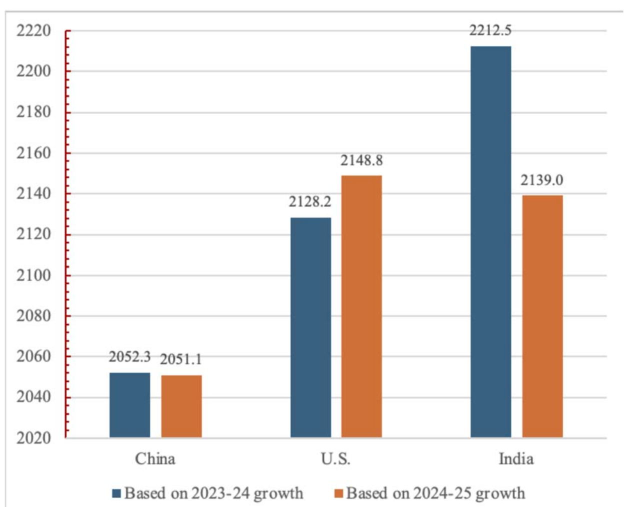

Fig. 2 Estimated year that China, the U.S., and India will meet 100% of their 2050 end-used demand across all energy sectors after electrification of all sectors, based on the WWS growth rate in the country between 2023 and 2024 and between 2024 and 2025. Derived from data in Table S1.

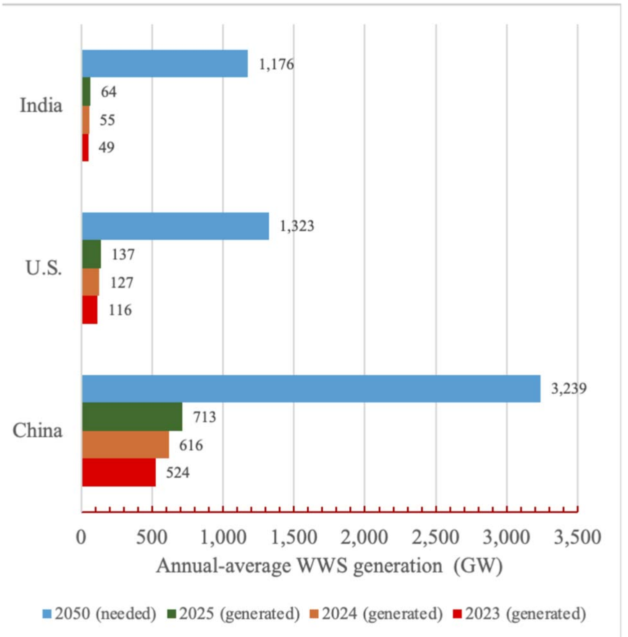

Fig. 3 Comparison of estimated 2050 annual-average WWS power generation (not nameplate capacity) needed to meet 100% of all-sector end-use demand while keeping the grid stable (blue) with estimated WWS generation already provided in 2023, 2024, and 2025, for China, the U.S., and India. In 2025, China is projected to produce 54% of the WWS output the U.S. needs in 2050. Derived from data in Table S1.

goal by 2051, 2148, and 2139, respectively, (Fig. 2 and 4). Thus, China is well on its way to a full transition, thereby eliminating 100% of its air-pollution- and climate-damaging emissions by 2051. Further, India has slightly surpassed the U.S. in terms of when it may reach 100% WWS. However, the U.S. still produced far more WWS output than India in 2025 (Fig. 3).

Several countries (Laos-95.9%, Iceland-83.1%, Norway-79.4%, Paraguay-71.6%, Tajikistan-61.4%, Switzerland-57.8%, and Albania-50.3%), were already very close to 100% WWS across all energy sectors in 2024 (Fig. 1b and 4). These countries all have substantial hydropower installed. Iceland also has geothermal electricity and heat and some wind (Fig. S1). Norway also has a lot of wind turbines installed (Fig. 5). Switzerland also has a lot of solar photovoltaics installed (Fig. S1). Most of these high-WWS countries are still far from achieving 100% WWS across all energy sectors because the growth rate of WWS between 2023 and 2024 in those countries was low. Exceptions are Laos, Norway, and Switzerland, discussed shortly.

4 Discussion

The most substantial and encouraging finding of this study is the rate by which China is transitioning its energy economy. China installed an astounding 70.01 GW-nameplate of wind, ~7.8 GW-nameplate of hydro, and 252.87 GW-nameplate of solar PV during the first 10 months of 2025[17] on top of installing 79.85 GW-nameplate of wind, 14.4 GW-nameplate of hydro, and 278.01 GW-nameplate of solar PV during all of 2024.[15] The 372.3 GW-nameplate of WWS China installed in 2024 is 95.5 times the 3.9 GW-nameplate of new nuclear connected to China's grid in 2024.[23] The 330.7 GW-nameplate of WWS installed by China during the first 10 months of 2025 puts the country on pace (assuming a linear extrapolation) to install ~397 GW-nameplate during all of 2025, ~7% more than in 2024. Accounting for capacity factors and transmission and distribution losses,

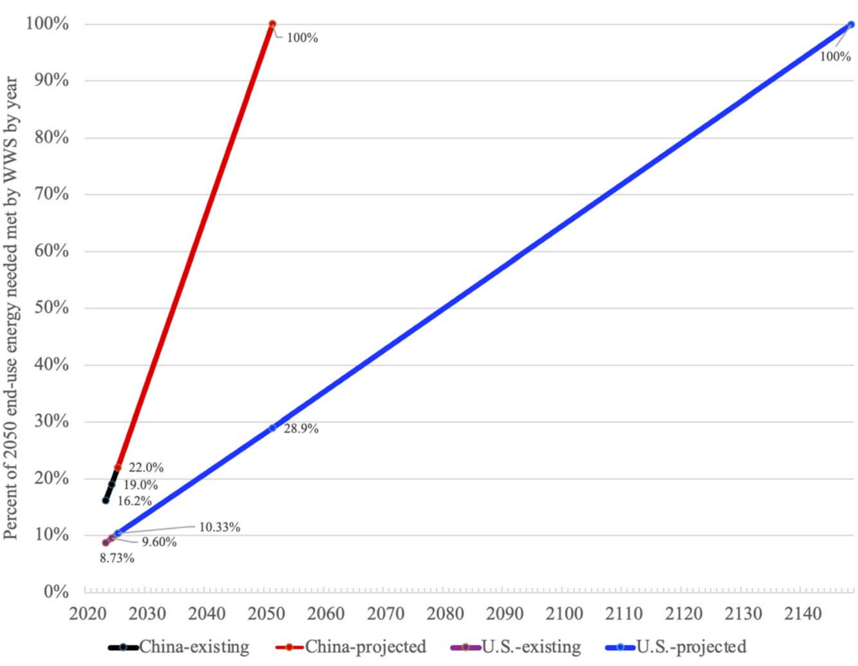

Fig. 4 Percent of 2050 end-use energy needed upon electrification of all energy sectors estimated to be met already by WWS in 2023, 2024, and 2025, and the year that 100% of end-use energy is projected to be met by WWS, in China (by 2051) and the U.S. (by 2148).

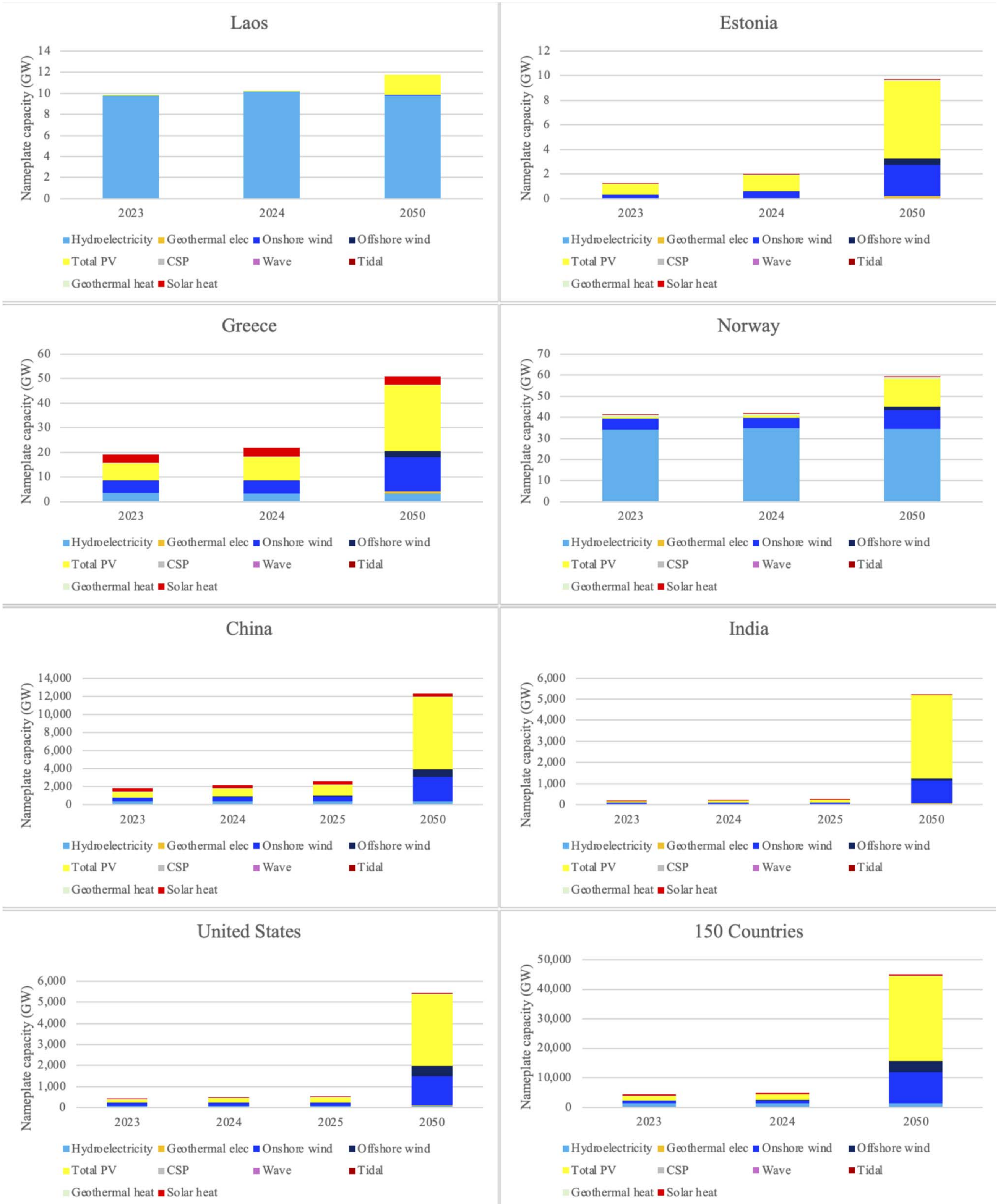

Fig. 5 Comparison, for selected countries, of estimated 2050 WWS nameplate capacities needed to power 100% of all-sector energy demand with WWS after electrification of all energy sectors, and accounting for grid stability, with actual WWS nameplate capacities installed in 2023, 2024, and (for China, the U.S., and India) 2025. Derived from data in Table S1. Figure S1 shows results for additional countries.

China's may produce 96.9 GW more annual-average WWS power output in 2025 than in 2024 (Fig. 3 and Table S1).

In comparison, the U.S. added 3.288 GW-nameplate of wind,[19] 4 MW-nameplate of hydro,[19] ~3.91 GW-nameplate of behind-the-meter PV,[20] and 16.05 GW-nameplate of utility PV[19] during the first 7 months of 2025, which linearly extrapolates to 42.7 GW-nameplate more WWS and 9.59 GW more annual-average WWS output after transmission and distribution losses, for all of 2025 (Table S1). During the first 9 months of 2025, India added 4.96 GW-nameplate of wind, ~1.95 GW-nameplate of hydro, and 29.47 GW-nameplate of solar,[18] which linearly extrapolates to 45.9 GW-nameplate more WWS and 9.75 GW more annual-average WWS output for all of 2025 (Table S1). Thus, the projected new 2025 WWS output in China is ~10.1 times that in the U.S. and ~9.9 times that in India.

China's 2025 rate of WWS output growth may be the fastest rate of growth in low-emitting energy in world history. For example, the 2024 annual-average power output of France's 61.37 GW-nameplate of active nuclear reactors was 41.2 GW.[24] These plants became operational between 1977 and 1999, with a peak addition of 7.2 GW-nameplate in 1981. Ignoring the long planning and construction times for these reactors and considering only the year they became operational, in 1981, France added ~4.8 GW-output from nuclear. This is only ~5% the WWS output China may add in 2025 (96.9 GW). If China's 2025 growth rate of WWS power output persists into the future, and if China electrifies all energy sectors to the greatest extent possible, China could become 100% WWS across all energy sectors, with a stable grid, by 2051 (Table S1, Fig. 2 and 4). Thus, China will accomplish far more than providing all its electricity demand growth with WWS: it will provide all energy for all electricity, all transportation, all building energy, and all industrial processes with WWS, eliminating energy-related air pollutants and climate-relevant pollutants as well as eliminating energy insecurity associated with fossil fuels.

The scale of China's installation of clean, renewable electricity has been so large that, in 2025, China may produce ~54% of the clean, renewable energy the U.S. needs by 2050 to power itself with 100% clean, renewable energy across all energy sectors (Fig. 3 and Table S1). Given the larger economy of the U.S. than China and the comparable land sizes of the two countries, this result suggests that the main barriers to the U.S. obtaining a WWS buildout as large as China's are social and political, not technical or economic.

The conclusion that China is on pace to reach 100% WWS across all energy sectors by 2051 is dependent on the assumption that it will keep building WWS at its 2025 pace (~397 GW year^{-1}) (Table S1). If China instead builds, after 2025, at its 2024 pace (~372 GW year^{-1}) (Table S1), which is 6.3% slower, it will reach 100% WWS by only 2052. If China builds at 300 GW year^{-1} (24.4% lower than 2025), it will reach 100% WWS by only 2058. As such, China's pace of adding WWS would need to decrease substantially relative to its pace in 2024 and 2025 for the country not to be able to transition completely before 2060.

A concern is that China's rapid transition to intermittent wind and solar will not be accompanied by sufficient additions of storage. However, in June 2025, China broke ground on the world's largest (60 GW) hydropower station, almost three-times the output of Three Gorges Dam.[25] Hydropower can be used for both baseload and peaking power and can back up an enormous amount of wind and solar. In addition, during July 2025, four-hour battery system prices decreased to USD $51.59/kWh in China, a price 30% lower than in 2024.[26] Such a low battery price almost eliminates a barrier to the large-scale implementation of battery storage for WWS generation.[10]

An uncertainty is whether China will electrify transportation, buildings, and industry by 2051, the year it can theoretically achieve 100% WWS across all energy sectors. Technically and economically, such a transition should be feasible, but for social and political reasons (*e.g.*, subsidy phaseouts, changes in priorities), such a transition may or may not occur on time. However, some recent data appear encouraging. In 2024, China sold 11 million battery-electric vehicles, which represent more than 50% of the vehicles sold in the country.[27] If China increases this number to 100% by 2030, they will replace almost their entire vehicle fleet to electric by 2051, given the typical-vehicle lifetime of 10–15 years.

The industrial sector is more challenging, not only because most energy in China is consumed in that sector, but also because the industrial sector is the least-transitioned sector worldwide. However, electric arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, electron beam heaters, and heat pumps are already commercially available to replace combustion fuels for industrial heat. In addition, firebricks are already available commercially to store high-temperature heat.[13] Methods also exist to transition cement and steel specifically.[5]

Buildings can be transitioned with a combination of electric heat pumps for air and water heating and air conditioning; electric induction cooktops for cooking, LED lights, more insulation, and energy-efficient appliances and machines. China is already the world's largest market for electric heat pumps and has the manufacturing base to ramp that up.[28] Given the availability of the electric-appliance and machine technologies needed to transition buildings, what is needed to convert China's buildings is primarily strong incentives. In sum, China appears poised to electrify its non-electric energy to meet 100% of its demand with WWS by 2051.

One other concern with China's transition is their continued building of coal plants. In 2024, China began operating 31 GW-nameplate of new coal plants.[29] This represents only 8.3% of the 372.3 GW-nameplate of WWS that China added in 2024, but these new additions are still of concern. However, during the first 8 months of 2025, China reduced its coal use for electric power by 1.5% *versus* the first 8 months of 2024. Thus, although China continues to increase its nameplate capacity of coal power plants, it is reducing its coal electricity output by replacing coal with WWS for electricity generation. In order for China to reach 100% WWS by 2051, it will need to reduce its coal-electricity output all the way to zero. This may or may not result in China decommissioning its coal plants. It is far less important for China to decommission its coal-electricity plants than to eliminate its coal use for electricity. Reducing coal-electricity output is cost-effective given that the energy costs and social costs of coal are much larger than are those of a WWS system.[5] Eliminating coal-electricity output will also help allow China's manufacturing to be produced with 100% WWS, ensuring that China's exports and the WWS equipment it is installing are also produced from clean, renewable sources.

Another concern is the potential for bottlenecks to slow down the transition to 100% WWS. Bottlenecks may arise due to limited availability of critical minerals, supply-chain constraints, or lack of financing.[14] This study does not assume such bottlenecks will not occur. Instead, it estimates the year that countries might reach 100% WWS across all energy sectors if they continue transitioning at their current rate because bottlenecks have been overcome. A benefit of a transition is the substantial reduction in the mass of mined material needed with 100% WWS *versus* with the current energy infrastructure.[14]

A final concern is that solar PV panels, wind turbines, and batteries have limited lifetimes, so must ultimately be replaced, slowing a transition. Whereas replacements of aged WWS technologies may extend the transition dates projected here, lifetimes of critical WWS technology have increased, mitigating this problem. For example, solar PV panels are now typically warrantied for 25–30 years and are expected to last up to 35 years.[30] The expected lifetime of a wind turbine is now 25–40 years, with an average of 30 years.[31] Some batteries today are warrantied for the lesser of 15 000 cycles (41 years if cycled once per day) or 15 years[32] thus can potentially last at least 25 years. As such, PV panels, wind turbines, and batteries installed today may all likely still be operating in 2050.

Another substantial finding of this study is that several smaller countries appear to be closer in time than China to reaching 100% WWS across all energy sectors. These countries have either (1) substantial 2024 WWS output and installations so are already close to 100% WWS supply across all sectors (*e.g.*, 95.9% of Laos' 2050 WWS needed output was already supplied in 2024 and Laos experienced a 4.07%/y WWS-output growth rate between 2023 and 2024; Norway 79.4%; 1.11% per y), (2) a moderate 2024 WWS output and a moderately-fast 2023–24 WWS-output growth rate (Greece 40.8%, 3.46% per y; Switzerland 57.8%, 1.86% per y), or (3) a low 2024 WWS output but a fast WWS-output growth rate (Estonia 19.6%, 7.22%/ per ; Lithuania 20.3%, 6.67% per y) (Table S1 and Fig. 5).

A relevant question is, why Laos so close to 100% WWS across all energy sectors? In 2024, Laos could reach 100% WWS, if it electrified all energy, by 2025 (Fig. 1b). The first reason is that it has an enormous amount of hydropower relative to its demand. In 2023, in fact, Laos met 263% of its electricity demand with hydropower alone.[33] Second, electrification and providing the electricity with WWS is projected to reduce Laos' 2050 end-use demand (TFC) across all energy sectors by 52%,[14] for the reasons described in Methods. Thus, despite a projected increase in energy demand due to population increase and economic growth, that increase will be offset largely by the conversion to electricity powered by WWS. The combination of these two factors means Laos is the country in the world closest to 100% WWS across all energy sectors if it electrifies all its energy sectors.

At the other end of the spectrum, several countries that have strong targets for decarbonization and already have substantial or some WWS installed, are moving much more slowly than expected. These countries may have a false sense of their progress and of what is needed. For example, in 2024, Iceland already produced 100% of its electricity from WWS[33] and 83.1% of the WWS electricity and heat it needs in 2050 to reach 100% WWS across all energy sectors upon electrifying all sectors (Table S1 and Fig. S1). It also has a target of becoming carbon neutral by 2040. However, because Iceland's WWS growth rate between 2023 and 2024 was so small, it cannot reach 100% WWS across all energy sectors until after the year 2350 if it continues building WWS at this slow pace. Similarly, the United Kingdom, and Canada, which both have 2050 decarbonization targets, were already producing, in 2024, 18.9% and 15.6%, respectively, of the WWS electricity and heat they need to reach 100% WWS across all energy sectors. Yet, at the slow rate they are increasing WWS, they will reach 100% WWS only by 2175 and beyond the year 2350, respectively. These examples illustrate a potential benefit of this study: to provide countries with a realistic sense of their progress toward moving to clean, renewable energy across all energy sectors so that they can then determine if faster progress is necessary.

5 Conclusions

The fact that the world's largest energy consumer and emitter, China, could eliminate its energy-related air pollution- and climate-relevant emissions by 2051 due to its rapid pace of WWS deployment should give hope to the world. The fact that China is already producing so much WWS electricity that it may supply, in 2025 ∼54% of what the U.S. needs in 2050 to go 100% WWS across all energy sectors, indicates there is no technical or economic barrier stopping the U.S. from reaching 100% WWS either. Because seven countries are further ahead than China in the transition, there is hope for other countries as well. These results suggest that the main barriers to a transition in any country are generally not technical or economic, but social and political.

China's energy transition is being carried out with enormous amounts of solar, wind, and hydro as well as electric vehicles and electric heat pumps. China is installing WWS electricity at a rate almost two orders of magnitude the rate it is installing new nuclear. The country is also not distracted much by carbon capture, direct air capture, blue hydrogen, biofuels, or biomass. The examples set by China and several other countries suggest that the world as a whole can succeed in a rapid transition if all countries make a strong social and political commitment to a transition and focus, like a laser, on clean, renewable energy.

Author contributions

Mark Z. Jacobson: conceptualization, methodology, investigation, software, visualization, writing – original draft, writing – review & editing.

Conflicts of interest

There are no competing interests to declare.

Note added after first publication

This article replaces the version published on 19 December 2025 in which ref. 17 was incorrect.

Nomenclature

BAU	Business-as-usual
GW	Gigawatts
LED	Light-emitting diode
PV	Photovoltaics
TFC	Total final consumption
USD	United States Dollars
WWS	Wind-water-solar

Data availability

All the data supporting the findings of this study are presented in the article, its supplementary information (SI) File, and its references. Supplementary information: additional tables and figures supporting this study. See DOI: https://doi.org/10.1039/d5su00912j.

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