# THE EXTERNAL COSTS OF ELECTRICITY GENERATION: A COMPARISON OF ENVIRONMENTAL DAMAGE OF SILICON PHOTOVOLTAIC ELECTRICITY, PRODUCED WITH DIFFERENT ELECTRICITY MIXES, VS NATURAL GAS AND COAL

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ABSTRACT: In this paper the environmental damages of crystalline silicon photovoltaics are calculated, using the most recent photovoltaics data, and compared with those of the prevalent conventional energy technologies. A life cycle assessment of selected environmental impacts of 1kWh of electricity generated by various technologies was performed using Simapro software (version 7.2.4) in conjunction with the Ecoinvent database (version 2.2). The environmental impacts were assessed using the ReCiPe methodology. Because of the important role of coal and natural gas in the global electricity generation portfolio, special attention is given to the comparison of PV with those technologies. The environmental consequences of manufacturing PV modules with renewable, UCTE or 100% coal electricity mixes are explored. A brief update of the estimated monetarization of damages due to coal and climate change is included. A rough estimate of the true cost of coal and PV electricity is made in $2011.
Keywords: c-Si, Economic Analysis, Environmental Effect, External costs, Electricity mix

## 1 INTRODUCTION

***The 2012 context of coal***: Coal consumption in Europe grew by 3.3% in 2011 compared to the previous year, which was the highest surge in European coal consumption since 2006 [1]. Cheap coal imports from the US to Europe, up 47.8% over 2011, boosted profits of coal plant operators despite Europe's market policies to penalize carbon emissions[2]. The cap-and-trade system continues to fall short, as the price of EU emission allowances remains at less than €8 per ton of $CO_2$, roughly 1/4th the price initially estimated to be required to change the energy system [3][4]. The global consumption of coal grew by 5.4% in 2011, largely financed by European and US banks. Indeed, global financing of coal mining and power stations has about doubled since 2005.[5]

The atmospheric $CO_2$ concentration continues its consistent, monotonic rise, overtaking 394.5 ppm in August 2012 [6]. In 2011, Dr. Fatih Birol, Chief Economist at the IEA warned that "As each year passes without clear signals to drive investment in clean energy, the "lock-in" of high-carbon infrastructure is making it harder and more expensive to meet our energy security and climate goals." [7]. Investments in a given energy technology are made based on the perception of its competitiveness, which largely depends on the market price.

***Competitiveness of photovoltaics (PV)*** In a recent communication, the European Commission said that the competitiveness in all market segments of renewables (onshore wind and photovoltaics) requires policies that support the removal of 'market distortions' [8]. This summer, the International Energy Agency (IEA) published a report directed at energy ministers, advising on how to lower emissions to meet the 2° global warming limit (the estimated amount of average global warming that can be tolerated without catastrophic consequences) and to realize the economic benefits of lower fossil fuel use. It sets out three key recommendations. The first one is to price energy appropriately, so that it reflects the 'true cost' of energy, and encourage investment in clean energy technology [9].

***What are "market distortions" and the "true cost" of energy?*** Because energy is embedded in every product and service, the energy system is the life force of the economy. Furthermore, the environmental and health consequences of the energy generating technology are ubiquitous in society. The 'true cost' of an energy technology includes not only the market price and subsidies but also the cost of the environmental and health impacts. These costs that are outside of the market price are also called 'external costs', or 'market distortions' because the market price does not reflect the entire cost or real value of the technology.

By making existing 'hidden' support of energy producers transparent, and establishing an inventory of the costs and benefits to society, true cost accounting is indispensable in providing an overview of the comparable value of energy technologies.

***Footprint of PV, manufactured with a range of electricity mixes, as compared to gas and coal:*** In this paper, the carbon footprint, as well as other major health and environmental indicators, are calculated for PV electricity manufactured with different electricity mixes, and compared to the electricity generated with natural gas and coal. Over the past decade, efficiencies of PV energy conversion and manufacturing processes have steadily improved, reducing considerably the carbon footprints and energy payback times of PV modules. For example, the carbon footprint of multi-crystalline silicon PV modules has decreased from ~170 in the 1990's to as small as <25 g $CO_2$-eq/kWh in 2011, and the energy payback time at an insolation of 1700 kWh/$m^2$ per year has decreased from ~2 in 2005 to ~1 year in 2011. The carbon footprint of PV electricity is highly dependent on the electricity mix used in its fabrication [10]. A brief discussion of the monetarization of these damages follows.

## 2 METHODS

### 2.1 Life Cycle Assessment

A Life Cycle Assessment (LCA) evaluates the environmental impact of a product or service over its lifetime. This analysis follows the guidelines set out in the international standard ISO14040, which describes the principles and framework for LCA, as well as the Methodology for Life Cycle Assessment of Photovoltaic Electricity by the IEA.[11] The software used in this analysis is Simapro 7.3 with the ecoinvent 2.2 database. Since the ecoinvent database is used, the ecoinvent methodology is also used for internal consistency.

2.2 Life Cycle Impact Assessment

This analysis uses the ReCiPe method as applied in Simapro.[12] The calculation was executed to the mid-point level, which presents the unaggregated environmental indicators, but which is valid to a higher degree of certainty, than the endpoint level, which aggregates all the data. The environmental indicators give a qualitative as well as quantitative indication of the nature of the pollution, while an aggregated monetary sum is abstract and has no context. A long term perspective was used, which is the most indicative of the actual extent of the impact. The carbon footprint is a measure of the emissions of greenhouse gases (in kg of $CO_2$ equivalents), using the GWP100a method as defined by the Intergovernmental Panel on Climate Change (IPCC) in 2007, effective over a period of 100 years[13].

## 3 DATA & KEY PARAMETERS

The key parameters of the poly-silicon PV modules are given in Table 1.

**Table 1. Key Parameters for PV system**

| | |
|---|---|
| Wafer thickness | 180 μm |
| Cell size | 156 mm x 156 mm |
| Module size | 60 cells |
| Glass | Single |
| Frame | Yes |
| Mounting on roof | Schletter |
| Inverter | 2.5 kW |
| Module efficiency (%) | 14.4 |
| Degradation (%/yr) | 0.7 |
| Performance ratio | 0.8 |
| Lifetime (yrs) | 30 |
| Irradiation (kWh/m$^2$/yr) | 1700 |

The environmental indicators are calculated for the electricity as it exits the power plant (i.e. coal or natural gas power plant, or PV module) and also after power conditioning to the low voltage distribution level. A 12,4 kWp PV system, mounted on-roof, with cabling and inverter is taken as a typical PV system. Electricity directly from the module is considered to be comparable to electricity from the power plant. The power conditioning between the power plant and the low voltage distribution point is compared in the two cases: either the electricity is stepped from the high voltage, through medium voltage to the low voltage distribution grid, or the power conditioning occurs in the balance of system of a PV plant.

The environmental profile of electricity from three different PV modules is calculated: 1) fabricated using electricity produced by 100% coal generation in European (UCTE) power plants, 2) manufactured using the average European (UCTE 2000) electricity mix (47% conventional thermal, 37% nuclear, 16% hydro); and 3) made using hydro power in the production of the silicon feedstock, and natural gas electricity in the manufacturing of the cell and module. The manufacturing, based on the most recent 2011 processes, of the three PV modules are in every other way identical. The environmental profile of natural gas electricity is also calculated and all the results are normalized to electricity generated with coal, in order to put them into a broader perspective. The electricity from hard coal represents the output at the busbar produced by the average hard coal plant in UCTE in 2000, as specified in the ecoinvent data base 2.2. The electricity from natural gas uses the average net efficiency of natural gas power plants in UCTE (estimated from IEA 2001) as specified in ecoinvent 2.2.

## 4 RESULTS & DISCUSSION

### 4.1 Environmental impact, at the power plant

The air pollutant emissions by 1 kWh electricity from multi-crystalline silicon PV modules (19, 38 or 39 g $CO_2$ eq) as compared to electricity derived from burning gas (620 g $CO_2$ eq) or coal (1020 g $CO_2$ eq) is shown in Figure 1. The emissions of greenhouse gases that contribute to climate change (kg $CO_2$ eq) from PV modules manufactured with 100% coal electricity are double those manufactured with hydro power and natural gas electricity, but are still 96% less than the emissions of electricity generated by coal. Coal electricity is also a leading cause of mercury emissions that may be inhaled or ingested by humans causing neurological damage and contributes to the human toxicity indicator. Non-methane volatile organic compounds (NMVOC) are organic compounds (e.g. benzene) that typically have compounding long-term health effects. Many are carcinogens. Particulate matter is suspended in air as an aerosol, and is associated with lung cancer and respiratory disease. Emissions of sulfur oxides leads to acid rain which affects the biology of soil and vegetation and accelerates degradation of buildings and structures. The emissions calculated here are the average emissions of UCTE coal plants in 2000. $SO_2$ emissions have decreased between 2000 and 2006 on average by ~40% in up-to-date coal plants [14].

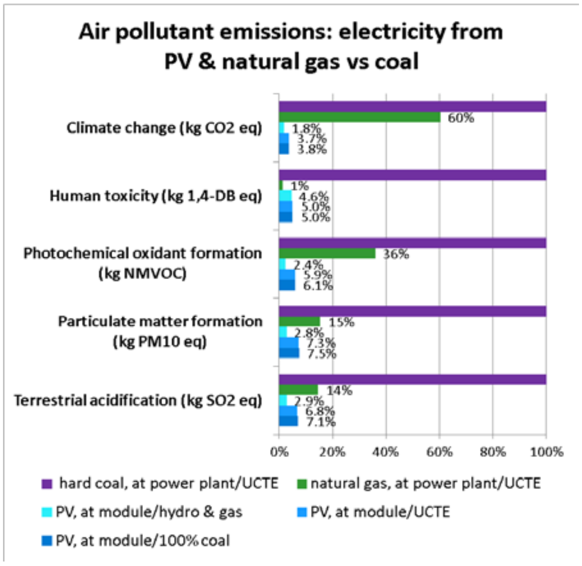


**Figure 1. Comparison of air pollution emissions of electricity produced by PV and natural gas, at power plant, relevant to climate change (kg $CO_2$ eq), human toxicity (kg 1,4 dichlorobenzene (DB)), reactive organic pollutants (kg non-methane volatile organic compounds (NMVOC)), and atmospheric particulate loading (kg of particulate matter 10 smaller than ~10**

**μm (PM10)), normalized to the impacts of hard coal electricity.**

The results for the formation of photochemical oxidants and particulates and for terrestrial acidification follow the same pattern: the PV module made using hydro and natural gas electricity produces electricity with only ~2-3% of the impact of coal. The PV modules made with UCTE electricity (~50% fossil fuel), and with 100% coal electricity roughly double the impact of the cleaner PV module (~6-7.5%). Electricity generated with natural gas provides 60% of the greenhouse gas emissions of coal, 36% of the volatile organic compounds, 15% of the particulates and 14% of the acidification.

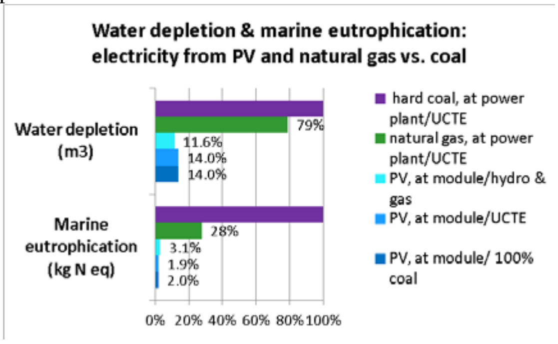


**Figure 2. Comparison of the water depletion and marine eutrophication by electricity from various sources normalized to the effects of coal.**

Water depletion and eutrophication are two critical issues for water management, now and in the future. Water depletion for the average UCTE coal electricity is calculated to be 2,782 liters/MWh, which is consistent with recent estimates for pulverized coal plants.[15] It is a measure of the water the technology withdraws for use, and accounts for the water intake (which may damage eco-systems), the consumption (which reduces water availability) and the discharged water (which may present water quality issues). The eutrophication, or the accumulation of reactive nitrogen in the environment, is a leading cause of water quality impairment, and a serious threat to the health of marine systems. The comparative results for these two indicators are shown in Figure 2.

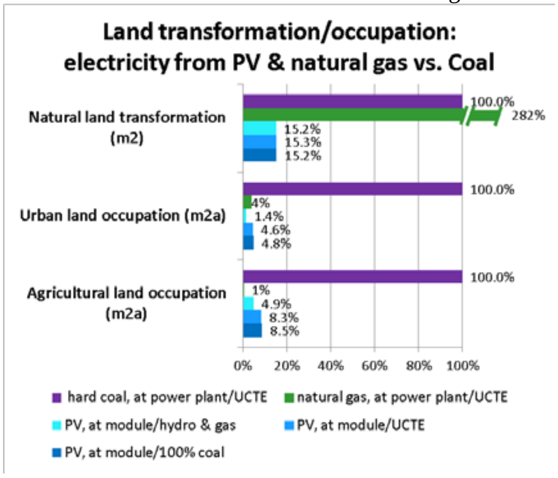


**Figure 3. Land occupation and transformation of electricity for electricity (kWh) from PV, natural gas and coal.**

The water demand by thermal generation of electricity using coal or natural gas dwarfs the demand from PV electricity. Coal and, to a lesser extent, natural gas both contribute to marine eutrophication.

The transformation of natural land, as well as the occupation of urban and agricultural land is large for hard coal due to the mining and infrastructure. Electricity from natural gas requires about 3 times as much transformation of natural land than coal, due to the requirements of the gas pipelines.

4.2 Environmental impact of power conditioning link between the power plant and the low voltage distribution

It is interesting to compare the environmental impact of the power conditioning link between the power plant and a low voltage distribution level. The PV system results reflect the environmental impact of the balance of system for a 12,4 kWp roof mounted system, according to the parameters in section 3. The ecoinvent database provided the average UCTE inputs to step from the high voltage network to the low voltage network. All results were calculated per kWh.

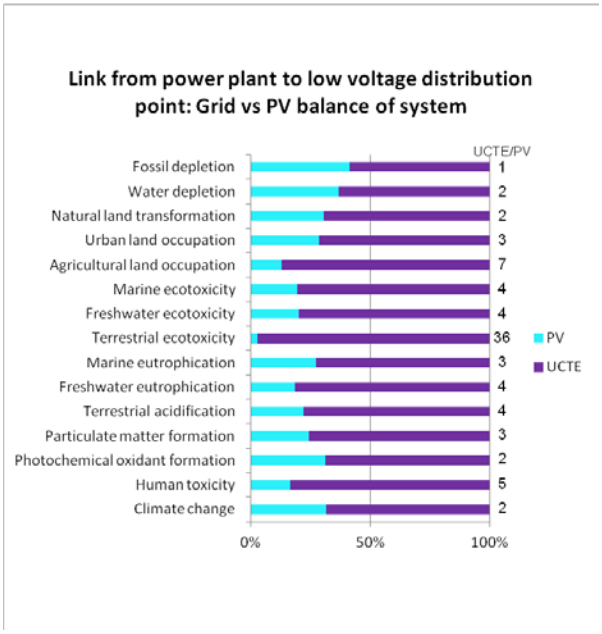


**Figure 4. The environmental impact of the power conditioning link, achieved either with PV balance of system, or by stepping from high, through medium to low grid voltage distribution.**

The column to the right of the bar graph in Figure 4 shows the value of the UCTE distribution divided by the PV value. The UCTE grid has a much higher environmental impact, across all categories, than does the balance of system for a mid-sized PV system for the delivery of electricity from the power plant to a low voltage distribution point.

As compared to coal, PV uses 89-86% less water, occupies or transforms over 80% less land, presents ~95% less toxicity to humans, contributes 92-97% less to terrestrial acidification, 97-98% to marine eutrophication, and 96-98% less to climate change

4.3 Estimate of 'true cost' of PV

Epstein et al. presented their best (their high) estimate of the true cost of coal as costing the U.S. public on the order of US$ 0.35 (0.52) trillion per year ($ 2008), or an additional 17.84 (26.90) ¢/kWh above the market price. The breakdown is as follows: 9.31 (9.31) ¢/kWh is due to air pollution (NMVOC, PM10 and $SO_2$), 4.69 (6.08) ¢/kWh to human toxicity, 3.15 (10.55) ¢/kWh to climate change, 0.16 (0.27) ¢/kWh for subsidies and the rest due to issues with land use and coal transport. [16]

We can now roughly estimate the external costs for PV by taking the appropriate percentage of the monetary amounts for the impacts of coal as given above by Epstein et al. This rough calculation leads to an estimate of about 1.0 (1.5) ¢/kWh for the environmental costs for a PV module manufactured with coal electricity. The EIA reports that in 2007, US solar PV received $14 million in subsidies and NREL reports (centralized and decentralized) US 2007 generation of 1,718 GWh, equivalent to 0.8 ¢/kWh [17][18]. However, the subsidies for an relatively new industry such as PV and those for a mature industry such as coal plants cannot be directly compared [19]. The German feed-in-tariff anticipates that the support cost will go to zero as the market penetration increases. In this work we therefore use 0.0 (0.8) ¢/kWh for the subsidies for PV.

The true cost of coal, as per Epstein et al., for a residential customer is the 2008 market price (10.64 ¢/kWh) plus the environmental costs, 17.68 (26.9) ¢/kWh and the subsidies 0.16 (0.26) ¢/kWh, which add up to 29.7 (37.6) ¢/kWh in 2008 dollars. The 2011 residential market price was 11.8¢/kWh. In 2011 dollars, the external costs become 19 (28) ¢/kWh, leading to the true cost of coal of 30.8 (39.8 ¢/kWh).

The true cost of PV, using the environmental costs calculated above, 1 (1.5) ¢/kWh, $2008, and figuring in subsidies 0.00-(0.8) ¢/kWh, $2007, and market price 10 (25) ¢/kWh, $2012, comes to 11 (27.3) ¢/kWh, $2011.

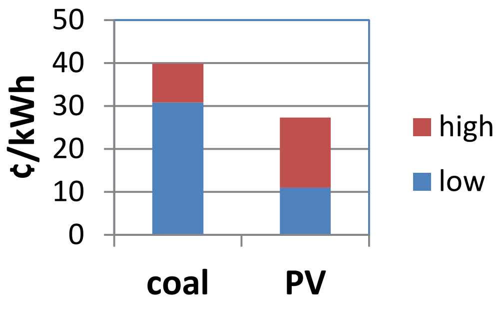


**Figure 5. The estimated true cost of coal and PV in 2011$. The difference between the coal low and high estimates is due primarily to the monetarization of the effects of climate change. On the other hand, the difference between the high and low estimate for PV is mainly due to the range in the market price.**

Cooling water scarcity is becoming a threat to the operation of thermal electric plants in Europe during warm, dry summers, when cooling water temperatures are too high, or sufficient volumes of water are not available [20]. Monetarization of this impact is not undertaken here. "Regulations, not price signals, are usually the drivers of water-related power plant decisions"[15]. Water is usually available at low or no cost. With the tightening of water regulations, there may be the need to include expensive equipment to mitigate the issues associated with water intake, consumption or discharge.

A United Nations Environmental Programme Finance Initiative (UNEP FI) recently ascribed an annual price tag to the impacts of climate change of US $6.6 trillion, 11% of the global domestic product (2008 GDP) [21]. This value (~12 ¢/kWh) is in line with the high estimate (10.55 ¢/kWh) used by the authors of the report on the true cost of coal. This report based its assessment on the Stern Review [22], which synthesized the 2006 knowledge in climate science and set a new standard for climate-economics analysis. Current observations of climate change are signaling a faster evolution than anticipated even 6 years ago [23]. This will most likely affect the cost estimates.

The Stern review was controversial because it put into relief issues that plague climate-economic models, including 1) the degree to which the inputs (data, risk etc.) are aligned and up-to-date with the findings of climate science, 2) the need for explicit and ethical reasoning about the discount rate, and 3) more sophisticated modeling of society, to allow for public policy choices to be made differently than private investment choices [23]. External cost studies which do not take the Stern study as a benchmark, still "use outdated estimates of physical impacts, trivialize economic damages from climate change, and oversimplify the climate problem"[24].

Ascribing a monetary amount to the damage on human life and health is also fraught with legal and ethical issues [25]. It is unnecessary to monetarize human life and health in order to set health standards. What is more enlightening is a clear picture, in all its dimensions, of the consequences of a technology.

## 4 CONCLUSIONS

Electric power generation was responsible for 37% of the EU's $CO_2$ emissions, which made it the single largest sector to contribute to climate change [9]. The environmental impact of photovoltaics, even if the modules are produced with electricity from coal, is extremely small as compared to natural gas and coal electricity.

The immense price tag of climate change is still evolving, but the stakes are clear. If the cost of climate change is tagged on the responsible technologies (i.e. fossil fuels) then photovoltaics present less risk than conventional thermal power. Indeed, the financial markets list carbon assets on their accounts that cannot be burned if the 2° global warming limit is to be attained [26]. This means there are assets currently valued, which in the future may be worth nothing. When placed in the context of this 'carbon bubble' that may be on the horizon of the global markets, photovoltaics, and renewable energy in general, may be viewed as a increasingly secure investment opportunity.

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