Journal of Management and Sustainability; Vol. 12, No. 1; 2022
ISSN 1925-4725 E-ISSN 1925-4733
Published by Canadian Center of Science and Education

Full Cost of Electricity "FCOE" and Energy Returns "eROI"

Lars Schernikau[1], William Hayden Smith[2] & Rosemary Falcon[3]

[1] An energy economist, entrepreneur, and commodity trader in the energy raw materials industry, Zurich, Switzerland; affiliation Technical University of Berlin, Germany

[2] Professor of Earth and Planetary Sciences at McDonnell Center for Space Sciences at Washington University, St. Louis, MO, USA

[3] Recently retired DSI-NRF SARChI Professor at Engineering Faculty at the University of the Witwatersrand, Johannesburg, South Africa

Correspondence: Dr. Lars Schernikau, entrepreneur, and commodity trader in the energy raw materials industry, Zurich, Switzerland; affiliation HMS Bergbau AG, Germany and Singapore.

Received: March 2, 2022 Accepted: April 15, 2022 Online Published: May 23, 2022

doi:10.5539/jms.v12n1p96 URL: https://doi.org/10.5539/jms.v12n1p96

Selected Abbreviations

CCUS – Carbon capture utilization and storage

eROI – Energy return in energy invested

VRE – Variable renewable energy, such as wind and solar

HELE – High efficiency, low emission

IEA – International Energy Agency in Paris

FCOE – Full cost of electricity

LCOE – Levelized cost of electricity

MIPS – Material input per unit of service (or output)

PES – Primary energy supply, or PE for primary energy

PV – Photovoltaic

USC – Ultra-super-critical

VRE – Variable renewable energy

~ – Approximately

Preface:

- ***Energy*** (in Watt-hour or Wh, in German "Arbeit oder Energie") vs. ***Power*** (in Watt or W, in German "Leistung")
  - Energy is the capacity to do work. Power is energy per unit of time. Thus, energy is what makes change happen and can be transferred form one object to another. Energy can also be transformed from one form to another. Power is the rate at which energy is transferred.
  - Once you know both the energy storage capacity (i.e., MWh) of a battery and the output power (i.e., MW), you can simply divide these numbers to find how long the battery will last.
  - Energy is stored in a Tesla battery (i.e., 100 kWh). "Horse"-power, let's say 150 kW, is what moves the car forward. The battery, filled with energy (kWh), drains over time depending on how much power (kW) is required for moving the car, which depends on how you drive and the surrounding conditions.
- ***Capacity Factor "CF"*** (in German "Nutzungsgrad") is the percentage of power output achieved from the installed capacity for a given site, usually stated on an annual basis.
  - Capacity factor is different from the efficiency factor. For comparison, efficiency measures the

percentage of input energy transformed to usable or output energy.

- In Germany, photovoltaics ("PV") achieves an average annual capacity factor of ~10–11%, while California reaches an annual average CF of 25% (Schernikau & Smith, 2021). Thus, California yields almost 2,5x the output of an identical PV plant in Germany.
- It is important to distinguish between the average annual capacity factor and the monthly or better weekly and daily capacity factor, which is very relevant when keeping an electricity system stable that requires demand to always equal supply for the electric frequency to remain stable.

- ***Conservation of Energy – the 1st Law of Thermodynamics*** essentially states that energy can never be created from nothing nor lost into nothing, only converted from one form to another. Different forms of energy include thermal, mechanical, electrical, chemical, nuclear, and radiant energy.
- ***Entropy of Energy – the 2nd Law of Thermodynamics*** essentially distinguishes between useful energy (low entropy) that can perform work and less useful energy (high entropy) that cannot easily perform work.
  - Entropy is a measure of randomness, disorder, or diffusion in an energy system where greater disorder = greater entropy.
  - Whenever energy is converted from one form to another, there is always some fraction of useful energy that becomes useless (entropy/disorder increases).
  - Planck said in other words "Every process occurring in nature always increases the sum of the entropies of all bodies taking part in the process, at the limit – for reversible processes – the sum remains unchanged."
  - The 2nd Law of Thermodynamics thus explains why perpetual motion machines are not possible.
  - Thus, the more complex energy processes are, the more useful energy is lost.

Abstract

Understanding electricity generation's true cost is paramount to choosing and prioritizing our future energy systems. This paper introduces the full cost of electricity (FCOE) and discusses energy returns (eROI). The authors conclude with suggestions for energy policy considering the new challenges that come with global efforts to "decarbonize".

In 2021, debate started to occur regarding energy security (or rather electricity security) which was driven by an increase in electricity demand, shortage of energy raw material supply, insufficient electricity generation from wind and solar, and geopolitical challenges, which in turn resulted in high prices and volatility in major economies. This was witnessed around the world, for instance in China, India, the US, and of course Europe. Reliable electricity supply is crucial for social and economic stability and growth which in turn leads to eradication of poverty.

The authors explain and quantify the gap between installed energy capacity and actual electricity generation when it comes to variable renewable energy. The main challenges for wind and solar are its intermittency and low energy density, and as a result practically every wind mill or solar panel requires either a backup or storage, which adds to system costs.

Widely used levelized cost of electricity, LCOE, is inadequate to compare intermittent forms of energy generation with dispatchable ones and when making decisions at a country or society level. We introduce and describe the methodology for determining the full cost of electricity (FCOE) or the full cost to society. FCOE explains why wind and solar are not cheaper than conventional fuels and in fact become more expensive the higher their penetration in the energy system. The IEA confirms "*...the system value of variable renewables such as wind and solar decreases as their share in the power supply increases*". This is illustrated by the high cost of the "green" energy transition.

We conclude with suggestions for a revised energy policy. Energy policy and investors should not favor wind, solar, biomass, geothermal, hydro, nuclear, gas, or coal but should support all energy systems in a manner which avoids energy shortage and energy poverty. All energy always requires taking resources from our planet and processing them, thus negatively impacting the environment. It must be humanity's goal to minimize these negative impacts in a meaningful way through investments – not divestments – by increasing, not decreasing, energy and material efficiencies.

Therefore, the authors suggest energy policy makers to refocus on the three objectives, energy security, energy affordability, and environmental protection. This translates into two pathways for the future of energy:

(1) invest in education and base research to pave the path towards a **New Energy Revolution** where energy systems can sustainably wean off fossil fuels.

(2) In parallel, energy policy must support **investment in conventional energy** systems to improve their efficiencies and reduce the environmental burden of generating the energy required for our lives.

Additional research is required to better understand eROI, true cost of energy, material input, and effects of current energy transition pathways on global energy security.

Keywords: energy, electricity, fossil fuels, natural gas, coal, nuclear, wind, solar, renewables, energy, energy policy, clean coal technology, USC

1. Introduction (Today's Global Electricity Systems)

In 2019, fossil fuels – in order of importance – ***oil, coal, and gas made up ~80% of global primary energy ("PE") production*** totaling ~170.000 TWh or ~600 EJ. Despite Covid and significant wind and solar capacity additions, the percentage has not changed in 2021, quite the contrary, coal made a comeback (IEA, 2022a). Coal and gas made up ~60% of global gross electricity production totaling ~28.400 TWh in 2021. It is important to note that global electricity production makes up ~40% of primary energy with transportation, heating, and industry accounting for the remaining ~60% (Figure 1).

Current energy policy focuses on the electrification of energy, thus significantly increasing electricity's share of primary energy by using electricity more for transportation (see EVs), heating (see heat pumps), and industry (see DRI, producing steel using hydrogen). Therefore, this paper focuses on electricity. For a more comprehensive discussion on transportation, the authors recommend Kiefer 2013 *Twenty-First Century Snake Oil*, that includes details on hydrocarbons and biofuels for transportation which are not covered herein in greater detail.

Despite trillions of US dollar spent globally on the "energy transition", the proportion of fossil fuels as part of total energy supply has been largely constant at around 80% since the 1970s when energy consumption was less than half as high (WEF, 2020). Also in Europe, fossil fuels share is still above 70%. Kober et al. 2020 among others, confirm that total primary energy consumption more than doubled in the 40 years between 1978 to 2018. At the same time, energy intensity of GDP improved by a little less than 1% confirming *Jevon's Paradox* that energy efficiency improvements are always offset by higher energy demand (Polimeni et al., 2015).

Variable "renewables" in the form of wind and solar – while not the subject of this paper – accounted for ~3% of global primary energy and ~8% of global gross electricity production in 2019, and this was largely unchanged in 2020 and 2021 (refer to Schernikau & Smith, 2021 for more details on solar and Schernikau & Smith, 2022b on wind). Other forms of energy supply usually categorized as "renewables" – such as biomass, hydro, geothermal, or tidal power – are not detailed further as they are not considered variable and have a different quality. For comparison, coal and gas combined accounted for ~50% of global primary energy and ~60% of global gross electricity production. Thus, fossil fuels still exceeded wind and solar by a "Fossil to Wind-Solar Factor" of 27x for primary energy and 8x for electrical power production (IEA, 2021a).

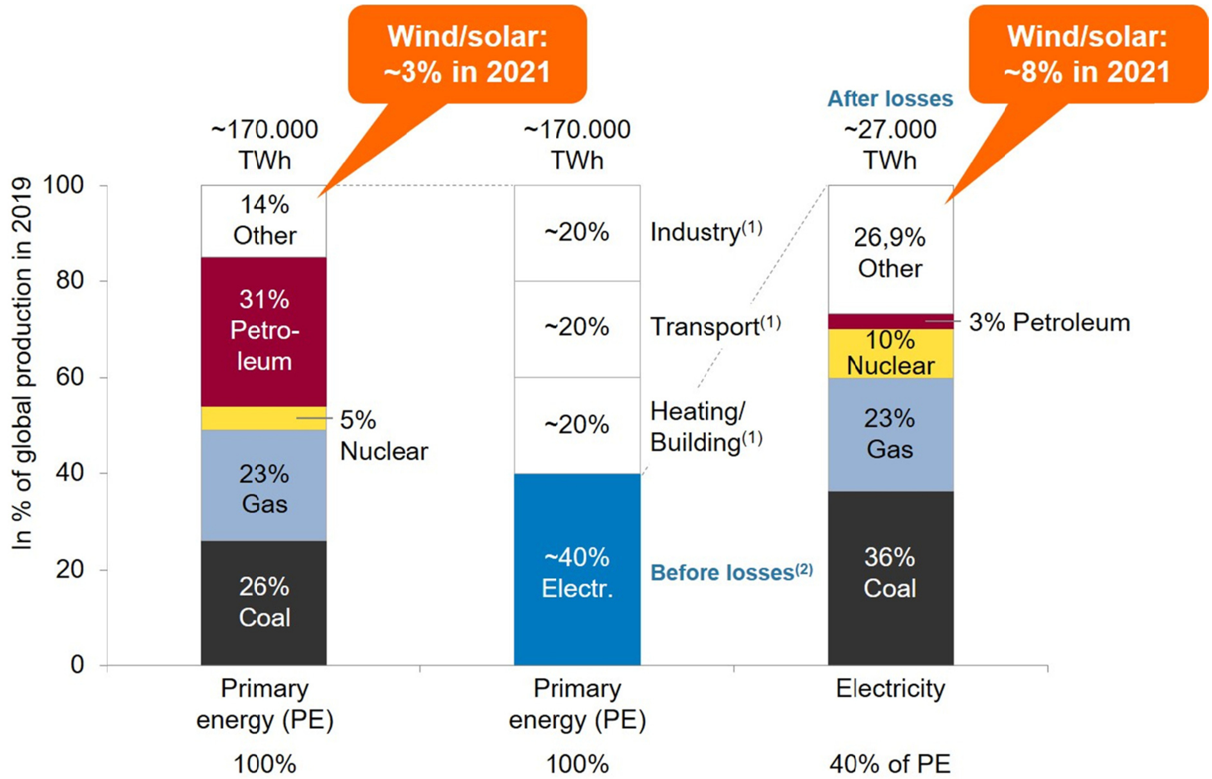

Figure 1. Overview of global primary energy and electricity

Note: (1) Only the portion of industry/transport/building that is not included under electricity; (2) assumed worldwide net efficiency of about 33% for nuclear, 37% for coal, 42% for gas, assume generous avg. ~40% efficiency => 27.000TWh becomes 68.000 TWh or 40% of 170.000TWh

Sources: Schernikau Research and Analysis based on BP, 2021, IEA, 2021a.

Germany is the foremost industrialized nation in the move toward decarbonization and has invested at least EUR ~360 billion since 2000 (Note 1) in the "energy transition" reducing the share of nuclear and fossil fuels (BfWE 2020). It shall be noted that nuclear is the most net energy efficient (see section 0 on eROI) and least polluting way of producing electricity but faces other challenges. However, as Europe has been reducing its own production of fossil fuels, the continent's dependence on energy raw material imports increased significantly, mostly from Russia, over the past two decades.

With the money invested in the "energy transition" – until 2021 – Germany has reached a wind/solar share for gross electricity production of ~28%. The primary energy share of wind and solar (Note 2), however, was still only 5%. To achieve this "transition", Germany's installed power capacity had to double (Figure 2). Consequently, the renewable energy sector grossly underperformed, compared to its investment in real energy terms, and Germany's electricity prices reached the highest among the G20. This underperformance, however, is due to the low-capacity factor, low energy efficiency, and other inherent shortcomings of variable renewable energy discussed herein (Figure 3), not due to bad implementation or bad intent.

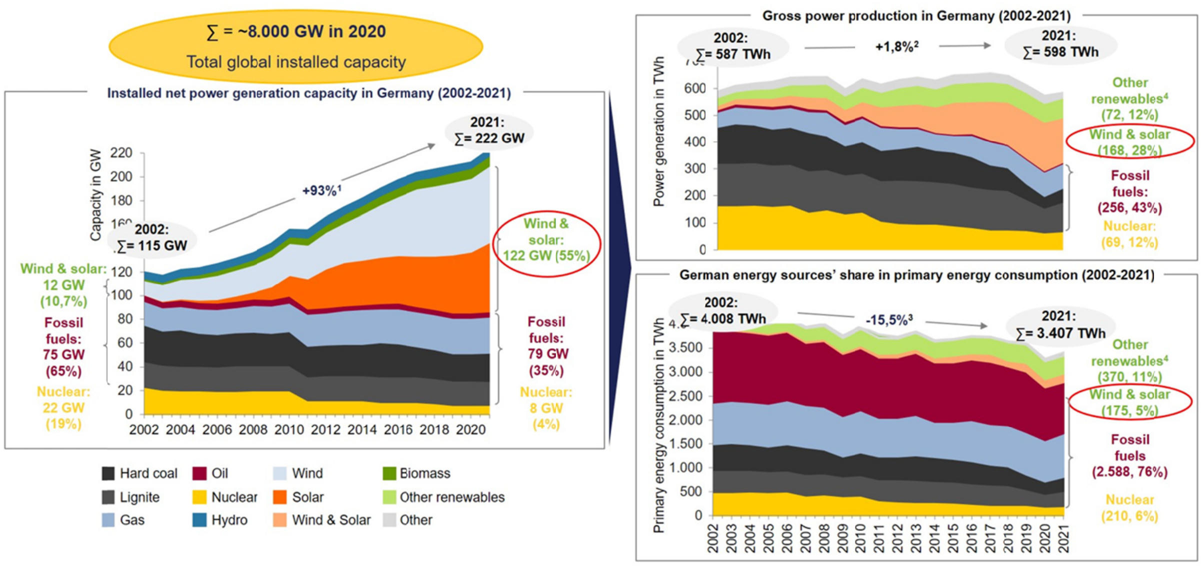

Figure 2. German installed power capacity, electricity production, and primary energy

Note: (1) CAGR: +3,5%; (2) CAGR: +0,1%; (3) CAGR -0,9%; (4) Including hydro & biomass.
Source: Schernikau Research and Analysis based on Fraunhofer, 2022, AGE, 2021, Agora, 2022 (Note 2).

During the 20 years from 2002 to 2021, Germany's installed power capacity almost doubled from 115 GW to 222 GW while total electricity consumption was essentially flat and primary energy fell over 15% (Figure 2, Note 2). Over the next decades, Germany expects a significant increase in electricity consumption for the electrification of transportation, heating, and industrial processes to satisfy increased demand from consumers and industry as required by the German "Energiewende".

The global average looks slightly better. Of the total 2020 global installed energy capacity of ~8.000 GW or 8 TW (Figure 10), about 18% or ~1.400 GW was wind and solar which contributed ~8% to global electricity and ~3% to primary energy (BP, 2021; IEA, 2019b; IEA, 2021a). After installation of almost 200 GW of solar PV in 2021, in March 2022, the world celebrated the first 1 TW of installed solar capacity (PV-Mag, 2022).

Figure 2 illustrates the substantial disconnect between installed capacity and generated electricity. It appears that in countries such as Germany, given the average capacity factors for wind and solar, a doubling in installed capacity will lead to less than 1/3 of electricity supply and less than 10% contribution to primary energy. The reasons for this disconnect are multifold and impact the world of electricity in many ways. Figure 3 lists the shortcomings of variable renewable energy (VRE) for electricity generation in the form of wind and solar which explain the reasons for the apparent divide between capacity and power generation. These deficiencies of VRE can only partially be reduced through technological improvements.

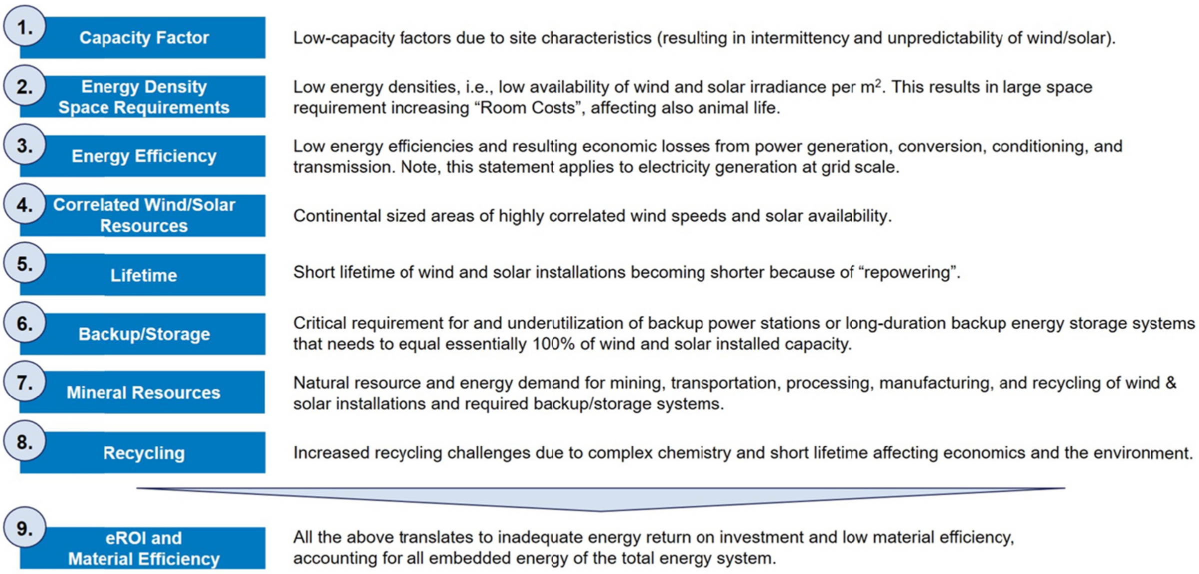

Figure 3. Summary of shortcomings of variable renewable energy for electricity generation

Source: Schernikau Research and Analysis.

Despite the sun's immense power, the energy available per m^2 from natural wind and solar resources are limited and too small to allow efficient electricity generation at grid scale (low energy density). Additional negative effects of wind and solar on vegetation, local and regional climate, animal life, seaways, bird flyways, and bird, bat, and even insect populations also must be considered. These effects originate primarily from the required large land area (Schernkau and Smith 2022b).

Technological advances will further increase net efficiencies of wind and solar installations. However, physical boundaries, as described by the Betz Law and Schockler-Queisser Limit, dismiss the possibility of ten-fold improvements. There is no prospect of a paradigm shift in energy from PV or wind as is promised for quantum computing. ***One cannot compare energy with computing, they follow different laws*** (Figure 7).

The 33% quantum efficiency Schockler-Quiesser Limit for silicon can be exceeded with multi-layer PVs which so far are unstable and less durable than silicon PV panels. Today, they already surpass mono-crystalline silicon's quantum efficiency by about 50%, but 20-year operational life for multilayer PV are not in reach. Technological improvements and new materials, such as perovskites and quantum dots, may overcome the stability and durability problems in time, but 100% quantum efficiency is the absolute physical maximum that will never be reached. Larger scale wind parks with high density wind turbine installations show reduced yields due to wake effects and wind energy extraction (Schernikau & Smith, 2022b).

Thus, ***technological improvements may improve PV's quantum efficiencies by a factor of two, but not by the required multiple to compete with conventional energy generation and to surpass the required eROI hurdle*** at grid scale. Be reminiscent that also conventional energy generation improves its efficiency over time.

2. Literature Review, Methodology, and Results (Cost of Electricity and eROI)

Schernikau has completed a total of over 70 interviews in Europe, Africa, Asia, and North America during the past 3 years. Discussions have taken place at various ministries, economic government organizations, with universities, and industrial conglomerates. The overarching theme from these interviews was a lack of understanding of the true full cost of electricity and continued misuse of the marginal cost measure LCOE to compare costs of VRE with conventional sources of power. In all interviews, the principal desire – especially in developing nations – was to support a sustainable yet economically viable energy policy to transition away from fossil fuels as fast as possible. The costs and downsides associated with such a transition were rarely understood or researched.

Schernikau has contacted energy think tanks such as the IEA, the IEEJ, and the ACE (ASEAN Center for Energy) and discussed some of the above topics in detail. The conclusions herein are also a result from these interchanges. The political component inherent in the work at all of the mentioned organization was removed and attention was put on the economic impacts of the proposed transition to VRE. The literature researched is referenced at the specific elements detailed in the paper.

The cost of electricity is important for a country's global competitiveness and a key element for economic development as well as the discussion on energy policy at large. Electricity systems are complex, which is also driven by the fact that ***a functioning electricity system can only supply usable power if and only if electricity demand equals electricity supply at all times***, every second. This unique characteristic of electricity systems drives costs. We need to differentiate between cost, value, and price, which are not the same. Further below we discuss only cost.

- **Cost** – the resources and work required for production.
- **Value** – the intrinsic value or utility to the consumer for a particular application as compared to its alternatives.
- **Price** – what consumers or the market are willing to pay. The price is influenced, or distorted, by government or company intervention, such as laws, mandates, subsidies, geopolitics, and more.

The true full cost of electricity, FCOE, is detailed in the following section. Cost of electricity has been studied in detail by several government organizations and universities. The Full cost of electricity donated as FCe was described in a number of white papers published at the University of Texas 2018. UT however focuses on transmission and distribution, paying less attention to backup, storage, and the intermittency of VRE. Also, the lower asset utilization of backup systems is not discussed in greater detail.

The OECD (OECD NEA, 2018) references the full cost of electricity separating between (a) plant-level costs, (b) grid-level system costs, and (c) external or social cost outside the electricity system. The argument is that that the full cost must include all three categories, which the authors agree with. The OECD study pays more attention to higher volatility and complexity with added VRE in the system, but energy required or cost for recycling is not considered. In the OECD's discussion on pollution and GHGs, the life-cycle emission and non-emission impact of energy systems is not considered, the focus is on combustion/operation and CO_2 (OECD NEA, 2018, p. 101). The study also only marginally considers resource and space consideration. On costs the following OECD statements are important:

- "*When VREs increase the cost of the total system, ..., they impose such technical externalities or social costs through increased balancing costs, more costly transport and distribution networks and the need for more costly residual systems to provide security of supply around the clock*" (OECD NEA, 2018, p. 39).
- "*From the point of view of economic theory, VREs should be taxed for these surplus costs [integration costs above] in order to achieve their economically optimal deployment*" (OECD NEA, 2018, p. 39).

Various other electricity-cost-metrics exist (Note 3) such as LCOE, VALCOE, LACE, LCOS, Integrations Costs of VRE, etc. For a complete cost picture, the authors introduce the full cost of electricity to society, FCOE. The authors' FCOE falls into ten different categories that illustrate its complexity and many are not easily measurable (see Figure 5). The authors have not yet found these 10 categories considered in full by any energy economic institutions, government, university, private company, or any of the media. Usually only a few cost categories are discussed, and levelized cost of electricity (LCOE) is erroneously used most often. The socio-economic and environmental benefit of understanding the methods for electricity cost determination are substantial and require further study.

2.1 Full Cost of Electricity – FCOE

Since the question of electricity is one at society level, or at least at country level, the authors attempt to define the true full cost of electricity FCOE. Ten cost categories determine what we refer to as the ***Full Cost of Electricity "FCOE"*** to society:

1) ***Cost of Building*** electricity generation/processing equipment such as a solar panel, power plant, a mine, a gas well, or a refinery, etc. (often referred to as investment costs).

2) ***Cost of Fuel***, such as oil, coal, gas, uranium, biomass, solar, or wind (which has a zero cost of fuel). This would include processing, upgrading, and transporting the fuel through pipelines, on vessels, rail, or trucks. It would also include costs for rehabilitating the source of the fuel, such as mines or wells. LCOE often assumes that the price for CO_2 is part of the Cost of Fuel, but to be correct we define a separate category 7: Cost of Emissions.

3) ***Cost of Operating*** and maintaining the electricity generation/processing equipment.

4) ***Cost of (Electricity) Transportation/Balancing*** systems to the end user, such as transmission grids, charging stations, load balancing, smart meters, other IT technology, and its increasing threat from cyber-attacks. Refer to BCG Guide to Cyber Security (BCG, 2021a) and the March 2022 cyber-attack on satellite infrastructure targeting German windmills (Willuhn, 2022). Also refer to the 2017 attack on Ukrainian energy infrastructure described in the excellent book *Sandworm – a new era of cyberwar* (Greenberg, 2019).

5) ***Cost of Storage***, if required medium and long-term (different from load balancing), that should include cost of building and operating, for example, pumped hydro, batteries, hydrogen, etc. Keep in mind that oil, coal, gas, uranium, and biomass are storage of energy in themselves.

a. Full Cost of Storage must include just for storage alone (1) Cost of Building, (3) Cost of Operation, (7) Cost of Emissions, (8) Cost of Recycling, and (10) other metrics MIPS, lifetime, eROI.

6) ***Cost of Backup*** technology; electricity systems include redundancy in case something happens to a power plant or equipment. All reliable electricity systems are overdesigned, usually by ~20% of the highest (peak) power demand. In addition:

a. Every single VRE installation equipment such as wind and solar require 100% backup, storage, or combination of both as by nature they are not dispatchable or predictable.

b. Conventional power plants are often used as a backup for VRE. The higher the share of VRE in the electricity system, the less such backup capacity will be used causing lower asset utilization. Thus, the cost of backup increases logarithmically as the VRE share in the energy system increases beyond a certain point (see also IEEJ, 2020, p. 124).

c. Thus, backup capacity may and currently does substitute long-term storage and is included herein as a separate category since it has a different quality and cost. It is important to avoid double counting.

7) ***Cost of Emissions*** includes the true cost (not arbitrary taxes or subsidies) of all air-borne emissions from power generation technology along the entire value chain. This would include but not be limited to particulate matters, SO_x, NO_x, as well as life cycle greenhouse gases including from building and recycling the equipment. Benefits of CO_2 because of its proven fertilization effects for all plant life would also have to be incorporated (Zhu et al., 2016; NASA, 2019; WEF, 2019). For cost of global warming the authors refer to Nordhaus 2018, Lomborg 2020, and Kahn 2021.

8) ***Cost of Recycling***, decommissioning, or rehabilitation of electricity generation and, separately as part of point 6 above, backup equipment after its lifetime expired. See also *The Hidden Cost of Solar Energy* published by INSEAD and Harvard (Atasu et al., 2021).

9) ***Room Cost*** (sometimes called *land footprint* or *energy sprawl*) is a new cost category relevant for low energy density "renewable" energy such as wind, solar, or biomass. Due to the low energy density per m^2 of wind, solar, or biomass, they take up significantly more space than conventional energy generation installations where room costs tend to be negligible, at least relatively to VRE. These larger space requirements negatively impact our environment and need to be considered.

a. Room cost includes direct costs and opportunity costs related to the larger space required and the impact on, i.e., sea transportation routes, crop land, forests, urban areas, affected bird and animal life, changing wind and local climate, increasing temperatures, increasing water scarcity in aridic areas, noise pollution, etc.

b. Climatic and warming effects of large-scale wind and solar installations are well documented but remain mostly ignored by the industry, policy makers, and investors (see Barron-Gafford et al., 2016; Miller & Keith, 2018; Lu et al., 2020; Schernikau & Smith, 2022b).

c. A new coal power plant in India would require about 2,8 km^2 per 1 GW installed capacity plus the space for the coal mining (Zalk & Behrens, 2018; CEA, 2020). A new solar park would take about 17 km^2 per 1 GW installed capacity, plus the space for mining the resources to build solar. 1 GW installed solar capacity would generate much less electricity due to solar's low-capacity factor. Adjusting for a 16,5% average Spanish solar capacity factor, this would translate to a comparable 93 km^2 for solar, or a multiple of 33x compared to coal. Additional space is required for backup and/or storage due to solar's intermittent nature (Schernikau & Smith, 2021).

d. The room costs per installed MW of VRE increases the higher the installed capacity reaches. The reason has to do with reduced capacity factor for wind in larger wind farms (see wake effect) as well the reduced value of additional VRE beyond an optimal penetration level (NEA, 2018, p. 84).

10) ***Other Metrics***: Three more elements of the Full Cost of Electricity FCOE are metrics that are not measured in US$ but are important for environmental efficiency of electricity generation. None of these metrics are included in LCOE:

a. ***Material Input Per Unit of Service (MIPS)*** measures the material or resource efficiency of building energy equipment in tons of raw materials per MW capacity and per MWh produced electricity. *MIPS* for energy equipment thus measures an important element of environmental impact. The US Department of Energy DOE and the IEA document the high material input for renewable technology and capacity (see Figure 4, DOE, 2015; IEA, 2020d, p. 6).

b. ***Lifetime***: measures how long the equipment is used before it is retired or replaced. We need to consider that repowering of wind and solar significantly reduces the designed lifetime.

c. ***energy Return on Investment (eROI)***: in a way summarizes a large portion of all measures mentioned above. eROI also accounts for the net energy efficiency of building, operating, and recycling the equipment. It includes all embedded energy. An *eROI* of 2:1 means investing 1 kWh input energy for every 2 kWh of output energy. As per Weissbach et al. (2013), solar and biomass in Northern Europe have a buffered eROI of about 2–4. Nuclear has an eROI of about 75, and coal and gas about 30 (which the authors consider to be too optimistic). Roman culture, the most efficient pre-industrial civilization, reached an eROI of 2:1. Much uncertainty remains about actual eROI values and further research is required.

The authors emphasize here that the ***Full Cost of Electricity "FCOE" to society does not include taxes or subsidies*** which in fact are arbitrary (Note 4). Governments sometimes impose government set prices or taxes in an attempt to emulate such true costs or to support research & development. FCOE will account for all "true costs" and therefore may not be the right metric for all investment decisions that have to incorporate taxes, subsidies, or prices (rather than costs) of certain elements.

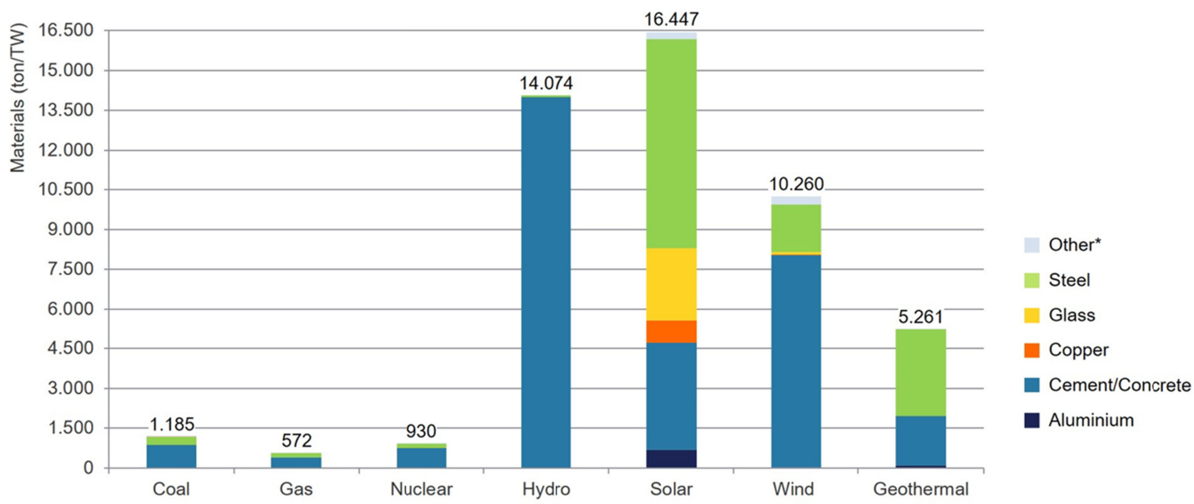

Figure 4. Base-material input per 1 TW generation

Note: Other includes iron, lead, plastic, and silicon

Source: Adapted from DOE, 2015, Table 10.4, p. 390.

FCOE attempts to estimate the true cost to society that is relevant when estimating the global cost of the energy transition to the global cost of any human-caused climatic changes. Therefore, fossil fuel subsidies are not included as a separate item (Note 4). Neither are subsidies for wind and solar included, such as missing CO_2 taxes even though the production and recycling of solar and wind capacity and backup systems incur significant GHG emissions, or missing integration costs for VRE as explained before and detailed in OECD NEA 2018, p. 39. Please note that to date, CO_2 or "carbon" taxes include only direct CO_2 emissions from fuel-combustion leaving out life-cycle emissions along the entire value chain, such as methane and other GHGs. Additionally, less than half of anthropogenic CO_2 emissions end up air-borne with the remainder taken up by nature (see Schernikau & Smith, 2022a on *Climate Impacts of Fossil Fuels*). Therefore, ***CO_2 taxes are misleading and***

wrong, causing economic and environmental undesired distortions such as the switch from coal to gas for climate reasons, dismissing the higher climate impact of methane emissions associated with gas and especially LNG production.

From the above analysis (see also Schernikau and Smith 2022a), it can be concluded that Levelized Cost of Electricity LCOE – which only includes Cost of Building (1), Cost of Fuel (2), Cost of Operation (3), and sometimes certain CO_2 taxes (part of Cost of Emissions 7) – is not a reliable, nor environmentally or economically viable measure with which to evaluate different forms of energy generation at country or society level. Only FCOE includes all relevant economic and environmental costs from emissions and non-emissions, though its true value is difficult – but not impossible – to determine.

Renowned energy think-tanks such as the International Energy Agency (IEA) in France, the International Energy Economics Institute (IEEJ) in Japan, the OECD, or the ***US Energy Information Agency (EIA) have pointed out the incompleteness of LCOE multiple times. Yet LCOE continuess to be widely used despite its failings***, usually without clear disclaimers and notes, even by these agencies themselves, by governments, banks, institutions, NGOs, companies, many scientists, and the common press.

Undesirable effects occur when conventional fuels and variable renewable energy VRE (wind and solar) are mixed to provide a country's electricity. These effects would be measured completely by FCOE categories 1–10 above. For instance, beyond a certain point, usually about a 10-20% capacity share, the cost to a nation's electricity system always increases with higher shares of variable renewable energy VRE, such as wind and solar (IEEJ, 2020, p. 124; IEA, 2019a, 2020c, p. 13). The reasons include but are not limited to the previously discussed differential energy density and efficiency, intermittency and thus backup/storage requirement, low-capacity factors, interconnection costs, material and energy costs, low eROI, efficiency losses of backup capacity, room costs for the space required and plant/animal life destroyed, recycling needs, and so forth.

The IEA confirmed in December 2020 (IEA 2020c, p. 14): "*...the system value of variable renewables such as wind and solar decreases as their share in the power supply increases*". This would also remain true if the price of renewable capacity (cost item 1: Cost of Building) continues to decline or even were to reach zero. For example, it doesn't change the conclusion even if the price of solar panels produced with coal power in China partially using forced labor reaches zero. This would also remain true if wind or solar technology would reach an impossible 100% quantum efficiency.

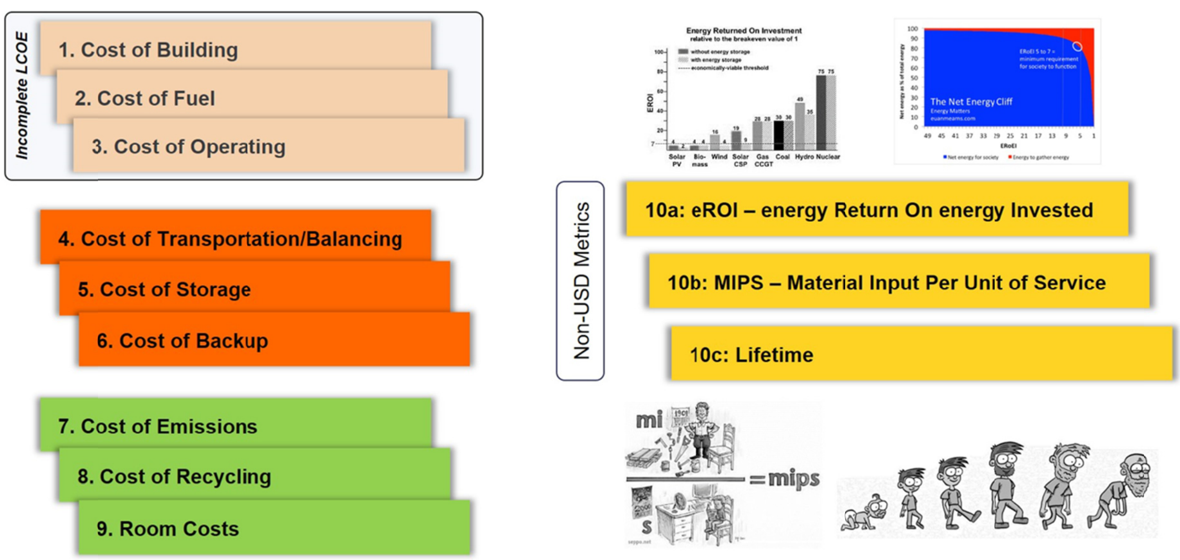

Figure 5. Full cost of electricity to society – A complete picture

Note: Age cartoon original from Alexandra Martin; energy cliff from eROI for beginners; MIPS cartoon from Seppo.net, eROI Weissbach et al., 2013.

Source: Schernikau Research and Analysis.

LCOE is inadequate to compare intermittent forms of energy generation with dispatchable ones, and therefore when making energy policy decisions at a country or society level. LCOE may, however, be used selectively to compare dispatchable generation methods with similar material and energy inputs, such as coal and gas. Using FCOE, or the full cost to society, wind and solar are not cheaper than conventional power generation and in fact become more expensive the higher their penetration in the energy system. This is also illustrated by the high cost of the so-called "green" energy transition especially to poorer nations (McKinsey, 2022; Wood Mackenzie, 2022). If wind and solar were truly cheaper – in a free market economy – they would not require trillions of dollars of government funding or subsidies, or laws to force their installation.

2.2 Energy Return on Energy Invested – eROI

The authors suggest that environmental efficiency of energy is more complex than GHG emissions alone. Especially energy return on energy invested, or energy return – ***eROI, material input, lifetime, and recycling efficiency need to be considered as they determine additional very important environmental and economic elements for evaluating electricity generation***.

eROI measures the energy efficiency of an energy gathering system. Higher eROI translates to lower environmental and economic costs, thus lower prices and higher utility. Lower eROI translates to higher environmental and economic costs, thus higher prices and lower utility. When we use less input energy to produce the same output energy, our systems become environmentally and economically more viable. ***When we use relatively more input energy for each unit of output energy, we risk what is referred to as "energy starvation"*** (see Appendix on energy shortages). At an eROI of 1 or below, we are running our systems at an energy deficit.

> Note: Vaclav Smil's *Energy and Civilization – a History* (Smil, 2017) is an excellent, highly-acclaimed book on the subject of energy. In addition, the authors recommend Kiefer (2013) and Delannoy et al. (2021) for more detailed discussions on eROI. Kis et al. (2018) approach eROI by using GER (Gross Energy Ratio) and GEER (Gross External Energy Ratio). Kis et al. define GEER as life-cycle eROI and find a global average for GEER of approx. 11:1. Due to the complexity of eROI, more research is required in harmonizing the approach for its determination.

The eROI is generally higher for wind than for solar, also driven by the higher average capacity factor. According to Carbajales-Dale et al. (2014), the average solar PV from a net energy efficiency point of view can only "afford" 1,3 days of battery storage "*before the industry operates at an energy deficit*". Wind, from a net energy efficiency point of view, can "afford" over 80 days of geological storage (12 days of battery storage). However, for the mentioned net energy efficiency calculations, the researchers made the simplifying yet unrealistically generous assumption that a generation technology is supplied with enough energy flow (either wind or sunlight) to deliver 24h of average electrical power output every single day. This means days or weeks with no sun or wind would multiply the storage requirement and therefore further diminish the net energy efficiency or eROI. Carbajales-Dale et al. included the proportion of electricity output consumed in manufacturing and deploying new capacity.

It can be concluded that wind and solar have a very low eROI and are therefore a step backward in history in terms of system energy efficiency. Their grid-scale employment risks energy starvation and is therefore not desirable economically nor environmentally. The authors would like to point out that for certain applications, i.e., heating a pool that is not connected to the grid or heating water for personal use in remote areas, solar and wind may be a desirable complement to our energy systems. The installation of wind and solar does reduce the amount of fossil fuels combusted assuming no increase in power demand, which is the only positive of their employment. This positive aspect comes at high costs summarized illustratively in Figure 3: *Summary of shortcomings of variable renewable energy for electricity generation*.

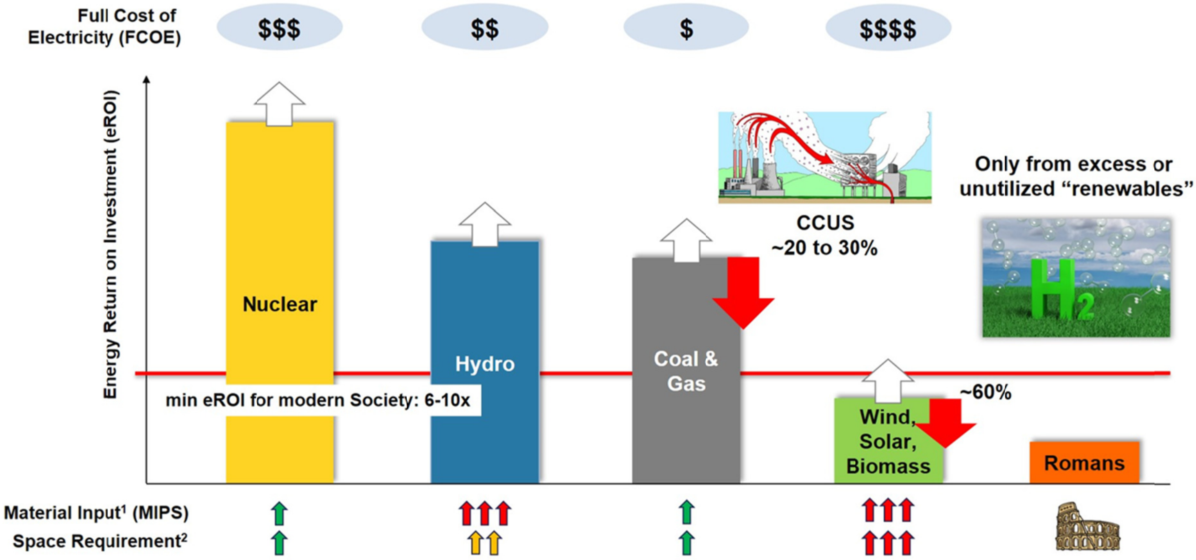

Figure 6. The concepts of eROI and material efficiency – Illustrative

Note:White arrows illustrate future technological improvements, red arrows illustrate loss of energy and therefore loss of eROI from CCUS or "green" H_2; (1) Material Input MIPS measures the resource efficiency, i.e., material input required per unit of output, here for example per MW capacity or per MWh of produced electricity which includes the materials required to build the generation capacity.

(2) Space requirement measures the land footprint per unit of electricity produced.

Source: Schernikau Research and Analysis.

The industrial revolution reduced humanity's dependency on biomass, hydro, and wind. Based on the new-found **high-eROI-coal-energy**, this energy revolution allowed for the dramatic increase in standards of living, life-expectancy, industrialization, decrease of heavy human labor, and abandonment of slavery. This revolution and its positive impact on human life was only possible due to a drastic increase in energy availability, energy efficiency, or eROI. The energy revolution came with a diversification away from biomass burning towards fossil fuels, hydro, and later nuclear.

Prior to the industrial revolution human development peaked during the Roman Empire at an estimated sustained eROI of around 2:1 (Figure 6). During the 20th century, petroleum's high eROI, higher energy density, and versatility enabled the transportation revolution with cars, aircraft, and rockets. To appreciate the magnitude of petroleum's discovery, consider that ***three tablespoons of crude oil contain the equivalent of eight hours of human labor*** (Kiefer, 2013, Note 5). Figure schematically illustrates the concepts of eROI and material efficiency in today's electricity systems and the impact of CCUS or hydrogen storage on energy efficiencies (Supekar & Skerlos, 2015).

Dr. Euan Mearns 2016 based on Kiefer's work explains eROI and points out that modern life requires a minimum eROI of 5–7 while most solar and many wind installations depending on location have a lower eROI and are therefore inherently energy insufficient to support society at large. As per Weissbach et al. (2013), solar and biomass in Northern Europe have a buffered eROI of about 2–4. Kiefer defines "*The Net Energy Cliff*" which demonstrates how – with declining eROI – society would commit ever larger amounts of available energy to energy gathering activities.

One example is employment. Below an eROI of 5–7, such great numbers of people would be working for energy gathering industries that there would not be enough people left to fill all other positions our current altruistic society requires. Some, however, may argue that this is desirable due to artificial intelligence's long-term threat to human labor. IEA's recent World Energy Outlook (IEA, 2021b) confirmed that global employment would rise from "renewable" energy systems, therefore providing evidence for the lower eROI of "renewable" technologies. McKinsey 2018, though not considering the eROI concept, argues that automation will replace low-level workers; this trend is already well underway. Those without higher technical and intellectual skills may become unemployable in the future workforce. In essence, McKinsey does not seem to see a problem with a higher employment in energy related industries.

The principle of energy return on investment eROI is at the core of society's energy efficiency which is at the core of humanity's development and survival.

2.3 The 2nd Law of Thermodynamics' Impact on Energy Systems

The preface already introduced the 1st and 2nd Law of Thermodynamics. Figure 7 tries to summarize the laws' function. The 1st law simply states that energy can never be lost, only be converted from one form to another.

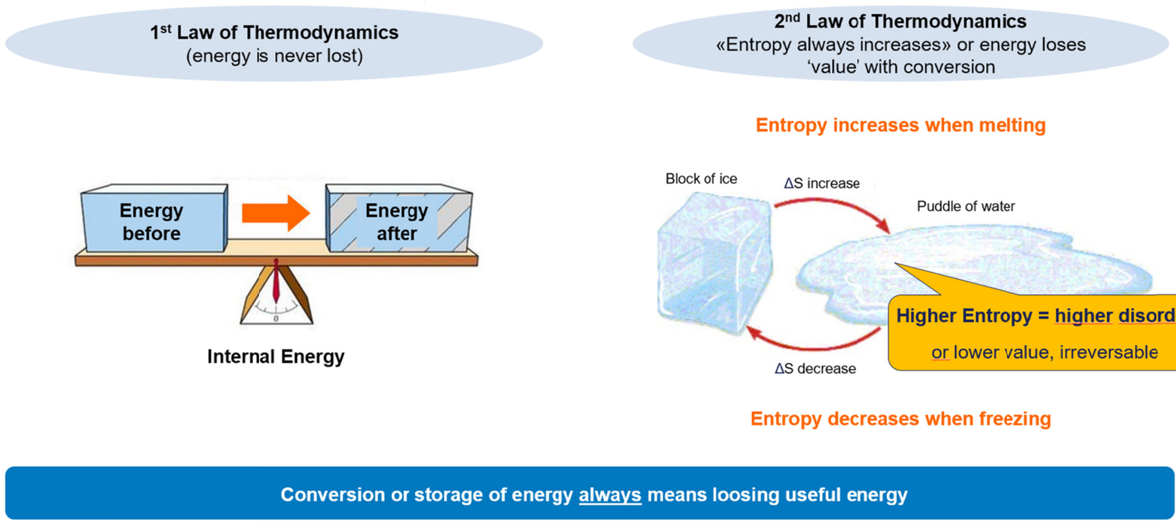

Figure 7. 1st and 2nd Law of Thermodynamics

Source: Schernikau Illustration, graph from https://i.ytimg.com/vi/IyNNzOT4jO0/maxresdefault.jpg

The 2nd Law introduces the concept of entropy, another word for usefulness or value of energy (high entropy = high disorder, or low value of energy). Essentially, the 2nd law explains why in a natural state heat always moves from warm to cold and not the other way around. When energy is converted from one form to another, entropy always increases, or "useful" energy is lost. The logical conclusion for our modern energy systems is that ***we need to avoid conversion and storage of energy as well as complexity of our energy systems as much as possible***, as all of these result in loss of useful energy.

This loss of useful energy is important because it directly translates into reduced system energy efficiency. It directly results in lowering the eROI when we convert wind power to hydrogen, when we store hydrogen, when we convert hydrogen back to power. It also directly results in warming of our biosphere. The net efficiency of a gas or coal-fired power plant is also the result of the 2nd Law of Thermodynamics. Every process that takes place in the boiler, the turbine, or the generator "costs" energy that is lost in form of low value heat to our surroundings.

We established in chapter 2 that the "green" energy transition towards variable renewable energy in form of wind and solar will substantially increase the cost of electricity. The rise in cost will primarily burden poorer people and developing nations (McKinsey, 2022; Wood Mackenzie, 2022). With the concept of the 2nd Law of Thermodynamics, we can now demonstrate part of reason why ***the "green" energy transition will reduce global net energy efficiencies, because they require more complex energy systems and increased storage***. The IEA summarized the issue of increasing complexity in their article *Energy transitions require innovation in power system planning* (IEA, 2022a, see Figure 8) as follows:

- "*Shifting away from centralized thermal power plants as the main providers of electricity makes power systems more complex. Multiple services are needed to maintain secure electricity supply.*
- *In addition to supplying enough energy, these include meeting peak capacity requirements, keeping the power system stable during short-term disturbances, and having enough flexibility to ramp up and down in response to changes in supply or demand.*"

More importantly, ***the 1st Law of Thermodynamics proves that most of our produced and consumed energy will end up in low-value or high-entropy heat and thus warms our biosphere adding to measured temperature increase.*** The authors note that there is also embedded energy in the products that we produce that is not released in form of heat. These products are primarily used for housing or end up being consumables. The well-documented heat island effect is also a manifestation of the heat emitted from our energy systems to our surroundings.

When we produce energy from sources such as nuclear, oil, coal, gas, or even geothermal, then we take energy that is "inside our planet" and in the end convert it to low-value heat warming our biosphere. When we use energy from solar radiation by employing photovoltaics, we will not "net" warm our planet, only if we disregard the warming from solar panel's absorption and shifting atmospheric circulation (Lu et all., 2020), and if we disregard the energy for building and recycling the equipment or systems required to extract and use solar energy. Taking the energy from wind has additional climatic warming consequences as detailed by Miller and Keith 2018. High CO_2 emitting forms of producing energy such as coal or gas partially off-set the warming of the biosphere through CO_2-driven fertilization and greening that reduces solar warming (solar radiation can only do one thing, grow a plant, or warm the Earth, see Schernikau & Smith, 2022a).

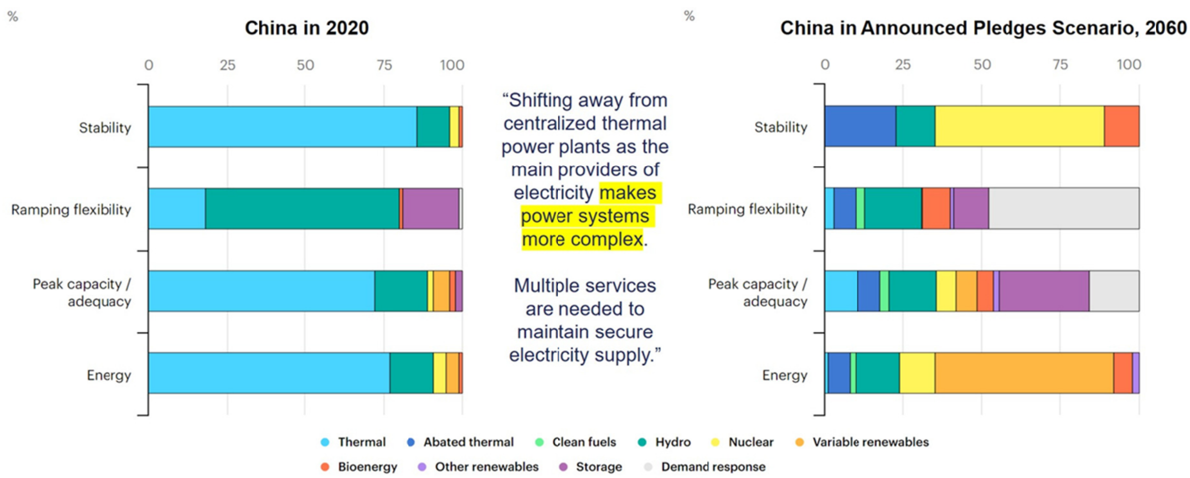

Figure 8. Current and Future Energy Security in China

Source: Based on IEA, 2022a.

3. Discussion (Projected Future of Energy and Suggestions for a Revised Energy Policy)

To allow for a "clean energy transition", The Boston Consulting Group (BCG, 2021b) projects global wind and solar power capacity to increase similar to Germany's past 20-year overbuilding (see Figures 2 and 9). 2020 global power generation capacity totaled about 8.000 GW, of which over 1.400 GW were wind and solar. In 8 years (at time of writing), by 2030, BCG projects that wind and solar alone will have to reach 8.600 GW, doubling today's entire global electricity capacity, the same as what happened in Germany from 2002 until 2021. Based on 2021 IRENA outlook data, BCG also forecasts that global wind and solar installed capacity must reach 22.000 GW by 2050, almost quadruple today's entire global electricity generation capacity. It is the authors' opinion that ***these name-plate capacities will not be reached as the world would run out of energy, raw materials, and money before*** it happens, and if they were reached, the economic and environmental impact to society would be distressing as explained in this paper.

Such dramatic expansion of wind and solar will result in more fragile and expensive energy systems. It will also negatively impact the environment (see space requirements, backup, material input, eROI, recycling needs, local climate impacts, etc.) offsetting any desired – entirely modeled – positive effects on the global climate from GHG emissions reductions. On the positive side, in the authors' view the only positive aspect, such expansion will limit the use of *fossil* raw materials mined. The question is, however, if it would truly reduce *total* raw material use when honestly and truly accounting for the entire life cycle from resource mining, via material transportation, processing, manufacturing and operation, to recycling (Figures 4 and 11). Further research is required here.

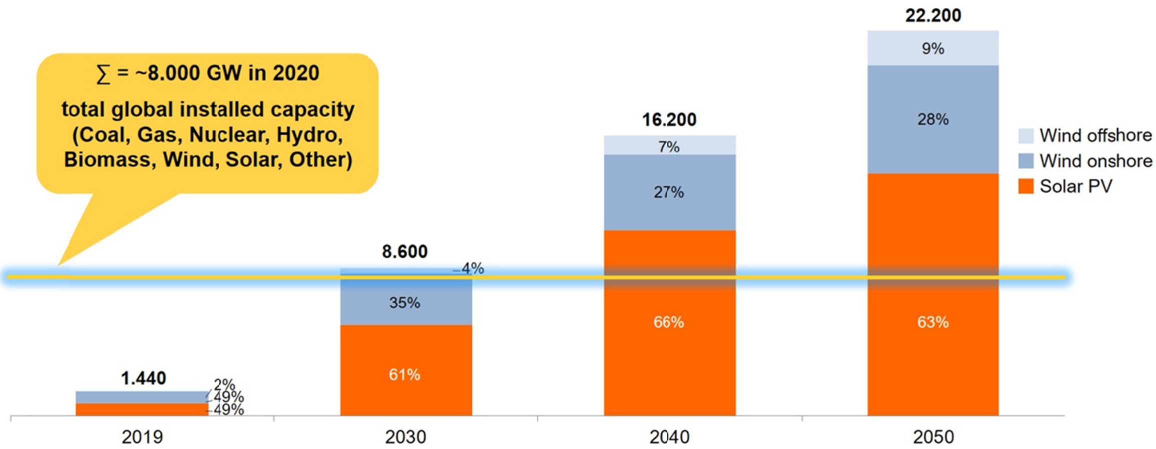

Figure 9. Wind/Solar capacity forecast for 2050 to be almost 4x today's total capacity

Source: Schernikau Research and Analysis based on IRENA, 2021 and BCG, 2021b.

After having risen from ~2 billion to ~8 billion in the past 100 years, the UN projects that global population will rise further from currently ~8 billion to ~10 billion until 2050 (OurWorldInData, 2021). Population may peak around 11–12 billion by the end of the century. Despite continued improvements in energy efficiencies, rising living standards in developing nations are forecasted to increase global average annual per capita energy consumption from ~21.000 kWh to ~25.000 kWh by 2050 (Lomborg, 2020; BP, 2019).

As a result, and as illustrated in Figure 10, ***global primary energy consumption could rise by up to 50% by 2050*** (~25% population increase and ~20% PE/capita increase translates to ~50% PE demand increase). Energy demand growth is fueled by developing nations in Asia, Africa, and South America. Developed nations are expected to consume less energy in the decades to come, driven by population decrease/stagnation and efficiency increases. However, historically, energy efficiency improvements have always increased energy demand (see *Jevons Paradox*, Polimeni et al., 2015). To illustrate, please refer to the authors recommended book *Life After Google* (Gilder, 2018) explaining the increased requirement for energy for global computing.

The authors reiterate that recent models by McKinsey estimate that global primary energy demand will only increase by 14% by 2050, while IEA's 2021 Net-Zero Pathway models a reduction by ~10% in primary energy by 2030, in 8 years from writing of this paper, although this is questioned by the energy industry and the authors (IEA, 2021e; McKinsey, 2021). The same reports estimate that global electricity generation will almost double from 2020 to 2050 also driven by the projected electrification of transportation. The Institute for Energy Economics in Japan (IEEJ, 2021) predicts global primary energy demand to increase by 30% by 2050 while the American EIA predicts a ~50% increase (EIA, 2021). Kober et al. 2020 compare various energy scenarios and point out that essentially all energy scenarios assume a decoupling of economic growth and energy consumption in the future.

Growth in electricity demand will surpass primary energy growth partially due to the global electrification of operations. Electricity's share of primary energy will also increase because our lives become more computerized and "gadgetized". Electricity is also planned to replace significant non-electricity energy consumption for transportation (i.e., EVs), heating (i.e., heat pump), and industry (i.e., DRI for steel production).

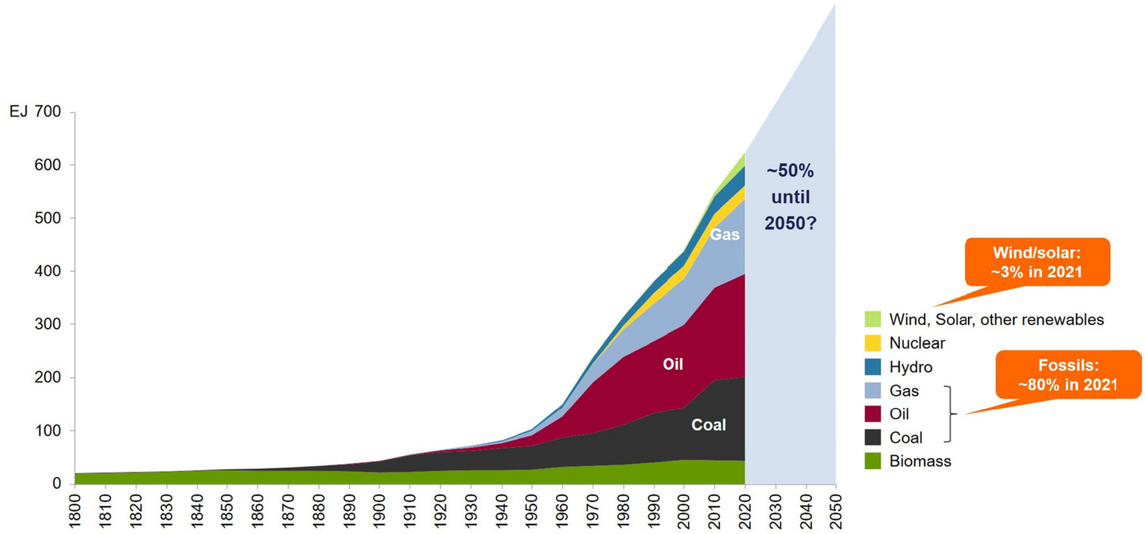

Figure 10. Global primary energy from 1750 to 2050

Note: Primary electricity converted by direct equivalent method. Exa-Joule (EJ), where 600 EJ approximates 170.000 TWh

Source: Schernikau Research and Analysis based on data compiled by J. David Hughes. Post-1965 data from BP, Statistical Review of World Energy (https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html). Pre-1965 data from Arnulf Grubler (1998): "Technology and Global Change: Data Appendix" (https://user.iiasa.ac.at/~gruebler/Data/TechnologyAndGlobalChange/), and World Energy Council (2013): World Energy Scenarios Composing energy futures to 2050 (https://www.worldenergy.org/assets/downloads/World-Energy-Scenarios_Composing-energy-futures-to-2050_Executive-summary.pdf).

Despite hoped-for technological improvements, ***it is a prudent assumption that wind and solar alone will not be able to generate enough total electricity to match the expected demand increase to 2050***. This is confirmed by the IEEJ 2021 forecasting an absolute increase in fossil fuels share in primary energy in its reference case by 2050. In July 2021, the IEA confirmed that "…[renewables] are expected to be able to serve only around half of the projected growth in global [electricity] demand in 2021 and 2022" (IEA, 2021c). For primary energy growth, the renewable share will be only a fraction, perhaps 20%, as today about 2/5th of primary energy is consumed in electricity production.

Even if wind and solar were to fulfil all future increases in primary energy demand, it becomes evident that for the next 30 years and beyond we will continue to depend on conventional energy resources for a large portion, if not the vast majority, of our global energy needs. For recent "Net-Zero" pathways (IEA, 2021e) and scenarios to succeed on paper, they require a number of highly optimistic, often unrealistic, assumptions related to rapid advances in technology development, hydrogen penetration, demand curtailments, raw materials with controllable prices and supply availability, and so forth. They also largely dismiss eROI, material input, lifetime, and realistic recycling assumptions and thus "renewables'" negative economic and environmental impact.

4. Conclusions and Future Research (Future Energy Policy)

Energy policy is of utmost importance and has three objectives:

(1) Security of supply,

(2) Affordability of supply, and

(3) Environmental protection.

Today's energy policy, however, focuses simplistically on reducing anthropogenic (human-caused-energy) CO_2 emissions to limit or reduce future global warming (Figure 11). As demonstrated by Glasgow's COP26 meeting results from November 2021 including but not limited to the "*Global Coal to Clean Power Transition Statement*" (UN-COP26 2021), many nations' energy policy decisions today pay less attention onto objectives (1) and (2), and even most aspects of (3) such as plant/animal life, land/space use, material & energy input, recycling efficiency (see Figures 3, 11, and 12). The 2022 Russia/Ukraine crisis has put new focus on energy security at least in Europe which to a large extent has relied on Russian energy raw material supply and spent 20 years reducing its own energy independence (see Germany's political decisions to abandon coal and nuclear and the EU's extensive initiatives to divest from reliable fossil fuel energy sources). This new focus, however, seems rather ad-hoc than strategic.

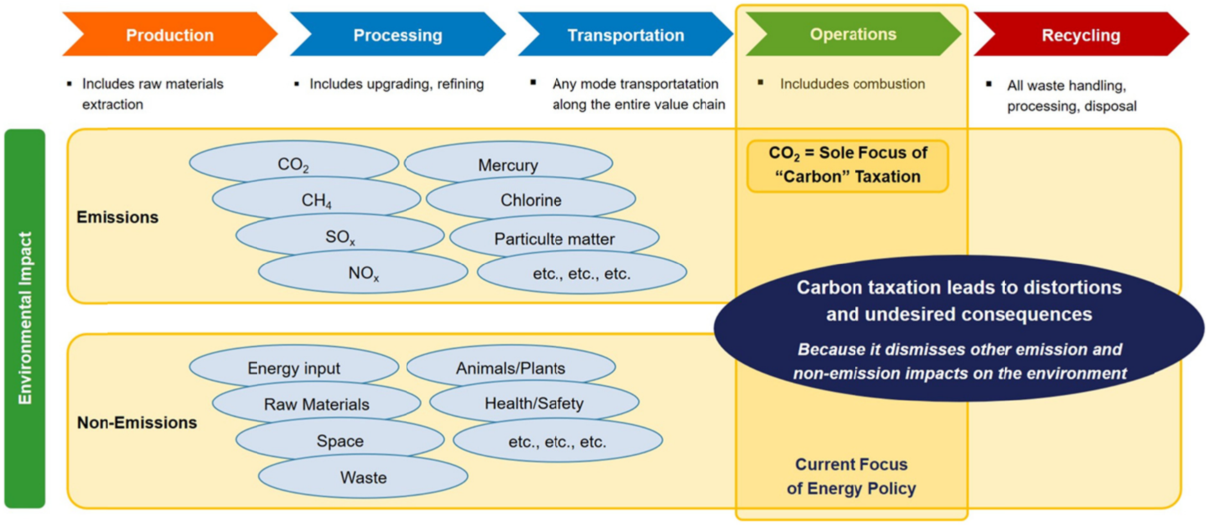

Figure 11. Environmental impact of energy systems – Why carbon taxation leads to distortions and undesired consequences

Source: Schernikau Illustration.

The objective of global investments in the "energy transition" should be to meet all three prime goals of energy policy, not only one sub-goal, to reduce human-energy CO_2 emissions. ***Today's misguided energy investment focus on wind and solar increases the risk of energy starvation with all its consequences*** (see Appendix).

The full cost of electricity FCOE and eROI illustrate that wind and solar are, unfortunately, not the solution to humanity's energy problem. At grid scale, they will lead to undesired economic and environmental outcomes. The use of LCOE for the purpose of discussing the "green" energy transition must cease because it continues to mislead decision makers. Governments, industries, and educational institutions are urgently encouraged to spend additional time on learning and discussing energy economic realities before forcing the basis of today's existence away from proven and relatively affordable energy systems. It takes only energy to solve the food and water crisis, it takes only energy to withstand natural disasters, it takes only energy to eradicate poverty.

It must be understood that the dramatic planned increase in installed solar and wind capacity as detailed in Figure 10 has one advantage, it reduces the amount of required fossil or nuclear fuel consumed, assuming no increase in power demand. However, this one "advantage" comes at significant costs to our environment and economies that have been detailed herein. The costs to the environment originate from the intermittency and inherent low eROI of VRE when considering the entire value chain and life-cycle (Figure 11).

The **New Energy Revolution** is a point in time where humanity can sustainably wean off fossil fuels. Such new energy system may be completely new, possible a combination of fusion or fission, solar, geothermal, or a presently unknown energy source (see also Manheimer, 2022). It would likely harness the power of the nuclear force, the power of our planetary system (i.e., sun), and the energy from within our planet. It will have little to do with today's wind and photovoltaic technologies due to the physical limits of energy density, or energy available per m^2, and intermittency.

The authors suggest that to reach this **New Energy Revolution**, more must be invested in education and base research (energy generation, material extraction & processing, storage, superconductors, efficient recycling, etc.). Just as important is the second suggestion for continued simultaneous investment in conventional energy to make it more efficient and environmentally friendly. It must be noted, however, that non-CO_2 emitting forms of energy generation will have no heat-offset in the form of greening and fertilizing CO_2 (see Harverd et al., 2019; Idso, 2021 for an extensive list of peer-reviewed literature). The reduced energy efficiency of VRE and the increased generation of energy from non-fossil origins will logically cause an increase in low-value or high-entropy heat that will continue to warm our planet even if no GHGs were emitted.

The authors suggest that future research and development should concentrate on understanding the true eROI of energy systems to aid prioritization, and on reducing emissions and non-emissions environmental impact of existing energy systems. Future research should detail and quantify FCOE and eROI for conventional and variable renewable energy systems, this work requires funding, a larger team, and will be a global effort.

To further optimize conventional energy systems, the authors suggest that ultra-super-critical power plants (USC) and high-efficiency, low-emissions (HELE) technologies should be further researched and implemented for increasing their efficiencies. USC technology would have an immediate positive effect on nature at significantly lower costs than installing grid-scale variable renewable energy systems with the required backup (see also Tramosljika et al., 2021). If CO_2 emissions need to be reduced, one of the most energy and material efficient ways would be to equip USC power plants with CCUS technology. However, the undisputed benefits of increased CO_2 concentrations in the atmosphere because of its photosynthetic and growth effects (fertilization) on plants need to be considered in energy policy decisions as well.

Investment in – not divestment from – fossil fuel is the logical conclusion not only to eradicate (energy) poverty, improve environmental and economic efficiency of fossil-fuel-installed capacity *(whether it be for transportation, heating, or generating electricity),* but also to avoid a prolonged energy crisis that started in second half of 2021.

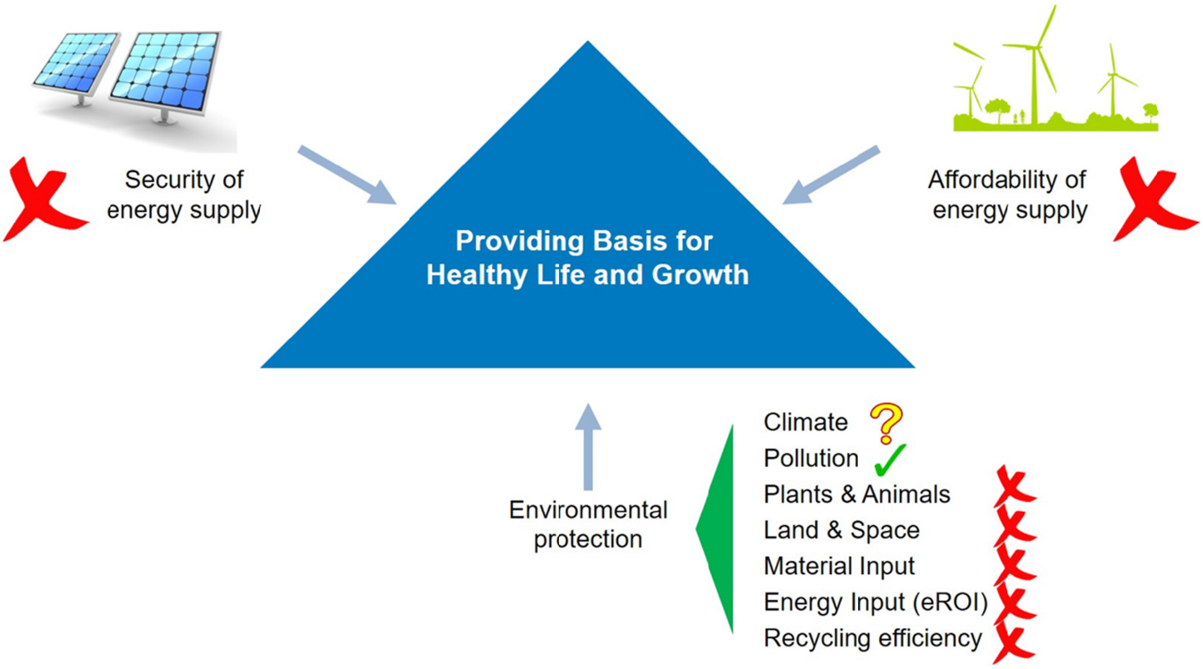

Figure 12. Variable renewable energy does not fulfil objectives of energy policy

Source: Schernikau Illustration.

5. Appendix: Energy Shortages, Impacts and Causes

The apparent energy shortage in Europe and other parts of the world starting in 2021 illustrates FCOE and the explained high cost of variable renewable energy. The lack of investment in conventional forms of energy resulted in undersupply while at the same time wind and solar were not able to satisfy increased demand. Germany's highest consumer power prices of any industrialized nations is further evidence of FCOE and thus also driven by Germany's relatively high penetration of VRE.

BCG and IEF International Energy Forum warned in their December 2020 Energy report *Oil and Gas Investment in the New Risk Environment* that ***"… by 2030, investment levels [in oil and gas] will need to rise by at least US$ 225 billion from 2020 levels to stave off a [energy] crisis"*** (BCG & IEF, 2020)**.** Investments in coal are pro rata even lower than in oil and gas (Figure 13). The press started to pick up this subject in the third quarter of 2021 when energy resources and electricity prices started to soar and first signs of a global energy shortages surfaced.

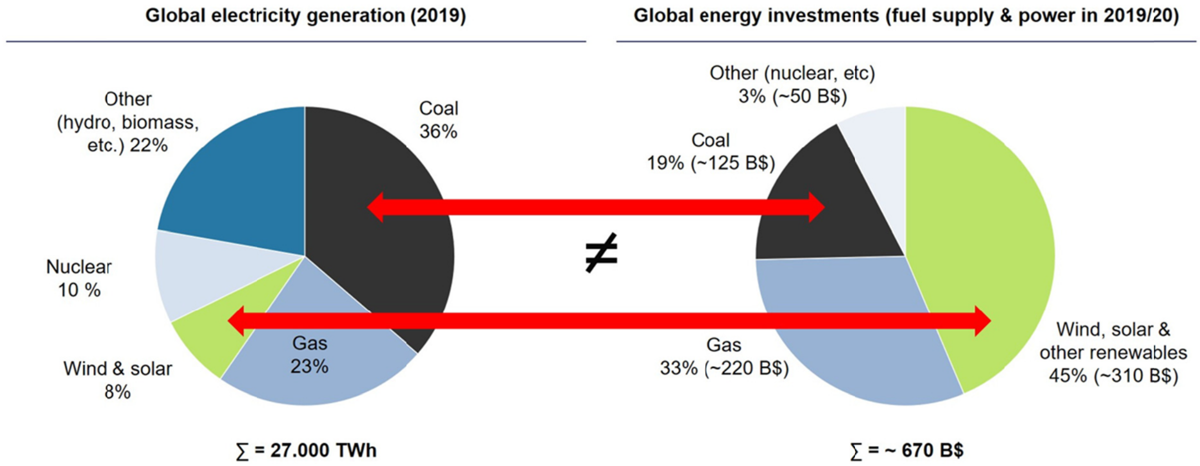

Figure 13. Investments in coal less than half of wind/solar, while coal provides 4x more power

Note: Right side includes investments in fuel supply and power; for Gas it is assumed that 50% of total "oil & gas" fuel supply investments went into gas (511 B$ x 0,5 = 255 B$).

Sources: Schernikau Research and Analysis based no IEA and BNEF Data; IEA's World Energy Investment 2020.

The 2022 Russian invasion of the Ukraine also illustrated the fragility of global energy systems and how intertwined energy and politics are, especially when it comes to oil, gas, and nuclear. Of the dispatchable forms of energy, coal, hydro, and geothermal energy are the least political. Below a list of selected press articles on the topic of the "new energy crisis", for links see Note 6.

1) Bjarne Schieldrop, chief commodities analyst at SEB, Mar 2022: "*The global economy is facing energy starvation right now*' and '*demand destruction will set a limit to the upside eventually*".

2) Vaclav Smil wrote in Feb. 2022 referring to the Russian invasion to the Ukraine: "*This war will have many long-term consequences, but possibly none more important than its effects on the future of the European energy supply*".

3) The N24 wrote in Feb 2022: "*The worst energy crisis since 1973*".

4) CNN wrote in Nov 2021: "*... anti-poverty organizations and environmental campaigners have warned that millions of people across Europe may not be able to afford to heat their homes this winter ...*".

5) Wikipedia set up a separate page and referenced the 2021 Global Energy Crisis in November 2021: "*The 2021 global energy crisis is an ongoing shortage of energy across the world, affecting countries such as the United Kingdom and China, among others*".

6) Bloomberg wrote in Oct 2021: "*The world is living through the first major energy crisis of the clean-power transition. It won't be the last*".

7) The Globe and Mail wrote in Oct 2021: "*India's coal crisis brews as power demand surges, record global prices bite*".

8) Bloomberg wrote in Sep 2021: "*Europe is short of gas and coal and if the wind doesn't blow, the worst-case scenario could play out: widespread blackouts that force businesses and factories to shut. The unprecedented energy crunch has been brewing for years, with Europe growing increasingly dependent on intermittent sources of energy such as wind and solar while investments in fossil fuels declined*".

9) Nikkei Asia wrote in Sep 2021: "*Key Apple, Tesla suppliers halt production amid China power crunch*. Bloomberg follows in the same month that *China may be diving head first into a power supply shock that could hit Asia's largest economy hard just as the Evergrande crisis sends shockwaves through its financial system*".

10) Bloomberg quoted a gas executive in Aug 2021 warning that current energy policy could disrupt delivery of adequate and affordable fuel supply to consumers: "*The lack of capital investments in future natural gas projects does not lead us to an energy transition, but instead leads us down an inevitable path toward an energy crisis*".

The human and economic costs from shortages in electricity supply are apparent from several examples worldwide. A European example includes the 28th September 2003 Italian power outages. That day, the North of Italy experienced up to 3h-outage and the South (Sicily) up to 16h. A loss of 200 GWh to customers resulted in an estimated EUR 1,2 billion economic loss (Baruya, 2019, former IEA Clean Coal Center). Baruya summarizes "*In developing regions, such as sub-Saharan Africa, shortages in energy supplies impede business and economic growth. In advanced economies, failure in the power grid and generating capacity has also led to measurable economic losses, such as those seen in Italy in recent years*". Another direct impact of electricity outages will be loss to human lives and health. It must be noted, that none of the "Net-Zero" models or scenarios account for any cost resulting from energy shortage or energy starvation.

We have shown that ***the "energy transition" to variable renewable forms of energies such as wind and solar will result in higher electricity costs.*** Energy-transition-supporting strategy consultant McKinsey 2022 summarizes "*A Net-Zero transition would have a significant and often front-loaded effect on demand, capital allocation, costs, and jobs*". Research shows that a rise in electricity prices impacts economic output. Baruya 2019 summarized the impact of rising electricity costs to industries in China, the US, Russia, Mexico, Turkey, and Europe based on scientific research. The coefficients of elasticity between economic output and electricity prices were irrefutably negative. Output declined faster in the non-metallic minerals (cement) sector, metal smelting and processing, chemical industry, and mining and metal products. For example, in Vietnam, impacts of an increase in the electricity tariff on the long-run marginal cost of products manufactured using electricity-intensive processes were examined in 2008. An increase in tariffs drove price inflation of all affected goods and services (Baruya, 2019).

Baruya (2019) continues and confirms the authors' analysis how the retirement of fossil fuel-fired power plants without adequate, reliable, and affordable alternatives will "*reduce the amount of backup power to less than the amount required to meet capacity shortages during peak electricity demand*". Developing and industrializing nations, such as India, Indonesia, Bangladesh, and Pakistan will be negatively affected by the cessation of funding from Western financial institutions. Alternative funding may lead to the adoption of less efficient generating technologies resulting in increased environmental burden. Consequently, industrializing countries that do not invest in high-efficiency, low-emissions (HELE) conventional fuel technologies could face higher costs of generation, higher emissions reducing their competitiveness, and as a result slowing economic growth.

If investments in fossil fuels will not increase substantially and very soon, a prolonged global energy crisis will be difficult to avoid this decade. This remains true, even if all sustainability goals are achieved and wind and solar capacity continues to increase as planned or hoped. Global energy markets during the 2021 Covid recovery in Europe and Asia and the Russian/Ukrainian war in 2022 are testimonies to the impact of energy shortages.

The authors refer to Kiefer 2013 and reiterate that today oil, coal, gas, and uranium are the primary energy sources that nourish rather than starve governments and economies. A true primary energy source, like a true food source, need not to be subsidized. It must, by definition, yield many times more energy (and wealth) than it consumes, or else it is a sink, not a source. It is not by subsidies, but rather by the merits of eROI, material efficiency, and energy density, and in spite of heavy taxation and fierce competition with other energy alternatives, that oil, coal, gas, and nuclear have grown to dominate the global energy economy by over 80%.

References

AGE. (2021). *AG Energiebilanzen e.V. 2021*. Zusatzinformationen. Retrieved from https://ag-energiebilanzen.de/28-0-Zusatzinformationen.html%20und%20https:/ag-energiebilanzen.de/10-0-Auswertungstabellen.html

Agora. (2022). *Agora Energiewende, Energiewende Deutschland Stand 2021*. Retrieved from https://static.agora-energiewende.de/fileadmin/Projekte/2022/2022_01_DE-JAW2021/A-EW_247_Energiewende-Deutschland Stand-2021_WEB.pdf

Air Products. (2021). *ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility*. Retrieved July, 2020, from https://www.airproducts.com/news-center/2020/07/0707-air-products-agreement-for-green-ammonia-production-facility-for-export-to-hydrogen-market

Atasu et al. (2021). *INSEAD, The Hidden Cost of Solar Energy*. Retrieved December, 2021, from https://knowledge.insead.edu/responsibility/the-hidden-cost-of-solar-energy-17926

Barron-Gafford et al. (2016). *The Photovoltaic Heat Island Effect: Larger Solar Power Plants Increase Local*

Temperatures. Scientific Reports 6, no. 1. https://doi.org/10.1038/srep35070

Baruya. (2019). *Former IEA-Clean Coal Center: The Economic and Strategic Value of Coal*. CCC/296. Retrieved from https://www.sustainable-carbon.org/report/report-the-economic-and-strategic-value-of-coal-paul-baruya/

BCG. (2021a). *BCG CEO Guide to Cyber Security*. Retrieved September, 2021, from https://www.bcg.com/en-ch/featured-insights/executive-perspectives

BCG. (2021b). *Mastering Scale in Renewables*. Retrieved June, 2021, from https://www.bcg.com/publications/2021/maximizing-value-from-scale-renewable-energy

BCG. (2021c). *Executive Perspectives: The time for climate action is now*. Retrieved from https://media-publications.bcg.com/BCG-Executive-Perspectives-Time-for-Climate-Action.pdf

BCG and IEF. (2020). *Oil and Gas Investment in the New Risk Environment*. Retrieved from https://web-assets.bcg.com/5e/73/dcd6e1544ba2a964e6c082d684e8/bcg-oil-and-gas-investment-in-the-new-risk-environment-dec-2020.pdf

BfWE. (2020). *Bundesministerium für Wirtschaft und Energie*. EEG in Zahlen: Vergütung, Differenzkosten und EEG-Umlage 2000–2021. Retrieved from https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/eeg-in-zahlen-xls.html

BNEF. (2021). *Bloomberg New Energy Finance: Energy Transition Investment Trends*. Retrieved from https://assets.bbhub.io/professional/sites/24/Energy-Transition-Investment-Trends_Free-Summary_Jan2021.pdf

Bossel et al. (2003). The Future of the Hydrogen Economy: Bright or Bleak? *Cogeneration and Competitive Power Journal*, *18*(3). https://doi.org/10.1080/15453660309509023

BP. (2019). *BP Statistical Review of World Energy*. Primary Energy. Retrieved from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/primary-energy.html

BP. (2020). *BP Statistical Review of World Energy 2020*. Retrieved from https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

BP. (2021). *BP Statistical Review of World Energy 2021*. Retrieved from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Carbajales-Dale et al. (2014). Can We Afford Storage? A Dynamic Net Energy Analysis of Renewable Electricity Generation Supported by Energy Storage. *Energy & Environmental Science*, *7*(5). https://doi.org/10.1039/c3ee42125b

CDIAC. (2021). *Historical Carbon Dioxide Record from the Vostok Ice Core*. Retrieved December, 2021, from https://cdiac.ess-dive.lbl.gov/trends/co2/vostok.html

CEA. (2020). *Central Electricity Authority, Indian coal space requirement from CEA*. Retrieved April, 2020, from https://cea.nic.in/?lang=en

Chen et al. (2019). The Potential of Photovoltaics to Power the Belt and Road Initiative. *Joule*, *3*(8). https://doi.org/10.1016/j.joule.2019.06.006

Delannoy et al. (2021). EROI – peak oil and the low-carbon energy transition: A net-energy perspective. *Applied Energy*, *304*, 117843. https://doi.org/10.1016/j.apenergy.2021.117843

DOE. (2015). Department of Energy. *Quadrennial Technology Review*, 390. Retrieved September, 2015, from https://www.energy.gov/quadrennial-technology-review-2015

EC. (2022). *EC Subsidies – Energy Taxation, Carbon Pricing and Energy Subsidies*. Retrieved January, 2022, from https://www.eca.europa.eu/en/Pages/DocItem.aspx?did=60760

Economist. (2021). *The Climate Issue: Hitting "Net-Zero" by 2050*. The Economist. Retrieved March, 2021, from https://view.e.economist.com/?qs=4cdea30c55776c93354f740a2968d740a6c2aa7711c3b98abeec8c225481b2e3a5a6d8a3b267c9bb10277a1cc7a1ffc902d15ee18205f6ab75af7ae100e83af7e4c2947559a38107fb27f12061f5193f

EIA. (2021). *US Energy Information Administration*. Annual Energy Outlook. Retrieved February, 2021, from https://www.eia.gov/outlooks/aeo/

Eschenbach, W. (2017). *The Cruelest Tax of All | Skating Under the Ice* (wordpress.com). Detail: The Energy Information Agency (EIA) collects relevant data, with exception of gasoline usage. Eschenbach collected most recent data, for 2009 (Excel workbook). Gasoline usage figures are here from the US Bureau of Labor Statistics. Income averages by tiers are available here from the US Census Bureau.

Frauenhofer. (2022). *Frauenhofer Institute*. Energy Charts. Retrieved from https://energy-charts.info/charts/installed_power/chart.htm?l=de&c=DE&stacking=sorted&expansion=installed_power&sum=0&partsum=0&year=-1

Fujimuri et al. (2020). An assessment of the potential of using carbon tax revenue to tackle poverty. *Environ. Res. Lett.*, *15*, 114063. https://doi.org/10.1088/1748-9326/abb55d

Gilder. (2018). *Life After Google: The Fall of Big Data and the Rise of the Blockchain Economy* (Chapter 8). ISBN: 9781621575764. Retrieved from https://www.amazon.com/Life-After-Google-Blockchain-Economy/dp/1621575764

Global Solar Atlas. (2022b). *Solar map*. Retrieved from http://www.globalsolaratlas.info/

Global Wind Atlas. (2022a). *Wind map*. Retrieved from https://globalwindatlas.info/

Greenberg, A. (2019). *Sandworm – a new era of cyberwar and the hunt for the Kremlin's most dangerous hackers Nov. 2019*. ISBN 978-0-385-54440-5. https://www.orellfuessli.ch/shop/

GSU. (2021). *Georgia State University, on heat pumps*. Retrieved Deceber, 2021, from http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/heatpump.html

H_2-View. (2021). *\$9.4bn H_2 Megaproject Set for Namibia*. Retrieved November, 2021, from https://www.h2-view.com/story/9-4bn-hydrogen-megaproject-set-for-namibia/

Harvey, F. (2021). *The Guardian*. Retrieved May, 2021, from https://www.theguardian.com/environment/2021/may/18/no-new-investment-in-fossil-fuels-demands-top-energy-economist#:~:text=Fatih%20Birol%2C%20the%20IEA's%20executive,now%20%E2%80%93%20from%20this%20year.%E2%80%9D&text=If%20governments%20are%20planning%20investments%2C%20it%20is%20up%20to%20them

Haverd et al. (2019). Higher than Expected CO_2 Fertilization Inferred from Leaf to Global Observations. *Global Change Biology*, *26*(4), 2390–2402. https://doi.org/10.1111/gcb.14950

HC Group. (2021). *Hydrogen: Hope, Hype and Thermodynamics with Paul Martin*. Retrieved October, 2021, from https://www.hcgroup.global/hc-insider/hc-insider-podcast/hydrogen-hope-hype-and-thermodynamics-with-paul-martin

Idso, C. (2021). Extensive list of peer-reviewed academic papers confirming CO2 fertilization. *CO2 Science*. Retrieved from http://www.co2science.org/subject/b/bioproductivity.php

IEA. (2019a). *Is Exponential Growth of Solar PV the Obvious Conclusion*? by Brent Wanner. Retrieved February, 2019, from https://www.iea.org/commentaries/is-exponential-growth-of-solar-pv-the-obvious-conclusion

IEA. (2019b). *Installed power generation capacity in the Stated Policies Scenario*. Retrieved November, 2019, from https://www.iea.org/data-and-statistics/charts/installed-power-generation-capacity-in-the-stated-policies-scenario-2000-2040

IEA. (2019c). *Statistics Questionnaire FAQ*. Retrieved November, 2019, from https://www.iea.org/statistics-questionnaires-faq

IEA. (2020a). *World Energy Investments 2020*. Retrieved from https://www.iea.org/reports/world-energy-investment-2020/key-findings

IEA. (2020b). *World Energy Outlook 2020*. Retrieved from https://www.iea.org/reports/world-energy-outlook-2020

IEA. (2020c). *Projected Costs of Generating Electricity 2020*. Retrieved December, 2020, from https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

IEA. (2020d). *The Role of Critical Minerals in Clean Energy Transitions*. Retrieved May, 2021, from https://www.iea.org/articles/clean-energy-progress-after-the-covid-19-crisis-will-need-reliable-supplies-of-c ritical-minerals

IEA. (2021a). *Key World Energy Statistics*. Retrieved September, 2021, from https://www.iea.org/reports/key-world-energy-statistics-2021

IEA. (2021b). *World Energy Investments 2021*. Retrieved from https://www.iea.org/reports/world-energy-investment-2021

IEA. (2021c). *Electricity Market Report*. Retrieved July, 2021, from https://www.iea.org/reports/electricity-market-report-july-2021

IEA. (2021d). *World Energy Outlook 2021*. Retrieved from https://www.iea.org/reports/world-energy-outlook-2021

IEA. (2021e). *Net Zero by 2050 – Analysis*. Retrieved May, 2020, from https://www.iea.org/reports/net-zero-by-2050

IEA. (2022a). *Energy transitions require innovation in power system planning*. Retrieved January 2022, from https://www.iea.org/articles/energy-transitions-require-innovation-in-power-system-planning?utm_source=SendGrid&utm_medium=Email&utm_campaign=IEA+newsletters

IEA. (2022b). *Electricity market report*. Retrieved January, 2022, from https://www.iea.org/reports/electricity-market-report-january-2022

IEEJ. (2020). *Institute of Energy Economics Japan*. IEEJ Energy Outlook 2020. Retrieved January, 2020, from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Energy_subsidies_2020.pdf

IEEJ. (2021). *Institute of Energy Economics Japan*. IEEJ Energy Outlook 2021. Retrieved October, 2020, from https://eneken.ieej.or.jp/en/report_detail.php?article_info__id=9176

IMF. (2021). *A Global and Country Update of Fossil Fuel Subsidies*. Retrieved September, 2021, from https://doi.org/10.5089/9781513595405.001

IRENA. (2020). *Energy Subsidies – Evolution in the Global Energy Transformation to 2050*. Retrieved from https://www.irena.org//media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Energy_subsidies_2020.pdf

IRENA. (2021). *World Energy Transitions Outlook: 1.5°C Pathway*. Retrieved Junuary, 2021, from https://doilink)/

Kahn et al. (2021). Long-Term Macroeconomic Effects of Climate Change. *Energy Economics*, *104*. https://doi.org/10.1016/j.eneco.2021.105624

Kemfert, C. (2021). *Translated from Prof. Kemfert in RND*. Wasserstoff ist nicht das neue Öl. Retrieved September, 2021, from https://wlink)/

Kiefer, C. I. (2013). *Twenty-First Century Snake Oil*. Retrieved February, 2013, from https://doi.org/10.1016/j.enpol.2018.05.033

Kis et al. (2018). Electricity Generation Technologies: Comparison of Materials Use, Energy Return on Investment, Jobs Creation and CO2 Emissions Reduction. *Energy Policy*, *120*, https://doi.org/10.1016/j.enpol.2018.05.033

Kober et al. (2020). Global energy perspectives to 2060. WEC's World Energy Scenarios 2019. *Energy Strategy Reviews*, *31*, 100523. https://doi.org/10.1016/j.esr.2020.100523

Lomborg, B. (2020). Welfare in the 21st century. *Technological Forecasting & Social Change*, *156*, 119981. https://doi.org/10.1016/j.techfore.2020.119981

Lu et al. (2020). Impacts of Large-Scale Sahara Solar Farms on Global Climate and Vegetation Cover. *Geophysical Research Letters*, *48*, e2020GL090789. https://doi.org/10.1029/2020GL090789

Manheimer, W. (2022). Civilization Needs Sustainable Energy – Fusion Breeding May Be Best. *Journal of Sustainable Development*, *15*(2), 98. https://doi.org/10.5539/jsd.v15n2p98

Mearns, E. (2016). *ERoEI for Beginners. Energy Matters* (blog). Retrieved from http://euanmearns.com/eroei-for-beginners/

Miller, L., & Keith, D. (2018). Climatic Impacts of Wind Power. *Joule*, *2*. https://doi.org/10.1016/j.joule.2018.09.009

McKinsey. (2018). *Automation and the Workforce of the Future*. Retrieved May, 2018, from https://www.mckinsey.com/featured-insights/future-of-work/skill-shift-automation-and-the-future-of-the-workforce

McKinsey. (2021). *Global Energy Perspectives 2021*. Retrieved from https://www.mckinsey.com/~/media/McKinsey/Industries/Oil%20and%20Gas/Our%20Insights/Global%20Energy%20Perspective%202021/Global-Energy-Perspective-2021-final.pdf

McKinsey. (2022). *The Net-Zero Transition: Its Cost and Benefits*. Retrieved January, 2022, from https://www.mckinsey.com/business-functions/sustainability/our-insights/the-net-zero-transition-what-it-would-cost-what-it-could-bring

Morris et al. (2019). A manganese hydride molecular sieve for practical hydrogen storage under ambient conditions. *Energy & Environmental Science*, *5*. https://doi.org/10.1039/C8EE02499E

NASA. (2019). *NASA Earth Observatory 2019*. Online 2021. Retrieved from https://earthobservatory.nasa.gov/images/144540/china-and-india-lead-the-way-in-greening

NDR3. (2020). *Nord Deutscher Rundfunk - Extra 3, Ein Gaskraftwerk in Frührente*. Retrieved March, 2019, from https://www.bayerische-staatszeitung.de/staatszeitung/wirtschaft/detailansicht-wirtschaft/artikel/der-irrsinn-von-irsching.html#topPosition

Nordhaus, T. (2018). Projections and Uncertainties about Climate Change. *American Economic Journal*, *10*(3). https://doi.org/10.1257/pol.20170046

NU. (2020). *Northwestern University, Gas storage method could help next-generation clean energy vehicles*. Retrieved from https://news.northwestern.edu/stories/2020/04/gas-storage-method-could-help-next-generation-clean-energy-vehicles/

OECD NEA. (2018). *The Full Costs of Electricity Provision*. Paris: OECD Publishing. https://doi.org/10.1787/9789264303119-en

OurWorldInData. (2020). *Energy Mix*. Retrieved November, 2020, from https://ourworldindata.org/energy-mix

OurWorldInData. (2021). *World Population Growth, Our World in Data based on HYDE, UN, and UN Population Division* (2019 Revision). Retrieved from https://ourworldindata.org/world-population-growth

Pielke, R., & Richie, J. (2021). Distorting the View of Our Climate Future. *Energy Res. & Social Sc.*, *72*, 101890, https://doi.org/10.1016/j.erss.2020.101890

Polimeni et al. (2015). *Book, The Myth of Resource Efficiency: The Jevons Paradox*. ISBN 978-1-138-42297-1. Retrieved from https://www.amazon.com/Myth-Resource-Efficiency-Earthscan-Research-ebook/dp/B018W7SD0G

PV-Mag. (2022). *World Has Installed 1TW of Solar Capacity, pv magazine Internationald*. Retrieved March, 2022, from https://www.pv-magazine.com/2022/03/15/humans-have-installed-1-terawatt-of-solar-capacity/

REN21. (2021). *Renewables Global Status Report*. Retrieved from https://www.ren21.net/reports/global-status-report/

Ruhnau, O., & Qvist, S. (2021). Storage Requirements in 100% Ren. Elec. System: Extreme Events and Inter-Annual Variabilit. *Environmental Research Letters*, *17*(4), 044018. https://doi.org/10.1088/1748-9326/ac4dc8

S&P. (2021). *S&P Platts, Coal Trader International*. Dec 2021

Schernikau, L., & Smith, W. (2021). Solar in Spain to Power Germany. *SSRN Electronic Journal*, Apr 2021. https://doi.org/10.2139/ssrn.3730155

Schernikau, L., & Smith, W. (2022a). Climate impacts of fossil fuels in today's electricity systems. *SAIMM*, *122*(3). https://doi.org/10.17159/2411-9717/1874/2022

Schernikau, L., & Smith, W. (2022b).
An introduction to wind and wind turbines, , unpublished draft paper. *SSRN Electronic Journal*, Apr 2022. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4096843

Smil, V. (2016). *Energy Transitions: Global and National Perspectives*. Retrieved from https://vaclavsmil.com/2016/12/14/energy-transitions-global-and-national-perspectives-second-expanded-a nd-updated-edition/

Smil, V. (2017). *Energy and Civilization: A History*. ISBN 0262035774. https://doi.org/10.7551/mitpress/9780262035774.001.0001

Soon et al. (2015). Re-evaluating the role of solar variability on Northern Hemisphere temperature trends. *Earth-Science Reviews*, *150*, 409–452. https://doi.org/10.1016/j.earscirev.2015.08.010

Supekar, S., & Skerlos, S. (2015). Reassessing the Efficiency Penalty from Carbon Capture in Coal-Fired Power Plants. *Environmental Science & Technology*, *49*. https://doi.org/10.1021/acs.est.5b03052

Toke. (2021). *Options for energy storage, 100% Renewable UK*. Retrieved October, 2021, from https://100percentrenewableuk.org/storage

Tramosljika et al. (2021). Advanced Ultra-Supercritical Coal-Fired Power Plant with Post-Combustion Carbon Capture. *Sustainability*, *12*(2), 801. https://doi.org/10.3390/su13020801

UN-COP26. (2021). *UN Climate Change Conference* (COP26). Glasgow 2021, Global Coal to Clean Power Transition Statement. Retrieved November, 2021, from https://ukcop26.org/global-coal-to-clean-power-transition-statement/

University of Texas. (2018). *Full Cost of Electricity, Energy Institute*. The University of Texas at Austin. Retrieved April, 2018, from https://energy.utexas.edu/policy/fce

Voosen. (2021). *IPCC Confronts Implausibly Hot Forecasts of Future Warming*. Science, AAAS. Retrieved July, 2021, from https://doi.org/10.1126/science.373.6554.474

WEF. (2019). *World Economic Forum 2019, video on vegetation cover*. Retrieved from https://www.weforum.org/agenda/2019/02/one-third-of-world-s-new-vegetation-in-china-and-india-satellite-data-shows

WEF. (2020). *World Economic Forum, Charts on global energy supply*. Retrieved September, 2020, from https://www.weforum.org/agenda/2020/09/energy-mix-1970s-today/

Weissbach et al. (2013). Energy intensities, EROIs, and energy payback. *Energy*, *52*, 210–221. https://doi.org/10.1016/j.energy.2013.01.029

Wijngaarden, W. A., & Happer, W. (2020). *Dependence of Earth's Thermal Radiation on Five Most Abundant GHGs*. Retrieved from https://arxiv.org/abs/2006.03098?

Willuhn, M. (2022). *Pv-magazine, Satellite Cyber Attack Paralyzes 11GW of German Wind Turbines*. Retrieved from https://www.pv-magazine.com/2022/03/01/satellite-cyber-attack-paralyzes-11gw-of-german-wind-turbines/

WMO. (2021). *World Meterological Organization, Greenhouse gases*. Retrieved from https://public.wmo.int/en/our-mandate/focus-areas/environment/greenhouse%20gases

Wolf, B. (2021). *Der Beitrag der Menschen zur Erwärmung der Biosphäre sind nicht Kohlendioxid-sondern Wärmeemissionen*. December, 2021

Wood, M. (2022). *No Pain, No Gain – the Economic Consequences of Accelerating the Energy Transition*. Retrieved January, 2022, from https://www.woodmac.com/horizons/no-pain-no-gain-the-economic-consequences-of-accelerating-the-energy-transition/?promo_name=horizonsjanuary22&promo_creative=roadblock

Zalk, J., & Behrens, P. (2018). The Spatial Extent of Renewable and Non-Renewable Power Generation. *Energy Policy*, *123*. https://doi.org/10.1016/j.enpol.2018.08.023

Zhu et al. (2016). Greening of the Earth and Its Drivers. *Nature Climate Change*, *6*(8), 791–795. https://doi.org/10.1038/nclimate3004

Notes

Note 1. The numbers include only "EEG-Gesamtvergütung" (EEG compensation package), but no other investments, research, subsidies, etc.

Note 2. The fall of primary energy, among others, has to do with the assumed 100% efficiency of wind and solar electricity when calculating its share in PE. In other words, it is mistakenly assumed that wind and solar electricity generation was converted, conditioned, balanced, and transmitted at 100% efficiency without any losses or energy costs, or at least at the same efficiency as conventionals, which is not the case. If one were to assume a more realistic lower net efficiency, the primary energy share of wind and solar would increase and reported total primary energy in Germany wouldn't fall as much.

Note 3. LCOE = Levelized Cost of Electricity; VALCOE = Value-Adjusted Cost of Electricity; LACE = Levelized Avoided Cost of Electricity; LCOS = Levelized Cost of Storage; VRE = Variable Renewable Energy.

Note 4. The IMF reported about US$ 450 billion of global "explicit" fossil fuel subsidies in 2020 and about US$ 5,5 trillion in so called "implicit" subsidies for fossil fuels (IMF, 2021). IRENA estimates that "renewables" received around US$ 130 billion of subsidies in 2017 (IRENA, 2020), thus per MWh significantly more than fossil fuels. The EU spends already more subsidies on "renewables" than on fossil fuels in absolute terms (EC 2022, p. 30). The authors dismiss the logic of implicit subsidies as virtually any number can be calculated depending on the assumptions made, and all forms of energy receive "implicit" subsidies, whether it be solar, wind, biomass, hydro, gas, coal, or nuclear. For example, wind and solar are not CO_2-taxed even though their production and recycling emit significant amounts of GHGs. For projected cost of global warming, please refer to Nordhaus 2018, Lomborg 2020, and Kahn 2021. To truly compare subsidies, they will always have to be baselined on a per unit of output energy basis and include the full value chain, which is rarely done.

Note 5. Based on Kiefer 2013: eROI for humans and oxen as ratio of max work output divided by food calorie input calculated from Homer-Dixon's online data as 0,175:1. eROI for Roman wheat as ratio of food calorie output divided by labor and seed grain inputs was 10,5:1. eROI for alfalfa was 27:1. Humans eating wheat yield heavy labor eROI of 0,175 x 10,5 = 1,8:1. Oxen eating alfalfa yield eROI of 0,175 x 27 = 4,7:1. Teaming humans with oxen and applying reductions for idle time and for light work/skilled labor versus heavy labor gives ~4,2:1 peak eROI and ~1,8:1 sustained eROI.

Note 6. Sources in order:

(1) Telegraph 2 March 2022 (https://www.telegraph.co.uk/business/2022/03/02/world-faces-energy-starvation-oil-gas-prices-soar/);

(2) Vaclav Smil, 28 Feb 2021 (https://spectrum.ieee.org/russia-ukraine-fossil-fuels);

(3) The N24, 24 Feb 2022 (https://then24.com/2022/02/24/the-worst-energy-crisis-since-1973-the-invasion-of-ukraine-has-triggered-gas-by-55-and-rising/);

(4) CNN, 18 Nov 2021 (https://edition.cnn.com/2021/11/18/energy/nord-stream-2-europe-energy/index.html);

(5) Wikipedia 5 Dec 2021 (https://en.wikipedia.org/wiki/2021_global_energy_crisis);

(6) Bloomberg, 5 Oct 2021 (https://www.bloomberg.com/news/articles/2021-10-05/global-energy-crisis-is-the-first-of-many-in-the-clean-power-era);

(7) Globe and Mail, 1 Oct 2021 (https://www.theglobeandmail.com/world/article-indias-coal-crisis-brews-as-power-demand-surges-record-global-prices/);

(8) Bloomberg, 18 Sep 2021 (https://www.bloomberg.com/news/articles/2021-09-18/europe-faces-bleak-winter-energy-crisis-years-in-the-making);

(9) Nikkei Asia, 27 Sep 21 (https://asia.nikkei.com/Business/Technology/Key-Apple-Tesla-suppliers-halt-production-amid-China-power-crunch);

(10) Moneyweb, 8 Aug 2021 (https://www.moneyweb.co.za/news/international/the-era-of-cheap-natural-gas-ends-as-prices-surge-by-1-000/).