TOTAL COST ELECTRICITY PRICING OF PHOTOVOLTAICS

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ABSTRACT: Previous analysis of photovoltaic (PV) life cycles has documented significant environmental benefits from replacing conventional grid electricity with PV systems. However, environmental attributes are traditionally considered economic externalities and not factored into the levelized cost of electricity (LCOE). In contrast, total cost electricity pricing uses environmental and performance adders to account for externalities. Rather than imposing costs on existing electricity generation sources, adders are used for evaluating new generation sources on the basis of total cost, equal to the private cost (LCOE) plus the environmental and performance adder. Though utilities are not actually charged the adder, they can be required to rank technology options based on total cost, thus allowing environmental and other societal attributes to be part of the decision-making process. The total cost of ground-mount cadmium telluride (CdTe) PV systems ranges from $73-151/MWh, with a midrange value of $112/MWh ($0.11/kWh). The total cost of rooftop multi-crystalline silicon (multi-c-Si) PV systems ranges from $78-241/MWh, with a midrange value of $137/MWh ($0.14/kWh). These values are competitive with conventional combined cycle and combustion turbine natural gas ($71-213/MWh) and conventional coal ($105-257/MWh). Mid-range environmental costs are $1, $2, $26, and $50 for CdTe PV, multi-c-Si PV, natural gas, and coal, respectively. Although electricity is typically considered a commodity, total cost pricing indicates that solar PV electricity provides additional benefits with regards to impacts on climate, air quality, and water resources that are valued at $24-49/MWh ($0.02-0.05/kWh) relative to conventional gas and coal electricity. In addition to external costs of conventional generation, there are opportunity costs for the utilities' rate payers and society's tax payers of foregone value from not using renewable energy. There are opportunity costs related to energy infrastructure that range from $64-507/MWh ($0.06-0.51/kWh) still excluding the tax payers' cost for the missing insurance cost of nuclear power plants valued at $190-5385/MWh ($0.19-5.39/kWh) for the case of Germany. There are also opportunity costs related to non-energetic uses for fossil fuels that are approximately $0.21/kWh for the case of Germany. As market subsidies for renewable energy decline, total cost methodology provides an alternative framework for recognizing the societal benefits of clean energy when choosing between technology options.

Keywords: External cost, externalities, environmental costing, life cycle costing, life cycle assessment, PV

1 INTRODUCTION

Previous analysis of photovoltaic (PV) life cycles has documented significant environmental benefits from replacing conventional grid electricity with PV systems, including 89–98% reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species [1]. However, environmental impacts are traditionally considered economic externalities and not factored into the levelized cost of electricity (LCOE). In a cost-driven industry such as power generation, externalities may get ignored when choosing between technology options. In contrast, total cost electricity pricing uses environmental and performance adders to account for externalities. Rather than imposing costs on existing electricity generation sources (e.g., carbon tax), adders are used for evaluating new generation sources on the basis of total cost, equal to the private cost (LCOE) plus the environmental and performance adder. Though utilities are not actually charged the adder, they can be required to rank technology options based on total cost, thus allowing environmental attributes to be part of the decision-making process [2].

2 METHODS

Keske et al. [3][4] have provided an analytical framework for total cost electricity pricing in the state of Colorado in the United States.

$$\text{Total Cost} = \text{LCOE} + \Sigma(\text{Attribute}\times\text{Damage}) + \text{Variable Power Cost} \quad (1)$$

Emissions of regulated pollutants (SO_2, NO_x, CO_2e, Hg, $PM_{2.5}$) and water usage were combined with marginal damage factors as the basis for the environmental adder (Eq. 1). In addition, electricity from variable power sources (e.g., wind and solar) were assigned a performance adder for not providing dispatchable power. These adders were combined with the LCOE to obtain the total cost of a technology.

In developing the environmental adder, Keske et al. considered only operating emissions and water usage from electricity generation. In this evaluation, emissions and water usage over the technology life cycle are considered to provide a more complete representation of the environmental attributes of a technology. In this evaluation, life cycle emissions of Pb and Cd are considered in addition to Hg, as well as emissions of non-methane volatile organic compounds (NMVOC) which along with NO_x are precursors to tropospheric O_3 formation.

Life cycle assessment (LCA) has been conducted with Simapro (V. 7.3.3) software and Ecoinvent (V. 2.2) unit processes. Life cycle impacts for PV systems were assessed in accordance with International Energy Agency Photovoltaic Power Systems Program (IEA PVPS) Task 12 guidelines for LCA of PV [5]. Life cycle inventory (LCI) data for cadmium telluride (CdTe) PV is from publicly available sources for module manufacturing [6] and fixed-tilt balance of systems (BOS) [7]. CdTe PV represents a fixed-tilt utility-scale installation in the southwest United States with 2012 average module conversion efficiency of 12.7% [8], performance ratio of 0.812, plane of array irradiation of 2199 kWh/m^2/yr, 0.70%/yr module degradation rate, and 30 year lifetime [7].

LCI data for multi-crystalline silicon (multi-c-Si) PV [9] includes silicon, ingot, wafer, cell and module produced with Chinese electricity mix. BOS data is based on Schletter Eco05/EcoG on-roof support structure and roof cabling. The inverter is based on the Ecoinvent unit process “inverter, 2500W, at plant/RER/I U” assuming 15 yr life and inverter sizing ratio of 0.89 kW/kWp [10]. Multi-c-Si PV represents a fixed-tilt rooftop installation in the southwest United States with 2012 average module conversion efficiency of 14.7% [9], performance ratio of 0.75 [5], plane of array irradiation of 2199 kWh/m^2/yr, 0.70%/yr module degradation rate, and 30 year lifetime.

End-of-life collection and recycling for PV systems is not considered because LCI data is available for CdTe PV but not for multi-c-Si PV. For perspective, end-of-life collection and recycling, including semiconductor refining, accounts for approximately 10% of the total life cycle carbon footprint and energy payback time of CdTe PV [11].

Life cycle assessment of conventional energy is based on the Ecoinvent unit processes “Electricity, natural gas, at power plant/US U” and “Electricity, hard coal, at power plant/US U”. Life cycle emissions to air of SO_2, NO_x, CO_2e, Hg, Pb, Cd, $PM_{2.5}$, and NMVOC were estimated for each technology. Water usage reflects life cycle off-stream water withdrawal (excluding water used in running hydroelectric turbines).

Damage factors are from Keske et al. except for those for Pb, Cd, and NMVOC which are from the ExternE [12] and NEEDS [13] projects (Table 1). The variable power cost estimate ($5/MWh) is from Keske et al. LCOE estimates for conventional energy are from the U.S. Energy Information Administration for new generation sources installed in 2018 [14], reflecting the multi-year process for developing utility-scale power systems. For CdTe PV, LCOE of utility-scale systems currently (in 2013) varies from $70 to $150 per MWh [15], depending on the project region and other factors including irradiance levels, interest rates, and development costs. As with conventional energy, there is a multi-year process for permitting and constructing a utility-scale PV plant. For multi-c-Si PV, LCOE currently (in 2013) ranges from $75 to $240 per MWh [16; excluding an outlier value of $440 per MWh]. For both CdTe PV and multi-c-Si PV, $\$_{2013}$ was converted to $\$_{2011}$ based on an inflation factor of 4% (http://www.usinflationcalculator.com). In this study, costs are provided in $\$_{2011}$.

3 RESULTS

When the LCOE costs are combined with the life cycle environmental adder and variable power cost (Table 2), the total cost of ground-mount CdTe PV ranges from $73-151/MWh, with a midrange value of $112/MWh ($0.11/kWh). The total cost of rooftop multi-crystalline PV ranges from $78-241/MWh, with a midrange value of $137/MWh ($0.14/kWh). These values are competitive with conventional combined cycle (CC) and combustion turbine (CT) natural gas ($71-213/MWh) and conventional coal ($105-257/MWh) (Fig. 1).

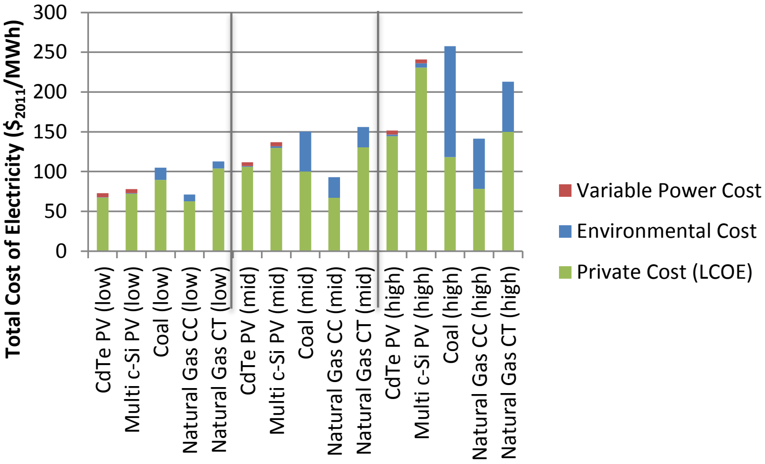

Figure 1: Range of total cost electricity pricing for conventional coal, conventional combined cycle (CC) and combustion turbine (CT) natural gas, and photovoltaic (PV) power generation

Table I: Marginal damage estimates ($\$_{2011}$/metric ton)

	Low	Mid	High
Sulfur Dioxide[a] [4]	$690.64	$1,339.85	$1,381.28
Nitrogen Oxides[a] [4]	$276.25	$414.39	$2,458.69
Carbon Dioxide[a] [4]	$6.00	$25.16	$77.90
Mercury[a] [4]	$145,438.09	$1,716,400.39	$2,574,023.43
Cadmium[b] [12][13]	$66,300.00	$104,317.10	$142,334.20
Lead[b] [12][13]	$473,082.80	$1,596,541.40	$2,720,000.00
NMVOC[b] [12][13]	$1,802.00	$1,856.40	$1,910.80
$PM_{2.5}$ [a] [4]	$13,812.84	$20,719.26	$27,625.68
Water [a] [4]	$0.07	$0.24	$0.71

[a] Marginal damage estimates in $\$_{2010}$ converted to $\$_{2011}$ based on an inflation factor of 3.2% (http://www.usinflationcalculator.com/)

[b] Marginal damage estimates in €$_{2000}$ converted to €$_{2011}$ based on an inflation factor of 25% (http://fxtop.com/en/inflation-calculator.php) and converted to $\$_{2011}$ based on an exchange rate of 1.36$\$_{2011}$/€$_{2011}$ (http://www.freecurrencyrates.com/exchange-rate-history/EUR-USD/2011)

For PV, the total cost is nearly equal to the LCOE, with a mid-range environmental cost of approximately \$1-2/MWh and a variable power cost of \$5/MWh. In contrast, while natural gas and coal can have lower LCOE than CdTe PV, they have considerable environmental costs. For natural gas, a mid-range environmental cost of approximately \$26/MWh is largely attributable to greenhouse gas (GHG) and sulfur dioxide emissions, and for coal, a mid-range environmental cost of approximately \$50/MWh is largely attributable to GHG emissions, sulfur dioxide emissions, and water usage (Fig. 2).

Based on these results, solar PV electricity provides mid-range benefits with regards to impacts on climate, air quality, and water resources that are valued at \$24-49/MWh relative to conventional gas and coal electricity.

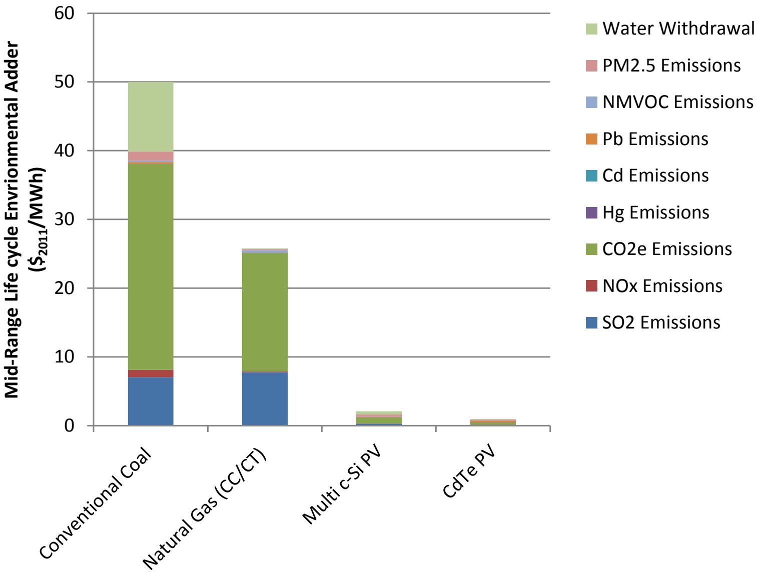

Figure 2: Mid-range environmental cost of conventional coal, conventional combined cycle (CC) and combustion turbine (CT) natural gas, and photovoltaic (PV) power generation

Table II: Total cost electricity pricing of conventional and photovoltaic generation (in $\$_{2011}$)

	Conventional Coal	**Conventional Combined Cycle Natural Gas**	**Conventional Combustion Turbine Natural Gas**	**Rooftop multi-c-Si PV**[a]	**Ground-mount CdTe PV**[b]
	Private Costs (LCOE; $\$_{2011}$/MWh) [14] [15][16]				
Low	\$89.50	\$62.50	\$104.00	\$72.12	\$67.31
Mid	\$100.10	\$67.10	\$130.30	\$129.81	\$105.77
High	\$118.30	\$78.20	\$149.80	\$230.77	\$144.23
	Life Cycle Emissions/Usage (metric ton/MWh)				
Sulfur Dioxide (to air)	5.27×10^{-3}	5.79×10^{-3}		2.01×10^{-4}	9.61×10^{-5}
Nitrogen Oxides (to air)	2.55×10^{-3}	3.75×10^{-4}		1.01×10^{-4}	4.94×10^{-5}
Carbon Dioxide (to air)	1.19	6.84×10^{-1}		3.44×10^{-2}	1.40×10^{-2}
Mercury (to air)	2.89×10^{-8}	1.97×10^{-9}		1.28×10^{-9}	2.41×10^{-9}
Cadmium (to air)[c]	1.51×10^{-8}	5.81×10^{-9}		2.85×10^{-9}	1.21×10^{-8}
Lead (to air)[c]	1.38×10^{-7}	9.78×10^{-9}		4.59×10^{-8}	1.25×10^{-7}
NMVOC (to air)	1.26×10^{-4}	1.84×10^{-4}		8.73×10^{-6}	5.77×10^{-6}
$PM_{2.5}$ (to air)	6.23×10^{-5}	9.31×10^{-6}		1.68×10^{-5}	8.33×10^{-6}
Offstream Water Withdrawal	42.7	4.00×10^{-1}		2.03	3.18×10^{-1}
	Variable Power Costs ($\$_{2011}$/MWh) [4]				
	\$0.00	\$0.00		\$5.00	
	Total Social Costs ($\$_{2011}$/MWh)				
Low	\$104.95	\$71.20	\$112.70	\$77.89	\$72.68
Mid	\$150.11	\$92.88	\$156.08	\$136.91	\$111.74
High	\$257.41	\$141.33	\$212.93	\$241.03	\$151.40

[a] Based on fixed-tilt rooftop installation in the southwest United States with 2012 average module conversion efficiency of 14.7% [9], performance ratio of 0.75 [5], plane of array irradiation of 2199 kWh/m^2/yr, 0.70%/yr module degradation rate, and 30 year lifetime.

[b] Based on fixed-tilt utility-scale installation in the southwest United States with 2012 average module conversion efficiency of 12.7% [8], performance ratio of 0.812, plane of array irradiation of 2199 kWh/m^2/yr, 0.70%/yr module degradation rate, and 30 year lifetime [7].

[c] Direct Cd emissions from controlled air exhaust in CdTe PV module manufacturing are 5.34×10^{-9} kg per m^2 module [6] (or 8.77×10^{-13} metric ton/MWh), and emissions of Pb are indirect. Over 90% of life cycle Cd and Pb emissions for CdTe PV are associated with balance of systems, primarily related to copper usage.

4 UNCERTAINTY

While accounting for emissions from electricity generation can be reasonably straightforward, assigning an external cost to those emissions is dependent on damage factors which assign economic value to impacts on health and natural resources. In the European Union, recent efforts have been undertaken to develop consensus methodologies for evaluating external costs of energy technologies (ExternE project which was later updated by the NEEDS project). The damage factors from Keske et al. considered in this evaluation are within or lower than the range of these prior estimates (Table 3), indicating that the external cost estimates in this evaluation are conservatively low.

Table III: Damage Factor Comparison ($\$_{2011}$/metric ton)[a]

	Keske et al [4]	ExternE [12]	NEEDS [13]
SO_2	691-1381	4996	11478
NO_x	276-2459	4944	12007
CO_2e	6-78	32	12-167
$PM_{2.5}$	13813-27626	33216	41769

[a] See Table 1 for conversion factors to $\$_{2011}$.

The environmental adder for CdTe PV systems in this study ranges from $0.37-2.16/MWh with a mid-range estimate of $0.97. This range is consistent with a previous estimate of 0.126 €-ct$_{2000}$/kWh at 1700 kWh/m^2/yr irradiation (~1.65 $\$_{2011}$/MWh at 2199 kWh/m^2/yr irradiation) for CdTe PV [17] based on ExternE damage factors. For multi-c-Si PV systems, the environmental adder in this study ranges from $0.78-5.26/MWh with a mid-range estimate of $2.10. This range is consistent with a previous estimate of 0.177 €-ct$_{2000}$/kWh at 1700 kWh/m^2/yr irradiation (~2.33 $\$_{2011}$/MWh at 2199 kWh/m^2/yr irradiation) for c-Si PV [17] based on ExternE damage factors. Another recent estimate for the environmental adder was $10-15/MWh at 1700 kWh/m^2/yr irradiation ($8-12/MWh at 2199 kWh/m^2/yr irradiation) for life cycle impacts to air pollution, human toxicity, and climate change for c-Si PV manufactured with coal electricity [18].

While it is possible to look at emissions of additional chemicals beyond those considered in Table 1, in previous analysis, these chemicals accounted for over 99% of the total environmental adder [17]. In particular, emissions of CO_2e and SO_2 and water use account for a large proportion of the environmental adder for the various energy options considered here.

In better understanding the external costs of electricity generation, particular focus can be placed on understanding the damage factors for CO_2e, SO_2, and water. In particular, CO_2e impacts account for the largest proportion of the environmental adder (Fig. 2). In a recent assessment of the life cycle impacts of coal power, Epstein et al. [19] considered CO_2e damage factors ranging from approximately $10-100/MWh with a best estimate of $30/MWh, overlapping with the range in Table 2.

While addressing climate change has been an important driver for renewable energy adoption, the external cost analysis indicates that water security provides an additional driver. For example in the United States, thermoelectric power plants have recently accounted for over 40% of total freshwater withdrawals, even more than for agriculture [20]. Unlike thermal power generation, solar PV directly converts sunlight to electricity, using little to no water during operation. Therefore, solar PV provides a potential path forward for addressing the energy-water nexus. For example, when deployed in the U.S. Southwest, a thin-film CdTe PV array can provide net displacement of life cycle water withdrawal of over 1,700-5,600 L/MWh relative to grid electricity [21].

In addition to the environmental adder, there are uncertainties associated with the variable power cost estimate ($5/MWh) which was assigned for solar PV not providing dispatchable power. The estimate is based on a wind power integration study conducted for Xcel Energy in the U.S. [22] based on varying penetration rates of wind energy (10-20%) in the state of Colorado. The study assumes displacement of natural gas electricity with a gas price of $5 per million BTU and assumes that gas-burning units are used to back up variable generation. The renewable power integration cost estimate ranges from $3.51 to $5.13/MWh and is influenced by the geographic distribution of renewable generation and accuracy of forecasting technology for predicting variability. Increasing gas prices can increase integration costs but also increases the value of gas displacement.

In addition, some utility-scale PV power plants now have power plant controller architecture to regulate real and reactive power output from the PV plant, such that it behaves like a single large generator. Plant-level control functions include dynamic voltage and/or power factor regulation, power output curtailment, ramp-rate and frequency controls, and start-up and shut-down control [23]. An example of a utility-scale PV power plant with power plant controller architecture is shown in Figure 3.

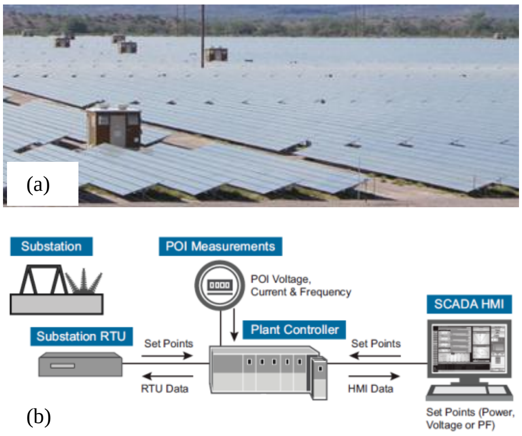

Figure 3: a) A utility-scale CdTe PV system (290 MWac Agua Caliente solar project, Yuma County, Arizona, USA) with b) power plant controller architecture [23]

5 OPPORTUNITY COSTS

In addition to external costs of conventional generation, there are opportunity costs of foregone value from not using renewable energy. These opportunity costs are related to energy infrastructure and non-energetic uses for fossil fuels.

5.1 Energy infrastructure

The opportunity cost of non-use of renewable energy, in particular PV, comprise a loss of value for the utilities' rate payers and society's tax payers. Cost for rate payers include the lost value of hedging of fuel price fluctuations, as well as demand response capacity actions on the transmission level. Central PV systems located close to the load demand help to displace aforementioned capacity actions due to the synergy of load demand and solar resource availability. The cost for tax payers are the lost value of grid security enhancement, long term finite fuel hedge value (beyond the commodity futures's 5 year horizon) and economic growth induced by renewables investments. The cost is estimated to about $90-250/MWh for rate payers and $80-100/MWh for tax payers [24]. In addition, the insurance cost for nuclear power plants have to be fully covered by the tax payers and can be quantified to €140-3960/MWh ($190-5385/MWh) for the case of Germany [25].

Further opportunity costs of non-use of renewable energy are subsidies incurred for the conventional energy system, e.g. financial aid, tax incentives and state rules outside of budget (in particular the allowance to invoice the emission trading certificates allocated for free), which accounted in total to €102/MWh ($133/MWh) in 2012 for the case of Germany, whereas the support of renewables cost only €36/MWh ($47/MWh) in the same period of time [26].

Similar subsidies have been recorded in the US [27], since the cumulative historical federal subsidies reached $671bn until 2010, partitioned on oil and gas (66.6%), nuclear (27.6%), biofuels (4.8%) and renewables (0.9%).

A review report conducted by the Rocky Mountain Institute [28] summarizes a broad variety of publications concerning the benefits of solar PV, which can only be realized when solar PV is in use, i.e. these benefits equal the opportunity cost of non-use of solar PV. These costs are: value of saved energy being lost in the conventional system due to inherent inefficiencies in the transmission and distribution (T&D) system of $25-110/MWh, further losses in the T&D system of $1-45/MWh, value for avoided generation capacity of $1-110/MWh, value for avoided T&D capacity upgrades of $1-80/MWh, value for grid support services of $1-15/MWh, value for financial fuel price hedging of $5-35/MWh, value for market price response to higher renewable energy supply contribution of $10-45/MWh, value for grid security of $10-22/MWh and value for additional economic development due to the use of renewables (mainly solar PV) of $10-45/MWh. All these benefits of the use of solar PV convert into cost of non-use and add up to a range of $64-507/MWh.

5.2 Non-energetic use

In addition to energy infrastructure, there are opportunity costs related to non-energetic uses for fossil fuels. Kroll [29] developed an approach to calculate the opportunity costs incurred when the use of a free and abundant commodity (solar radiation) is supplanted by the use of a finite commodity (fossil fuels), which is destroyed and thus unusable in the future. Through substitution of fossil fuel energy generation, the value of the finite resource is preserved for future non-energetic uses. For example in Germany, approximately 1-15% of fossil fuel resources such as hard coal, oil, and natural gas have non-energetic uses (Table 4).

Table IV: Proportion of annual non-energetic uses for fossil fuel resources in Germany [30]

Fossil fuel resource [FFR]	Total consump-tion (TJ)	Non-energetic use (TJ) [NEU]	Import price (€$_{2012}$/TJ) [IP]	Proportion of non-energetic use (%)
Hard coal	1,790,071	20,448	308	1.1
Crude Oil	5,376,496	805,769	15354	15.0
Natural Gas	3,656,602	183,041	8018	5.0

By applying the conservative assumption that current fossil fuel import prices in Germany [31] equal the future value of the fossil fuel resources for non-energetic uses, an annual opportunity value (AOV*;* 13.9 billion €$_{2012}$; 18.4 billion $\$_{2011}$) can be estimated based on Equation 2 and Table 4. The AOV represents the value which would be lost if these fossil fuel resources would be used for one-time energy generation purposes instead of non-energetic uses.

$$AOV = \sum_{FFR} (NEU \times IP) \tag{2}$$

By substituting one-time fossil fuel energy generation with renewable resources like PV, a positive substitution value (SV; ~0.16 €$_{2012}$/kWh; ~0.21 $\$_{2011}$/kWh) is estimated based on Equation 3 and Table 4. The SV represents the value of conserving finite fossil fuel resources for future non-energetic use.

$$SV = \left(AOV / \sum_{FFR} NEU \right) \times \eta \tag{3}$$

where η: German grid efficiency (1.16×10^{-5} TJ/kWh) based on Cumulative Energy Demand Version 1.08 characterization method in Simapro.

6 CONCLUSIONS

Although electricity is typically considered a commodity, total cost pricing indicates that solar PV electricity provides additional benefits with regards to impacts on climate, air quality, and water resources that are valued at $25-49/MWh ($0.02-0.05/kWh) relative to conventional gas and coal electricity. In addition to external costs of conventional generation, there are opportunity costs from not using renewable energy related to energy infrastructure ($0.06-0.51/kWh) and non-energetic uses for fossil fuels (~$0.21/kWh).

In summary, when compared on a total cost basis, photovoltaic power systems are competitive with conventional power generation. The total cost methodology can be used as a policy tool for ranking technology options while incorporating their environmental impacts. As market subsidies for renewable energy decline, total cost methodology provides an alternative framework for recognizing the societal benefits of clean energy when choosing between technology options.

7 REFERENCES

[1] V.M. Fthenakis, H.C. Kim, E. Alsema, Emissions from Photovoltaic Life Cycles, Environmental Science and Technology 42 (2008) 2169-2174.

[2] European Commission, Life-cycle costing (Available at: http://ec.europa.eu/environment/gpp/lcc.htm).

[3] C. M. H. Keske, S. G. Evans, T. Iverson, Total Cost Electricity Pricing: A Market Solution for Increasingly Rigorous Environmental Standards, The Electricity Journal 25 (2012) 7-15.

[4] C.M.H. Keske, T. Iverson, G. Graff, Designing a Technology-Neutral, Benefit Pricing Policy for the Electric Power Sector in Colorado, Technical Report Submitted to Colorado Governor's Energy Office, (2010) 1-49.

[5] V. Fthenakis, R. Frischknecht, M. Raugei, H. C. Kim, E. Alsema, M. Held and M. de Wild-Scholten, Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 2nd edition, IEA PVPS Task 12, International Energy Agency Photovoltaic Power systems Programme (2011) 1-13.

[6] N. Jungbluth, M. Stucki, K. Flury, R. Frischknecht, S. Büsser, Life Cycle Inventories of Photovoltaics, ESU Services (2012) 75-81.

[7] P. Sinha, M. de Wild-Scholten, Life Cycle Assessment of Utility-Scale CdTe PV Balance of Systems, 27th EU PVSEC, Frankfurt, Germany (2012) 4657–4660.

[8] First Solar, Key Quarterly Financial Data, Q1 2013 (Available at: http://investor.firstsolar.com).

[9] M. de Wild-Scholten, Energy payback time and carbon footprint of commercial photovoltaic systems, Solar Energy Materials & Solar Cells 119 (2013) 296-305.

[10] T. Stetz, J. von Appen, M. Braun, G. Wirth, Cost-Optimal Inverter Sizing for Ancillary Services – Field Experience in Germany and Future Considerations, 26th EU PVSEC, Hamburg, Germany (2011) 3069 – 3074.

[11] P. Sinha, M. Cossette, J.-F. Ménard. End-of-Life CdTe PV Recycling with Semiconductor Refining, 27th EU PVSEC, Frankfurt, Germany (2012) 4653–4656.

[12] R. Dones, T. Heck, C. Bauer, S. Hirschberg, P. Bickel, P. Preiss, L.I. Panis, I. de Vlieger, ExternE-Pol Externalities of Energy: Extension of Accounting Framework and Policy Applications, New energy technologies, Release 2 (2005) 1-76.

[13] NEEDS, External costs from emerging electricity generation technologies, Deliverable n° 6.1 – RS1a (2009) 1-50.

[14] U.S. Energy Information Administration, Annual Energy Outlook 2013, December 2012, DOE/EIA-0383(2012) (Available at: http://www.eia.gov/forecasts/aeo/electricity_generation.cfm)

[15] First Solar, First Solar Overview (2013) 1-37.

[16] Bloomberg New Energy Finance, Levelized cost of electricity: Q2 2013 (2013) 2.

[17] V. Fthenakis, E. Alsema, Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status, Prog. Photovolt: Res. Appl. 14 (2006) 275–280.

[18] C.L. Olson, A.C. Veltkamp, W.C. Sinke, 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, 27th EU PVSEC, Frankfurt, Germany (2012) 4604 – 4608.

[19] P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. 1219 (2011) 73-98.

[20] J.F. Kenny, N.L. Barber, S.S Hutson, K.S. Linsey, J.K. Lovelace, M.A. Maupin, Estimated use of water in the United States in 2005, U.S. Geological Survey, (2009).

[21] P. Sinha, A. Meader, M. de Wild-Scholten, Life Cycle Water Usage in CdTe Photovoltaics, IEEE Journal of Photovoltaics 3 (2013) 429-432.

[22] R.M. Zavadil, J. King, Wind Integration Study for Public Service Company of Colorado Addendum: Detailed Analysis of 20% Wind Penetration, Xcel Energy (2008) 1-55.

[23] M. Morjaria, and D. Anichkov, Grid-Friendly Utility-Scale PV Plants, Transmission & Distribution World (2013) 1-14.

[24] R. Perez, K. Zweibel, T.E. Hoff, Solar Power Generation in the US: Too expensive, or a bargain?, ISES Solar World Congress, Kassel, (2011) 1-16.

[25] Guenther, B., T. Karau, E.-M. Kastner, and W. Warmut, Berechnung einer risikoadaequaten Versicherungspraemie zur Deckung der Haftpflichtrisiken, die aus dem Betrieb von Kernkraftwerken resultieren, Versicherungsforen Leipzig, Leipzig, (2011).

[26] S. Küchler, B., Meyer, S. Blanck, The full costs of power generation – A comparison of subsidies and societal cost of renewable and conventional energy sources, study on behalf of German Wind Energy Association e.V. and Greenpeace Energy eG, (2012), http://www.foes.de/pdf/2013-03-full-costs-of-power-generation.pdf

[27] N. Pfund and B. Healey, What would Jefferson do? – The Historical Role of Federal Subsidies in Shaping America's Energy Future, DBL Investors, San Francisco, CA, (2011), http://www.dblinvestors.com/documents/What-Would-Jefferson-Do-Final-Version.pdf

[28] L. Hansen, V. Lacy, D. Glick, A Review of Solar PV Benefit & Cost Studies, Rocky Mountain Institute, Boulder, CO, (2013), www.rmi.org/elab_emPower

[29] Kroll, M., The Monetary Cost of the Non-Use of Renewable Energies, World Future Energy Council, (2013)

[30] AG Energiebilanzen e.V., http://www.ag-energiebilanzen.de,, Energieflussbild Deutschland 2011 (TJ)

[31] Rosenkranz, G., Quentin, J., Die Energiewende und die Strompreise in Deutschland – Dichtung und Wahrheit, Deutsche Umwelthilfe e.V., (2013), http://www.duh.de/uploads/media/DUH-Hintergrund_Energiewende_und_Strompreise_14-08-2014.pdf