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The hidden costs of solar photovoltaic power

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Introduction

Despite many optimistic predictions, solar photovoltaic (solar PV) power still represents only a small fraction of the global electricity supply as of 2020. More than two decades of near-exponential growth and investment in solar PV development have taken place, yet the amount of fossil fuels being burned for power is still increasing. [1] This apparent paradox has been attributed to a variety of economic or political issues, but a critically important factor may be missing from the discussion.

All modern technologies are dependent upon the supply of fossil fuels and fossil energy that made them possible. Similarly, every step in the production of solar PV requires an input of fossil fuels - as raw materials, as carbon reductants for silicon smelting, for process heat and power, for transportation, and for balance of system components. Regardless of any intentions, no quantity of banknotes or any number of mandates can yield a single watt of power unless a significant expenditure of raw materials and fossil energy takes place as well.

Therefore, the author of this article invites all interested parties including environmentalists, consumers and policy makers to consider the wider environmental impact, and the great debt of resources that actually must be paid before a PV system can be installed at any utility, workplace, or home. If we wish to recognize the hidden costs of this highly engineered industrial technology, we must first examine the non-renewable reality of the PV manufacturing process itself. To be even more realistic, we must also consider the additional consequences resulting from the fossil-fuel-powered global supply chains that are necessary for the mining, production, and implementation of PV power systems.

Moreover, as the power output of solar PV is intermittent, highly variable, and largely unpredictable, it is not equivalent to conventional power in availability, capacity, or dependability. As a result, a number of other fossil-based industrial technologies must be deployed alongside PV in order that it may be integrated into existing power grids at all. When viewed on this broader scale, the development of the solar PV industry may be held responsible for a number of other, indirect expenditures of fossil fuels that have not been fully accounted for in previous evaluations of solar PV alone.

This article introduces readers to the many types of fossil fuels that are used in PV production, and notes some of the other fossil energy inputs that are necessary before the delivery of a solar PV array can take place. We also highlight several environmental impacts and other issues that may have been excluded from previous analyses.

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[1] "…*despite the huge policy push encouraging a switch away from coal and the rapid expansion of renewable energy in recent years, there has been no improvement in the mix of fuels feeding the global power sector over the past 20 years. Astonishingly, the share of coal in 2017 was exactly the same as in 1998. The share of non-fossil fuels was actually lower, as growth in renewables has failed to compensate for the decline in nuclear energy."* Statistical Review of World Energy, 67th Edition, June 2018 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

1. An overview of silicon-based PV manufacturing (as of 2020):

Most commercial solar PV modules use photovoltaic cells (solar cells) made from highly purified silicon (Si). **[1]** Since the early 1900s, semi-metallic silicon has been reduced from quartz by the use of fossil carbon in submerged-arc furnaces powered by megawatts of electricity. **[2][3][4][5][6]**
See Figure 1

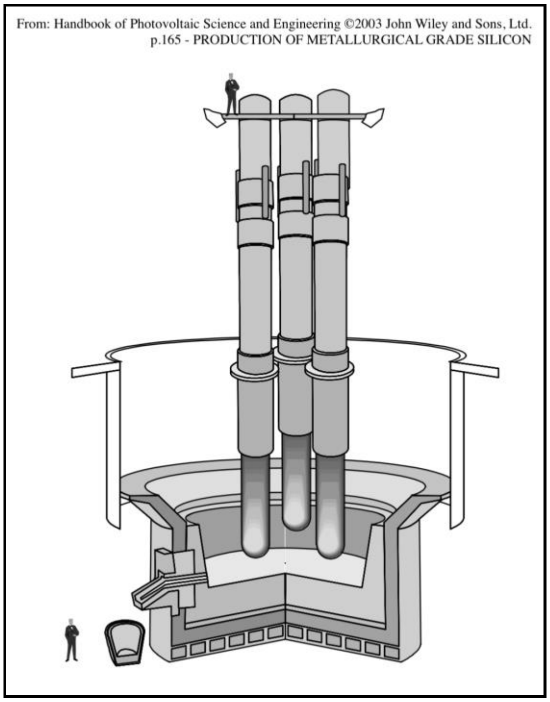

Figure 1. Diagram of a silicon smelter showing the three giant carbon electrodes that provide arc temperatures > 3,000ºF for smelting quartz into "metallurgical grade" silicon (mg-Si) using carbon as a reductant. ©2003 (John Wiley and Sons, Ltd.)

As we can see by this emissions permit from the New York State Department of Environmental Conservation (valid through the year 2021) - virtually nothing about the silicon smelting process has changed in more than a century:

"Globe Metallurgical produces high purity silicon metal...Reactants consisting of coal, charcoal, petroleum coke, or other forms of coke, wood chips, and quartz are mixed and added at the top of each furnace...The submerged electric arc process is a reduction smelting operation...At high temperatures in the reaction zone, the carbon sources react with silicon dioxide and oxygen to form carbon monoxide and reduce the ore to the base metal silicon...The facility is a major source of emissions of sulfur dioxide, carbon monoxide, hydrogen chloride and nitrogen oxides" [2]

The subsequent production of polysilicon, crystalline silicon, silicon wafers, and the assembly of PV modules also require a continuous supply of electrical power, fossil fuels, and dozens of other non-renewable mineral resources. [1-24] However, even if 100% free energy were available for all these processes, the ongoing production of PV is still heavily dependent on a supply of elemental carbon, which comes primarily from fossil fuels. [1-19]

2. Why is carbon needed for solar PV production?

Elemental silicon (Si) cannot be found by itself anywhere in nature. It must be extracted from the mineral quartz (SiO_2) using carbon (C) and heat (from an electric arc) in the "carbothermic" (carbon + heat) reduction process called smelting ($Si0_2 + 2C = Si + 2CO$).

Several commercially available solid fuels are typically used as carbon reductant sources in silicon smelting. The smelting plant requires ~20 MWh of electricity and releases up to 5 - 6 tons (t) of CO_2 (and CO) for every ton of metallurgical grade (mg-Si) silicon that is smelted from ore. [6]

Thus, the first step of commercial solar PV production is gathering, transporting, and burning millions of tons of coal, coke and petroleum coke - along with charcoal and wood chips made from hardwood trees to smelt >97% pure mg-Si from quartz ore (silica rocks). [21-25]

Figure 2. In the silicon smelter, three 1-meter diameter carbon electrodes penetrate the surface of the charge of coal, coke, woodchips, and quartz rock. Each electrode is 10-20 meters tall.

Even more fossil fuels are burned later, to generate heat and electricity for the subsequent polysilicon, ingot, wafer, cell, and module production steps. As a result of all these processes, the solar PV industry generates megatons of CO and CO_2 annually. [1-20] However, as shown in Figure 3, some of the most authoritative and frequently-cited descriptions of solar module production omit the raw materials, fossil fuels, and burnt trees from their PV supply chain. This obscures the inherent necessity of fossil fuels as raw materials for PV manufacturing, and sidesteps the potential for social or political conflict that could result from disclosing the significant amount of deforestation that is necessary for solar PV production to take place. [21-25]

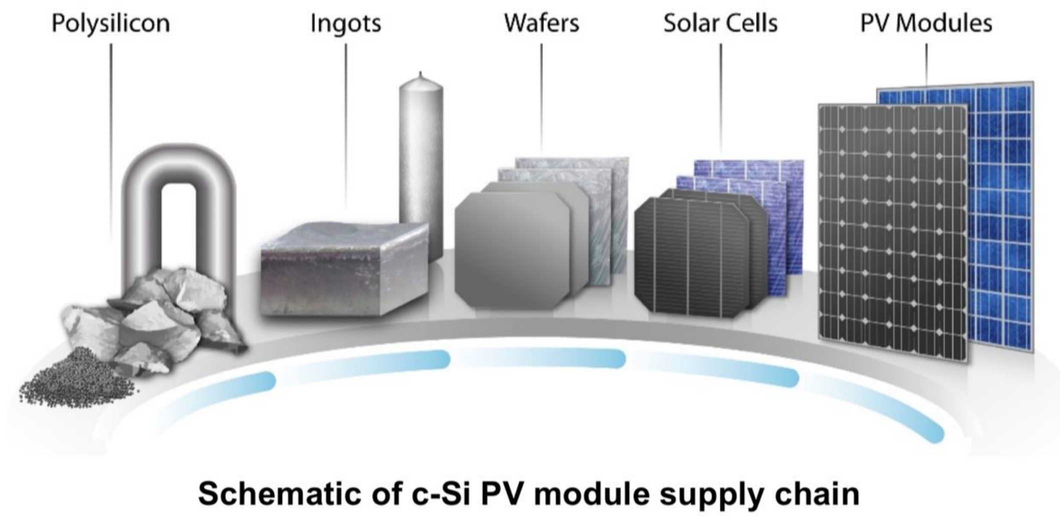

Figure 3. This NREL supply chain schematic omits all of the coal, trees, quartz, and other raw materials needed for smelting metallurgical silicon from ore. (Source: National Renewable Energy Laboratory, 2018) [44]

3. Raw materials needed for metallurgical-grade silicon

Raw materials for one ton (t) MG-Si (Kato, et. al) [13]
Quartz 2.4 t (ton)
Coal 550 kg
Oil coke 200 kg
Charcoal 600 kg
Wood chip 300 kg.

Raw materials for one ton (t) MG-Si (Globe) [1]
Quartz 2.8 t
Coal 1.4 t
Wood chips 2.4 t.

For 110,000 tpy (tons per year) MG-Si (Thorsil) [6]
Quartz 310,000 tpy
Coal, coke and anodes 195,000 tpy
Wood 185,000 tpy
Total 380,000 tpy.

When estimating the CO_2 emissions from the silicon smelting process, several previous authors "by joint agreement"[22] excluded the CO_2 emissions from all non-fossil carbon sources (charcoal, wood chips), from power generation, and the transportation of raw material. [22] This illustrates an important issue. The validity of any estimate depends on where the study boundaries are drawn. If the range of inputs is too narrow, the overall environmental impact of a real-world industry may not be adequately documented. Over time, the assumptions inherent in one study may propagate into all the subsequent literature, resulting in conclusions that are incomplete, and therefore unrealistic.

4. Sources of carbon for solar silicon smelting

Coal - Is a dense, rock-like fuel extracted from mines. The low ash coal used directly in silicon smelters is mostly the ”Blue Gem" from Cerrajón, Columbia, Kentucky, USA, or Venezuela. It must be washed before smelter use; the byproduct is then sold as fuel. [6][8][10][15-18] See Figure 4.

Figure 4 The Cerrejón open-pit mine in Columbia supplies “Blue Gem” coal, a primary source of carbon for solar silicon smelters around the world.

Metallurgical Coke (metcoke) - is a tough, cinder-like solid fuel made by coking previously-mined coal in large slot ovens - to drive out most of the volatile tars, etc. to the atmosphere as smoke, flame, carbon monoxide, carbon dioxide, sulfur dioxide, other gasses, and water vapor. The coking process is nearly identical to the process used for making charcoal from wood (see wood charcoal production). Restricting the air supply to a large mass of burning coal allows about 40% of the coal to burn off - leaving behind a solid residue (coke) with a higher carbon content per ton that the original coal. It takes about 1.3-1.6 t of coal to make a ton of metcoke. Metcoke looks like porous, silvery grey coal. [19][20[21]

Petroleum Coke (Petcoke) - is a solid fuel in the form of dense, pellet-like granules, which are a carbon-rich byproduct of crude oil refineries. Millions of tons of petcoke are also made directly from raw bitumen (tar). Due to its low market price and high carbon content, petcoke made in American refineries from "Canadian Tar Sands” has already been exported from the U.S. to silicon manufacturers in China by the millions of tons. In addition, the full extent of CO_2 emissions resulting from petcoke is not well documented. [23] *“Because it is considered a refinery byproduct, petcoke emissions are not included in most assessments of the climate impact of tar sands.”* [22]

Wood Charcoal - Many hardwood trees must be burned to make wood charcoal. In the traditional process, wood is stacked into "beehive ovens," ignited, then mostly smothered with earth or clay to prevent the wood from burning completely to ash. See Figure 5.

Figure 5. Beehive charcoal kilns in Brazil. Many trees must be burned, as the traditional process requires up to ten tons of hardwood to make one ton of wood charcoal.

By weight, up to ~90% of the wood harvested is lost to the atmosphere as CO, CO_2, smoke, and heat, so as much as ten tons of raw wood must be burned to produce a single ton of wood charcoal. [28][33] A few silicon producers claim to use dedicated "charcoal plantations," but such plantations are limited in scope, so they can only supply a fraction of the overall demand for carbon in silicon production. [29-31]

The rest of the carbon supply for silicon production has to come from imported coal or coke, or the cutting and burning of "virgin" rainforest. [30][35][36] In Brazil, it is estimated that as of 2015, more than a third of the country's charcoal supply is still produced illegally from protected species. [30] Brazil is also a charcoal exporter to silicon producers in several other countries, including the United States. [30-34] Silicon smelters around the world use charcoal from many sources, so solar silicon may be smelted with charcoal made directly from rainforest trees that were not grown on plantations. [30][35][36]

Hardwood Chips (also called Metchips) - Matchbox-sized fragments of shredded hardwood must be mixed into the silicon smelter pot for several reasons - to allow the reactive gasses to circulate, so the liquid silicon that forms can settle to the bottom for tapping, and to allow the resulting CO (and other gasses) to escape the smelter charge safely. [24] No silicon smelter can function without this moist, low-impurity bulking agent added to the charge as up to ~60% of the mixture. Thus, perpetual deforestation is an inherent component of solar PV production. [1][10][11][24-32]

As these biological CO_2 emissions have been omitted from the CO_2 balance of solar PV production, their negative environmental effects may have not been adequately quantified. [27] However, the negative effects of deforestation can extend far beyond the mere emissions of CO_2 to include land erosion, topsoil depletion, natural habitat destruction, possible species extinction, and many other issues. [34]

5. Sources of silicon ore (SiO_2) for solar silicon smelting and crucible production.

Quartz - (silica, silicon dioxide, SiO_2) Even if it were sufficiently pure, ordinary silica sand won't work in any silicon smelter because the particle size is much too fine. Instead, specially selected deposits of high-purity quartz (HPQ) are mined and graded into "lumpy" (fist-sized) gravel for solar silicon smelting applications. Worldwide, solar and electronic grade deposits of HPQ are somewhat scarce, and highly valued. [37][38][39]

Another issue for PV is the requirement for even higher grades of *ultra* high-purity quartz with contamination levels lower than 0.003% (99.998% SiO2). These grades are necessary for the production of the high temperature quartz crucibles consumed in Czochralski (Cz) process single-crystal silicon ingot pullers, which are also used to produce electronic grade wafers for integrated circuit (IC) production.

Source https://ultrahpq.com/markets/

See section 7. Crystal growing (ingot production). Virtually the entire global supply of crucible grade quartz is sourced from a single mining region in Spruce Pine, North Carolina, USA. [38] Which means that virtually the entire global production of all silicon-based semiconductors, computers, electronics, and solar PV is also dependent on the annual productivity of a single mineral deposit in the Earth's crust. This is a topic of critical strategic importance, which has not been previously addressed in PV literature. Other (very minor) sources of crucible-grade quartz exist, but it is uncertain if their production could be scaled up to provide more than a few percent of the current global demand for Cz crucibles, or how long the supply would last. [36-39]

6. Polysilicon production.

Metallurgical grade silicon (mg-Si) from the smelter is only about 97-99% pure, so it must undergo two more energy-intensive purification steps, before it can be made into wafers for solar cells (or electronics). First, the Siemens Process converts metallurgical silicon from the smelter into polycrystalline silicon (called polysilicon) by means of a high-temperature Continuous Vapor Deposition (CVD) method. This works a bit like growing rock candy on a string submerged in a jar of sugar water. But in this case, the polysilicon crystals are grown on thin, hyper-pure silicon 'strings' called filaments – which are mounted vertically inside a pressurized-gas filled bell-jar type reactor. As a mixture of silicon gas (made from the mg-Si) and hydrogen gas is pumped through the reactor vessel, some of the silicon gas molecules cling to the electrically pre-heated silicon filaments,

which slowly fatten into "rods" of 99.9999% pure (or better) polysilicon. When pre-heated to around 1100°C, the silicon filaments/rods growing beneath the reactor cover can catch about 20% of the silicon atoms that pass through the reactor in gaseous form. [1] See figure 5.

Figure 5. Polysilicon rods grown in a CVD reactor. In this photo the CVD process is complete, the "bell jar" reactor dome has been removed, and the rods are ready for harvest.

Each batch of polysilicon rods takes several days to grow, and a continuous, 24/7 supply of electricity to each reactor is essential to prevent a costly run abort. So all polysilicon refineries depend on highly reliable conventional power plants, and usually have two separate, incoming high-voltage supply feeds. [41][42] A polysilicon plant consumes anywhere from ~1.6 - 6 t of mg-Si and requires at least 175 MWh (or more) of additional electricity per ton of polysilicon produced. [15][42] After the rods are removed from the reactor, they are sawed into sections - or broken into chunks by hand (or by thermal fracturing) in a clean room environment. A single polysilicon plant (20,000t/year capacity) can draw 400 megawatts of electricity, enough power for about 300,000 homes. [42]

7. Crystal growing (ingot production)

For making single-crystal solar cells (also called mono PV) the PV industry uses the Czochralski (Cz) process to further purify the polysilicon, and align the silicon molecules into a single-crystal form with specific semiconductor properties. [43][46]

First, polysilicon chunks are melted (by induction) within a rotating, ultra-pure quartz crucible, and surrounded by an inert gas atmosphere (usually argon). Rare earth doping metals are added to the melt in minute quantities to provide the specific semiconductor properties desired in the finished cells. Then a small seed crystal of pure silicon is lowered into the molten polysilicon. As the crucible slowly turns, a new crystal of silicon begins to form on the tip of the seed. As the new, single crystal is slowly drawn from the liquid, it continues to grow into a tall cylindrical ingot (or "boule") - leaving most of the non-silicon impurities behind in the 5-10% of pot scrap remaining in the bottom of the crucible. This process requires several days, and uninterrupted power. [40] After slow cooling, the ingot's unusable crown and tail are cut off (about 10%), the cylindrical center section is then ground down, the four "chords" (long sides) are sawn off (about 25%) - leaving a nearly rectangular "brick" so the solar wafers will be almost square after slicing. [44][45] **See figure 6**

For multi-crystalline cells (also called multi PV), chunk polysilicon is melted in rectangular quartz molds under inert gas, and then cooled very carefully to encourage "directional solidification" into a rectangular ingot of multi-crystalline silicon. The quartz mold is then broken away, and the rectangular ingot is trimmed all over to remove the unusable external portions. Then the remaining core is sliced vertically into a cluster of 'bricks.' [44]

8. Wafer sawing.

Then, like a loaf of bread, the crystalline silicon bricks are sliced with wire saws into thin wafers, which will later be processed into cells. About half of each brick is lost as sawdust in the wafer slicing process, and this can't be recovered. Therefore, after all of the energy and materials that have gone into making each brick, much of the incoming polysilicon does not ever become finished wafers. See Figure 6

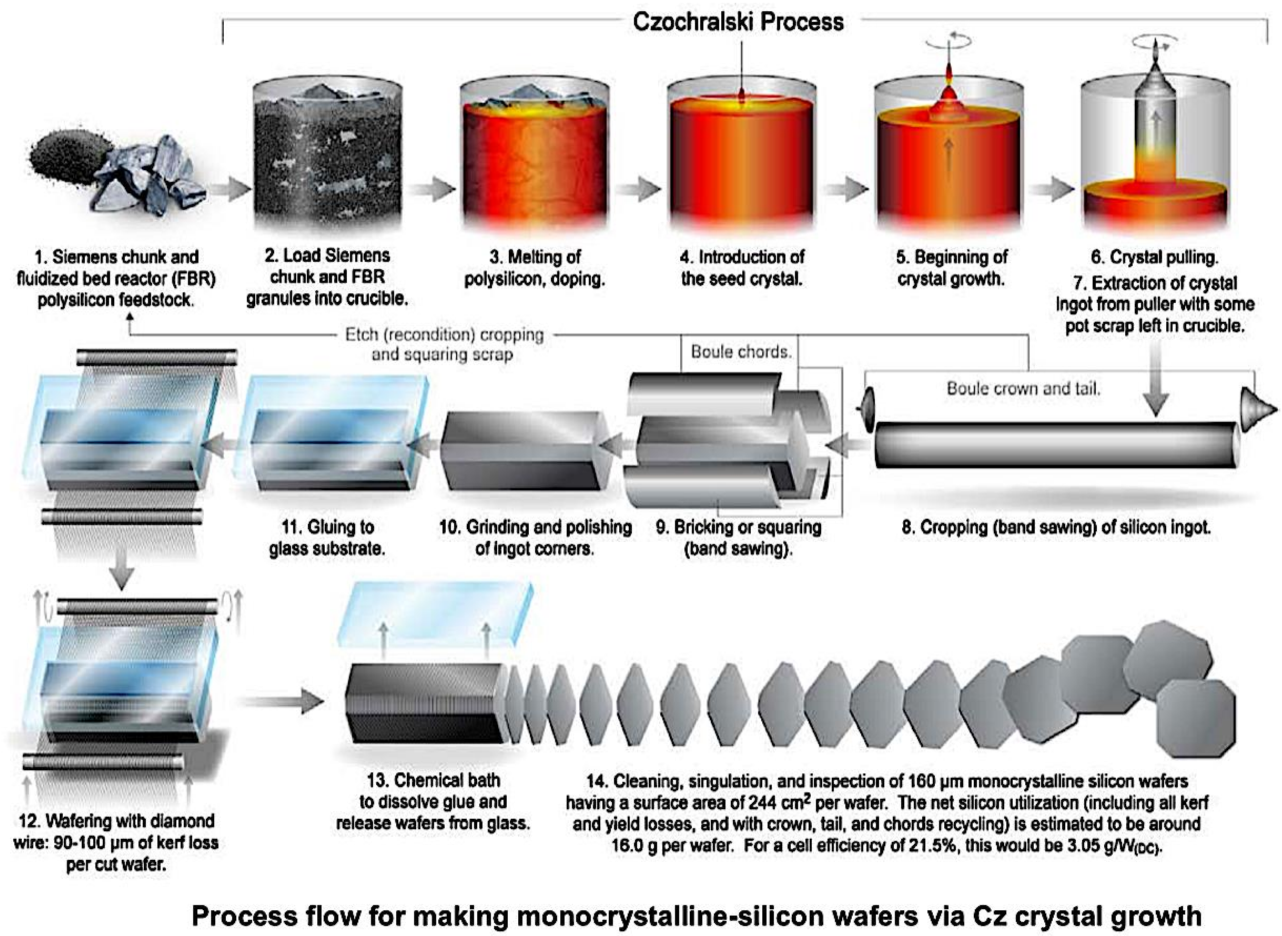

Figure 6. Cz Ingot-wafer process. Source NREL 2018 [45]

Some of the heads, tails, chords, and trimmings may be etched in acid to remove contamination and re-melted again later if the purity of the scrap is sufficient to justify the expense - otherwise they are discarded as waste. Depending on the particular combination of processes used, the ingot/wafer process can require an additional ~350 MWh of energy per MWp of modules. [45]

9. Cell and module production.

Once the wafers are sliced, they are made into photovoltaic "cells" by adding layers of other materials and components in a series of additional production steps. The amount of power needed for these processes varies depending on the type of cell. Then the finished cells are wired into strings of cells, and permanently encapsulated into weatherproof modules.

Beside silicon wafers, solar PV modules also require many other energy-intensive materials: glass, aluminum for the structural frame (if used), copper, silver, plastic - along with rare earth metals, acids, gases, and dozens of other materials that are needed for processing the polysilicon into cells and modules. [16] Additional electricity is needed to power the module assembly process, about 113 MWh/MWp of modules assembled. [45] A supply of natural gas is used to provide heat in the cell and module processes. The amount of additional primary energy needed for process heat is roughly equal to the primary energy needed for electricity. [45]

10. Balance of system components.

Once the modules are assembled and delivered, a commercial PV array usually needs some empty land, or a rooftop, steel or aluminum support framing and concrete foundations to position it securely toward the sun, and external wiring to connect the array to the existing power grid (through DC/AC inverters and transformers) - or directly to battery banks. Of course, it takes a lot of fossil energy and non-renewable resources to make steel, aluminum, concrete, DC/AC inverters, copper wiring, and all of these other "balance of system" components. In many cases, these can require as much (or more) “up-front” resources and energy to make as the modules. [40]

11. Transportation.

Throughout the solar PV manufacturing process all of the raw materials, intermediate stages, and finished products must be shipped to and from more than a dozen countries around the world in large barges, container ships, trains, or trucks - all powered by non-renewable oil. [51]

12. Power for PV production.

Worldwide, only a few silicon smelters, like those in Norway, are powered primarily by hydro-electricity. [6] In fact, most new PV plants are connected to dedicated coal-fired power plants.

From a 2020 polysilicon market analysis: *“...the electricity for the new factories comes from coal-fired power plants. The polysilicon produced – and the solar panels made out of it – thus leave a large carbon footprint.”* [3]

From a July 2020 industry report: *“...a new polysilicon plant...in northwestern China...started production in October 2018...By obtaining electricity from a nearby coal-fired power plant at a very low tariff...”* [4]

From a 2017 investor’s guide: *“...Photovoltaics is one of the rapidly growing renewable energy sources in the world…ironically...all this is driven by the low LCOE of coal-fired plants in China.”* [5]

Or as a 2018 proposal for PV manufacturing in India states:

“...Government could also provide a dedicated power plant facility to supply reliable and low-tariff power similar to China…A dedicated coal power plant is established in the vicinity of [the new] polysilicon plant” [6]

From the Poly Plant Project:

“...Upon completion of the polysilicon plant, Shansheng New Energy will be a vertically integrated PV company with its own coal and quartz mines, coal-fired power generation plant...” [11]

As the majority of smelters, polysilicon refineries, ingot growers, cell and module factories are running on grids powered mostly by fossil fuels, the additional quantity of coal, coke, or gas that is being burned to deliver power 24/7 to the PV factories may be greater than the amount needed as the carbon reductant used in smelting silicon from ore. So to be realistic, all of this must also be added to the "fossil fuel bill" for PV production and deployment. [40]

13. PV manufacturing infrastructure

A considerable up-front investment of fossil fuels and other nonrenewable mineral resources are required to construct and maintain the PV production facilities themselves. [40] Additional fossil resources must also be consumed on an ongoing basis for repair, maintenance, and eventual replacement of all the production equipment over time. [47] However, all of this embodied energy and all of those fossil fuels have been excluded from the previous "life cycle analysis" (LCA) and 'energy payback time' (EPBT) energy analysis of solar PV products by definition. [48] Therefore, these hidden costs of fossil resource depletion, fossil energy and emissions, and the environmental pollution resulting from the growth in PV manufacturing infrastructure have not even been considered in most previous analyses.

14. Grid integration of PV power systems

PV arrays can only produce power during daytime hours, and in clear weather. So, if PV is added to an existing power grid, 100% of conventional generation capacity must still be maintained for use at night, and during long periods of poor weather. In addition, the introduction of intermittent power sources into existing grids generally increases the cycling costs and CO_2 emissions of existing fossil thermal generation plants. The inherent variability of PV output due to daily weather changes may also require that "quick start" or "spinning reserve" gas turbines be added to the grid in equal measure with PV as backup to prevent grid collapse. [52]

In addition, if any power from PV arrays is desired after sunset, some means of converting PV electricity into some other form of energy for later use must be provided. At present, Li batteries are the most common form of energy "storage". However, previous studies have shown that the energy-intensive manufacture of Li batteries adds an excessive burden of embodied energy onto PV systems that are already operating at a net energy deficit. Thus, when Li batteries are added to any PV power system, the overall net energy return of the system becomes negative, as *"PV technologies [CIGS and sc-Si] cannot 'afford' any storage while still supplying an energy surplus to society… since they are already operating at a deficit."* [47]

Further, actual tests of three operational grid-scale EES storage systems were conducted, including the largest utility-scale Li battery installation in Europe as of 2015. The study found that *"The round trip efficiencies for the [Li-ion] EES systems have been calculated…between 41% and 69% where parasitic loads are included,"* Therefore on average, nearly half of the electricity supplied to the three grid-scale Li batteries was not returned to the grid as usable power. [50]

15. Disposal of PV power systems at the end of service life

Due to the many complex and irreversible material transformations taking place during production, the expired components of PV power systems cannot be wholly recycled. While commercial-scale reclamation streams may exist for the external glass, aluminum, copper or steel components, millions of fully encapsulated PV cell assemblies, DC/AC inverters, charge controllers, etc., constitute an ever-growing accumulation of non-recyclable "electronic waste" at the end of their typical service life:

"Lu Fang, secretary general of the photovoltaics decision in the China Renewable Energy Society, wrote...By 2050 these waste [PV] panels would add up to 20 million tonnes, or 2,000 times the weight of the Eiffel Tower"

"Tian Min, general manager of Nanjing Fangrun Materials, a recycling company in Jiangsu province that collects retired solar panels, said the solar power industry was a ticking time bomb. "It will explode with full force in two or three decades and wreck the environment, if the estimate is correct" [53]

16. Conclusions

Other than the continual deforestation necessary to provide the wood chips and charcoal used in PV manufacturing, no part of any PV power systems are self-reproducing in nature. Thus, the public perception of PV power as a source of "renewable energy" must be re-examined for validity. Like any other modern technology, every aspect of the development of solar PV requires an input of fossil fuels and power. Thus, government or institutional policies promoting PV power as a "carbon-free" substitute for fossil fuels must be reconsidered. Overall, the merit of further fossil-fuel expenditures into utility-scale, grid-connected PV systems can certainly be called into question. [40][47][50]

When all of the hidden costs of solar PV are taken into consideration, it becomes more evident that the technology that was intended to reduce CO_2 emission may turn out to be less beneficial for the environment as a whole than is commonly assumed. [19][40][47] It is certain that from this point onward, such intentions need to be more fully thought out, the previous assumptions tested, the potential consequences evaluated, and before determining the way ahead.

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