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Energy Economics and the Potential for Net Zero

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ENERGY ECONOMICS AND THE POTENTIAL FOR NET ZERO

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ABSTRACT

Countries in Europe and the Anglosphere have committed to eliminate carbon dioxide (CO_2) emissions from fossil fuel burning and offset any remaining greenhouse gas emissions by 2050; this is termed Net Zero. China and India have announced they will follow by 2060 and 2070, respectively, with some other countries having made similar commitments. The focus of Net Zero has been the electricity sector because power can be generated from any energy source, particularly renewable wind and solar. Electricity can be used for mobility via battery-driven vehicles or to make hydrogen fuel from water (H_2O) through electrolysis. This paper examines the potential for relying on wind and solar to replace fossil fuels in the production of electricity, given that nuclear energy is ruled out. Using real world examples and information from grid modelling exercises, we conclude that Net Zero is economically and physically unattainable without lowering living standards to where they were at least 150 years ago.

Key words: intermittent renewable energy; grid unreliability and blackouts

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1. INTRODUCTION

Many countries have pledged to reduce their greenhouse gas emissions and eliminate carbon dioxide (CO_2) emissions from fossil fuel burning by 2050, offsetting any remaining greenhouse gas emissions at that time through forest sinks and/or carbon capture and storage—both of which are expensive and remain untried at a large scale [International Energy Agency 2021; Brouwer and Bergkamp 2021]. This target is referred to as 'Net Zero'.

Climate change policies have focused on different sectors of the economy, but foremost of all on the electricity sector. Electricity accounts for only about 15% of the primary energy consumed globally.[1] Yet, the sector has been targeted because power can be generated from a large variety of energy sources, including fossil fuels, hydraulics, wind, solar, biomass, geothermal, tides and nuclear. Current policies of most countries require the phase-out of coal-fired power by as early as 2030, because coal releases more CO_2 to the atmosphere per unit of heat generated than any other energy source, except perhaps biomass.[2] Yet, China, India, Russia and most developing countries are ramping up coal capacity and production because coal is less expensive, ubiquitous and often domestically available, and more reliable than wind and solar sources of energy, which are currently considered to be the main replacement for coal. However, replacing coal-fired power plants with intermittent renewable energy sources, such as wind and solar, would impose significant economic costs, while only making modest reductions in greenhouse gas emissions.

Consider recent electricity blackouts experienced in the United Kingdom, California and Texas—jurisdictions that have all significantly increased their reliance on renewable energy in

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[1] In 2019, 25,900 TWh of electricity was generated, while primary energy consumption totaled 173,340 TWh (https://ourworldindata.org/energy-production-consumption).

[2] Biomass is assumed to be carbon neutral, because growing trees will eventually remove all of the CO_2 released at the time of burning. However, if there is some urgency to mitigate climate change, biomass energy should be avoided even more so than coal [van Kooten et al. 2021].

recent years. While several factors affect the reliability (and affordability) of power systems, renewable energy is largely to blame. Why? Because the wind doesn't always blow and the sun doesn't always shine—and the energy from these sources cannot be stored at adequate levels.

Unreliable wind and solar generating sources require conventional back-up power, which is generally provided by natural gas. The introduction of intermittent renewable energy sources into electricity systems stymies investment in reliable conventional fossil-fuel or hydroelectric capacity, thus exposing power networks to occasional imbalances between demand and supply that can only be covered by having sufficient fast-responding generation (normally gas plants) available when renewable sources of power are inadequate due to low wind speeds and/or too much cloudiness. This is largely what happened in the recent blackouts—electricity from renewable sources fell while there was insufficient fast-responding backup generation to cover the loss. The UK, California and Texas cases are briefly discussed in the next section.

Proponents of wind and solar energy have argued that the costs of these energy sources has come down to such an extent that society should transition to them as fast as possible. In a sense, they are correct: the levelized cost of energy (LCOE) for wind and solar sources of energy have fallen by some 70% and 90%, respectively, over the past decade [Lazard 2020]. Even on a marginal cost basis, it appears that solar and wind energy are competitive with fossil fuels. However, certain costs related to the intermittent nature of energy are ignored, which makes wind and solar less attractive as an alternative source of energy. These issues are discussed in section 3.

2. THE PROBLEM OF INTERMITTENCY: ILLUSTRATIONS

Various models of electricity grids have demonstrated how difficult and costly it would be to replace fossil-fuel generated power with power from intermittent wind and solar sources [e.g., Brouwer and Bergkamp 2021; van Kooten et al. 2020; Hughes 2020a, 2020b; van Kooten and

Mokhtarzadeh 2019; van Kooten 2017]. Models indicate that, while some wind and solar energy can easily be integrated into existing electricity grids, at high degrees of penetration renewable sources will create the types of problems experienced by the UK, California and Texas.

United Kingdom

The UK has gone further than other jurisdictions in its reliance on renewable sources for producing electricity. However, the power provided by intermittent renewable sources has fluctuated to such an extent that it has contributed to an energy crisis. In 2021, UK wind output peaked at 17,600 MW on May 4, but fell to only 409 MW on September 6, with the difference of over 17,000 MW representing the electricity that would normally be produced by some twenty large coal- or gas-fired power plants. Fossil-fuel plants have essentially been shuttered, with the required backup power sourced along transmission interties with Ireland and the Continent. When the Irish interconnect could not deliver, prices skyrocketed and blackouts occurred.

With wind regimes much lower than those experienced in the past decade, the UK was forced to reopen some of its shuttered fossil-fuel plants. However, with natural gas prices having nearly quadrupled since the beginning of the year, coal was a much cheaper option, even with coal providers having to pay more than \$100/tCO$_2$ (€75/tCO$_2$) for carbon offset permits. The cost of power rose, hitting £2300/MWh (\$3067/MWh) on September 9, 2021—the wholesale price rose to nearly 32 euro cents per kWh [Mellor 2021]. Critically low wind power in the first few days of November led to extremely high wholesale prices, with coal and other fossil fuel assets receiving some £4,000/MWh (\$5333/MWh), nearly 100 times the normal wholesale price, for three hours early on November 3. The daily cost of balancing the grid hit £44.7 million (\$59.6 million) on November 3, more than 20 times the normal cost, smashing a previous record by a margin of £6 million (\$8 million)—and then it hit £63.0 million (\$84.0 million) on November 4 [Constable

2021; ; NetZero Watch 2021]. The annual cost of the UK's Balancing Mechanism was £1.8 billion ($2.4 billion) in 2020/21, and expected to rise in 2021/22. Of course, these costs are borne by ratepayers.

California

The share of renewables in California's electricity grid has been increasing more rapidly than elsewhere in the U.S., although the actual share of renewable generation in some states exceeds that in California (see Appendix Table A1). In August 2020, California suffered a heat wave that resulted in blackouts as there was insufficient generation available to meet the load [Singh 2021]. For much of a week, there was a shortfall of some 4,400 megawatts of power. At one point the system lost 470 MW of capacity due to an unexpected plant shutdown and a downfall of 1,000 MW of energy from wind turbines due to less wind. However, the loss of solar power when the sun went down likely had the greatest impact—the loss in available electricity occurred as demand for cooling increased precipitously during the hottest part of the day and into the evening. Because surrounding states were also experiencing the same heat wave, no electricity was available across transmission interties. California's grid operator planned for power outages again in 2021 as wildfires threatened transmission lines between Oregon and northern California and another heat wave was underway [Baker et al. 2021].

In response to these developments, the grid operator delayed the retirement of several gas plants, encouraged people to conserve by implementing a higher temperature setting for air conditioning units, incentivized the import of more power during peak-demand periods, and encouraged power companies to install utility-scale batteries to store solar power to supply the grid in the evening and at night. It is assumed that these steps will boost available electricity by some 2,000 MW—the capacity of two coal plants or two nuclear reactors [Baker et al. 2021]. At the same time, the state is planning to shut down the 2,200 MW capacity Diablo Canyon nuclear power plant beginning in 2024, thereby ending reliance on nuclear energy. Legislation in the form of Senate Bill No. 1090 (passed September 19, 2018[3]) prevents the system operator from replacing power from Diablo Canyon with electricity from any source that would increase CO_2 emissions—no fossil fuel power can replace the lost nuclear energy.

As Germany and Denmark increased their reliance on wind and solar power, electricity prices have more than doubled so that their prices are the highest in the EU at €0.29/kWh ($0.39/kWh) and €0.31/kWh ($0.41/kWh), respectively, in 2018.[4] Likewise, "in California, with its increasing share of new renewables, electricity prices have been rising five times faster than the national mean" [Smil 2020, p.175], and are now 43 percent higher than the countrywide average (see Table A1).

Texas

In February 2021, a severe winter storm hit Texas resulting in major blackouts that lasted upwards of several weeks in some areas.[5] Several factors contributed to the problem. One was the loss of wind power caused by ice on turbine blades, along with solar power lost due to snow and ice on solar panels. These failures were exacerbated by a reduction in natural gas availability[6] and an inability to access electricity from other jurisdictions—transmission interties between the ERCOT grid and other grids are essentially non-existent. At times the wholesale price of electricity spiked to the system's price ceiling of $9,000/MWh, compared to a typical price of $50/MWh (5¢/kWh),

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[3] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB1090.

[4] In 2020/2021, only Hawaii had electricity prices that exceeded 30¢/kWh, with only three other states (Alaska, Connecticut and Massachusetts) with prices slightly above 20¢/kWh (see Table A1).

[5] See Wikipedia at https://en.wikipedia.org/wiki/2021_Texas_power_crisis [accessed November 3, 2021].

[6] An unverified story suggests that the Energy Reliability Council of Texas (ERCOT) asked previously-designated large power users to halt operations in an effort to reduce load at the time of the crisis. These included gas providers with the result that there was insufficient gas to run backup gas generators.

resulting in huge profits for owners of some generating assets.

The woes experienced by jurisdictions that replaced conventional power sources with wind and solar were predictable. Using information about the Alberta electricity grid, which is characterized by reliance on coal and gas with significant penetration of wind, van Kooten [2021] and van Kooten et al. [2020] demonstrated that it would be impossible for Alberta to produce all of its power requirements using renewable sources only. This would be the case even if storage was to be included in the mix of assets available to the system—even a perfect storage device would need to be too large and expensive to warrant construction. Indeed, as discussed in the next section, it would be necessary to add significant gas plant capacity to eliminate coal-fired power in the Alberta system even if adequate wind, solar and storage capacity were developed. One can only conclude that the intermittency of renewables, such as wind power, has come into particular focus in Europe and the United States in late 2021 as some of the slowest wind speeds in decades have exacerbated reliance on gas and even coal for electricity.

3. ECONOMIC COSTS OF TRANSITIONING TO NET ZERO

The shibboleth promoted by the environmental movement is that an electricity system based on renewable sources of energy will reduce overall generation costs, thereby benefitting ratepayers with lower prices. This is a fallacy as indicated by the real world examples provided in the preceding section. The case for lower costs is based on trends in the prices of various components comprising renewable engines—the costs of components used to make wind turbines and the cost of solar photovoltaic (PV) panels.[7] Essentially, it is based on cost studies that estimate the levelized cost of energy (LCOE)—the life-cycle cost of producing a kilowatt hour (kWh) of electricity.

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[7] The cost of PV panels has fallen from around $300 per watt (W) in the 1950s to $80/W in the 1970s, $10/W in the late 1980s, $1/W in 2011, and some $0.0–$012/W most recently [Smil 2020, p.154].

Cost of Electricity

Some notion of the life-cycle costs of electricity is provided in Table 1, which employs data from the financial advisory and asset management firm Lazard (www.lazard.com). Lazard data on electricity costs are considered the best available. The LCOE data in Table 1 strongly suggest that onshore wind and solar PV are now the least costly energy sources for generating electricity—the respective costs of producing wind and solar power fell by 70% and 90% over the past decade. When the marginal cost of energy is considered, however, the costs of fossil fuel and nuclear power generation are much closer to, and in some cases lie below, those of wind and solar generation. From a financial and asset management point of view, it appears that investing in wind and solar projects might make sense. Before concluding that this is the case, we examine this issue in greater detail.

Table 1: Unsubsidized Levelized Cost of Energy (LCOE), Change in Costs, and Marginal Cost of Electricity, 2020

Asset Type	LCOE ($/MWh)[a]	Change in LCOE 2009-2020 (%)[c]	Marginal cost of energy ($/MWh)[c]
Nuclear	$143–$200	+33%	$25–$32
Peak-gas (OCGT)	$113–$198	–36%	n.a.
CCGT (gas)	$53–$63	–29%	$23–$32
Coal	$82–$134	+1%	$34–$48
Wind (onshore)	$34–$45	–70%	$26–$54
Solar thermal	$103–$172	–16%	n.a.
Solar PV	$28–$44	–90%	$29–$38
Storage[b]	$165–$305	n.a.	n.a.

[a] Includes costs of decommissioning fossil fuel plants and disposal of nuclear waste
[b] Lithium-ion battery with capacity of 100MW and energy storage of 400MWh.
[c] n.a. = not available
Source: Lazard [2020] except storage, which is available from Lazard [2019].

The LCOE is based on a variety of assumptions, including fuel costs, asset lifespans, interest rates, rates of return on assets, and, importantly, assumed capacity factors (CF). The CF is defined as the electricity produced over some period, measured in energy terms (MWh), divided by the potential electricity that could be produced over the same period, which is calculated by multiplying the asset's capacity by the number of hours in the period under consideration (say, 8760 hours for a year). For example, suppose a wind farm has a capacity of 10 MW so it has the potential to produce 87,600 MWh (=10MW × 8760 hours) of energy annually under perfect wind conditions; if it actually generates 16,381 MWh of power over the year, its CF equals 18.7% (=16,381/87,600). Onshore wind assets rarely achieve CFs exceeding 30% over a period as long as a year, with most yielding CFs around 20 to 25 percent or much less; offshore wind assets achieve higher CFs, but they are also more costly to build and maintain, and their lifespans are generally shorter than those onshore. In comparison, coal-fired plants generally operate with CFs exceeding 80% while the CFs of nuclear assets now exceed 90%. Higher CFs imply lower costs.

While CFs are important, they tell us nothing about the timing of wind or solar output. Recall that California suffered blackouts when air conditioning requirements peaked as the sun went down and, as a result, not enough electricity was available to meet demand. Likewise, wind output is often lower during peak hours (early morning or late afternoon/early evening), but higher at night when demand is low. While storage devices could help in these situations, the LCOE for storage systems is higher than the LCOE associated with the generation of power from fossil fuels, especially peak gas (OCGT).[8] Storage is discussed further below in the context of energy density.

There are several other problems that LCOE data ignore. First, the lifespans of utility-level wind turbines and solar PV units are some 20 to perhaps 30 years, compared to 40 to 80 years for coal, nuclear and gas facilities. Decommissioning costs of thermal power plants, and disposal of nuclear wastes, are taken into account in calculating LCOE, but the costs of cutting up and burying

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[8] A peak gas asset constitutes an open-cycle gas turbine (OCGT)—power output increases when you open the throttle and falls as you close it. A baseload combined-cycle gas turbine (CCGT) operates much like an OCGT, except it uses the exhaust heat to heat a boiler that produces additional electricity. Because it is difficult and expensive to change the boiler's pressure quickly, CCGT units cannot ramp quickly enough to track changes in wind or solar output. To do so, requires energy from a storage device or an OCGT asset.

wind turbine blades are not taken into account. Nor are issues related to the disposal of toxic wastes associated with wind turbine components and, in particular, solar panel waste, which is considered to be 300 times more hazardous per unit of energy than nuclear waste [Atasu et al. 2021; Institute for Energy Research 2017].

Second, intermittency imposes costs on other assets in the system. Because wind and solar power are 'must-run'—the output must be taken by the system—and the power cannot be dispatched as needed, other assets in the system must change their output so as to track changes in wind or solar output in addition to changes in load. This is not a problem if OCGT assets are affected, nor is it a problem if a hydroelectric facility can rapidly adjust output.[9] In many cases, however, intermittency affects baseload power plants which do not easily ramp up and down and, when forced to do so, adds greatly to operating and maintenance costs. Further, baseload facilities might be forced to operate below their optimal capacity, which increases costs per unit of electricity that is produced.

Third, many electricity systems operate an energy market only. Investment in OCGT assets that are needed to backstop intermittent wind energy will occur only if they are able to recover their fixed costs. As more wind capacity enters a grid, the wholesale price of electricity is reduced and OCGT plants are called upon less often. Unless the OCGT unit can earn enough surplus through much higher prices during the reduced hours that it is called upon, the gas plant will eventually close and not be replaced. This 'missing money' problem can be resolved by operating a capacity market in addition to the energy market. In that case, the system operator will pay the lowest bidder to construct required backstop capacity. Of course, the costs result in higher retail prices.

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[9] A hydro facility with a reservoir constitutes a passive storage device, while pumped hydro is an example of active storage; the latter tends to have a poor return in terms of energy output relative to energy input.

In addition to these major costs, there are other costs that will vary greatly across a landscape. Some have been taken into account in the LCOE, but many have not. Land costs are often ignored, although they are likely small. For example, the annual return on farmland in southern Alberta averages some $478 per acre [Liu et al. 2020, p.808], while one acre can support a solar facility with a maximum capacity of 7.9 MW [Ong et al. 2013]. Given an average CF of 33%, the added cost amounts to just over $0.02/MWh—an insignificant amount. Likewise, because wind and solar facilities are not always located near main transmission lines, additional transmission infrastructure needs to be built. This cost is ignored in LCOE studies because it varies greatly among sites and may be relatively small.

More importantly, however, citizens increasingly oppose the location of wind and solar facilities and transmission lines; dealing with citizen opposition and re-siting wind and solar developments and transmission lines can significantly increase overall costs [Bryce 2021]. Likewise, environmental costs related to human health, and bird and bat strikes, can be a major downside of wind and solar energy [Peiser 2019].

Although policymakers consider storage as the answer to the intermittency problem, modeling efforts by Duan et al. [2020] and van Kooten and Mokhtarzadeh [2019] suggest otherwise. The required battery would simply need to be too large and expensive. These researchers also found that, even if a 'reasonable' storage device was forced on the system, it was baseload coal, gas or nuclear (if allowed) assets that would take advantage, outcompeting wind for access to the storage device.[10]

Finally, van Kooten and Mokhtarzadeh [2019] concluded that "when wind and/or solar

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[10] The reason is that baseload plants would expand, submitting power to the battery when output exceeded load and withdrawing power from the battery when load exceeded generation—that is, when price was highest. Baseload assets could operate without encountering any ramping costs.

energy enters the Alberta electricity grid, the maximum emissions reduction that can be achieved is about 56%, but, when nuclear power is permitted, emissions could be reduced by as much as 97%." Given that nuclear power plants take time to build, it would seem that an energy transition away from fossil fuels will require greater reliance on natural gas in the short term while allowing investment in nuclear power plants to take place [Prins 2021]. Even then, attaining Net Zero is unlikely to be realized at any time in the near future.

Energy Densities

There remains a powerful argument in favour of fossil fuels. Renewable sources of energy are simply too sparse in terms of energy per unit of mass, with too large a physical footprint when it comes to land use. Consider both energy density and land requirements.

Currently, pumped storage is considered to be the best available utility-grade storage option, accounting for more than 99% of the world's storage capacity even though it entails an energy loss of about 25% [Smil 2020, p.165]. Batteries are a poor alternative because of their low energy density. Low-quality residual oil or diesel has an energy density of 11,700 watt-hours per kilogram (Wh/kg), while gasoline has an energy density of 12,000 Wh/kg, coal and ethanol have densities around 8,000 Wh/kg, and oven-dried hardwood (burned to produce electricity) has an energy density of 4,500 Wh/kg [Bryce 2010, p.191]. In contrast, lithium-ion (Li-ion) batteries have an energy density of only 300 Wh/kg, which is why electric vehicles require a Li-ion battery that weighs 500 kg [Smil 2020, p.169].

Land use is also an important consideration when it comes to energy production. If land is used to produce trees as biomass for generating electricity, the cost is the forgone opportunity to grow food crops or energy crops. When land is used to produce energy crops, less land is allocated to food crops. This causes prices of food to rise, which, in turn, incentivizes converting marginal land that might be growing trees into cropland. Likewise, wind turbines and solar panels require the conversion of land from its original use in agriculture or forestry or some other use to the production of energy.[11]

Table 2 provides some notion of the tradeoffs when it comes to land use. Clearly, nuclear power is the least land intensive use, followed by a natural gas well. One must add to the gas well the footprint of a CCGT or OCGT plant, which turns out to be smaller than the footprint associated with a nuclear power plant. The most extensive use of land for energy is cropland that grows corn for ethanol or soybeans for biodiesel. Currently, some 51.5 million acres of the 81.0 million acres of land that the U.S. uses to produce renewable electricity is allocated to corn and soybeans; 6.7 million acres are covered by wind turbines; solar PV panels cover some 0.5 million acres; 4.8 million acres are allocated to transmission lines and their rights of way; but only 0.6 million acres are allocated to the production of coal-fired power [Merrill 2021]. Yet, electricity accounts for less than 17% of total primary energy consumption in the United States.

Table 2: Land-use Intensities by Energy Source, W/m^2

Energy Type	Energy Density (W/m^2)
Corn Ethanol	0.1
U.S. gas well	53.0
Biomass-fueled power plant	0.4
Wind	1.2
Solar PV	6.7
Nuclear power plant	56.0
Oil stripper well (10 bbls per day)	27.0
Oil stripper well (2 bbls per day)	5.5
Gas stripper well	28.0

[a] An oil stripper well is defined as producing less than 10 barrels (bbl) per day; a gas stripper well produces less than 60,000 cubic feet of natural gas per day.
Source: Bryce [2010, pp.86, 93]

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[11] Even the conversion of desert to solar PV panels has an opportunity cost. Extensive livestock grazing often occurs on lands considered to be desert or uninhabitable. Such lands might also support significant biodiversity.

If the U.S. were to rely on wind and solar power to provide 98% of its electric power needs by 2050, the energy footprint would need to quadruple, with wind farms occupying a land area equivalent to the combined area of Arkansas, Iowa, Kansas, Missouri, Nebraska and Oklahoma [Merrill 2020]. For the U.S. to eliminate fossil fuels entirely will pose an especially difficult challenge. Even if enough wind and solar facilities can be sited on lands that are currently considered marginal, and if sufficient modes by which energy is consumed can be electrified (which is an enormous challenge), the construction of the required transmission lines might be the greatest obstacle to overcome [Bryce 2021; Merrill 2020].

4. CONCLUDING DISCUSSION

Energy transitions take an inordinate amount of time [Smil 2017, 2020, pp.174-177]. If we consider the importance of fossil fuels—oil, natural gas and coal—in the globe's consumption of primary energy, we find that, over the past two decades, fossil fuel consumption declined from 86.0% of total energy consumption to 83.4%, despite great efforts on the part of rich countries to reduce dependence on fossil fuels. Indeed, consumption of fossil fuels increased by more than 337% since 1965 and by 145% since 2000, although the relative contribution of fossil fuels to the energy mix has declined.

As seen in Figure 1, the greatest reduction in our relative reliance on fossil fuels occurred between 1970 and 1995, prior to the implementation of specific policies to reduce CO_2 emissions. A further but smaller decline occurred since 2007. Given fossil fuels as a proportion of total energy consumption fell by only ten percentage points in 55 years, it is unlikely that, despite the IPCC's annual climate conferences, fossil fuels will decline below 50% of primary energy consumption in the next several decades.

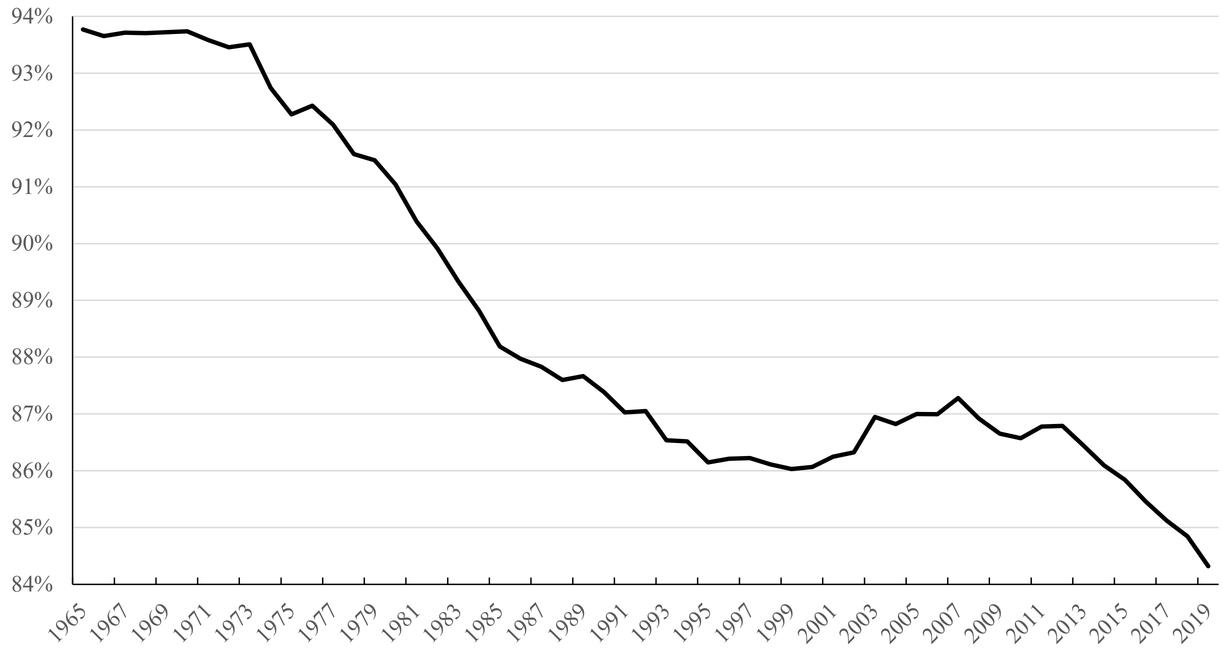

Figure 1: Global Reliance on Fossil Fuels, 1965–2019, Percent

As Vaclav Smil [2019] pointed out, "complete decarbonization of the global energy supply will be an extremely challenging undertaking of an unprecedented scale and complexity that will not be accomplished—even in the case of sustained, dedicated and extraordinarily costly commitment—in a matter of a few decades." Yet, politicians continue to pursue policies that are costly and might even threaten our way of life. It is important that they heed the advice of John Constable [2021]: "It is perfectly rational to have a decarbonisation policy, but the decarbonisation policy itself must be rational."

5. REFERENCES

Atasu, A., S. Duran and L.N. van Wassenhove, 2021. The Dark Side of Solar Power, *Harvard Business Review*, June 18. At https://hbr.org/2021/06/the-dark-side-of-solar-power [accessed November 4, 2021].

Baker, D.R., W. Wade and M. Chediak, 2021. California Orders Grid Emergency, Power Shortfalls Loom, *Bloomberg*. July 9. At https://www.bloomberg.com/news/articles/2021-07-10/california-orders-stage-2-grid-emergency-power-shortfalls-loom [accessed November 3, 2021].

Brouwer, K.M. and L. Bergkamp (eds), 2021. *Road to EU Climate Neutrality by 2050. Spatial Requirements of Wind/Solar and Nuclear Energy and Their Respective Costs*. 456pp. Brussels: ECR Group and Renew Europe, European Parliament. At https://roadtoclimateneutrality.eu/Energy_Study_Full.pdf [accessed February 18, 2021].

Bryce, R., 2021. *Not in Our Backyard.* A Report for the Center for the American Experiment. April 21. 48pp. Golden Valley, MN: Center for the American Experiment. https://www.americanexperiment.org/reports/not-in-our-backyard [accessed November 4, 2021].

Bryce, Robert, 2010. *Power Hungry. The Myths of 'Green' Energy and the Real Fuels of the Future*. New York, NY: Public Affairs.

Constable, J., 2021. Coal keeps lights on at COP26 as low wind strikes again, Energy News Blog online, NetZero Watch. November 3. https://www.netzerowatch.com/coal-keeps-lights-on-at-cop26-as-low-wind-strikes-again/?mc_cid=47f9a65a48&mc_eid=3e8db95649 [accessed November 3, 2021].

Duan, J., G.C. van Kooten and X. Liu, 2020. Renewable Electricity Grids, Battery Storage and Missing Money, *Resources, Conservation & Recycling* 161: 105001. https://doi.org/10.1016/j.resconrec.2020.105001.

Hughes, G., 2020a. Wind Power Economics Rhetoric & Reality. Volume I. Wind Power Costs in the United Kingdom. Renewable Energy Foundation. 62pp. At https://www.ref.org.uk/Files/performance-wind-power-uk.pdf [accessed November 3, 2021].

Hughes, G., 2020b. Wind Power Economics Rhetoric & Reality. Volume II. The Performance of Wind Power in Denmark. Renewable Energy Foundation. 76pp. At https://www.ref.org.uk/Files/performance-wind-power-dk.pdf [accessed November 3, 2021].

Institute for Energy Research, 2017. Will Solar Power Be at Fault for the Next Environmental Crisis? August 15. At https://www.instituteforenergyresearch.org/uncategorized/will-solar-power-fault-next-environmental-crisis/ [accessed November 4, 2021].

International Energy Agency, 2021. Net Zero by 2050. A Roadmap for the Global Energy Sector. IEA Special Report. 224pp. Paris: IEA. https://www.iea.org/reports/net-zero-by-2050 [accessed October 15, 2021].

Lazard, 2020. Levelized Cost of Energy Analysis—Version 14.0. October. At https://www.lazard.com/media/451419/lazards-levelized-cost-of-energy-version-140.pdf [accessed November 3, 2021].

Lazard, 2019. Lazard's Levelized Cost of Storage Analysis—Version 5.0. November. 47pp. At https://www.lazard.com/media/451087/lazards-levelized-cost-of-storage-version-50-vf.pdf [accessed November 3, 2021].

Liu, X., J. Duan and G.C. van Kooten, 2020. Calibration of Agricultural Risk Programming Models Using Positive Mathematical Programming, *Australian Journal of Agricultural and Resource Economics* 64:795-817.

Mellor, Sophie, 2021. Europe's ambitious net-zero pledges hit home—with eye-watering energy bills, *Fortune* Online 10-September. At https://fortune.com/2021/09/10/europe-net-zero-energy-bills-nord-stream-2-russia/?mc_cid=4ca9f7e579&mc_eid=3e8db95649 [accessed September 14, 2021].

Merrill, D., 2021. The U.S. Will Need a Lot of Land for a Zero-Carbon Economy. Bloomberg Green. June 3. At https://www.bloomberg.com/graphics/2021-energy-land-use-economy/ [accessed December 3, 2021].

NetZero Watch, 2021. Britons face record bill as wind farms perform poorly again. Press Release. November 25. At https://www.netzerowatch.com/britons-face-record-bill-as-wind-farms-perform-poorly-again/ [accessed November 29, 2021].

Ong, S., C. Campbell, P. Denholm, R. Margolis and G. Heath, 2013. Land-Use Requirements for Solar Power Plants in the United States. Technical Report NREL/TP-6A20-56290. 47pp. At https://www.nrel.gov/docs/fy13osti/56290.pdf [accessed November 5, 2021].

Peiser, B. (ed.), 2019. *The Impact of Wind Energy on Wildlife and the Environment. Papers from the Berlin Seminar*. GWPF Report 35. 50pp. London: Global Warming Policy Foundation.

Prins, Gwythian, 2021. *The Worm in the Rose*. October. London: NetZero Watch. https://www.netzerowatch.com/the-worm-in-the-rose/ [accessed November 5, 2021].

Singh, M., 2021. 'California and Texas are warnings': blackouts show US deeply unprepared for the climate crisis, The Guardian online. February 19. At https://www.theguardian.com/environment/2021/feb/19/power-outages-texas-california-climate-crisis [accessed November 3, 2021].

Smil, Vaclav, 2020. *Numbers Don't Lie*. New York, NY: Penguin Books.

Smil, V., 2019. What we need to know about the pace of decarbonisation, *Substantia* 3(2) Suppl. 2: 69-73. doi: 10.13128/Substantia-700.

Smil, Vaclav, 2017. *Energy and Civilization. A History*. Cambridge, MA: MIT Press.

van Kooten, G.C., 2021. Canadian Climate Policy and its Implications for Electricity Grids. Vancouver, BC: Fraser Institute. October 21. 50pp. At https://www.fraserinstitute.org/studies/canadian-climate-policy-and-its-implications-for-electricity-grids [accessed November 4, 2021].

van Kooten, G.C., 2017. California Dreaming: The Economics of Renewable Energy, *Canadian Journal of Agricultural Economics* 65(1): 19-41.

van Kooten, G.C. and F. Mokhtarzadeh, 2019. Optimal Investment in Electric Generating Capacity under Climate Policy, *Journal of Environmental Management* 232: 66-72.

van Kooten, G.C., P. Withey and C.M.T. Johnston, 2021. Climate Urgency and the Timing of Carbon Fluxes, *Biomass and Bioenergy* 151: 106162. https://doi.org/10.1016/j.biombioe.2021.106162.

van Kooten, G.C., P. Withey and J. Duan, 2020. How big a Battery? *Renewable Energy* 146: 196-204.

6. APPENDIX

Table A1: State Electricity Prices and Fuel Share of Renewables in Electricity Generation[a]

	Electricity Prices (¢/kWh)		Renewable Generation Share (%)	
State	Dec-21	Dec-20	Wind & solar	All renewables
Alabama	12.41	12.79	0.3	11.6
Alaska	**22.54**	**22.14**	2.8	**33.9**
Arizona	13.16	12.65	6.1	12.2
Arkansas	9.99	10.73	0.5	10.5
California	**19.90**	**19.39**	**22.7**	**43.2**
Colorado	12.28	12.75	**26.3**	**30.0**
Connecticut	**21.62**	**20.47**	0.6	4.9
DC	13.21	13.40	1.3	2.5
Delaware	12.05	12.59	8.8	**35.2**
Florida	11.37	12.02	2.6	5.5
Georgia	12.26	12.53	3.3	11.4
Hawaii	**32.76**	**30.45**	**11.9**	21.4
Idaho	10.58	11.42	**17.1**	**79.2**
Illinois	12.56	12.95	10.0	10.5
Indiana	12.02	12.05	7.8	9.2
Iowa	13.81	13.92	**57.5**	**59.3**
Kansas	11.56	13.56	**43.4**	**43.6**
Kentucky	10.56	10.68	0.1	8.1
Louisiana	9.37	10.19	0.1	4.0
Maine	**16.16**	**16.17**	**24.3**	**82.1**
Maryland	13.92	14.22	3.2	9.7
Massachusetts	**21.11**	**18.56**	10.0	23.7
Michigan	**16.07**	**15.86**	6.6	9.7
Minnesota	**14.09**	**13.96**	**24.7**	**29.4**
Mississippi	11.55	11.40	0.7	2.8
Missouri	13.23	13.25	4.8	8.0
Montana	11.85	11.73	**12.7**	**60.4**
Nebraska	11.31	12.06	**23.8**	**28.0**
Nevada	11.67	11.64	**13.8**	**29.0**
New Hampshire	**19.63**	**19.30**	3.1	18.1
New Jersey	**15.64**	**15.96**	2.6	4.6

Table xx: State Electricity Prices and Fuel Shares of Renewables in Electricity Generation[a] (cont)

	Electricity Price (¢/kWh)		Renewable Generation Share (%)	
State	Dec-21	Dec-20	Wind & solar	All renewables
New Mexico	13.37	13.41	**25.8**	**26.6**
New York	**19.30**	**18.76**	4.6	**30.5**
North Carolina	11.24	11.07	7.6	15.3
North Dakota	12.07	12.34	**30.8**	**39.0**
Ohio	12.64	12.67	2.1	3.0
Oklahoma	10.72	10.53	**35.5**	**40.5**
Oregon	11.02	10.97	**14.9**	**68.6**
Pennsylvania	**14.38**	**14.52**	1.8	4.3
Rhode Island	**18.64**	**16.65**	5.5	8.1
South Carolina	12.91	13.07	1.8	6.7
South Dakota	12.39	12.57	**32.9**	**83.4**
Tennessee	10.79	10.93	0.5	13.9
Texas	11.36	11.15	**21.3**	22.1
Utah	10.63	11.48	8.9	13.1
Vermont	**18.50**	**18.02**	**24.2**	**99.8**
Virginia	12.40	11.91	1.4	5.8
Washington	9.79	9.95	7.3	**74.8**
West Virginia	11.57	11.69	3.3	6.4
Wisconsin	**14.28**	**15.05**	3.1	10.0
Wyoming	12.30	12.21	**12.7**	15.5
AVERAGE	**13.93**	**13.92**	**11.8**	**26.1**

[a] Bolded entries indicate above U.S. average.

Source: Electricity prices are from https://www.electricchoice.com/electricity-prices-by-state/ and fuel shares from Nuclear Energy Institute at https://www.nei.org/resources/statistics/state-electricity-generation-fuel-shares [both accessed Nov 30, 2021].