

Pathway to 100% Renewable Electricity

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Abstract—Solar photovoltaics (PVs) and wind constitute more than 60% of global annual net new capacity additions. Balancing an electricity system with 30–100% variable PV and wind is straightforward using off-the-shelf techniques comprising stronger interconnection over large areas to smooth out local weather, storage, demand management, and occasional spillage of renewable electricity. The overwhelming dominance of PV, wind, and hydroelectricity in new renewable energy deployment means that renewable electricity is tracking toward near equivalence with renewable energy. A global survey of off-river (closed-loop) pumped hydro energy storage sites identified 616 000 promising sites around the world with a combined storage capacity of 23 million GWh, which is two orders of magnitude more than required to support 100% global renewable electricity. This is significant because pumped hydro storage is the lowest cost storage method and is available off-the-shelf in large scale. Australia is deploying PV and wind at a rate of 250 W per year per capita, which is four to five times faster than in the European Union, the USA, Japan, and China. This is significant because it demonstrates that rapid deployment of PV and wind is feasible, with consequent rapid reductions in greenhouse gas emissions.

Index Terms—Photovoltaics (PV), pumped hydro energy storage (PHES), wind energy, 100% renewable energy.

I. INTRODUCTION

THIS ARTICLE explores a pathway toward 100% renewable electricity and deep cuts in greenhouse gas emissions through the deployment of large amounts of variable photovoltaic (PV) and wind together with supporting measures to balance the grid.

In the longer term, following conversion of electricity supply to renewables, extensive electrification of transport, heating, and industry can displace most of the remaining fossil fuels, reducing greenhouse emissions by about three quarters. Indeed, PV and wind constitute the most realistic route to eliminating the use of coal, oil, and gas.

Ultimately, nearly 100% of energy supply could come via renewable electricity. This requires an approximate trebling of electricity production, which provides scope for continued large-scale deployment of PV and wind.

The novel features of this article are the following: 1) identification of off-river pumped hydro energy storage (PHES) as a highly industrially mature and lowest cost storage technology

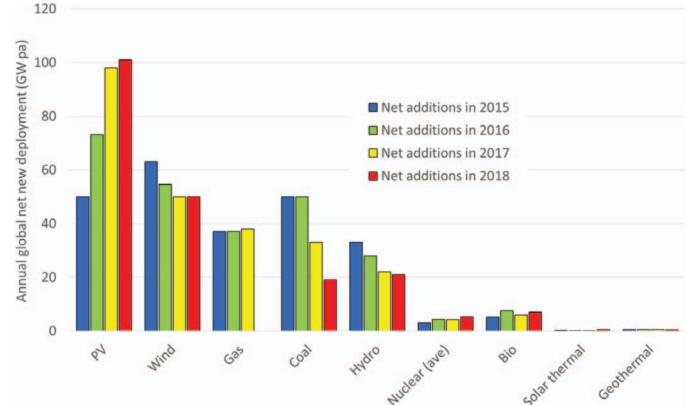


Fig. 1. Global net new capacity additions 2015–2018 illustrating the dominance of PV [9]–[15].

that is available nearly everywhere at a vastly larger scale than required to support 100% renewable electricity; and 2) identification of Australia as a global pathfinder in the transition to 100% renewable electricity.

Many studies have been made of 100% renewable electricity or energy. Some studies apply to regions and others to the whole world [1]–[7]. A review of such studies, and of papers offering a pessimistic view, has recently been published by Brown *et al.* [8]. Sustained rapid cost reductions and deployment growth of PV and wind means that some of the studies are outdated. Some studies rely on technologies that have minimal deployment compared with PV and wind (tidal, solar thermal, wave, and compressed air energy storage), or energy sources that have constrained resources (geothermal and biomass), or entail large extrapolations of battery deployment scale and price, or utilize electrosynthesis of energy-rich fuels (e.g., power to gas) with low technical maturity, low deployment scale, and low round trip or end use efficiency.

None of the studies take account of the vast capacity for off-river PHES to solve the storage problem while also delivering system services. PV, wind, PHES, and high-voltage transmission have all been deployed at scales above 100 GW and can combine to deliver a reliable 100% renewable electricity system. This is the path that Australia is following.

II. GLOBAL NEW GENERATION CAPACITY

Solar PV and wind together account for more than 60% of annual global net new electricity generation capacity additions (see Fig. 1). Gas, coal, and hydro comprise most of the balance [9]–[15]. Sustained price reductions mean that the PV and wind are competitive with fossil fuel generation in most countries.

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Thus, the PV/wind share of global generation could rapidly increase. PV, in particular, is growing faster than other technologies and is likely to become ever more important in global electricity markets.

China, the European Union, India, the USA, and Japan accounted for three quarters of global new renewable capacity deployment in 2018 [9]. Two-third of coal power stations newly commissioned in 2018 were in China [15]. Together, China and India accounted for more than 80% of the total. Construction of coal power stations has decreased to low levels in OECD countries. Deployment of new hydroelectricity systems is in continuous decline, as the number of undammed rivers diminishes and opposition to new developments increases. Deployment of net new nuclear, bio, geothermal, and solar thermal generation capacity continues at low levels compared with PV and wind. It is difficult to envisage these technologies bridging the large gap to PV and wind represented by current annual deployment rates.

The huge gap in annual deployment rates between PV and wind on the one hand and all other low-emission energy technologies on the other hand means that PV and wind are likely to dominate future energy markets.

III. BALANCING THE GRID

On current trends, PV and wind will make major inroads into energy markets during the 2020s. Legacy fossil fuels coupled with demand management can support and balance an electrical grid with a large proportion of variable PV and wind. However, additional measures to stabilize an electricity grid are required when 30–100% of the electricity is derived from variable PV and wind.

Fortunately, energy balance is relatively straightforward using off-the-shelf techniques that are already widely used. These techniques comprise energy storage, demand management, and strong interconnection over large areas using high-voltage transmission lines. Occasional spillage of energy on sunny/windy days when storages are full is cheaper than providing unlimited storage to avoid spillage. Deployment of both wind and solar can reduce the required storage capacity compared with equivalent capacity in either alone, because wind and solar availability are often countercorrelated.

Continental-scale transmission smooths out the effect of local weather and demand and greatly reduces the required storage [16]. State-of-the-art high-voltage direct current (HVdc) systems transmit 12 GW of electricity over 3000 km at voltages of 1.1 MV, and with losses of around 10% [17]. North–south transmission can assist with seasonal variation of solar energy, while east–west transmission helps to meet peak loads in the evening.

The cost of hourly balancing of the Australian National Electricity Market for 100% renewables has been estimated at about US\$18 per MWh [16]. This comprises additional storage and transmission and includes the cost of occasional spillage of electricity. The cost of hourly balancing is about half the cost of electricity generation from the corresponding wind and PV generators. The amount of storage required was determined to be about 500 GWh [16], corresponding to 1 GW of power per



Fig. 2. Presenzano hydroelectric plant in Italy showing the reservoirs (upper right and lower left). This closed-loop pumped storage system has a head of 500 m, a power capacity of 1 GW, and storage of about 6 GWh (Google Earth image).

million people with 20 h of storage (20 GWh). This is for a large-area electricity grid (1 million km²) with good wind and solar resources in a high-energy-use country. Local analysis is required for any other country. However, there is no reason to think that the above figures would be much different for another industrialized large country or region at low–moderate latitude (where most of the world's population lives).

An alternative rule of thumb is that the approximate amount of storage required for a large-area 100% electricity system based mainly on PV and wind is equal to one day's electricity consumption; in the case of Australia, it is 650 GWh.

IV. PUMPED HYDRO ENERGY STORAGE

By far, the leading energy storage technology is PHES [18], [19], which represents about 97% of global storage power (160 GW) and 99% of stored energy. Batteries are rapidly increasing in importance for short-term storage (subseconds to an hour) and for electric vehicles. A utility-scale battery [20] has a storage capacity of 0.13 GWh. As a comparison, the Snowy 2.0 pumped hydro project [21] under construction in Australia in response to rapid PV and wind deployment has a storage capacity of 350 GWh. The batteries in an electric vehicle fleet represent a very large potential storage.

Most of the existing PHES is associated with hydroelectric projects on rivers. Vigorous social and environmental opposition is sometimes encountered for new hydroelectric projects, and the number of remaining potential sites is reducing as more hydro is built. However, PHES systems can be closed loop and located away from rivers. Since most of the land surface of Earth is not adjacent to a river, a vastly larger number of potential sites are available for off-river PHES compared with river-based PHES.

Off-river PHES typically comprises a pair of artificial reservoirs (each a few square kilometers in area), located close to each other (separated by a few kilometers) but at different altitudes (200–1200 m altitude difference or “head”) and connected by a pipe or tunnel (see Fig. 2). Water is pumped uphill on



Fig. 3. 616 000 potential off-river PHES sites. Detailed zoomable maps and spreadsheets are available [22]. Background: [23].

sunny/windy days, and energy is recovered by allowing the stored water to flow back through the turbine.

The round-trip efficiency (after accounting for pumping, generation, friction, and other losses) is typically 80%. The water oscillates indefinitely between the two reservoirs, with occasional top-ups (to replace evaporation) from rainwater or by artificial means. System lifetime is many decades (with occasional refurbishment).

It is emphasized that off-river PHES utilizes completely standard technology. The significant differences from river-based PHES are that flood control measures (and associated costs) are largely avoided, and heads are generally better (because of far more choice of sites).

V. GLOBAL PUMPED HYDRO ATLAS

A global study by the authors found 616 000 potentially feasible off-river PHES sites with a storage potential of about 23 million GWh, by using geographic information system analysis (see Fig. 3) [22]. Identified sites have an energy storage potential in the range of 2–150 GWh. The latitude range covered in the global survey is between 60 degree north and 56 degree south. Each identified site comprises an upper and lower reservoir pair plus a hypothetical tunnel route between the reservoirs (see Fig. 4).

Urban areas and protected lands (national parks) were excluded from the survey. This survey covers “greenfield” sites. A future survey will cover “brownfield” sites, for which one or both reservoirs exists in the form of an existing reservoir or old mining pit. Unlike for greenfield sites, landform shape and water volume for brownfield sites cannot readily be obtained from satellite data.

Detailed zoomable maps for all of the reservoirs are available, together with spreadsheets containing data such as latitude, longitude, altitude, head, slope, water volume, water area, rock



Fig. 4. Three-dimensional visualization of a Class A off-river pumped hydro site in Southern Australia [22]. Image credit: Data61 hosting and Bing Map background.

volume, dam wall length, water/rock ratio, energy storage potential, and approximate relative cost (classes A–E) [22]. Many of the potential pumped hydro sites may prove to be unsuitable. However, only about 1% of the identified sites are required to support a 100% global renewable electricity grid. Developers and approval authorities can afford to be choosy.

The power capacity of a pumped hydro system can be selected largely independently of the energy storage. For a given reservoir pair, power depends on the cross-sectional area of the water conveyance and the capacity of the power components (pump/turbine, generator, and transmission). Typically, the storage power of an off-river PHES system is selected to exhaust the stored energy in 5–25 h. About 1 million GW of storage power could be accommodated in the vast number of available off-river

pumped hydro sites (assuming storage time at the maximum power output of 23 h per system). This far exceeds requirements for a 100% global renewable electricity system.

The water requirements of a renewable electricity system relying mostly on PV, wind, PHES, and wide-area transmission are substantially less than for a corresponding coal-based system because cooling towers are not needed [24]. Water requirements of a PHES system are the initial fill and replacement of evaporation losses. Evaporation suppressors can reduce losses by 80% or more, tipping the water balance in favor of rainfall in most locations.

For a typical head of 400 m, the energy storage of 1 GWh requires a water storage of approximately 1 GL. Modeling of the Australian electricity system suggests that the energy storage required to support 100% renewable electricity is about 20 GWh per million people [16], equivalent to about 20-kL water storage per person. Assuming that PHES storage is phased in over a 20-year transition period, this amounts to 3 L per person per day for reservoir filling. This is about 0.2% of annual Australian per-capita freshwater abstraction for all purposes and about 10% of the per capita water use of the electricity and gas industries [25].

The environmental impact of off-river pumped hydro can be relatively small [26]. The reservoirs are much smaller (typically 6 ha per GWh) than for a typical river-based system, and the vast number of potential off-river sites means that sensitive areas can be excluded. The area alienated by a PHES system is much smaller than the corresponding solar farm that it supports.

Pumped hydro storage can help make better use of existing transmission. For example, if a solar farm is planned for a region where building more transmission is difficult, then colocation of pumped hydro storage can make the existing transmission work harder by ensuring that it is operating near its load limit for most of the time (including at night).

VI. PUMPED HYDRO AND 100% RENEWABLE ENERGY

About three quarters of global greenhouse gas emissions are associated with the use of coal, oil, and gas [27] with most of the remainder being from the land sector. Electricity production, heating, and land transport cause about half of global emissions. Many studies recognize that conversion of electricity to renewables coupled with electrification of land transport and urban heating can make deep cuts in global emissions using technology that is already in mass production (including electric vehicles and heat pumps). This gives vast scope for deployment of additional PV and wind over the next two decades.

Renewable electrification of industrial processes and aviation (about a quarter of global emissions), either directly or via electrically driven chemical synthesis, is more difficult because there is as yet no mass production of the required infrastructure. However, there are no insuperable technical barriers.

Identification of a vast number of potential pumped hydro storage sites is significant because PHES is the lowest cost bulk storage method and is available off-the-shelf in large scale. PHES mitigates the need for low-efficiency and immature bulk storage techniques such as conversion of PV and wind electricity

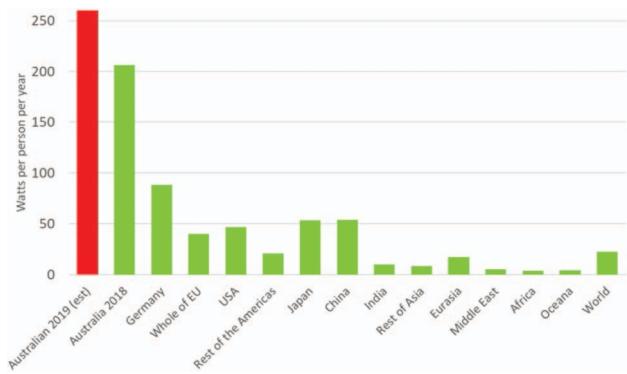


Fig. 5. Annual per capita renewables deployment rate for countries and regions. Data for Australia (2018 and 2019) are from [28], and data for other countries/regions (2018) are from [9].

to synthetic fuel (such as hydrogen, methane, or ammonia). Furthermore, pumped hydro offers system inertia, rapid start (20–200 s), and black start capability, which helps to overcome the void left for such services when coal and gas power stations retire.

When discussing 50–100% renewable electricity and energy, pumped hydro is an off-the-shelf bulk storage solution with a known (and moderate) price. It is not necessary to rely on projections of large future reductions in battery costs or other storage mechanisms. This allows a reliable upper bound to be placed on the cost of balancing 50–100% renewable energy. Further cost reductions in batteries or other technologies are positive upside.

VII. RAPID RENEWABLE ENERGY DEPLOYMENT IN AUSTRALIA

Australia is experiencing a remarkable renewable energy transition that has global significance. The pipeline for new wind and solar PV electricity systems is 6–7 GW per year. This equates to 250 W per person per year compared with about 50 W per person per year for the European Union, Japan, China, and the USA (see Fig. 5). This renewable energy pipeline is fast enough to reach 50% renewable electricity in 2024 and 100% in 2032.

In 2018, Australia (population 25 million) deployed 5.1 GW of PV and wind systems. Data from the Australian Government's Clean Energy Regulator [28] indicate that the ground-mounted PV and wind pipeline for 2019 exceeds 4 GW. Roof-mounted PV is likely to exceed 2 GW in 2019, for a total renewable energy deployment of 6–7 GW. More than 9 GW of roof-mounted solar PV has so far been deployed, which is the largest per capita rooftop-PV deployment in the world. PV and wind comprise nearly 100% of new power stations in Australia.

Developments in Australia have global significance because they demonstrate that rapid deployment of variable PV and wind is feasible in an isolated electricity market in an industrialized nation. Rapid deployment of PV and wind in Australia is taking place even though Australia is the world's largest exporter of both gas and coal.

The price of electricity from large-scale PV and wind farms in Australia is currently US\$35–40 per MWh, and falling. This

is below the cost of electricity from existing gas-fired power stations and is also below the cost of new-build gas and coal power stations. The cost of electricity from PV and wind is already similar to the cost of fueling and maintaining much of the black coal fleet. Premature retirement of many existing black coal power stations is likely during the 2020s, enlarging the market for PV and wind.

In response to rapid deployment of PV and wind, about a dozen new pumped hydro systems are being considered, including about 3 GW that is approved or is under construction [26] in an electricity system with a peak demand of 36 GW. Some utilize existing reservoirs [21], and others are located away from any significant river, for example [29]–[31].

Gigawatt-scale transmission and large battery systems are being planned and constructed. Continued development of storage and transmission is critical to continuation of the large Australian PV and wind pipeline.

Greenhouse gas emissions in the Australian electricity sector are declining rapidly as wind and PV displace coal generation [32]. Future increases in emissions outside the electricity system are likely to be smaller than decreases within the electricity sector, leading to an expected overall decrease in emissions. If wind and PV deployment rates remain at current levels, then this decrease could be fast enough to reach Australia's entire Paris greenhouse emissions reduction target in the late 2020s.

VIII. DEVELOPING COUNTRIES

If developing countries follow a fossil fuel intensive pathway, then very serious damage will be done to Earth's climate. On the other hand, following a renewables pathway in conjunction with ending land clearing decouples economic development from climate damage.

About three quarters of the world's population lives in the sunbelt ($\pm 35^\circ$ of latitude) [33], where most of the world's developing countries are located and where the fastest growth in population, emissions, and energy consumption is occurring. There are no cold winters, and heating loads are small. Space cooling requirements are generally well correlated with solar availability. This region has ample sunshine and low seasonal variation of both demand and solar insolation. There is low requirement for (expensive) seasonal storage, and there are vast numbers of excellent sites for off-river pumped hydro storage. Most countries are within a thousand kilometers of regions with excellent wind resources, which allows HVdc connection and gives access to potential countercorrelation of solar and wind.

Australia is experiencing rapid greenhouse emission reductions in its electricity sector at low net cost through renewable electrification via variable PV and wind. Sunbelt countries are more like Australia rather than the developed countries in Europe or North America or Northeast Asia. The sunbelt countries can transition rapidly to renewables with consequent large avoidance of future greenhouse emissions. Table I illustrates this theme by listing a variety of characteristics that influence the uptake of PV and wind, together with generalized categorization of sunbelt countries, Australia, and northern countries.

TABLE I
FACTORS THAT INFLUENCE RENEWABLE ENERGY UPTAKE

	Sunbelt	Australia	The north
Latitude	Low	Low	High
Solar resource	High	High	Low-moderate
Seasonality of solar	Low	Low	High
Access to wind	Moderate	High	High
Heating load	Low	Low	High
Need for seasonal storage	Low	Low	High
Pumped hydro site count	High	High	High
Wealth & technology	Low-Moderate	High	High
Current fossil fuel capacity	Low	High	High

IX. CONCLUSION

Sustained large-scale deployment of PV and wind coupled with electrification of most energy functions means that paths to 100% renewable electricity, 100% renewable energy, and zero energy-related emissions may converge. Large-scale deployment of storage and transmission is required for grid stability.

This article has described a pathway to 100% renewable electricity (and, at a later date, 100% renewable energy) that relies only on technologies deployed at scale larger than 100 GW, namely, PV, wind, PHES, and HVdc.

Off-river PHES is available in most places at a scale that is two orders of magnitude larger than required to support 100% renewable electricity. Effectively unlimited storage power can be attached to such systems.

Australia is a global pathfinder because its annual deployment rate of PV and wind is four to five times larger per capita than the EU, the USA, China, or Japan. In response to rapid deployment of PV and wind, Australia is following the pathway described in this article, with deployment of new gigawatt-scale pumped hydro storage and transmission, and also multiple large batteries.

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