REBUTTAL EXPERT REPORT
OF
MARK Z. JACOBSON, Ph.D.

Professor, Dept. of Civil and Environmental Engineering
Director, Atmosphere/Energy Program
Senior Fellow, Woods Institute for the Environment
Senior Fellow, Precourt Institute for Energy
Stanford University

Held et al.,

v.

The State of Montana et al.,

MONTANA FIRST JUDICIAL DISTRICT COURT
LEWIS AND CLARK COUNTY

(Case No. CDV-2020-307)

Prepared for Plaintiffs and Attorneys for Plaintiffs:

Roger Sullivan
Dustin Leftridge
McGarvey Law
345 1st Avenue East
Kalispell, MT 59901
rsullivan@mcgarveylaw.com
dleftridge@mcgarveylaw.com

Melissa Hornbein
Barbara Chillcott
Western Environmental Law Center
103 Reeder's Alley
Helena, MT 59601
hornbein@westernlaw.org
chillcott@westernlaw.org

Nathan Bellinger
Andrea Rodgers
Julia Olson
Our Children's Trust
1216 Lincoln Street
Eugene, OR 97401
nate@ourchildrenstrust.org
andrea@ourchildrenstrust.org
julia@ourchidrenstrust.org

Philip P. Gregory
Gregory Law Group
1250 Godetia Drive
Redwood City, CA 94062
pgregory@gregorylawgroup.com

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INTRODUCTION

I, Mark Jacobson, have been retained by Plaintiffs in the above-captioned matter to provide expert testimony about the feasibility of transitioning the State of Montana to 100% clean, renewable energy in all energy sectors by mid-century. All energy sectors include electricity, transportation, heating/cooling, and industry. I also have reviewed the expert report made by Judith Curry (October 27, 2022) and have been retained to express opinions in response to the Curry report.

The opinions expressed in this rebuttal expert report are my own and are based on the data and facts available to me at the time of writing. All opinions expressed herein are to a reasonable degree of scientific certainty, unless otherwise specifically stated. Should additional relevant or pertinent information become available, I reserve the right to supplement the discussion and findings in this expert report in this action.

EXPERT OPINION

Hundreds of scientific researchers have published on 100% renewable energy systems. Such researchers have published over 700 peer-reviewed scientific papers (Breyer et al., 2022). Prof. Curry is not one of these scientists. She is neither an expert on 100% renewable energy systems nor does she have, to my knowledge and based on my review of her CV, any experience whatsoever publishing on 100% renewable energy systems.

Prof. Curry claims that Montana has abundant energy resources, but such resources are "far from optimal for providing 24/365 electricity owing to the climatological and weather variability of renewable resources." (Page 16.) She then goes on to claim that hydropower is the "source of over 54% of Montana's electricity generation" as of June 2022, but claims that because of the year-to-year fluctuations of hydropower, it is not a reliable source of electricity. (Page 17.) She acknowledges that hydropower is already a critical part of Montana's electricity resources but that it is unlikely to expand much. (Page 17.)

The first flaw in Prof. Curry's analysis is that, during the last full year for which data were available (Q3-2021 to Q2-2022), hydropower met 69.5% (10.5 TWh) of Montana's annual electricity consumption (15.2 TWh), not 54%. Wind met another 22.5% (3.4 TWh). Rooftop solar PV met 0.32% (0.048 TWh) and utility PV met 0.2% (0.031 TWh). Thus, the sum of all clean, renewable wind-water-solar (WWS) electricity generation in Montana as a percent of electricity consumption was 92.6% (14.05 TWh) (EIA, 2022, https://www.eia.gov/electricity/data/browser/). Fossil fuels produced additional electricity such that the total generation compared with consumption exceeded 100%, with the difference being exported. Note that electricity is only about 20% of all end-use energy. The other energy sectors are transportation, buildings, and industry. Although most of Montana's electricity sector is renewable, only 15% of end-use energy among all energy sectors is renewable.

The advantage of conventional hydropower is that it is both a renewable source of electricity and an energy storage medium that is essentially a battery, in that it can be discharged largely when needed. Hydropower can be delivered at full (100%) power within 15 seconds (the time it takes water to fall from the sluice gate to the turbine) of a demand for backup electricity. This is much faster than a natural gas open cycle gas turbine, which requires 300 seconds (5 minutes) to deliver 100% power (Nonbol, 2013). Almost 70% of Montana's demand for electricity already has backup.

Thus, before any real growth of solar PV and before even realizing Montana's full wind potential, the state already meets 92.6% of its electricity consumption with clean, renewable electricity generation, and 70% of this consumption already has a reliable source of backup (conventional hydropower).

Upon transitioning Montana to 100% wind, water, solar (WWS) in all energy sectors (electricity, transportation, buildings, and industry), Montana's electricity demand is estimated to increase by ~86%, but its overall energy demand is estimated to decline by 61.4% (Jacobson et al., 2022a) for five reasons:

1) The efficiency of electric transportation over internal combustion engine transportation.
2) The efficiency of electric heat pumps for air and water heating and air conditioning.
3) The efficiency of electrified industrial high temperature processes over combustion processes.
4) Eliminating energy needed to mine, transport, and refine fossil fuels and uranium.
5) End-use energy efficiency improvements beyond those in a business-as-usual case.

Thus, whereas Montana will need no more coal, oil, natural gas, or bioenergy for energy, it will need about 86% more electricity. As Prof. Curry acknowledges, Montana has abundant renewable electricity-generating resources. In fact, without increasing hydropower at all (only increasing onshore wind to 4.5 GW, commercial/government rooftop PV to 2.95 GW, and utility-scale PV to 2.93 GW), and adding battery storage beyond existing hydropower storage, Montana can keep its electric power grid stable, after electrifying all energy sectors, at low cost when interconnected with the Western Electricity Coordinating Council (WECC) grid while using only 0.05% of its land for spacing between new wind turbines and 0.01% of its land for footprint on the ground for new utility PV (Jacobson et al., 2022a). That is only 0.06% of its land. What is more, 5/6th of that new land is open space between wind turbines that can be used for farming, ranching, or open space.

Prof. Curry claims that the solar PV capacity will "never reach that seen in the more southern states." (Page 18.) However, this is simply not true. The National Renewable Energy Laboratory (NREL) map Prof. Curry provides clearly indicates that the solar resources in southern Montana are similar to those in parts of South Dakota, Iowa, Illinois, Indiana, Kentucky, and West Virginia. Because of the large size of Montana, the area of Montana with this resource is larger than the area of the same resource in any of these other states. In a small portion of Montana, the resources are even similar to Nebraska, Missouri, and Tennessee. Indeed, the 2018 report *Understanding Energy in Montana*, prepared by the Montana Department of Environmental Quality, supports my position that Montana has significant solar potential. That report states, "Montana has respectable solar energy potential as compared against other U.S. cities." (Montana DEQ, 2018).

Further, at least three states at the same latitude as Montana (Washington State, New Hampshire, and Vermont) all, today, have about 10 times the installed and output solar PV as Montana (EIA, 2022). This demonstrates to me that it is feasible for PV to grow in Montana like it has in other states of the same latitude. This is not a technical barrier, but a policy one.

Prof. Curry's claim that solar output in Montana is low is also belied by the fact that the Drake Landing Solar Community, in Okotoks, Canada, which is about 240 kilometers north of the Montana-Canada border, provides up to 100% of its winter heat from summer solar. Starting in 2004, 52 homes were constructed. On the garage roof of each home, solar collectors were installed. The collectors contain a glycol solution (mix of water and non-toxic glycol) that absorbs solar heat, particularly during long summer days. The heated solution is transferred through underground, insulated pipes to a building, where the heat from the solution is transferred through a heat exchanger to water stored in a short-term hot water storage tank (boiler). The water temperature in the boiler is maintained at 40 to 50 °C. This tank is the connection source of all water and air heat for the 52 homes all year.

The hot water collected from the homes and sent to the boiler is then delivered through separate pipes to the borehole field. Each pipe containing hot water extends to the bottom of each borehole. The heat from the pipes is conducted to the surrounding soil, raising the soil temperature up to 80 °C by the end of summer. Each pipe returns upward with cooler water and is sent back to the solar collectors of each home to collect more heat. During winter or other times of the year, when the hot water tank alone cannot satisfy all building heat demand, cold water is piped through the boreholes to collect heat to bring back to the hot water tank. The hot water from the water tank is then distributed to the 52 homes for air and domestic water heating. With this system, up to 100 percent of winter heat is satisfied by summer heat collection. The Drake Landing system has been operational since 2007. The investment cost of borehole storage is less than $1/kWh-heat (Sorensen and Schmidt, 2018).

Prof. Curry acknowledges that Montana has a very high wind resource. However, she mistakenly claims wind provides only 11.5% of Montana's demand. (Page 19.) For the year Q3-2021 to Q2-2022, wind met 22.5% (3.4 TWh) of in-state demand for electricity (EIA, 2022). Prof. Curry also acknowledges the state's ample geothermal resources. (Page 20.)

Prof. Curry acknowledges that Montana has substantial hydropower and wind resources, but then states that "an electric power system based solely on hydropower, wind and solar is not viable without storage on a scale that is anywhere close to feasible or affordable by 2035 and 2050." (Page 20.)

What Prof. Curry is clearly unaware of is that hydropower, which currently supplies 69.5% of Montana's demand (EIA, 2022), is an ideal battery for backup, as discussed earlier. Second, she fails to acknowledge that no plan that my team of researchers or any group I am aware of has proposed for Montana relies only on solar, wind, and hydropower.

My research proposes (1) electrifying all energy sectors, which creates more electricity loads (such as electric vehicle charging and hot water production via electric heat pumps) that can be shifted in time, (2) producing electricity from hydropower, solar, wind, and small amounts of geothermal within Montana, (3) producing solar and geothermal heat within Montana, (4) importing out-of-state electricity when needed, just like already occurs today, (5) exporting excess electricity out-of-state, just like already occurs today, (6) using excess electricity to produce hydrogen for transportation, steel manufacturing, and ammonia manufacturing and to produce heat for district heating, (7) using demand response to reduce the demand for electricity at peak times of the day, (8) using batteries in addition to hydropower storage to store electricity, and (9) using heat and cold storage and hydrogen storage (Jacobson et al., 2022a).

We have calculated the time-dependent matching of power demand with supply, storage, and demand response every 30 seconds for two years across the WECC grid, which includes Montana, and the results indicate the overall annual cost of energy is 69% lower for Montana with WWS than with conventional fuels ($2.8 billion/year instead of $9.1 billion/year). The annual social cost (energy plus health plus climate cost) reduction is 91.3% (from $32 billion/year with conventional fuels to $2.8 billion/year with WWS) (Jacobson et al., 2022a).

Thus, Prof. Curry's claim is not only wrong, but it is also not based on any type of scientific analysis. The scientifically accepted way of carrying out an analysis of whether a future grid can stay stable at low cost upon a transition to renewable energy is through computer modeling (Breyer et al., 2022). Prof. Curry does not perform any modeling nor does she report results from any modeling analysis for Montana where 100% renewable energy in the future has been examined.

Prof. Curry claims that the plan for Montana outlined in my September expert report will not work because "current battery technology can provide electricity storage on time scales of minutes to hours, and long-term utility-scale energy storage using batteries may be infeasible." (Page 21.) This claim is simply not true and unsupported by any peer-reviewed science.

Most batteries today are four-hour batteries, meaning they can last four hours at their peak discharge rate. However, when 12 four-hour batteries are concatenated in series, we suddenly have 48 hours (2 days) of storage at the peak discharge rate of one battery. If we have 120 batteries concatenated, we have 480 hours (20 days) of storage. Not only that, but we can also run the batteries in parallel so that they provide four hours of storage at the peak discharge rate of the sum of all 480 batteries, or anything in-between. In my own garage, I have four 2-hour batteries and regularly run them in series to obtain 8 hours of storage. In sum, we already have long-duration battery storage. The ability of a future wind-water-solar energy system with hydropower and battery storage to keep the grid stable every 30 seconds for two years in the WECC grid, which Montana resides in, at low cost was demonstrated in the Jacobson et al. (2022a) paper.

Prof. Curry then claims that it would be difficult to keep the grid stable with only renewables and storage during a cold "Arctic outbreak," which occurs periodically over Montana. (Page 21.) She states that such outbreaks are due to cold Arctic anticyclones, and these are associated with low wind speeds. (Page 22.) First, whereas wind speeds are generally lower in an anticyclone than in a cyclone due to weaker pressure gradients in the former, the winds are never zero or even near zero. In fact, interconnecting geographically-dispersed winds over a geographic region of 850 km x 850 km, such as in the U.S. Great Plains, not only eliminates zero-power hours during a year but also smoothens out overall wind supply (Archer and Jacobson, 2007). This is because, when the wind is not blowing in one place, it is blowing somewhere else, even when a large-scale weather system arises.

More importantly, anticyclones are generally associated with clear skies, thus more solar PV potential, because air descends, compresses, and warms, thus evaporates clouds within an anticyclone. This is why wind and solar are complementary in nature (Jacobson, 2021). When the wind blows, the sun may not shine; when the sun is out, the wind may not blow. In addition, geothermal provides a steady source of electricity regardless of the weather. Hydroelectric fills in gaps in supply. Combining wind, solar, hydroelectric, and geothermal provides the perfect combination. Further, statistics over both the U.S. and Canada independently show that cold weather, on average, correlates well with greater wind power output (Jacobson, 2021).

Regardless, Montana has so much storage with hydropower and will have more storage with batteries, and will have access to electricity imports, and will have geothermal electricity and heat (geothermal produces energy independent of the weather), and will have stored winter heat underground (in boreholes, water pits, and aquifers) that was gathered from the sun in the summer, and will use electric heat pumps (which use one-fourth the energy as natural gas heaters). As shown in Jacobson et al. (2022a), combining these technologies and interconnecting states allows demand to be supplied continuously over the two-year period examined. Similar results have been found for 145 countries, including Canada and Iceland, which are both north of Montana and have cold climates (Jacobson et al., 2022b).

Prof. Curry states that an Arctic cold outbreak caused the electricity grid in Texas to fail. (Page 21.) This is just an admission of a major problem with the fossil fuel system today. Texas's grid failed primarily because natural gas, coal, and nuclear plants were shut down, with the largest source of failure being natural gas (Swenson and Lajka, 2021). Some wind turbines were frozen due to the lack of de-icing equipment (such equipment is normally installed in cold parts of the world, such as Iceland, Norway, Sweden, Alaska, Canada, and Russia, where de-icing equipment is standard practice), but the rest of the turbines continued operating and produced electricity, contradicting Prof. Curry's claim that an Arctic cold outbreak diminishes winds. In sum, the risk that Prof. Curry refers to is clearly a risk associated with the fossil-fuel system, as illustrated with Texas. But she has provided no evidence it is a risk with a 100% WWS system when de-icing equipment is used for wind turbines.

Prof. Curry claims that an Arctic cold outbreak would affect the entire WECC transmission grid. (Pages 21-22.) This is simply not true. Such an outbreak has no impact in California, which supplies by far the most electricity to the WECC grid. It also has no impact on the enormous hydropower resources of Washington State, Oregon, Idaho, Colorado, Montana, California, and other states that all supply electricity to the WECC grid, regardless of whether an outbreak occurs.

Prof. Curry falsely claims that wind and solar reduce the reliability of the grid and create energy insecurity. (Page 23.) The opposite is true. It is fossil fuels that create energy insecurity. Fossil fuels and nuclear power create four types of energy insecurity risks:

1) **Energy Insecurity due to Diminishing Availability of Fossil Fuels and Uranium**

The first type of energy insecurity is the economic, social, and political instability that results from the long-term depletion of non-renewable energy supplies. This is not a concern with WWS because minerals are either superabundant or the technology can use different minerals. Fossil fuels and uranium are limited resources and will run out at some point. As fossil fuel supplies dwindle, their prices will rise. Such price increases will first hit people who can least afford them – those with little or no income. These people will suffer, since they cannot warm their homes sufficiently during the winter, cool their homes sufficiently during the summer, or pay for vehicle fuel easily.

2) Energy Insecurity due to Reliance on Centralized Power Plants and Oil Refineries

A second type of energy insecurity is the risk of power loss due to a reliance on large, centralized electric power plants and oil refineries. If a city or an island relies on centralized power plants, and one or more plants or the transmission system goes down, power to a large portion of the city or island may be unavailable for an indeterminate period. Such an event can result from severe weather, a power plant failure, or terrorism. An accidental fire or act of terrorism at an oil refinery or gas storage facility can similarly cause a disruption in local and regional oil and gas supplies.

For example, a September 14, 2019, terrorist attack on two Saudi Arabia oil processing facilities knocked out the production of five million barrels of oil per day, or five percent of the world's and half of Saudi Arabia's daily oil production. Oil and gas refineries and storage facilities worldwide are continuously at risk of being attacked, and many become targets during conflict. Whereas decentralized power generation and storage facilities provided by WWS do not decrease the risk of attack to zero, they decrease the risk significantly due to the difficulty in taking down hundreds to thousands of smaller individual units rather than one or two larger ones.

A transition to WWS facilitates the use of more distributed energy sources, reducing the chance that severe weather, a power plant failure, or terrorism will deny people energy. Fossil fuel power plants and nuclear power plants do not solve this insecurity problem because these plants are large and centralized.

3) Energy Insecurity due to Reliance on Fuel Supplies Subject to Human Intervention

A third type of energy insecurity is the risk associated with fuel supplies that can be manipulated or fluctuate substantially in price. Such risks often arise when one country relies on another country to supply its energy. For example, many countries, particularly island countries, must import coal, oil, and/or natural gas to run their energy system. Similarly, prior to the 2022 war in Ukraine, over 40 percent of the European Union's natural gas was imported from Russia. During the war, bans placed on Russian fuel decreased the flow substantially. Japan imports over 75 percent of its oil, primarily from the Middle East. Israel imports over 90 percent of its oil, primarily from Azerbaijan and Kazakhstan. Importing fuel not only results in higher fuel prices, but it also creates reliance of one country on another. This reliance may be tested in times of international conflict. In some cases, a country that controls the energy may withhold it through a ban, an embargo, or price manipulation, or just may not be able to supply it anymore. Similarly, fossil fuel and uranium fuel supplies, even within a country, can be held up due to a labor dispute or civil war.

Fossil fuel power plants, with or without carbon capture, and nuclear power plants are particularly prone to this problem because they rely on fuels that must be supplied continuously, either from across country borders or from within the country. In many cases, especially for island countries, the fuels must be transported long distance.

A clean, renewable WWS energy system built within a country avoids this type of energy insecurity. This is mainly because WWS requires no mined fuels (oil, natural gas, coal, or uranium) to run. Instead, WWS relies only on natural energy sources. Eliminating mined fuels eliminates the energy insecurity associated with them.

Although a country that supplies 100 percent of its own energy with WWS minimizes the risk of energy insecurity due to international conflict and price manipulation, a benefit arises when adjacent countries trade WWS electricity between each other. Such trading, in the absence of conflict, reduces the overall cost of energy and improves the reliability of the overall energy system.

4) Energy Insecurity due to Fuels That Have Mining, Pollution, or Catastrophic Risk

A fourth type of energy insecurity is the risk associated with byproducts of energy use. For example, the perpetual mining of fossil fuels and uranium causes health damage to miners and major environmental degradation, in addition to climate change. For example, underground coal mining results in black lung disease to many miners. Underground uranium mining results in high cancer rates from the decay products of radon. In addition, plants and vehicles that burn fossil fuels produce air pollution that kills millions of people worldwide each year. Nuclear power plants produce radioactive waste that must be stored for hundreds of thousands of years. Nuclear plants also run the risk of a reactor core meltdown. The historic spread of nuclear energy to dozens of countries has also contributed to the proliferation of nuclear weapons in several of these countries.

Some claim that the need for metals, such as lithium, cobalt, and rare earth elements, in a transition to 100% WWS will merely replace the need for fossil fuels. This is not true, since the annual quantities of fossil fuels plus metals needed for conventional fuels is orders of magnitude larger than the annual quantities of metals alone needed in a 100% WWS world. This is because a fossil fuel world needs continuous mining for fuels, but a WWS world does not. For example, no fuel mining is needed, ever, for solar or wind electricity generation.

In fact, one recent study (Krane and Idel, 2021) that accounted for fuel mining plus infrastructure concluded that one gigawatt of wind capacity replacing coal-generated electricity on the Texas grid reduces total mining by 25 million tonnes over 20 years. Indeed, in North America alone, an average of fifty thousand new oil and gas wells are drilled yearly (Allred et al., 2015). The land required for these new wells is 2,500 square kilometers per year. Once a well is depleted, it is abandoned. The United States has 1.3 million active oil and gas wells and 3.2 million abandoned ones. Worldwide, about 29 million wells are abandoned (Groom, 2020). In Montana, there are 1,126 active oil and gas leases, according to the Montana Department of Natural Resources and Conservation 2021 Annual Report (DNRC, 2021).

Annually, the total amount of lithium plus cobalt plus rare earth elements mined worldwide is about 0.0032% of the world's mining in 2021. Specifically, the following materials were mined in 2021 (million tonnes): coal, 7,900; oil, 4,220; natural gas, 2,500; iron ore, 2,600; industrial metals, 182; lithium, 0.106; cobalt, 0.17; rare earths, 0.28; other metals, 0.92; and total, 17,404 (e.g., Bhutada for all but coal, oil, and gas). Thus, even with a 100-fold annual increase in lithium plus cobalt plus rare earth mining, which is not expected to occur, the total mining needed each year is still only 0.32% of current mining, thus trivial in comparison. In other words, a 100% WWS infrastructure world-wide may decrease mining by a factor of 200 or more.

A transition to clean, renewable energy avoids these risks and many other climate change-related risks to health, the environment, and public safety. The continued use of fossil fuels, with or without carbon capture, and of nuclear power, prolongs these energy security problems and causes further environmental degradation.

Prof. Curry claims that the IPCC report provides a less constraining and restrictive set of technologies than in our studies. (Page 23.) This is simply not the case. IPCC merely summarizes the literature and includes our studies as well. The IPCC does not have a policy prescription and summarizes a breadth of pathways. For example, the IPCC AR6 WG3 report cited by Prof. Curry, refers to our studies stating, "(Jacobson et al. 2017, 2019) find [100% renewable electricity generation by 2050] feasible for 143 countries . . . ." A more recent and comprehensive review of the literature (over 700 papers) on wholesale energy transitions (Breyer, 2022) finds that a transition to 100% renewable energy around the world is feasible at low cost.

Prof. Curry claims we should consider the financial benefit of the Crow Nation developing its own coal. (Page 24.) However, not only is there no demand for this coal due to the decline in coal throughout the U.S. in favor of renewables and natural gas, but such coal causes death and illness not only to coal miners through black lung disease and other illnesses, but also to citizens downwind of coal combustion. Prof. Curry is ignoring the social cost of fossil fuels in all her analysis and the social benefits that a transition to 100% renewable energy would bring, including economic benefits.

Prof. Curry claims the war in Ukraine is an example of why we need fossil fuels. (Pages 23, 25.) However, as mentioned, this is an example of why fossil fuels are a danger to the world. With fossil fuels, fuel supplies can be and have been manipulated during times of conflict. Some countries are held hostage over energy. This is impossible with WWS because once a WWS system is in place no fuel is mined or transported. Wind comes right to the turbine. Solar comes right to the panel. In contrast, a fossil-fuel energy system requires continuous mining.

Prof. Curry claims that local CO_2 does not affect local climate. (Page 27.) This is not true. Carbon dioxide increases near-surface ozone, a harmful air pollutant, where ozone levels are already high, by independently increasing temperature and water vapor (Jacobson, 2008). Carbon dioxide emissions in cities also increases local carbon dioxide mixing ratios in city air, increasing ozone there due to the same temperature and water vapor impacts (Jacobson, 2010). In addition, higher temperatures due to CO_2 increase wildfires, increasing air pollution even more over states. Wildfire prevalence, intensity, and duration have increased throughout the western U.S. due to higher temperatures and drier wood.

Prof. Curry says that Montana's CO_2 emissions are small compared with the global amount. (Page 27.) However, the CO_2 emissions per person in Montana (24.1 metric tonnes-CO_2/person) are the 6^{th} highest in the United States, behind only Wyoming (96.4), North Dakota (69.6), Alaska (49.1) West Virginia (43.0), and Louisiana (39.4) (EIA, 2022). Regardless, every tonne of carbon dioxide emitted matters. What is more, the same sources emitting CO_2 are also emitting health-affecting air pollutants that damage the children and adults of Montana.

Signed this 28th day of November, 2022 in Palo Alto, California.

Mark Jacobson, Ph.D.

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