Three Non-Economic Challenges Facing the Renewable-Energy Transition

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Executive Summary

Canada, as with many other environmentally conscientious governments, is pursuing an agenda of an energy transition: away from fossil fuels, and toward a society increasingly driven by wind power, solar power, and hydropower. Polling suggests about 2/3 of Canadians generally look upon this approach favorably both in terms of cost and energy security.

Costs of onshore wind power and stand-alone commercial-scale solar power have declined, as supporters of these technologies have long promised, with the latest estimates of combined-cycle natural gas, on-shore wind, geothermal power, and stand-alone solar power all fall in the range of $36-$39/MWh.

But cost is only one obstacle to the wind- water- solar powered future. Three other physical challenges remain. These challenges include:

- Massive land consumption of wind- and solar-power generation which, even in this early phase of the energy transition is causing public unease, and pushback against many new projects associated with these low-density power source. When measured in 2010, for example, renewable energies generated 525 GW of power, but consumed 398,000 square kilometers – a stark contrast with natural gas power production which generated 3.53 Terawatts of power while consuming only 1,800 square kilometers of land area.
- Massive land disruption that will be required to mine the metals needed for these technologies, which also faces public resistance and opposition from ENGOs.
- Massive new quantities of mining and refinement of metals and minerals will be required to produce and store wind- and solar-power at larger scales of deployment envisioned by advocates of the renewable energy transition. On average, building wind and solar systems needs over 10 times the material compared to hydrocarbon-based machines providing the same energy. The International Energy Agency estimates that some 388 new metal mines will be required by 2030 to meet international EV mandates, which is considered as part of the clean energy transition. For context, as of 2021, there were only 270 metal mines operating across the US, and only 70 in Canada. IEAs estimates of mine-development timelines are also a barrier to the renewable transition. Lithium production timelines, for example, are approximately 6 to 9 years, while production timelines for nickel are approximately 13 to 18 years.

- Wind and solar power, in contrast to conventional forms of electricity production, exhibit a lower Energy Return on Investment (EROI) as they produce lower levels of electricity per unit cost. Societies which direct resources into lower-return endeavors, such as wind- and solar power forsake the economic gains that would accrue from cleaving to energy sources that provide a higher economic return on investment, economic gains that are necessary for a society to prosper.

Background

Advocates of a "renewable energy" future—a world powered by wind, sunlight, and falling water—suggest these sources of energy, paired with battery storage systems or complex energy grids, can provide enough energy to replace that provided by current-day use of the much-maligned fossil fuels, as well as satisfying demand for the energy needed moving forward to sustain modern technological economies.

The Canadian public generally favours the idea. According to polling firm Abacus Data,

- Two thirds [of Canadians] think a clean energy system[1] would be more affordable than a fossil fuel energy system. This view is shared by a majority in every region or province, except for Alberta. Over seven in ten Liberal, NDP, and Green Party supporters feel this way, as do four in ten Conservative Party supporters.
- Two thirds [of Canadians] also think a clean energy system would be more secure—that is, a system where prices and supply are less influenced by global markets. This view is shared by a majority in every region or province, including in Alberta. Over three in four Liberal, NDP, and Green Party supporters feel this way, as do half of Conservative Party supporters. (Coletto, 2022)

One of the leading proponents of this idea is Professor Mark Jacobsen at Stanford University. Jacobsen has made a career of modeling scenarios under which wind power, solar power, and hydropower can provide all of the energy the world needs moving forward in a world of constrained greenhouse gas emissions. Jacobson's renewable green deal for Canada (Jacobson *et al*., 2019) calculates that Canada could get by with 100% energy generation from wind-, water-, and solar-power (WWS) by 2050. Still, "getting by" would not be the "same as"—Jacobson's analysis suggests:

- 62% less overall energy demand by 2050 in the switch from the Business as Usual (BAU—fossil fueled) scenario to wind, water, and solar, including the effects of reduced energy use

1 "Renewable energy," "clean energy," and "green energy" are essentially interchangeable terms for the same basic idea: energies generated from moving wind, falling water, and shining sunlight that does not result in significant emissions of harmful substances. Nuclear power was not included in the Abacus polling.

caused by the higher ratio of work output to energy input of electricity over combustion; eliminating energy used to mine, transport, and/or refine coal, oil, natural gas, biofuels, bioenergy, and uranium; and assumed policy-driven increases in end-use energy efficiency beyond those in the BAU case ;

- the capital cost for building out that new WWS system is estimated at a CA$700 billion;
- land consumption would be approximately 9 million km², with a combined footprint and "spacing" areas of approximately 0.1% of Canada's total land area;
- total jobs produced in Jacobson's scenario add up to about 433,000, while about 590,000 are lost, resulting in a net job-loss scenario of about 157,000.

The expansions of wind- and solar- electric power production in Jacobson's Canadian WWS scenario would be extremely aggressive. For example, wind power would grow from producing 12.8 GW of power (combined on- and off-shore) in 2018 to producing 212.8 GW in 2050 (a 17-fold expansion), while solar power would grow from producing 3.1 GW in 2018 (combined residential/commercial/utility) to producing 152.4 GW by 2050 (a 47-fold increase). Some of these expansions are beyond aggressive, starting with a baseline of zero generation in 2018 (**table 1**).

Table 1: Change in production capacity (GW) needed for the other forms of renewables in Jacobson's WWS-2050 scenario for Canada

	Onshore wind	Off-shore wind	Residential roof-top PV	Comm/gov't rooftop PV	Utility PV	CSP w/ storage
2050	183	29.8	11.7	98	34.3	0
2018	12.8	0	0.62	0.62	1.87	0
Increase factor	14	30	19	158	18	0
	Geothermal electricity	**Hydropower**	**Wave**	**Tidal**	**Solar thermal**	**Geothermal**
2050	5	80.8	4.05	2	8.42	1.47
2018	0	80.8	0	0.023	0	1.47
Increase factor	5	1	4	87	8	1

Source: Jacobson et al., 2019.

Economic challenges to the renewables transition

The economic feasibility of the renewable-energy transition has come to seem more plausible in recent years as the costs of wind- and solar- power have declined to rival that of traditional sources of power production such as combined-cycle natural gas power plants.

An example of this type of analysis can be seen in **table 2** in which the US International Energy Agency (EIA) has calculated comparative data on the costs of producing power—electricity, in this case—using different forms of generation. In table 2, the IEA shows the levelized cost of electrical power (weighted to account for different capacity factors of different energy sources). The capacity factor is a ratio of how much energy is actually produced by a given electricity generator compared to what its theoretical maximum capacity would be.

Table 2: Levelized cost of electricity (capacity-weighted) and levelized cost of storage for new resources entering service in 2027 (in 2021 USD per megawatthour)

Plant type	Capacity factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable cost	Levelized transmission cost	Total system LCOE or LCOS	Levelized tax credit	Total LCOE or LCOS including tax credit
Dispatchable technologies								
Ultra-supercritical coal	NB	NB	NB	NB	NB	NB	NB	NB
Combined cycle	87%	$8.56	$1.68	$25.80	$1.01	$37.05	NA	$37.05
Advanced nuclear	NB	NB	NB	NB	NB	NB	NB	NB
Geothermal	90%	$21.80	$15.20	$1.21	$1.40	$39.61	−$2.18	$37.43
Biomass	NB	NB	NB	NB	NB	NB	NB	NB
Resource-constrained technologies								
Wind, onshore	43%	$27.45	$7.44	$0.00	$2.91	$37.80	NA	$37.80
Wind, offshore	NB	NB	NB	NB	NB	NB	NB	NB
Solar, standaloned	29%	$26.35	$6.34	$0.00	$3.41	$36.09	−$2.64	$33.46
Solar, hybrid	26%	$39.12	$15.00	$0.00	$4.51	$58.62	−$3.91	$54.71
Hydroelectrice	NB	NB	NB	NB	NB	NB	NB	NB
Capacity resource technologies								
Combustion turbine	10%	$55.55	$8.37	$49.93	$10.00	$123.84	NA	$123.84
Battery storage	10%	$64.74	$29.64	$18.92	$11.54	$124.84	$0.00	$124.84

Note: Levelized cost of electricity (LCOE) refers to the estimated revenue required to build and operate a generator over a specified cost recovery period.
Source: EIA, 2022: table 1a.

Readers will observe that, from table 2, the total levelized costs of electricity production are relatively close to each other, with combined-cycle natural gas, on-shore wind, geothermal power, and stand-alone solar power all in the range of $36–$39/MWh. Hybrid solar-power systems, with solar tracking capability and diurnal/seasonal storage are considerably more expensive, coming in at $58.62/MWh. This higher price for solar with storage is not surprising when one looks at the data for battery storage in IEA's LCOE table. Battery storage, particularly, shows a levelized cost of electricity of $124/MWh (weighted), which is about three times the cost of generating a MWh of electricity directly from natural gas, on-shore wind, solar, or geothermal. However, it should also be noted that neither geothermal power systems nor natural-gas systems require battery backup power to generate dependable power. On this list, wind- and solar-power would require battery storage or other backup generation to accompany their direct output.

Caveats apply. EIA's levelized cost of electricity estimates are broadly accepted in global policy discussions, but are not without controversy. The largest caveat is to understand that EIA's levelized costs of power estimates are not the "pure cost" of generating electricity by the different means, but rather reflect that direct cost plus the costs of the regulatory systems (including environmental regulations) that have come to dominate power production. Thus, for example, some fuels that would have been included in the comparison matrix in the past are not even on the IEA's menu as they would have been in previous years. Most developed countries have banned, or otherwise discontinued the use of coal (formerly the low-cost fuel) for electric-power generation. IEA's current list only includes "ultra-supercritical coal", a technology that is vastly more expensive than conventional coal combustion. The same will be true of other forms of power-production: the levelized cost estimates are generated within a framework of diverse policies that can raise or lower the costs of production of any given type of energy.

It is also important to note that the EIA levelized cost of electricity estimates have come under criticism for artificially lowering the apparent costs of wind- and solar-power by omitting various cost contributors to their implementation. As Benjamin Zycher, an energy policy analyst with the American Enterprise Institute observes in testimony given before the US Senate Committee on the Budget (March 29, 2023), these numbers must be considered lower-end estimates because they omit the costs of backup power for wind and solar power, and do not include additional costs to the electricity grid as a whole needed to accommodate the intermittency of wind- and solar-power production (Zycher, 2023).

Non-Economic—physical—challenges to the renewables transition

Cost and economic considerations, however, are only one dimension to the challenge faced when contemplating the transition of the world's energy economy from its current admixture of sources (centered primarily in fossil-fuels and nuclear power) to the renewable energy world of proponents like Mark Jacobson. Other considerations, based more on the constraints of working within the limitations of physical laws or the limitations of engineering systems, have also gained attention in recent years. Much good work has been done on these questions by analysts such as Canada's own Vaclav Smil, Distinguished Professor Emeritus at the University of Manitoba, and Mark Mills, a physicist and energy scholar at the US-based Manhattan Institute. Most of these analyses focus on what energy scholars call "energy density" or "power density", but which are primarily discussions of what one might call the land-consumption cost of energy. Another physically based critique of renewable energies is grounded not in space consumed, but materials produced and consumed to produce renewable energy. Still a third critique is based on the fundamental question of the thermodynamic balance of energy use in society. This last thermodynamics challenge is more abstract, but in some ways more fundamental. It asks the critical question of any energy capturing or producing effort: does one get more energy out of an energy system than one must put into making it?

Land consumption

Several energy policy analysts have characterized the problem of the wind's diffuse nature mainly in terms of land consumption. Essentially, to generate wind power one has to capture the kinetic energy of the wind over very broad areas. Perhaps the best known (certainly in Canada) and most highly published critic of wind- and solar-power on the basis of their low energy density is Vaclav Smil. Smil's *Energy at the Crossroads: Global Perspectives and Uncertainties* is considered, by many, to be the authoritative text on this topic, still highly relevant though published back in 2005 (Smil, 2005).

In *Power Density: A Key to Understanding Energy Sources and Uses*, Smil delivers a thorough summation of power density and how it relates to the various types of power used in modern societies (Smil, 2015). Smil's particular focus has always been on land requirement, as the ultimate power density metric. What is immediately apparent from Smil's calculations (table 3) is how much more land is required for power sources like wind power, solar power, and biofuels compared with more conventional energy sources like coal, oil, and natural gas. Coal, oil, and natural gas production require smaller amounts of land to generate significantly larger quantities of power. In 2010, for example, coal power required 4,700 km^2 of land to support production of 4.72 Terawatts of power. Crude oil production needed 5,400 km^2 of land to support production of 5.38 Terawatts of power.

The story is very different for renewables such as wind and solar power. In table 3, renewables produced only 525 Gigawatts of power (a GW is 1,000th of a TW), yet occupied some 398,000 km^2 of land. That is mere thousandths of the energy generation capacity, requiring a thousand times more land. That reflects the concentration work that must go into generating equivalent power from renewable energy, compared with pre-concentrated conventional energy.

As indicated in table 4, the entire "modern energy system" had a small geographical footprint in 2010, of which wind and solar power were a small component. In 2010, the world's energy systems required about 250,000 km^2, less than 0.2% of ice-free land around the earth. Arable land and permanent crops accounted for 12.3% of the world's ice-free lands (~50 times as much). Land consumption (and concomitant vista degradation) is already triggering public resistance to the further deployment of wind- and solar-power systems, even at today's early progress on a path to a complete clean-energy transition.

Table 3: Aggregate land claim (areas used in production) of the global energy system as of 2010

Process	Power	W/m²	~km²	Process	Power	W/m²	~km²
Fossil fuel extraction	13.63 TW		12,000	Nuclear plants	316 GW	500.0	600
Coal	4.72 TW	1,000.0	4,700	Renewable energies	525 GW		398,000
Crude oil	5.38 TW	1,000.0	5,400	Hydroelectricity	395 GW	3.0	131,700
Natural gas	3.53 TW	2,000.0	1,800	Geothermal electricity	8 GW	50.0	200
Crude oil refining	5.10 TW	5,000.0	1,000	Solar electricity	3 GW	5.0	600
Fuel transportation			27,000	Wind electricity			
Hydrocarbon pipelines	8.03 TW	300.0	27,000	Turbine spacing	40 GW	1.0	40,000
Tanker terminals	2.21 TW	10,000.0	200	Footprint	40 GW	50.0	800
LNG terminals	364 GW	5,000.0	100	Modern biofuels	79 GW	0.3	263,300
Thermal electricity generation	1.86 TW		2,100	Electricity transmission	2.30 TW	30.0	58,000
Fossil-fueled electricity	1.54 TW	1,000.0	1,500				

Note: The author is aware that these data from 2010 are by definition, dated, and current values will differ. It is offered only to give a relative sense of scale regarding the land consumed by various sources of energy production. The author was unable to find a more recent compilation that showed this relationship at the global scale.
Source: Smil, 2015.

Table 4: Land areas modified by all human actions, as of 2010

Activity	Area (1,000km²)	Percentage of ice-free land	Activity	Area (1,000km²)	Percentage of ice-free land
Arable land and permanent crops	16,000	12.3	Reservoirs	600	0.5
Area affected by logging	3,000	2.3	Fossil fuels extraction	15	0.01
Forest and tree plantations	3,000	2.3	Rights-of-way (pipelines, HV lines)	90	0.07
Urban areas (incl. roads)	4,000	3.1	Hydro reservoirs	150	0.1
Impermeable surfaces	600	0.5	Modern energy system	~250	<0.2

Source: Smil, 2015.

Production and consumption of metals and minerals

Mark Mills a physicist and prolific energy-policy scholar associated with the Manhattan Institute is one of the leading voices in discussions about the role of metals and minerals in the production of the technologies required for renewables and vehicle electrification. In his book, *Mines, Minerals and "Green" Energy: A Reality Check*, Mills looks at the materials side of the equation for renewable energy sources, also known as "green energy" sources (Mills, 2020). At the start of the study, Mills observes that:

> … all energy-producing machinery must be fabricated from materials extracted from the earth. No energy system, in short, is actually "renewable", since all machines require the continual mining and processing of millions of tons of primary materials and the disposal of hardware that inevitably wears out. Compared with hydrocarbons, green machines entail, on average, a 10-fold increase in the quantities of materials extracted and processed to produce the same amount of energy. (Mills, 2020: 4)

For example, Mills observes, "replacing the energy output from a single 100-MW natural gas-fired turbine, itself about the size of a residential house (producing enough electricity for 75,000 homes), requires at least 20 wind turbines, each one about the size of the Washington Monument, occupying some 10 square miles of land" (Mills, 2020: 6).

But the land requirement (as calculated by Smil) is really only half the point. Mills goes on to explain that "building a single 100-MW wind farm—never mind thousands of them—requires some 30,000 tons of iron ore and 50,000 tons of concrete, as well as 900 tons of nonrecyclable plastics for the huge blades. With solar hardware, the tonnage in cement, steel, and glass is 150% greater than for wind, for the same energy output" (Mills, 2020: 6).

Mills raises another aspect about the materials needed for renewable energy generation that also gets little attention in the mainstream press, the issue of "overburden", that is, the quantity of raw materials that must be moved and processed to reach needed ores, such as copper. Mills observes, for example: "While ore grades vary widely, copper ores typically contain only about a half percent, by weight, of the element itself: thus, roughly 200 tons of ore are dug up, moved, crushed, and processed to get to one ton of copper. For rare earths, some 20 to 160 tons of ore are mined per ton of element. For cobalt, roughly 1,500 tons of ore are mined to get to one ton of the element" (Mills, 2020: 6).

Interestingly, in this study, Mills debunks an old idea heavily favoured by conservative and libertarian policy analysts in the past, which is the idea made most famous by economist Jesse Ausubel and his collegues in their seminal paper, Dematerialization (Herman, Ardekani, and Ausubel, 1990) and updated later in *Dematerialization: Variety, Caution, and Persistence*, that modern economies "dematerialize" over time: that is, they use less and less material (in both absolute terms and per-unit of GDP growth) simply as a result of the market's pressure to seek efficiencies (Ausubel and Waggoner, 2008). But, as Mills observes in the case of various global materials, the dematerialization is not offsetting growth in net consumption: "Wealthy economies have become more efficient, and the rate of economic growth has outpaced a slower rise in overall material use. But greater economic efficiency in material use slows the growth rate—it is not a fundamental decoupling of materials from growth" (Mills, 2020: 10).

Mills offers more examples of the materials intensity of components of a renewable energy future in testimony given to the Unites States Senate:

> The battery for a single electric-car weighs about 1,000 pounds. About 50 pounds of oil can provide the same vehicle range. Fabricating that single battery involves digging up, moving and processing more than 500,000 pounds of raw materials somewhere on the planet. Meanwhile, measured over the lifespan of the battery (seven years), using oil involves one tenth as much in cumulative material weight extracted from the earth to deliver the same vehicle-miles.
>
> Or consider one more example. Building one wind turbine requires 1,500 tons of iron ore, 2,500 tons of concrete, and 45 tons of non-recyclable plastic. For an equal amount of energy production, solar power requires even more cement, steel and glass—not to mention other metals. Increasing the wind and solar share to, say, just a one-third share of America's energy arithmetically requires a 1,000% increase in the materials already consumed to produce such machines. (Mills, 2019: 2)

A caveat is warranted here: as readers will have noted, systematic data on these issues are limited, that is, there is no broad survey listing the power output and land consumed by all of the county's energy facilities. Both Smil and Mills have generated and reported small slices of data in time—snapshots of a subset of representative facilities.

Recently, as part of a longer study on the metal/mineral requirements of the world's proclaimed Electric Vehicle (EV) transition, I looked into the question of whether the world's metals and minerals production could keep pace with demand (Green, 2023). My conclusion was that this is dubious. The International Energy Agency (IEA) projects growth in mineral demand for EVs through 2040 under two scenarios, one called the Stated Policy Scenarios, which is based on what world government's have pledged to achieve pursuant to the Paris climate accord, and Sustainable Development Scenarios developed by the EIA. Mineral demand for EV's in the Sustainable Development Scenarios is projected to grow 30-fold between 2020 and 2040, with demand for lithium and nickel growing approximately 40-fold (IEA, 2021b). The IEA also projects expected mineral demand specifically from battery storage in EVs, from 2020 to 2040. Mineral demand for storage, according to the IEA, is expected to grow 30-fold from 2020 to 2040, while demand for nickel and cobalt will grow 140-fold, and 70-fold, respectively (IEA, 2021b).

How will all of this play out with regard to mining of EV battery metals and minerals? In its Global Electric Vehicle Outlook 2022 (IEA. 2021a), the IEA again offers estimates for two scenarios, an "Announced Pledges" scenario—a variation on the STEPS scenario based on established government pledges—and a Stated Policies scenario based on additional proposed government policies. In these scenarios, the IEA suggests that fifty new Lithium mines are needed by 2030, along with 60 more Nickel mines; and 17 more cobalt mines. The materials needed for cathode production will require 50 more mines, and anode materials another 40. The battery cells will require 90 more mines, and the EVs themselves another 81 (IEA, 2021a). The IEA suggests that to meet international targets for renewables deployment 388 new mines will be required by 2030.

For context, as of 2021, there were only 270 metal mines operating across the United States, and only 70 in Canada. Such expanded mining is entirely unlikely to appear, considering that mining and refining facilities are both slow to develop and are highly uncertain endeavours plagued by regulatory uncertainty and by environmental and regulatory barriers. Lithium production timelines, for example, are approximately six to nine years, while production timelines (from application to production) for nickel are approximately 13 to 18 years according to the IEA (IEA, 2021a).

However, historic trends in mining, at least in the United States, do not provide mwuch confidence to the idea of a massive, rapid increase in the production of EV metals or other mined materials. The US National Institute of Occupational Safety and Health (NIOSH) data show that, in the United States at least, the number of active mines has declined steadily since 1983 (approximately 17,000 active mines), with metals production rising briefly from 2000 to 2010 (to about 15,000 active mines, and slowly declining to 2021 to a bit more than 12,000 active mines operating in the United States (CDC, 2023).

Energy Return on Investment—a Thermodynamic Frame of Analysis

Another way to compare different forms of energy in a more physical, less economic framework, is to look at something called the Energy Return on Investment, or EROI. The concept is developed in *Energy Return on Investment: A Unifying Principle for Biology, Economics, and Sustainability*, by Charles A.S. Hall (Hall, 2017). The "EROI stands for Energy Return On Investment, and refers most explicitly to the ratio of energy delivered to an organism or society from one energy unit invested in getting that particular energy" (Hall, 2017: 107).

EROI is formally defined as a ratio:

$$\text{EROI} = \frac{\text{Energy returned from an energy-gathering activity}}{\text{Energy used to get that energy}}$$

Hall views achieving a net-positive EROI as an imperative for human societies as well as individual organisms; and not a small one. He develops the argument with analogy to a farmer delivering food to the consumer.

> Hall et al. (2014) examined the EROI required to actually run a truck and found that if the energy included was enough to build and maintain the truck and the roads and bridges required to use it (i.e., depreciation), one would need at least a 3:1 EROI at the wellhead to put one unit of gasoline into the truck. Now if you wanted to put something in the truck, say some grain, and deliver it that would require an EROI of, perhaps, 5:1 to grow the grain. If you wanted to include depreciation on the oil field worker, the refinery worker, the truck driver and the farmer you would need an EROI of say 7 or 8:1 to support the families. If the children were to be educated you would need perhaps 9 or 10:1, have health care 12:1, have arts in their life maybe 14:1 and so on (the numbers below 3:1 are fairly accurate, and above are speculative). (Hall, 2017: 154)

Hall's work, combined with that of others, suggests that "the EROI to run modern industrial-consumer societies is probably much higher, probably from 10:1 to 15:1 at a minimum if we are to support families, health care, education, the more complex arts, and so on" (Hall, 2017: 154).

Hall's Mean EROI values for thermal fuels are shown in table 5, below (values extracted from graphic representations, and are visual estimates of the author). Table 6 below shows the EROIs for today's common forms of energy (thermal fuels and electricity production)

Table 5: Mean EROI values for thermal fuels based on published values

Fuel	EROI
Coal	~45:1
Oil and Gas (world)	~20:1
Oil Shale	~10:1
Ethanol from biomass	~8:1
Tar Sands	~5:1
Diesel from biomass	~2:1

Source: Hall, Lambert, and Bologh, 2014.

Table 6: Mean EROI values for electricity generation systems based on published values

Generation system	EROI
Hydroelectric	~80:1
Wind	~24:1
Coal	~12.:1
Nuclear	~12:1
Solar (Photovoltaic)	~11:1
Geothermal	~10:1
Natural gas	~5:1

Source: Hall, Lambert, and Bologh, 2014.

One immediately notes from table 5 that the high-energy density of coal, oil, and natural gas, come in well above the 10:1–15:1 EROI threshold. Oil shale and oil sands (as will be discussed more below) are near the cut-off, while biofuels fall short. In table 6, we can see that taking advantage of the Earth's supply of falling water (hydroelectric power) commands a huge EROI advantage, perhaps explaining why water-wheels were some of the earliest technologies known to harness power. Other sources of electric-power production hover much closer to the 10:1–15:1 EROI threshold.

Hall's computations are of particular interest to Canadian readers, as he shows the trends for EROI for Canada's oil sands (sometimes referred to as "tar sands"). EROI for depletable resources changes over time, which is an important distinction when comparing renewable and depletable forms of energy production. As the highest quality sources of depletable production are consumed, lower quality sources produce less fuel, generally at higher costs. Hall notes a declining EROI for oil sands from approximately 35:1 in 1989 to only about 15:1 in 2010. It should be noted that this data series ended in 2010, and there have been significant changes in the way that oil (tar) sands are produced in Canada that could have shifted their EROIs higher (Hall, 2014). The author could not identify any more recent EROI analysis of Canadian energy production.

Hall's work is not without controversy, however, particularly his assessments of the EROI of renewable energies, other than hydroelectric power. Advocates of wind- and solar-power, not surprisingly, are strongly critical of the idea both on technical and ideological grounds. A 2019 study, Estimation of Global Final-Stage Energy-Return-on-Investment for Fossil Fuels with Comparison to Renewable Energy Sources, conducted by a research team at the University of Leeds, looks at EROI both as a stand-alone calculation, as well as EROI as delivered to end use. The authors find that EROIs without final delivery costs, while declining over time as highest quality reserves are consumed to still be reflective of Hall's earlier work and far higher than EROIs of renewables (Brockway, Owen, Brand-Correa, and Hardt, 2019):

We estimate that the average EROI for all fossil fuels has declined by around 23% in the 16-year period considered (37:1 to 29:1). These are similar magnitudes (see table 1) and rates of decline to other published estimates. The aggregate results for all fossil fuels represent a combination of different trends for different kinds of fuel. All types of fossil fuels show a declining trend. The EROI for coal starts at the highest value (50:1) in 1995 but declines sharply, by 42%, to reach ratios similar to the other fossil fuels in 2011 (about 29:1). This strong decline is largely driven by increasing use of indirect energy in Chinese coal production. EROI ratios for oil and gas are much lower but also decline less strongly. EROI for oil production declines by 19% from 35:1 to 28:1. EROI for gas production declines by 10% from 32:1 to 29:1.

Brockway and his colleagues also calculate EROI as final delivered energy, that is, energy not simply at the point of first generation, but on arrival to the individual user (end-use). After this calculation, the EROI for all of the fossil fuels declines to 6:1, only slightly better than that of recent renewables. However, the author believes that extending EROI analysis to the point of end-point delivery clouds the situation more than it reveals, since the points post production of the "first" energy carrier—the barrel of oil, the ton of coal, the cubic meter of natural gas, the first electrons off the solar cells, the first electrons out of the wind turbines—are far more subject to governmental decision making, more than the intrinsic thermodynamic estimation of EROI.

In their article, Energy Return on Investment of Major Energy Carriers, Murphy and his colleagues also make a strong rebuttal to previous EROI research that showed wind- and solar-power to have insufficiently strong EROIs to be considered economically viable (Murphy, Raugei, Carbajales-Dale, and Estrada, 2022). Their final EROI analysis, in fact, stands previous understandings on their heads and suggests that, while wind- and solar-power (and hydropower) all have EROIs above 10 (the threshold for economic viability), conventional fossil fuels are the energy sources that come up short on EROI, being well below a 10-fold return on investment. However, as with the Leed's study, the work of Murphy and his colleagues is not directly comparable to the works mentioned previously as their framework of analysis is different. While Hall studied the EROI at the point of production (the well-head for oil, for example), they extend the framework of analysis out to the point of end use. What this means, in essence, is that they include the "pure EROI" but adds in the costs of energy conversions, transmission, and then final use. While this analytic framework will be satisfying to renewables champions, it will not likely convince the originators of the EROI framework of analysis (as it does not convince the author), because the majority of these parts of the overall energy distribution system are overwhelmingly subject to government intervention, regulation, and development, and are therefore, properly, not seen as something intrinsic to the thermodynamic nature of the various forms of energy transformed and consumed in modern societies.

Conclusion and Policy Implications

A "clean energy transition" has been proposed, and is widely viewed positively, in which developed societies (such as Canada) transition from the use of fossil fuels to produce power, to using wind-, solar-, and hydro-power exclusively for this purpose. But looking outside direct economic evaluations of feasibility, it is clear that there are physical barriers to the wind, water, solar transition that still pose significant challenges to its feasibility.

- Land consumption (or occupation by wind- and solar-farms) is one such barrier. Wind and solar power must channel and concentrate the diffuse energy of wind and sunlight over very large expanses of terrain: orders of magnitude larger than conventional fossil-fuel, nuclear, or hydro-power production. This land consumption has already resulted in resistance to development of new wind and solar installations in several countries further along in the quest for the clean energy transition, such as Germany, the United Kingdom, and the United States (Bryce, 2021).
- Land disruption for mining, and the needed increase in mining of metals also remains a significant barrier to the clean energy transition as wind- and solar-power, as well as vehicle electrification, which is often included in the concept of the clean energy transition, require massive increases in the production of a number of metals which require extensive mining and refinement, and the movement of massive amounts of material in the process.
- Thermodynamic constraints of energy consuming societies—the need for society to obtain a strong, positive net return on energy investment, that is, to get at least 10 times to 15 times more power out of an energy production system than must be invested into it up front poses a serious challenge to the utility of wind- and solar-power. Wind- and solar-power generate modest energy returns on investment (below the 10:1–15:1 EROI considered needed for viability in powering society) while conventional forms of power production fare much better in a thermodynamics-based "Energy Return on Investment" framework, producing well above the 10:1–15:1 return on energy investment needed to be considered economically viable for energy-intensive societies.

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