The Dirty Secret of the Solar Industry

Enrico Mariutti
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The author declares no conflict of interest

INTRODUCTION

Would we trust car manufacturers to self-certify combustion engines emissions? Would we trust pharmaceutical companies to self-certify the safety of their products? Would we trust the heavy industry to self-certify the air quality around their plants?

Definitely not.

On the contrary, when we talk about green technologies, the idea that stakeholders might be interested in manipulating the scientific consensus vanishes.

We are investing hundreds of billions of dollars a year in technologies that are low-carbon only because someone wrote it down somewhere. There aren't any national or international authorities who have bothered to understand on what basis and how this "paper knowledge" was assembled.

In the shadow of this unconditional trust, the field of life cycle assessment (LCA) of photovoltaic energy has turned into an echo chamber that has gradually marginalised the empirical verification of data and the adherence of models to reality. And all this happened with the complicity of the field's scientific community, who have turned a blind eye to the poor quality of data and models.

THE PROBLEM

What is meant by the carbon intensity of energy? Carbon intensity defines the CO_2 emissions per unit of energy produced.

How is the carbon intensity of energy calculated?

In the case of fuels, it is simple: by multiplying the amount of energy produced by the emission factor of the fuel burned.

The case of wind and photovoltaic plants is a little more complicated since they do not burn anything to produce energy. In this case, it is necessary to measure the CO_2 emitted to build the plant (carbon footprint) and divide it by the expected energy production over the plant's life. This process is called Life Cycle Assessment (LCA).

Therefore, in the case of wind and photovoltaic energy, it is essential to accurately model the characteristics of the industrial system in which wind turbines and solar panels are produced.

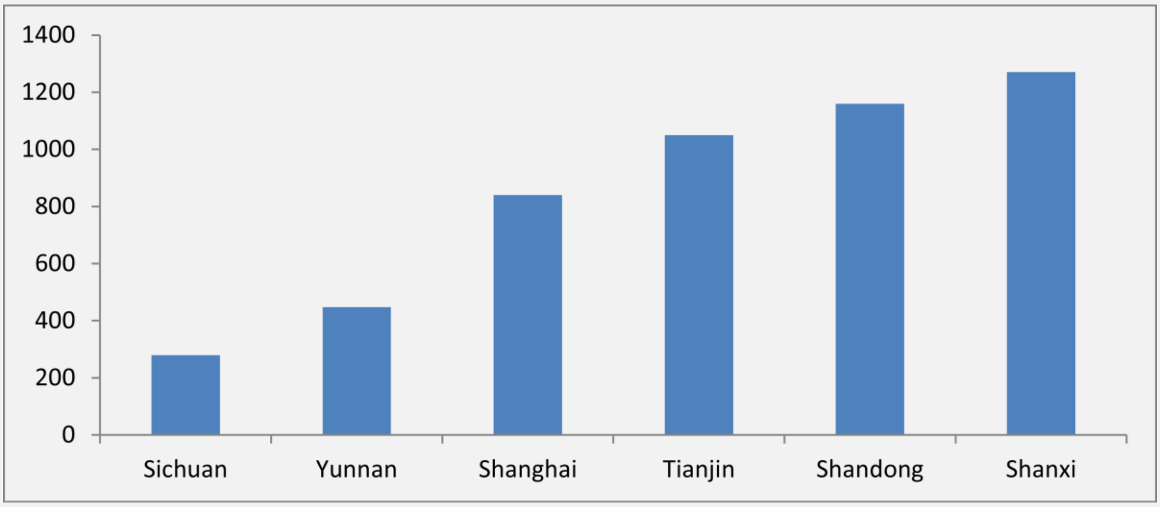
BOX 1 THE COAL ADDICTION OF THE CHINESE PHOTOVOLTAIC INDUSTRY

Over the past six years, China has installed almost 450 GW of renewable power capacity. However, this investment should not raise the hopes of those who wish for the rapid decarbonisation of the Chinese photovoltaic industry.

Earlier this year, Longi, one the world's leading manufacturers of photovoltaic wafers, announced the construction of a colossal new manufacturing plant, which will double the company's current production capacity. The factory will be completed at the end of 2024 and will be able to produce 100 GW of wafers per year.

Of particular relevance in this context, however, is the location of the plant. In fact, the factory will be located in Shanxi, one of the Chinese provinces with the highest grid carbon intensity.

China, grid carbon intensity by selected Provinces
gCO_2/kWh



SimaPro, in Recot 2022

For about twenty years, the databases with which the LCAs of photovoltaic panels are made have not entail the use of coal for industrial heating. Until six or seven years ago, virtually all studies in this field estimated the carbon intensity of photovoltaic energy based on an idealized industrial system in which the production cycle of panels was powered by hydroelectric energy, European grid electricity, natural gas, and waste heat. Even nowadays, the carbon footprint of materials and industrial processes is usually calculated starting from the efficiencies and conversion factors of the best technologies currently available.

Reliance on this methodological framework has had the effect of distorting the estimates of the carbon intensity and the ERoEI (Energy Return on Energy Investment) of photovoltaic energy.

In fact, as Marco Raugei writes in a valuable Commentary published in Nature, the "Net Energy Analysis must not compare apples and oranges." When compiling the LCA of an industrial cycle, the origin of the energy inputs must be accurately attributed, given that the conversion factors into primary energy change from source to source. Therefore replacing coal electricity with hydroelectric power or industrial heat from coal with industrial heat from high-efficiency natural gas boilers significantly reduces the primary energy balance.

Conversion factors to primary energy

ENERGY SOURCE	CONVERSION FACTOR
Electricity	
Coal	0.3/0.45
Natural gas (combined cycle)	0.5/0.6
Hydropower	0.9+
Thermal energy	
Oxygen Blast Furnace	0.1/0.2
Standard Industrial Boiler	0.7/0.85
High-Efficiency Natural Gas Boiler	0.9+
Waste heat	1+

To offer an overview of the state of this research field, I will analyze three reports holding normative value: the IPCC Fifth Assessment Report (2014), the IPCC Sixth Assessment Report (2022), and the IEA PVPS Task 12 Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems (2020).

The analysis of these three reports virtually embraces all scientifc literature on this research area, since it allows for following the evolution of the Ecoinvent database, by far the most used Life Cycle Inventory (LCI) in the field of LCA.

By re-elaborating the estimates of the IPCC and the IEA in light of an energy and technological framework compatible with the Chinese industry characteristics, it becomes clear that the values presented are vastly underestimated.

In 2015 the carbon intensity of energy produced by a made-in-China photovoltaic panel could exceed 400 gCO2/kWh while the ERoEI was less than 3. In 2022, the carbon intensity of energy produced by a made-in-China photovoltaic panel can reach 300 gCO2/kWh, while the ERoEI is less than 4.

IPCC FIFTH ASSESSMENT REPORT (A.R.5, 2014)

The carbon intensity of photovoltaic energy (crystalline modules) is estimated starting from a single review of thirteen papers: Hsu et al. 2012.

Sources reviewed by Hsu et al. 2012

MONOCRYSTALLINE SILICON
Alsema and de Wild-Scholten 2006
Frankl et al. 2005
Jungbluth et al. 2009
Pacca 2003
POLYCRYSTALLINE SILICON
Alsema 2000, mistakenly quoted as Alsema and de Wild-Scholten 2000
Alsema and de Wild-Scholten 2006, mistakenly quoted as Alsema 2006
Frankl et al. 2005
Fthenakis and Alsema 2006
Hondo 2005
Jungbluth et al. 2009
Lenzen et al. 2006
Pacca et al. 2006
Pehnt et al. 2002
Pehnt 2006
Stoppato 2008
Tripanagnostopoulos et al. 2006

And there arises the first problem. In fact, photovoltaic LCA boundaries are not standardized. Consequently, relying on a single review means making all modelling choices based on a single perspective.

BOX 2 THE SOURCES PROBLEM: THE STRANGE CASE OF GLASS

In 2018, Hu et al. conducted an extensive LCA of the Chinese glass industry. Based on data from the China Development and Reform Commission, the researchers found that about 70% of the energy demand is met by coal and estimated the emission factor of the container glass (20% recycled glass) to be 0.68.

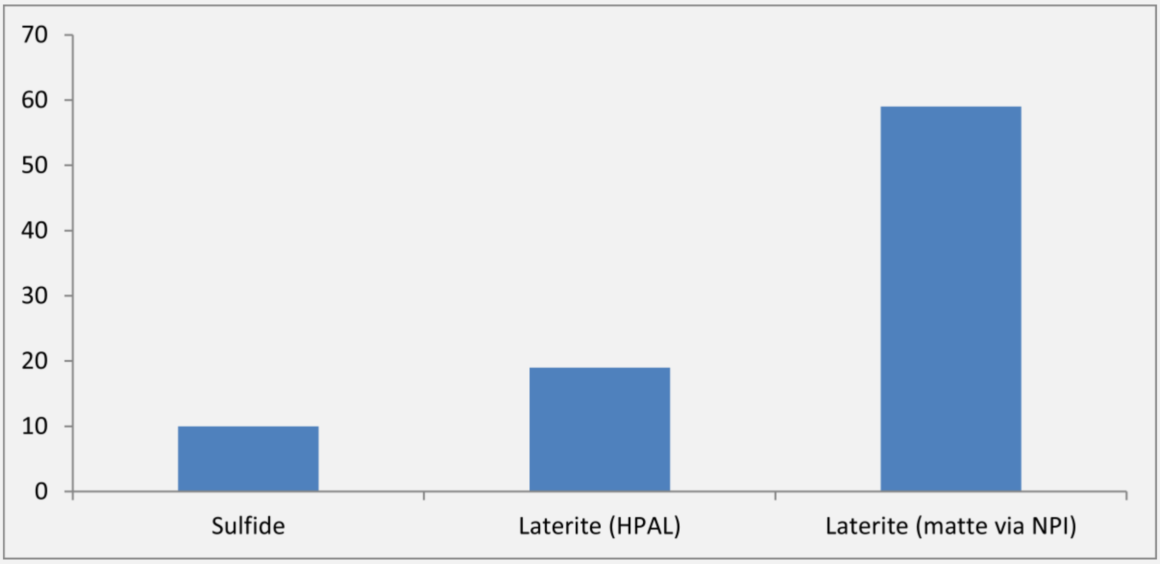
In 2022, Hartwell et al. conducted an extensive LCA of the UK glass industry. Based on data from Eurostat and Guardian Europe, the researchers found that 100% of the energy demand is met by natural gas and estimated the emission factor of the container glass (virgin) to be 1.12.

The discrepancy in the two results is due to the adoption of inconsistent methodologies and primary data sources. This is a widespread problem in this field of research, which goes far beyond the glass industry.

The databases used as primary sources in LCAs usually estimate the carbon footprint of materials and processes based on partial data, which do not reflect the global industrial standard. Ecoinvent, for example, estimates the carbon footprint of materials based on energy mixes that often include hydropower and biomass. In some cases, the energy mix is 100% natural gas (Nuss and Eckelman 2014, Supporting Information).

Moreover, usually only the most efficient extraction/refining processes are taken into account, even if they are not the only one used. Also with regard to the origin of the minerals, only the ores with the highest concentration are taken into account, even if they are not the only ones from which the mineral is extracted.

CO_2 Emission Factor for Nickel by Ore and Processing Rout



IEA

Consequently, the adoption of one emission factor instead of another must pass through a careful verification of primary sources and calculation methodology to ensure adherence to the characteristics of the scenario to be reproduced.

Moreover, in light of the watchwords of the public and institutional debate on climate, a second methodological problem arises: seven of the thirteen sources reviewed by Hsu et al. 2012 have not been peer-reviewed.

Sources reviewed by Hsu et al. 2012

MONOCRYSTALLINE SILICON	
Alsema and de Wild-Scholten 2006	*Not peer-reviewed*
Frankl et al. 2005	*Not peer-reviewed*
Jungbluth et al. 2009	*Not peer-reviewed*
Pacca 2003	*Not peer-reviewed*
POLYCRYSTALLINE SILICON	
Alsema 2000, mistakenly quoted as Alsema and de Wild-Scholten 2000	*Peer-reviewed*
Alsema and de Wild-Scholten 2006, mistakenly quoted as Alsema 2006	*Not peer-reviewed*
Frankl et al. 2005	*Not peer-reviewed*
Fthenakis and Alsema 2006	*Peer-reviewed*
Hondo 2005	*Peer-reviewed*
Jungbluth et al. 2009	*Not peer-reviewed*
Lenzen et al. 2006	*Not peer-reviewed*
Pacca et al. 2006	*Not peer-reviewed*
Pehnt et al. 2002	*Not peer-reviewed*
Pehnt 2006	*Peer-reviewed*
Stoppato 2008	*Peer-reviewed*
Tripanagnostopoulos et al. 2006	*Peer-reviewed*

Besides the methodological issues, in seven of the studies reviewed by Hsu et al. 2012 the production cycle is powered by hydroelectricity, natural gas, European grid electricity, and waste heat; the supply chain is European.

We are therefore dealing with a modelling framework that in 2015 did not in any way reflect the structure of the global photovoltaic industry, given that China was already the world's leading exporter of solar panels. And which reflects it even less today, given that 90% of photovoltaic cells and 75% of the modules on the market are produced in China.

Only two sources recalculate carbon intensity on the basis of actual national energy mixes: Jungbluth et al. (2009) on the basis of the Swiss energy mix (low carbon, low irradiation), and Lenzen et al. (2006) on the basis of the Australian energy mix (high carbon, high irradiation). And the discrepancy between the estimates is revealing: 57-62 (Switzerland) vs 53-217 gCO_2/kWh (Australia).

As a consequence, the choice made by the IPCC authors to refer to a median value represents a misleading interpretation of the data, for two reasons. On the one hand, if at least seven of the thirteen reviewed sources use quite the same database, the median value can only be the reflected image of this database. On the other hand, we are led to believe that the wide range of values is attributable to some form of uncertainty regarding the data, when they actually reflect different scenarios.

Finally, in the IPCC estimates, the albedo effect is only incorporated within the carbon balance of bio-energies deriving from monoculture, in which the variations in the radiosity of the surfaces are negligible. For what pertains to solar energy, in which the plants' installation might decrease the albedo of the surfaces by as much as 30%, the albedo effect is not considered.

What is albedo? Albedo is a well-known climate forcing, just like carbon dioxide. It measures the fraction of solar radiation reflected by a surface. Zero corresponds to a surface that absorbs all incident radiation, and 100 to a surface which reflects all incident radiation. For example, fresh snow has an albedo of 80/90 and fresh asphalt of 5. This is why people dress in light colors in the summer or why there are white houses in

Greece. Solar panels are black and textured to absorb as much solar radiation as possible. As a result, usually, they worsen the albedo of the surface where they are installed.

I submitted to the authors of the IEA PVPS reports and the IPCC sources the question: *"In your opinion, should the albedo effect of photovoltaic panels be included in the estimates of the carbon intensity of photovoltaic energy, as the IPCC already does for bioenergy?"*. Mariska de Wild-Scholten, Garvin Heath and Goufu Hou answered in the affirmative. Thomas Wetzel and David Hsu preferred not to answer.

IPCC SISXT ASSESSMENT REPORT (A.R.6, 2022)

A.R.6 does not provide any new reference data and treats the matter hastily, dedicating only a few lines to it. In any case, it almost seems to go backward with respect to A.R.5. In fact, the 2022 report refers to the knowledge acquired from a wider range than that declared in the 2014 report (9-250 gCO2/kWh). Moreover, the median value has disappeared. However, A.R.6 attached four *"recent studies that reflect higher efficiencies and manufacturing improvements"*.

Wetzel and Borchers 2015 use the Ecoinvent 3.1 methodology but reduce the energy requirement on the basis of confidential data, coming from two large unspecified producers, which *"can be regarded as representative for the assessment of crystalline silicon-based modules in Europe in general"*. In any case, they continue to calculate the carbon footprint of photovoltaic energy as if the production cycles were fueled with an energy mix consisting of hydroelectricity, natural gas, European electricity grid, and waste heat.

Louwen et al. 2016 use the data processed by Wetzel and Borchers 2015 as source and further lower the carbon intensity estimates by introducing a learning ratio based on the evolution of the values published in literature. However, due to the success of Ecoinvent, which rapidly became predominant, starting from 2005 a growing amount of LCAs began to calculate the carbon intensity of photovoltaic energy starting from a standard low-carbon energy mix (hydroelectric power, natural gas, European grid electricity and waste heat), in contrast to the sources of the previous period, which usually calculated the carbon footprint of solar systems starting from energy mixes more carbon intensive (i.e. more realistic, usually based on actual national energy mixes). As a result, the historical perspective is distorted.

Hou et al. 2016 adapt the estimates to the characteristics of the Chinese energy mix, which is not specified. It is unclear whether the estimates include thermal energy, which is not mentioned. The sources of the technical data are confidential. Moreover, the raw material underlying the production cycle is Upgraded Metallurgical Grade Silicon (UMG-Si), a chimera of the photovoltaic industry: currently, there aren't any commercial photovoltaic cells manufactured from UMG-Si.

None of the three sources mention the calculation equations, and all three sources integrate the estimates with confidential industry data. None of the three studies includes the necessary data to reproduce the results.

The fourth source, Nugent and Sovacool 2014, is a review of sixteen LCAs of photovoltaic energy. Two of these studies analyze the production cycle of cadmium telluride panels, which currently cover a few percentage points of the global market. Three other studies analyze the production cycle of some types of solar panels that do not exist on the market. Of the eleven sources that analyze the production cycle of crystalline panels, nine use Ecoinvent's 1 or 2 inventories, the tenth is Hsu et al. 2012, and the eleventh uses another database to compile the LCI, in the end, estimating the carbon intensity of photovoltaic energy at 217 gCO2/kWh.

I asked the authors of the chapter the following questions but received no response.

The statement "recent studies that reflect higher efficiencies and manufacturing improvements find lower life-cycle emissions" (p. 217) is accompanied by four references. Three of these four papers base their estimates on confidential data and do not present the calculation equations (Wetzel and Borchers 2015, Hou et al. 2016, Louwen et al. 2016). Consequently, the results are not reproducible. In your opinion, is this aspect problematic from a methodological point of view?

The statement "recent studies that reflect higher efficiencies and manufacturing improvements find lower life-cycle emissions" is accompanied by four references. Two of these four papers review production cycles based in Europe (Wetzel and Borchers 2015, Louwen et al. 2016). Given that Europe has for some time now played a marginal role in the supply chain of the global photovoltaic industry, how can these two studies represent "recent studies"?

The statement "recent studies that reflect higher efficiencies and manufacturing improvements find lower life-cycle emissions" is accompanied by four sources. One of these sources reviews a production cycle that should represent the state of the art of the Chinese photovoltaic industry (Hou et al. 2016) but based on the upgraded metallurgical grade silicon (UMG-Si). Currently, however, no commercial photovoltaic cells are produced starting from UMG-Si. Could you please explain this contradiction?

INTERNATIONAL ENERGY AGENCY, PVPS TASK 12 LIFE CYCLE INVENTORIES AND LIFE CYCLE ASSESSMENTS OF PHOTOVOLTAIC SYSTEMS (2020)

The IEA report Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems collects an inventory of materials and energy inputs related to the construction of a photovoltaic system. The report does not feature explicit carbon footprint estimates. The demand for materials and energy is calibrated to different geographical contexts, including China.

Regarding the cumulative energy demand needed for module manufacture, the report shows values in line with the most recent literature.

IEA 2020 vs recent literature

STUDIES	MG-SI	SOG-SI	CZ	WAFERING	CELL	MODULE
IEA 2015	11 kWh/kg	110 kWh/kg	68 kWh/kg	26 kWh/m^2	14 kWh/m^2	4 kWh/m^2
IEA 2020	***11 kWh/kg***	***49 kWh/kg***	***32 kWh/kg***	***5 kWh/m^2***	***18 kWh/m^2***	***14 kWh/m^2***
Fthenakis and Leccisi 2021	11 kWh/kg	49 kWh/kg	32 kWh/kg	5 kWh/m^2	18 kWh/m^2	14 kWh/m^2
Muller et al. 2021	11 kWh/kg	72 kWh/kg	38 kWh/kg	2 kWh/m^2	6 kWh/m^2	3 kWh/m^2

More specifically, the energy demand for silicon purification is drastically lower than in previous literature. However, compared to the previous generation of studies, the efficiency of the module has increased dramatically (from 13-15% to 19-20%). This increase in efficiency was only possible due to a sharp increase in silicon purity.

This trend does not seem consistent with the reduction of energy demand.

BOX 3 THE SILICON PURIFICATION CONUNDRUM

In 2015, the functional unit in the LCA of monocrystalline photovoltaics was usually a module with 14% efficiency, produced from a mix of 99.999% pure silicon (5N), electronic-grade silicon, and off-grade silicon. These purity standards were modelled on Ecoinvent's LCI (Jungbluth et al. 2012), which in turn drew on scientific literature dating back to the 1980s (Pizzini 1982).

In the most recent LCAs of monocrystalline photovoltaics, the functional unit is a module with 19-20% efficiency, produced from 99.9999/99.999999% (6N/9N) pure SoG-Si.

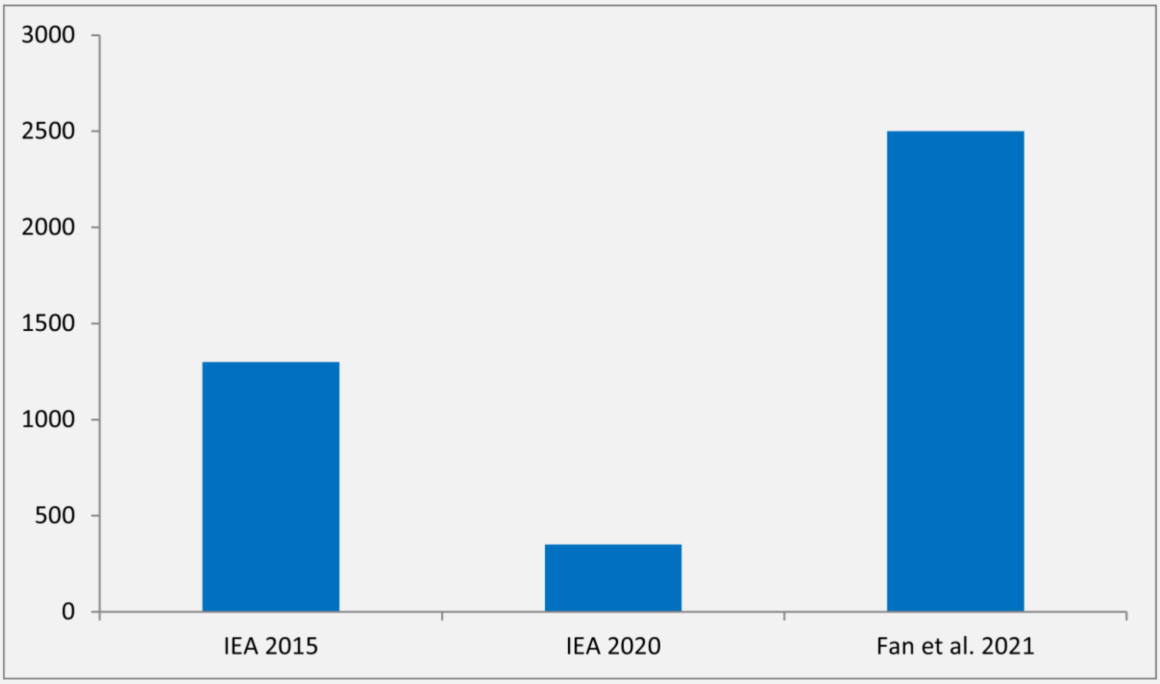
The processes by which the silicon is purified have remained the same (the Siemens process and the Czochralski process).

Paradoxically, the underlying energy mix has become slightly more carbon intensive, as the IEA has meanwhile corrected some methodological choices that underestimated the carbon intensity of the Chinese energy system.

So how is it possible that the estimate of the emissions related to silicon purification has shrunk by about four-fifths?

Recent studies, based on confidential data from Chinese factories, describe an opposite trend, which seems more logically consistent. For example, Fan et al. 2021 estimated a carbon footprint that is apporximately twice as large as the one estimated ten years earlier.

SoG-Si + CZ process + Wafering
Carbon footprint, China manufacturing
kgCO2 per kWp



The manufacturing technologies and module characteristics employed by authors are compatible with the latest scientific literature.

Mono-Si module efficiency is set at 19.5%, in line with recent literature (e.g. Fthenakis and Leccisi 2021). The module weight is about 13 kg per m^2, 15% lower than that of modules used in Europe's largest photovoltaic power plant, currently under construction in Turkey.

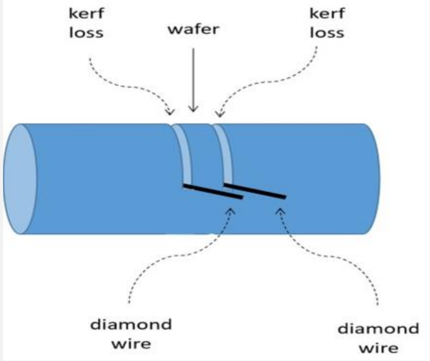
The manufacturing process involves the most updated technologies. However, the modelling of technological parameters is rudimentary and poses some methodological problems.

For example, the report assumes a drastic reduction in silicon consumption through the adoption of diamond wire sawing technology.

BOX 4 THE WIRE SAWING

Conventionally, silicon ingots are sliced with a wire saw machine. Until a few years ago, the wire was assumed to be steel, with a diameter of around 150 µm. This meant that each cut literally pulverised a 150 µm thick sheet of silicon (kerf losses). This step has a particularly large impact on the module's carbon footprint, since the silicon that is lost has already gone through all the purification processes and the wafers are in the order of 180 µm thick. In the IEA report, the 150 µm steel wire is replaced with 60 µm diamond wire, so that kerf losses are sharply reduced. However, the prevalence of this technology is attested only on the basis of industrial sources (VDMA). In contrast, in more recent literature, the topic is controversial. For example, Fan et al. 2021 document the use of steel wire.

Wire sawing



Furthermore, the diamond wire sawing parameters are incomplete and set close to the limits of the technology, again based on VDMA data. For example, recent literature (Liu et al. 2022) analysing diamond wire sawing of silicon wafers sets the diamond wire thickness at 100 µm. At the same time, it shows that the introduction of diamond wire increases the probability of wafers breaking during the cutting process. As a result, the eventual introduction of diamond wire may have had an overall minimal effect on silicon consumption.

Moreover, as even the authors of the report admit, there are no data on the LCA of diamond wire. This is another important point. The wire, in fact, wears out. The authors of the IEA report estimate consumption of 1.56 grams per m^2 of wafer. This figure may seem insignificant, but since the carbon footprint of diamonds can be as high as 160 kg of CO_2 per carat (one carat = 0.2 grams), it could turn out to be rather significant instead.

On the other hand, the inventory of materials required to build a utility-scale ground-mounted system is much more detailed compared to the recent literature, even if it has some gaps.

The data on material demand for mounting structures comes from a small Swiss plant used for research purposes. Although the plant is old, the data can be considered updated because the demand for materials is measured per m^2 of panels, not per kW of installed power.

Depending on the plant design, the steel demand for foundation may be overestimated. In this case, the beams are driven into the reinforced concrete. Alternatively, they may be driven into the bare ground.

On the contrary, the steel demand for mounting frames, nuts, bolts, and fasteners seems largely underestimated when compared to manufacturers' data sheets or actual projects. Single-axis tracker, which alone can raise the metal demand by 70 kg per kWp, is not included in the inventory.

Moreover, many manufacturers do not use low-alloyed steel or do not use only steel to make these components. For example, the mounting frame (racking) may be made of aluminium alloy. Nuts, bolts, and fasteners may be made of stainless steel. All the moving parts usually are made of stainless steel or aluminium. Although the use of aluminium can reduce the weight of the structure, both materials have a significantly higher carbon footprint than low-alloyed steel.

Basic materials, carbon footprint

MATERIAL	GEOGRAPHY	ENERGY FEEDSTOCK	CARBON FOOTPRINT	SOURCE
Steel, virgin	China	Coal	2	World Steel
Stainless steel, virgin	China	Coal	6-8	Based on International Stainless Steel
Alluminium, virgin	China	Coal	15-20	International Alluminium
Zinc, virgin	China	Coal	4-6	Ecoinvent 2.2
Glass, virgin	China	Coal	2-3	Based on Hartwell et al. 2022

However, by adding up the emissions related to the primary production alone of barely six raw materials used in standard components, it is possible to estimate a carbon footprint of approximately 1,200-1,600 kgCO$_2$/kWp.

Photovoltaic system, basic components

COMPONENT	MATERIAL	QUANTITY[1]	CARBON FOOTPRINT[2]
Single-axis tracker and racking	Various	9-15 kg m^2, 45-75 kg per kWp	560-800 kgCO2/kWp
Foundation	Steel	40 kg m^2, 200 kg per kWp	400 kgCO2/kWp
Module frame	Aluminium	2.13 kg m^2, 10.6 kg per kWp	160-210 kgCO2/kWp
Module glass sheet	Glass	8.81 kg per m^2, 44 kg per kWp	90-130 kgCO2/kWp
Coatings	Zinc	3 kg per m^2, 15 kg per kWp	60-90 kgCO2/kWp

[1] Materials quantity data are collected from the IEA report Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems (2020), with the exception of the single-axis tracker [2] Primary production of materials

Single-axis tracker materials data, sources

MANUFACTURER	MODEL
Array Technologies	DuraTrack® HZ v3
Array Technologies	Array OmniTrack™
DEGER	S100-SR
Mechatron	S250
Metaloumin	M-TRC-270
PIAsolar	ContouR$^+$Tracker
Powerway	PowerFit-Blade
PVH	Monoline
SatControl	STL24
SatControl	STL36

What is primary production? Primary production refers to the production of an ingot of metal or a sheet of raw glass. However, before it becomes a frame, an aluminium ingot must be extruded. Afterwards, it must be anodized. Both processes are energy-intensive. Steel must also be extruded and protected from corrosion by another energy-intensive process: galvanising. Solar glass is usually laminated and coated. Laminating increases the carbon footprint of glass by up to 50%, coating by up to 20% (Hartwell et al. 2022).

Thoroughly estimating the carbon footprint of these processes is almost impossible since the studies on this subject are few, depends on industrial data, and, as in the case of photovoltaic panels, would have to be adapted to the Chinese industrial context (which is unknown).

In addition, it must be taken into account that once intermediate goods are included, the manufacture of a photovoltaic system requires the input of dozens of different materials.

Selected materials, module[1]

MATERIAL	QUANTITY[2]	
Silver	50 g/kWp	Quantity uncertain (-50/+100%). The carbon footprint of silver is huge (up to 200 kgCO$_2$/kg)
Diamond wire	1.56 g per m^2 of wafer	The carbon footprint of natural diamonds is astonishing (up to 800,000 kgCO$_2$/kg)
Copper	0.5 kg/ kWp	Depending on the refining process and energy feedstock, the carbon footprint of copper can be up to 8 kgCO$_2$/kg
Tin	100 g/kWp	Depending on the energy feedstock, the carbon footprint of tin can be up to 15 kgCO$_2$/kg
Ethylvinylacetate, EVA	~ 5 kg/kWp	Uncertain carbon footprint (for sure >2 kgCO$_2$/kg)
Polyethylene terephthalate, PET	~ 2 kg/kWp	Uncertain carbon footprint (for sure >3 kgCO$_2$/kg)
Polyvinylfluoride, PVF	~ 0.5 kg/kWp	Serious concerns about the impact on the environment and human health
Liquid Nitrogen	1.15 kg per m^2 of cell	It must be transported and stored at -190° C
Liquid Argon	~ 3 kg/kWp	Uncertain carbon footprint (for sure >2 kgCO$_2$/kg)
Water	~ 10 m^3/kWp	Depending on origin and treatments, the energy intensity of water in U.S. ranging from 0.3 to 10 kWh/m^3
Others	Various	Silicone products, liquid oxygen, hydrochloric acid, liquid hydrogen, hydrogen fluoride, nitric acid, sodium hydroxide, ceramic tiles, lime, deionised water, acetic acid, dipropylene glycol monomethyl ether, alkyl benzene sulfonate, acrylic binder, brass, metallization paste, ammonia, phosphoric acid, phosphoryl chloride, isopropanol, solvents, calcium chloride, etc

[1] Transformer, inverter, cables, mounting system, tracking system, foundation excluded [2] Materials quantity data are collected from the IEA report Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems (2020)

Consequently, we are analysing a very small piece of the puzzle.

In any case, 1,200-1,600 kgCO$_2$/kWp is already much more than the carbon footprint of photovoltaic energy estimated by the IEA.

In its flagship estimates, which only feature emissions related to module manufacture, the IEA estimates an average carbon footprint of 200-300 kgCO$_2$/kWp. However, based on the 2020 IEA photovoltaic inventory, it is possible to calculate that emissions related to the primary production of aluminium for the frame and glass for the glass sheet alone can exceed 300 kgCO$_2$/kWp.

In the Special Report on Solar PV Global Supply Chains (2022), it is specified that the all-inclusive average carbon footprint of a photovoltaic system could be two or three times higher than flagship estimates, hence up to 600-900 kgCO_2/kWp.

However, we are still far away from 1,200-1,600 kgCO_2/kWp and even further away from a realistic estimate of the overall carbon footprint of a utility-scale ground-mounted photovoltaic system.

BASIC RECALCULATION

To recalculate the real carbon intensity of photovoltaic energy, I will start from Lenzen et al. 2006, the most complete source among those reviewed in the A.R.5. Obviously, since this is a 2006 study, the technical specifications of the module need to be updated: the efficiency of the cells must be increased from 13.4% to 19.5% and the wafer thickness must be reduced from 285 µm to 180.

The parameterization of the average efficiency of monocrystalline panels is slightly lower than the figure published in the last Photovoltaic Report by Fraunhofer Institute for Solar Energy System (20.4%), usually used as a reference in photovoltaic LCAs.

However, Fraunhofer ISE elaborates the median estimate on the basis of the price lists of the ten major producers in the world, not on sales data. In any other product sector, this methodological choice would over-represent the market share of high-performance models.

Why not start directly from the most recent literature? Because the inventory used by Lenzen et al. 2006 is derived from the Crystal Clear Project, an initiative funded by the European Commission in order to map the European photovoltaic industry. Thus, we are speaking of empirical data certified by an authority with supervisory power. The background data (the carbon footprint of materials, for example) are transparent and in line with actual global reference values. The results of the study are totally reproducible. Consequently, uncertainty is concentrated in what we cannot know for sure in any case: the evolution of proprietary technologies, the characteristics of manufacturing plants, the supply chain of materials.

In contrast, more recent literature relies upon inventories based on confidential data or non-transparent databases. Background data (the demand for materials, for example) are not matched by available empirical data, such as manufacturers' technical sheets. The results of the papers are not reproducible. Consequently, choosing one or the other paper or report means accepting a significantly higher burden of uncertainty.

BOX 5 ANOTHER FUNDAMENAL REASON NOT TO STAR FROM RECENT SOURCES

The first generations of photovoltaic LCAs may appear more rudimentary than the newer generations, but they tried to be as accurate as possible. Usually, the use of pre-assembled inventories was limited to the LCI of solar cells, while all other parameters were extrapolated from more robust sources, such as national inventories, plant surveys, etc.

For at least a decade now, however, photovoltaic LCAs have relied on databases that already contain all the parameters necessary to calculate the final results: the LCI of all components, supply chain, energy mix, solar irradiation, background data, etc. However, these parameters are not combined transparently and are based on assumptions that have never been empirically verified.

As a consequence, modifying the methodology would require deconstructing the database and reconstructing it on the basis of unbaised, verifyable evidence.

Here, however, two problems arise.

On one hand, as already pointed out, no international authority with supervisory powers systematically collects unbiased data from the photovoltaic industry. Thus, the risk of digressing into sterile polemics regarding the precise definition of each parameter would be high, as there are no universally accepted points.

On the other hand, in the course of time, licences for these databases have become increasingly expensive, and the terms and conditions have increasingly restricted the disclosure of data and methodology.

As a result, basing the findings on more recent sources would drastically reduce the reproducibility of the results of this study.

Moreover, reanalysing the data of Lenzen et al. 2006 in light of increased module efficiency and reduced wafer thickness appears to be a conservative choice, as this study overestimates the impact of innovation on the demand of the materials.

Demand of materials
Kg per m^2

MATERIAL	IEA 2020	RECALCULATION FROM LENZEN ET AL. 2006
Glass	8.81	6.2
Aluminium	2.13	2
EVA	0.9	0.54

But there is also another reason to start from the data of Lenzen et al. 2006.

When the Paris Agreement was signed, the database used by Lenzen et al. 2006 (Ecoinvent 1) was compatible with the most used ones (Steubing et al. 2016).

Therefore, starting the data of Lenzen et al. 2006 allows for clarifying two different aspects of the issue: what are the actual carbon intensity and ERoEI of photovoltaic energy in 2022, and what were the actual carbon intensity and ERoEI of photovoltaic energy in 2015, when 195 countries approved legally binding agreement which turned the development of the photovoltaic industry into a strategic priority.

To estimate the PV plant's energy production, the average production of the Italian photovoltaic power plants in 2021 has been used: 1,137 equivalent hours per year.

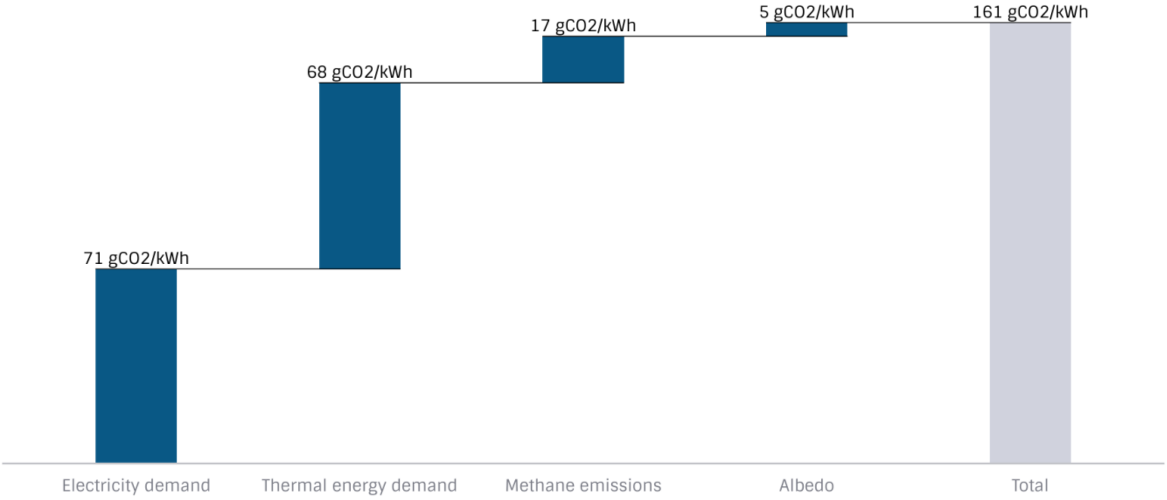
The Italian data is particularly interesting for four reasons: it is measured and not estimated; it is the average of all the photovoltaic systems installed in Italy, not of a sample; it implicitly includes some systemic variables that are difficult to model (the ratio of domestic systems to utility-scale systems, the geographic disposition, the average efficiency of the modules, etc.); Italy is a Mediterranean country.

Recalculation

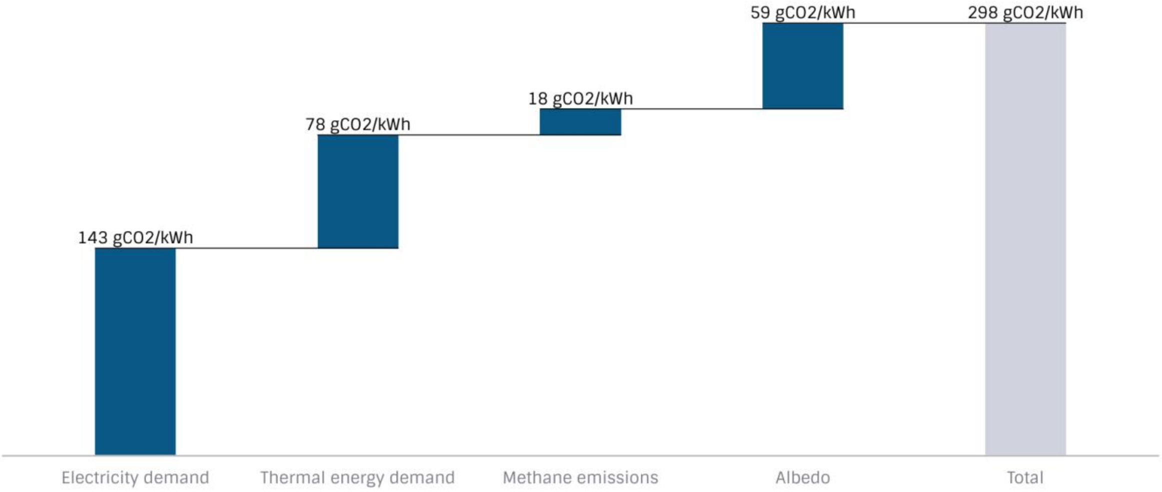
PARAMETERS	**BEST SCENARIO**	**WORST SCENARIO**
ORIGINAL SETTINGS (LENZEN ET AL. 2006)		
Electricity demand per MWp	2.75 GWh	
Thermal energy demand per MWp	19 TJ (5.3 GWh)	
Electricity demand for silicon purification per MWp	1.61 GWh	
Thermal energy demand for silicon purification per MWp	2.7 TJ (0.75 GWh)	
Plant	ground-mounted, utility scale	
Module area per MWp	9,050 m^2	
Thermal energy to primary energy conversion factor	1	
RECALCULATION PARAMETERS		
Carbon intensity of electricity	600 gCO_2/kWh (62% coal, 3% natural gas, 35% low-carbon sources)	1,200 gCO_2/kWh (coal)
Thermal energy supply	70% hard coal, 30% natural gas	100% hard coal
Albedo's difference	0.03 (crops)	0.30 (sand)
Module efficiency increase[1]	+48%	
Wafer thickness reduction[2]	-37%	
Equivalent hours	1,137 per year	
Grid losses	5.6%	
Plant life expectancy	25 years	
Module degradation rate	2% the first year, 0.5% thereafter	
Average Chinese coal plants' efficiency	42%	
Average Chinese grid efficiency in 600 gCO_2/kWh scenario	60%	
Hard coal CO_2 emissions per GJ	94 kg	
Natural gas CO_2 emissions per GJ	56 kg	
Methane GWP100	29.8	
Albedo to CO_2 equivalence	Decreasing the albedo of 1 m^2 of a surface by 0.01 equals 5 Kg of CO_2 emissions	

[1] Module efficiency increase affects cumulative energy demand, methane emissions and land occupation [2] Wafer thickness reduction affects cumulative energy demand for silicon purification and methane emissions related

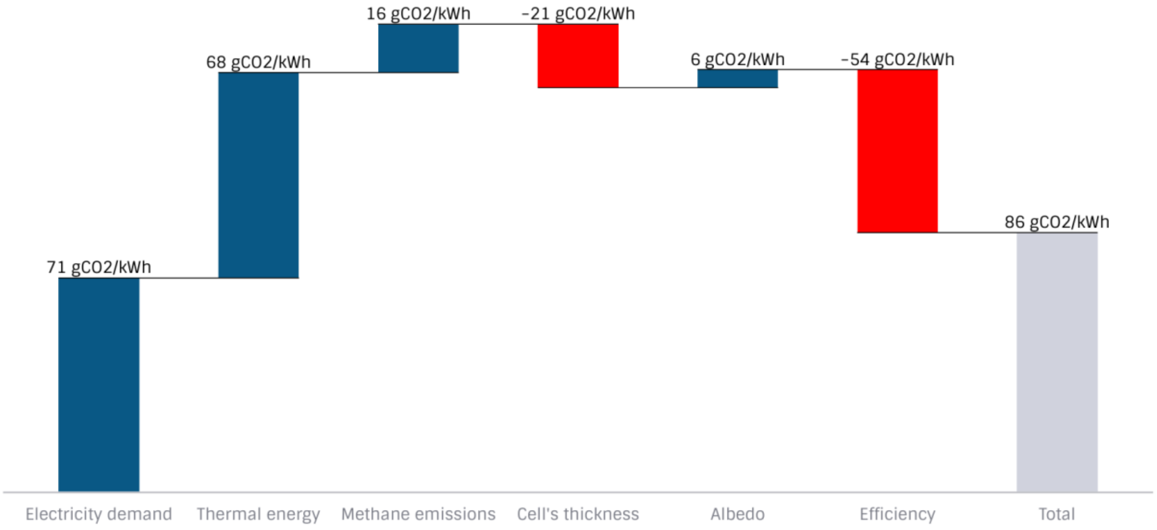
2015
Carbon intensity, Best Scenario



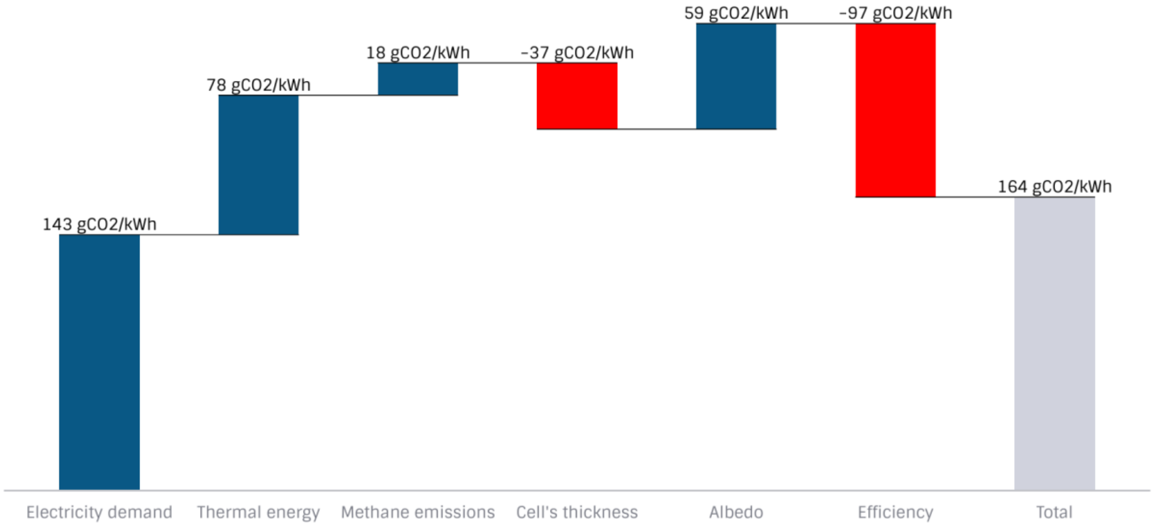
2015
Carbon intensity, Worst Scenario



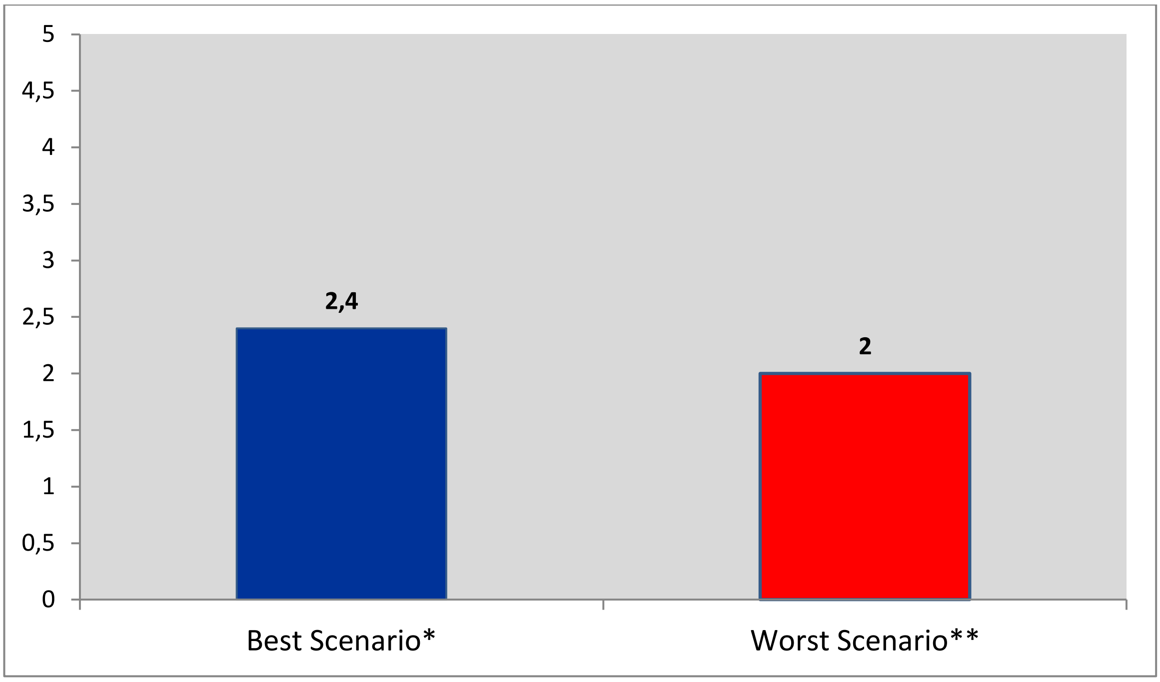
2022
Carbon intensity, Best Scenario



2022
Carbon intensity, Worst Scenario



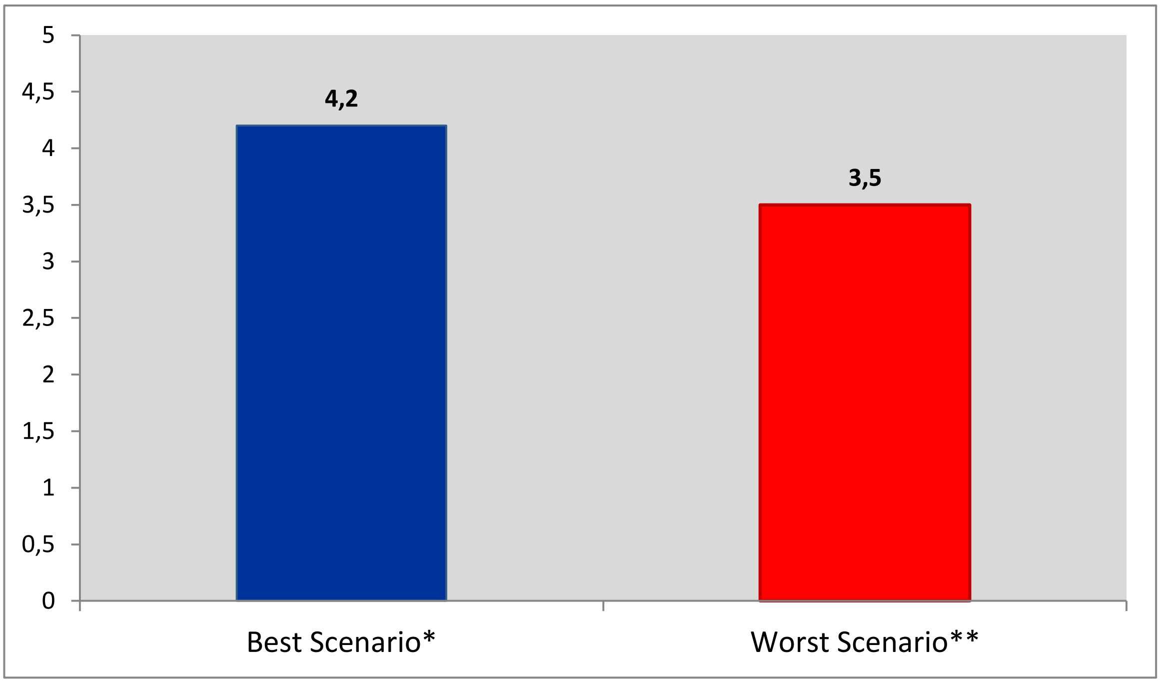
2015
Energy Return on Energy Investment (ERoEI)



* Electricity to primary energy conversion factor: 0.6. Thermal energy to primary energy conversion factor: 1

** Electricity to primary energy conversion factor: 0.42. Thermal energy to primary energy conversion factor: 1

2022
Energy Return on Energy Investment (ERoEI)



*Electricity to primary energy conversion factor: 0.6. Thermal energy to primary energy conversion factor: 1

** Electricity to primary energy conversion factor: 0.42. Thermal energy to primary energy conversion factor:

ADVANCED RECALCULATION

Beyond the emission factors of energy sources, efficiency rates, carbon footprint of materials and calculation models, there is also something to say about the methodological perimeter of photovoltaic LCA.

I submitted to the authors of the IEA PVPS reports and the IPCC sources the question: *"In your opinion, should the energy investment on the enhancement of the power grid to transmit and distribute the electricity produced by a photovoltaic plant be included in the estimates of the carbon footprint of photovoltaic plants?"*. Mariska de Wild-Scholten answered in the affirmative. Garvin Heath answered in the affirmative, with some reservations. Thomas Wetzel and David Hsu preferred not to answer.

Based on Ecoinvent data and assuming the installation of 20 km of distribution lines per MW of photovoltaic power installed (a scenario consistent with the current power grid structure of the main European countries), the plant's carbon footprint would increase by approximately 1,000 tons of CO_2 per MW.

At the same time, a similar argument should be made about batteries, but in this case, the scientific literature is rapidly filling the gap.

I submitted to the authors of the IEA PVPS reports and the IPCC sources the question: *"In your opinion, should the carbon footprint of batteries coupled with photovoltaic plants be included in the estimates of the carbon intensity of photovoltaic energy?"*. Mariska de Wild-Scholten answered in the affirmative. Garvin Heath and Goufu Hou answered in the affirmative, with some reservations. Thomas Wetzel and David Hsu preferred not to answer.

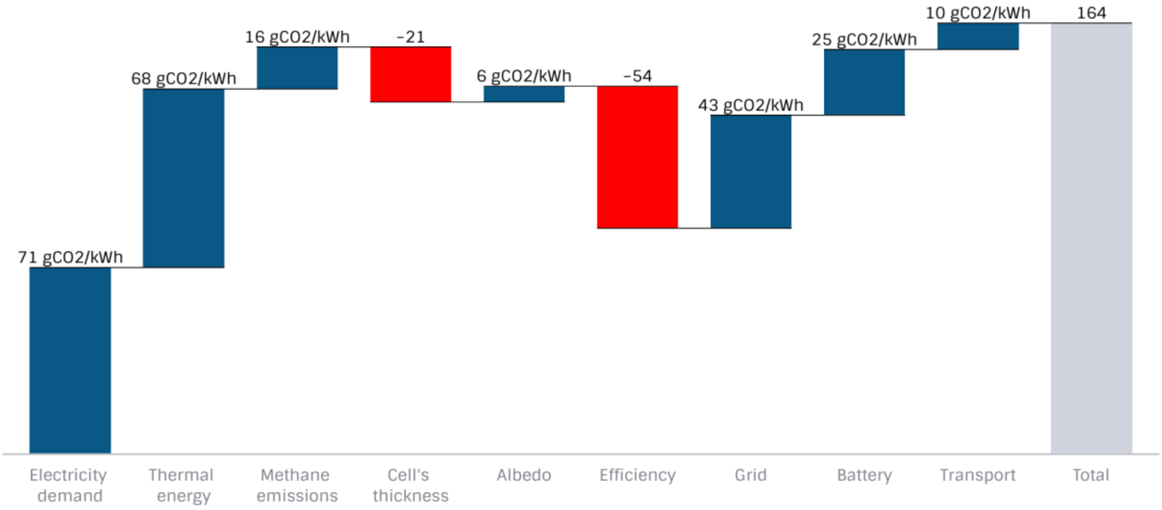
The IEA recently calculated that coupling a 20 kWh battery to a 10 kW photovoltaic raises the carbon intensity of the system by 25 gCO_2/kWh.

Intuitively, utility-scale battery storage systems had lower global warming potential (GWP) impact per kWh stored. However, this consideration can lead to misleading conclusions as the ratio between the power of the photovoltaic system and the power of the battery pack adopted in the IEA battery report is lower than that generally applicable to utility-scale projects. And also because the battery life cycle assessment sector has shortcomings similar to that of photovoltaic energy (the IEA formulates its estimates on the basis of data provided by a Norwegian manufacturer).

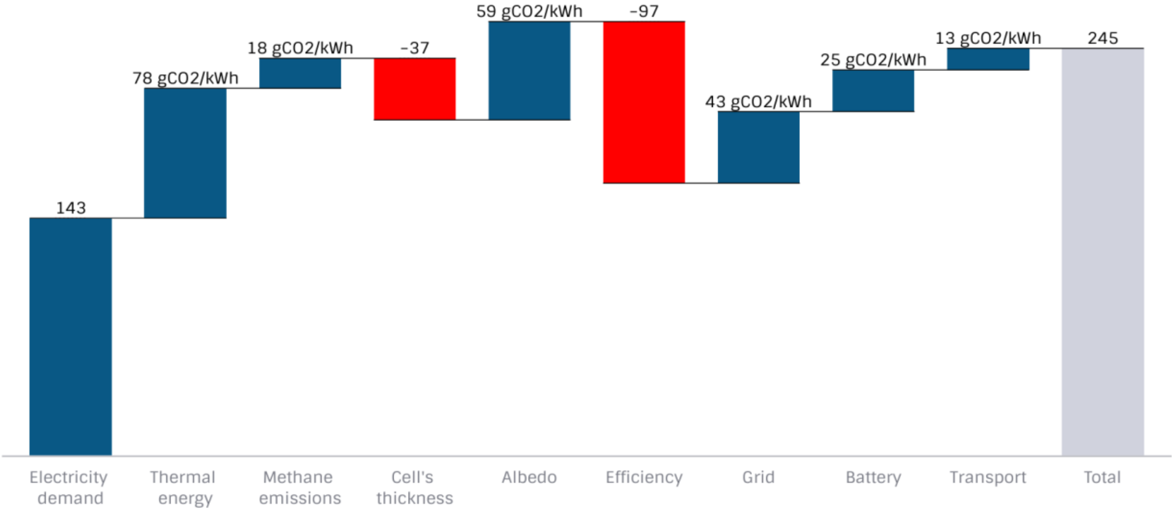
Then there are transports. The life cycle assessments of photovoltaic energy do not seem to have captured the global economy's transition from the trade-in-goods to the trade-in-services paradigm (what we call globalization). Most of the materials and semi-finished products involved in the production process of a photovoltaic panel are accounted "at the plant", i.e. as if they did not have their own supply chain.

In the absence of specific data, the global ratio between shipping and industrial emissions (7%) can be used to formulate a rough estimate.

2022
Carbon intensity, Best Scenario



2022
Carbon intensity, Worst Scenario



UNKNOWNS

Curtailments and charge/discharge cycle of batteries. Scenarios characterized by high penetration of VRE predict an increase in network losses due to curtailments and the charge/discharge cycle of batteries. For example, in the latest version of the model developed by Mark Jacobson - highly cited by experts who advocate the transition to renewable energy – the total losses in Italy leap to 11% (that is twice the current ones). To date, it is premature to formulate estimates. However, this variable must be taken into account because it will inevitably reduce the productivity of the photovoltaic systems we install today.

Module deterioration. The latest generation cells are particularly susceptible to high temperatures. Consequently, in warmer climates, the degradation rate could be higher than that declared by the manufacturers.

Quality deviations. When the PV market heats up, quality controls see a surge in the number of high-risk deviations requested by suppliers during the contracting process. This could be detrimental to the quality specifications of the modules.

Early Retirement. Currently, the life expectancy of a photovoltaic module is estimated based on the manufacturer's warranty. This approach risks overestimating the plant's lifespan, given that the combination of incentives and continuous efficiency increase could make it convenient to replace the plant well before it reaches its lifetime.

Methane emissions. Recent studies have shown that methane emissions from China's coal industry are vastly underreported. This evidence could triple the methane emission estimates used in the previous paragraphs.

Albedo effect. The construction of a photovoltaic system does not only impact the albedo of the surface covered by the modules. On average, the total area occupied by a photovoltaic plant is about 2-3 hectares per MWp. Recent studies that have analyzed the albedo variation over the entire plant's surface area have found that "*the land use change examined here has a large impact on the surface energy budget and its surrounding environments*". However, for the moment, data are too scarce to establish standard parameters.

CONCLUSIONS

Delving into the scientific literature of the field, it is difficult not to perceive a Far West atmosphere. For example, it is common to come across studies that present results in open contradiction with each other. The methodologies are not standardized; therefore the boundaries and the calculation methodologies are not homogeneous. The use of unverified industrial data is the norm.

Broadly speaking, frequently when analyzing LCAs of photovoltaic panels the doubt arises that the authors' mission is not to investigate the real carbon intensity photovoltaic energy but to convince the readers that the carbon intensity of photovoltaic energy is very low. In fact, in the face of the spasmodic interest in any innovation that could lower carbon intensity's reference values and raise the ERoEI, there is a total lack of curiosity towards those factors which could raise the carbon intensity's reference value and lower the ERoEI.

But if the primary production of materials with which we manufacture plants and power lines generates a carbon footprint of thousands of tons of CO_2 per MWp, we should begin to wonder whether this technology will ever produce low-carbon energy.

We need photovoltaic panels to produce low-carbon energy. But we need low-carbon energy to assemble panels otherwise, they will not produce low-carbon energy.

Widening the vision, after years of being told to listen to the scientists, it is impressive to see how easily the scientific consensus can be broken if there is no rigorous application of the scientific method at its base.

Identity politics seems to have made us forget that every scientist is a prisoner of an individual with biases, interests, a career, and social relationships. An individual who may be highly competent in his field but totally ignorant of others, may be fascinated by an ideology, may be corrupted by stakeholders, or may live in an authoritarian regime with many interests in the photovoltaic industry. Nothing outrageous in thinking about these possibilities; they are the very reason for the EPA and FDA existence.

But if we talk about photovoltaic panels, wind turbines, and batteries, there is no authority in charge of overseeing the research process. Consequently, the field is based on "paper knowledge": if an authoritative source writes it, it is true. No one has been verifying anything for 20 years.

Hence, while we rant about climate justice and generational justice, we have probably fueled the greatest speculation in History.

“When the time for marching comes, many do not know / That their enemy marches at their head”

Bertolt Brecht, German War Primer, 1955