

6 **Potential Lives Saved by Replacing Coal with Solar Photovoltaic Electricity Production in the** 7 **U.S.**

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16

17 **Abstract**

18
19 Poor air quality from coal combustion adversely impacts human health including mortality and
20 morbidity effects on respiratory, cardiovascular, nervous, urinary, and digestive systems. However, the
21 continued use of coal are no longer necessary to provide for society's electrical needs because of
22 advances in solar photovoltaic (PV) technology. In order to inform health policy this paper reviews the
23 data for quantifying the lives saved by a replacement of U.S. coal-fired electricity with solar PV
24 systems. First the geospatial correlation with coal fired power plants and mortality is determined for the
25 U.S. at the state level. Then, current life cycle mortality rates due to coal combustion are calculated and
26 current energy generation data is collated. Deaths/kWh/year of coal and PV are calculated, and the
27 results showed that 51,999 American lives/year could be saved by transitioning from coal to PV-
28 powered electrical generation in the U.S. To accomplish this, 755GW of U.S. PV installations are
29 needed. The first costs for the approach was found to be roughly \$1.45 trillion. Over the 25 year
30 warranty on the PV modules the first cost per life saved is approximately \$1.1 million, which is
31 comparable to the value of a human life used in other studies. However, as the solar electricity has
32 value, the cost per life is determined while including the revenue of the solar electric generation using a
33 sensitivity analysis on the value of the electricity. These results found that for most estimations of the
34 value, saving a life by offsetting coal with PV actually saved money as well, in some cases several
35 million dollars per life. It is concluded that it is profitable to save lives in the U.S. with the substitution
36 of coal-fired electricity with solar power and that the conversion is a substantial health and
37 environmental benefit.
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39 **Keywords:** public health; pollution; photovoltaic; lives; coal; solar energy
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41 **1. Introduction**

42 Coal combustion for electrical generation not only contributes to high levels of carbon dioxide
43 emissions [1-3] with the concomitant climate disruption [3-6], but also to conventional air pollution
44 [5,7]. Coal fired electrical power plants released 23% of air pollutants [8] and the largest contributors to
45 U.S. carbon dioxide emission is electrical generation (31%) [9]. While coal use is declining due to
46 natural gas resources and renewable energy growth [10], coal combustion still accounts for roughly 30-
47 40% of U.S. carbon dioxide pollution, contributing to ever-expanding climate change [3,12]. Air

48 pollutants are classified into four groups: gaseous, persistent organic, heavy metals, and particulate
 49 matter [11]. The literature shows a positive correlation between mortality and morbidity due to outdoor
 50 air pollution [12-15]. Specifically, it is well established in the historical and current literature that coal
 51 combustion results in emissions of carbon dioxide, methane (gaseous pollutants), particulate matter,
 52 nitrogen and sulfur oxides (gaseous), and mercury (heavy metal) [2,4,7,12,16-19]. A review of poor air
 53 quality from coal combustion is shown in Table 1. Poor air quality from coal is well known to
 54 adversely affect human health including: mortality and morbidity effects on respiratory, cardiovascular,
 55 nervous, urinary, and digestive systems. This paper will focus on a review of the mortality due to
 56 emissions from coal-fired electrical generation.

57

58 Table 1. Major health effects from coal combustion emissions.

59

	Medical Condition	Estimated Affected Individuals*	Coal Emissions Responsible
Respiratory	Asthma	22.9 million	NO _x , PM _x *
	Chronic Obstructive Pulmonary Disease	12.1 million	NO _x , PM _x
	Lung Cancer	159,217*	PM _x
Cardiovascular	Heart Attack	7.9 million	PM _x
	Congestive Heart Failure	5.7 million	PM _x
Neurological	Ischemic Stroke	104,000	NO _x , PM _x , SO ₂
	Developmental delays	637,233	Mercury ⁷⁰

60 *Estimated affected individuals include both mortality and morbidity rates. PM_x (particulate matter)
 61 encompasses particulate matter size between 2.5 and 10 micrometers. NO_x (nitrogen oxide) [3,11-
 62 13,20].

63

64 A full life cycle accounting of coal reveals an estimated \$523.3 billion in damages (including
 65 social and environmental externalities), which is roughly \$0.27/kWh generated [7]. Thus, the
 66 externalities of coal-fired electricity are more than double the average cost of residential electricity in
 67 the U.S. of \$0.12/kWh [21]. Although coal is detrimental in all stages of its life cycle, combustion is
 68 the stage with the heaviest health burden [16] in the form of mortality and morbidity effects due to
 69 outdoor air pollutants/emissions (see Table 1).

70 Most research devoted to addressing issues of coal degraded air quality has focused on
 71 mitigation of coal plant emissions using regulations and mechanisms such as cap and trade through
 72 permits [22], which are vigorously opposed by the coal industry [23]. These mechanisms decreased
 73 some gaseous pollutants by targeting sulfur and nitrogen oxides through a cap and trade regulatory

74 policy [24]. Particulate matter (absorbed through inhalation and ingestion) and carbon dioxide (impacts
75 climate processes) continue to pose severe risks [17,25]. Particulate matter is directly linked to
76 increased mortality due to lung cancer and respiratory disease [12,26].

77 Fortunately, the continued use of coal and the required complicated emissions controls are no
78 longer necessary to provide for society's electrical needs because of advances in renewable energy
79 sources such as solar photovoltaic (PV) technology [1,4,27]. PV produces no emissions or generate
80 liquid or solid wastes during use and has a well-established environmentally-friendly ecological
81 balance sheet [28-33]. The environmental benefits of PV are found in net energy studies [28], life cycle
82 analysis studies [29,32], emission studies from PV [30], sustainability indicators [31] and when
83 compared to other energy sources [33]. Integrating rooftop solar has potential to provide 39% of the
84 total U.S. electrical generation [34] and with the potential to build solar farms on unused tracks of land
85 [35], transitioning to solar PV has potential to replace coal as an energy source entirely [36-37]. Thus,
86 by replacing coal-fired electricity with PV-generated electricity there is an expected decrease in air and
87 waste emissions (e.g. greenhouse gases and air pollution particulates) that affect overall air quality and
88 would be expected to improve human health. However, how significant this health impact would be is
89 not known.

90 In order to inform health policy the objective of this review is to evaluate past research to
91 quantify the American lives saved by a complete elimination of the domestic coal industry with the
92 scale up of solar PV systems. First the geospatial correlation with coal fired power plants and mortality
93 is determined for the U.S. at the state level. Then, current life cycle mortality and morbidity rates due to
94 coal combustion are reviewed and current energy generation data is used to determine the current lives
95 saved by PV and the increase in U.S. PV installations to replace coal-fired electrical generation entirely.
96 Then, American deaths/kWh of coal and PV per year are calculated, enabling health policy analysts to
97 determine the number of lives currently saved by existing PV production and the potential for
98 eliminating all premature deaths from coal combustion in the U.S. The first costs for the approach is
99 calculated per lives saved over the life time of the PV systems. Finally, the cost per life is determined
100 while including the revenue of the solar electric generation using a sensitivity analysis on the value of
101 the electricity. Public health impact results and policy interventions are discussed.

102

103 2. Methods

104 Coal-fired electricity emissions [38] were geolocated in the U.S to illustrate the geospatial
105 relationship between coal emissions related mortality. Two shapefiles were obtained from the ArcGis
106 database to analyze current air pollution due to coal-fired electrical production in the United States: (1)
107 a shapefile of the U.S. [39], and (2) a shapefile of the current U.S. coal electrical plants [40]. This data
108 was then transcribed on a map utilizing ArcMap 10.3.1 to indicate potential areas for PV penetration.
109 Then annual mortality due to coal emissions per 100,000 people was added to the map [41].

110 Total U.S. electrical generation was obtained to quantify the percentage of kWh produced by
111 coal and solar PV in the U.S. [42]. Current U.S. solar penetration data was obtained to provide for the
112 baseline of PV lives saved now and in order to calculate the amount of PV needed to replace coal-fired
113 electrical generation entirely. Current solar PV penetration has reached roughly 27.4 GW [43]. This
114 aggregate of solar PV produces 2.32×10^7 kWhrs/year [44].

115 In order for PV to completely eliminate coal, the total DC rated power of PV needed, S_T , is
116 calculated as follows:

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$$118 \quad S_T = \frac{C_T}{(I \times 365)} * 10^{-6} \text{ [GW]} \quad (1)$$

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where C_T is the total amount of coal-fired electricity produced per year (1.32×10^{12} kWh/year) [45], and I , which is measured in kWh/m²/day, is the population weighted average U.S. peak sun hours per day that represents solar flux for solar PV generation and is determined by:

$$I = \sum_{s=1}^{50} \frac{(P_s I_s)}{P_T} \quad [\text{kWh/m}^2/\text{day}] \quad (2)$$

125 Where P_s is the 2015 population of each state [46], I_s is the average solar flux in each state [47],
126 and P_T is the total 2015 U.S. population [40]. It was found to be 4.79 kWh/m²/day.

127 There is a rich history of mortality studies on energy sources. The contribution to mortality was
128 quantified utilizing a review of the secondary sources for coal [13,14,48-50] and PV [29,32,51,52]. A
129 quantification of emissions throughout the entire life cycle of coal was necessary to determine the
130 average U.S. number of premature deaths per year, F_c . The coal-fired electricity life cycle is divided
131 into four components: extraction, transport, processing, and combustion [7]. The solar-photovoltaic
132 system life cycle is divided into 5 components: mining, purification, manufacturing, operation, and
133 recycling [30]. Waste, in the form of emissions, is calculated at each stage of the technologies life
134 cycle and is aggregated.

135 Thus, the electricity generation death rate for coal, r_c is given by:

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$$r_c = \frac{D_{TC}}{C_T} \quad [\text{American deaths/kWh/year}] \quad (3)$$

138

139 where D_{TC} is the total number of deaths due to coal fired electrical emissions, which is
140 52,000/year [53].

141 The electricity generation death rate for solar photovoltaic technology, r_{PV} , is given by:

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$$r_{PV} = \frac{D_{TPV}}{E_{TPV}} \quad [\text{U.S. deaths/kWh/year}] \quad (4)$$

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145 where the total energy generated by PV, E_{TPV} is 2.32×10^7 kWh/year [44] or 2.65×10^{-3} GW-
146 yr/year, where the GW-yr is a unit of energy. The total deaths per year due to PV is more challenging to
147 determine. For thin film amorphous silicon PV the value is currently zero based on the limited number
148 of cases in the U.S. Environmental Protection Agencies Risk Management Program database [29]. The
149 actual values of deaths from other PV materials is similarly not available. To remain conservative, the
150 values for crystalline silicon-based PV (both mono- and multi-crystalline silicon) with crystal silicon
151 (c-Si)-based semiconductor industry. This assumption is reasonable because both the semiconductor
152 industry and the PV industry are dominated by the processing of silicon materials [54]. c-Si-base solar
153 cells can be fabricated via a chemical route (quartz, carbothermic reaction, chemical purification and
154 then wafer and cell production) or a metallurgical route (quartz, carbothermic reduction, metallurgical
155 purification and then wafer and cell production). Up to the wafer stage the processing is identical for
156 both industries with the semiconductor industry refining the silicon only to a higher purity for wafers.
157 In addition, many of the processes for cleaning are used by both industries as well (e.g. the use of four
158 step RCA clean using water, ammonium hydroxide, and hydrogen peroxide (5:1:1); aqueous
159 hydrofluoric acid (1:50 or 1:100); water, hydrochloric acid and hydrogen peroxide (6:1:1); and

160 deionized water). For device fabrication the doping processes are also the same (e.g. p doping boron
 161 with and n doping with phosphorus). The steps to form a transistor in the semiconductor are different
 162 from a p-n junction PV device, however, they result in the deposition of relatively small amounts of
 163 other materials (e.g. gate oxides and contacts). Thus, the deaths for c-Si-based PV will be estimated
 164 from the values of material used weighted number of deaths from chemical accidents in the larger
 165 chemical industry involving listed hazardous substances that are also used in solar cell or PV module
 166 manufacturing (e.g. SiHCl₃ and SiH₄ for silicon processing AsH₃, PH₃, and B₂H₆ for doping, and HF
 167 and HCl for cleaning). This provides less than 10⁻⁴ deaths per GWyr, which is far safer than coal
 168 [29,32]. The D_{TPV}, deaths per year from PV, is currently amounts to 2.648x10⁻⁷deaths/year (e.g. far less
 169 than 1).

170 The total lives (L) saved per kWh of solar PV electricity production offsetting coal-fired
 171 electrical generation is given by:

$$172 \quad L = r_c - r_{pv} \quad \text{[U.S. lives saved/kWh]} \quad (5)$$

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 174
 175 Utilizing current industrial PV costs, P, of \$1.92/W [55], the first cost per life, C_{FL}, saved by
 176 purchasing a PV system to offset coal use nationally is calculated as follows:

$$177 \quad C_{FL} = \frac{\left[\left(S_T \times 10^9 \frac{W}{GW} \times P \right) \right]}{(l_{pv} \times F_c)} \quad \text{[First cost \$ invested/U.S. lives saved in PV lifetime]} \quad (6)$$

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 179
 180 Where S_T x 10⁹ is total solar in GW converted to W, and F_c represents the number of fatalities due to
 181 coal combustion emissions per year and l_{pv} is the lifetime of the PV. However, unlike conventional
 182 health policy interventions that only have a first cost, this policy would also generate revenue, which
 183 must be taken into account, which allows for a cost per life, C_L, over a specific period, T:

$$184 \quad C_L(T) = \frac{\left[\left(S_T \times 10^9 \frac{W}{GW} \times P \right) - (C_T \times T \times v) \right]}{(T \times F_c)} \quad \text{[$/U.S. lives saved over T years]} \quad (7)$$

185 Where v is the \$/kW-hrs of the PV generated electricity replacing all of coal. A sensitivity analysis is
 186 run on v and to avoid complications the energy cost escalation rate is assumed to track with inflation.

187 3. Results

188
 189 There is a clear correlation between annual mortality due to coal emissions and the geographic
 190 locations of coal fired power plants in the U.S. as can be seen in Figure 1. Dense regions of mortality
 191 are correlated with high coal-fired electrical emissions in the central and northeast of the U.S.
 192 Emissions from coal-fired electricity total 1.57x10⁹ million metric tons in 2013 [9].

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198 Using equations 1 and 2, to completely replace coal-fired electricity would require 755 GW of solar
199 PV. As the death rate from coal is 3.9393939×10^{-8} deaths/kWh from equation 3 and that of PV is
200 1.14×10^{-14} deaths/kW-hr from equation 4. It is clear that from a human mortality standpoint PV is far
201 safer than coal produced electricity. This is quantified in equation 5, which provides 3.9393927×10^{-8}
202 lives saved per kW-hr as the respective death rates are 6 orders of magnitude larger for coal than PV. If
203 the entire U.S. coal fired electricity production were switched to PV production. This would result in
204 51,999 American lives saved per year.

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206 Installing 755GW of PV in the U.S. at \$1.92/W [56], would cost the U.S roughly \$1.45 trillion dollars.
207 Following equation 6 and using a 25 year warranty on the PV modules as the lifetime this results in a
208 first cost per American life saved of roughly \$1.1 million per life. However, there are several
209 complicating factors, first the output efficiency of PV modules degrades with time. For most technical
210 studies this has been shown to be 0.5% per year degradation rate or less and that is what is used in PV
211 economic studies [57]. The warranty for PV and its effective lifetime is set at 25 years, although it is
212 clear the real lifetime of the PV would be much greater than that. In general the 25 year warranty for
213 PV guarantees the PV power is performing at 80% of the initial rated power or better. Thus, to remain
214 conservative these factors both decrease and increase cost per life respectively, they have been assumed
215 to roughly cancel out and be ignored. The far more important complicating factor of using PV
216 replacement of coal as a public health policy measure is the value of PV-generated electricity. Using 25
217 years again and equation 7 the cost per life varies substantially depending on the value assigned to the
218 electricity as seen in Table 2, which ranges from over \$1.1 million per life saved if the electricity has no
219 value, through coal generation with zero value placed on externalities [57], and net metering through
220 various scenarios [58], the calculated value for solar [59] to -\$4.6m per life saved if the residential
221 retail rate is used in an isolated rural community [60].

222 Table 2. The Value of solar PV-generated electricity and the impact on the cost per life saved.

Method of Valuing Solar Electricity	US\$/kWhr	Solar PV US\$ value/year	Cost per Life (US\$/life)
No value	0	0	\$1,115,076
Coal generation only [57]	\$0.0323	4.26×10^{10}	\$295,153
Net metering industrial [58]	\$0.068	8.98×10^{10}	-\$611,077
Net metering commercial [58]	\$0.1050	1.39×10^{11}	-\$1,550,308
Net metering residential [58]	\$0.1261	1.66×10^{11}	-\$2,085,923
Value of Solar Minnesota [59]	\$0.145	1.91×10^{11}	-\$2,565,693
Net metering Houghton, MI [60]	\$0.2273	3.00×10^{11}	-\$4,654,847

223

224 4. Discussion

225

226 Although, Figure 1 illustrates areas of high emissions due to coal-production, it is important to
227 note that air pollution can be dispersed through the air and affect regions at large distances from the
228 source [5, 15]. Carbon dioxide indirectly results in premature death due to climate change events and
229 according to WHO analyses, climate change is expected to cause 250,000 additional deaths per year
230 between 2030 and 2050 [3,64]. Decreases in sulfur dioxides results from burning “clean coal”, washing
231 coal, and utilizing scrubbers to chemically remove sulfur dioxide from coal burning smokestacks,

232 resulted in decreasing sulfur dioxide levels from 15.7 m tons in 1990 to 10.2 m tons in 2005 [61]. This
233 was completed through cap and trade-based policy. The EPA issued control standards under clean air
234 act, which includes NO_x, SO₂, and PM_x. Decreases in particulate matter may not be correlated with
235 decreased mortality as there is no well-defined safe threshold for particulate matter [12]. Particulate
236 matter made up of smaller particles, which travel deep into respiratory tract and become lodged
237 permanently [62]. Thus, despite improvements coal emissions remain a significant threat to mortality
238 rates in the U.S. This paper found that a large number of premature deaths, about 52,000 in the U.S.
239 due to coal-fired emissions during electrical generation, could be eliminated by a conversion to PV-
240 based electrical generation.

241 To accomplish this national health benefit the amount solar PV needed to mitigate premature
242 death due to coal-fired electrical production was 755 GW. 755GW is a significant increase over current
243 U.S. PV penetration levels (27.4GW). Thus, only 3.6% of the PV necessary to prevent the current life
244 loss from coal pollution is available. It should also be pointed out that there are some lifecycle
245 emissions from PV [7, 30, 51, 63]. However, the full life cycle of PV produces a fraction of the carbon
246 dioxide equivalent emissions when compared to coal [30, 64, 65]. Air pollution throughout full life
247 cycle of PV tends to vary with materials used during manufacture and mining [63], however, the
248 negative environmental impacts of PV generally involve accidental operation error [66,67]. In
249 summary, the substitution of coal-fired electricity with solar power is a substantial health and
250 environmental benefit and clear path towards a more sustainable state [27].

251 This study made several estimations to obtain these values, which should be pointed out. First,
252 the population weighted average of solar flux was used to determine the energy generation rather than a
253 detailed analysis of the geographic variation of PV production potential across the U.S. For the
254 purposes of this study the error introduced with this method is small, but more detailed studies on both
255 the rooftop PV potential [68-70] and the solar farm [35] and even agrivoltaic [71,72] potential, would
256 provide a more granular (e.g. including shading losses) estimates for decision makers (e.g. at the state
257 or community level). Second, the premature deaths from coal related emissions are actually
258 conservative. This study provided analyses of only the combustion step in coal electrical generation in
259 the United States. To capture the full scope of mortality rates in the U.S., analyses must be expanded to
260 include the full life cycle of coal; this includes sectors other than electrical (industry, manufacture of
261 synthetic fuel, or manufacturing steel) that utilize coal. Other externalities exist for coal, including land
262 use, water pollution, natural resource depletion, habitat destruction [73]. These uncertainties must be
263 quantified for both coal and solar PV to determine accurate measure of lives saved by replacing one
264 electrical generation source for another. However, it is clear from the results that the potential
265 American lives at stake, which can be saved by a policy intervention is warranted that encourages more
266 rapid deployment of PV.

267 Performing a similar analysis at a global scale could be of use to policy makers and the United
268 Nations to satisfy Sustainable Development Goal #7: Ensure access to affordable, reliable, sustainable,
269 and modern energy for all [74], while significantly reducing global lives sacrificed to current coal
270 combustion. Current global outdoor air pollution is concentrated in developing nations due to continued
271 increase of coal use [18]. As a result, larger mortality rates of developing nations are expected to
272 continue [12,48]. The World Health Organization estimates 7 million deaths per year due to air
273 pollution (of these 2.6 million are linked to outdoor air pollution), making it the single largest
274 environmental risk today [75]. Air pollution related mortality outweighs global car accidents (1.3
275 million people [76]) by a factor of five and natural disasters by a factor of 28 (mortality ranging from
276 20,000-250,000 people depending on the year) [77]. It can thus be assumed that the deaths per unit
277 energy will be even more extreme on the global scale as the U.S. environmental protection standards
278 are more advanced than much of the world. In addition, this does not take into account the potential

279 premature deaths aggravated by climate change for which the Intergovernmental Panel on Climate
280 Change (IPCC) already recommends immediate action to reduce emissions by 2050 [78].

281 To meet the health-related demand of eliminating coal pollution with solar power in the U.S.,
282 \$1.45 trillion dollars would need to be invested in new PV generation. This is the total cost to save all
283 future lives in the U.S. from coal-related electricity over the next twenty-five years. Even with no
284 value the cost per life is only \$1.1m, which is on the lower end of the values normally ascribed to
285 human life (between \$1 and \$9 million) [79-81]. However, unlike other health policy interventions,
286 which only cost money up front [82], PV replacement of coal production also has the potential to
287 generate significant revenue as shown in the third column of Table 2. Table 2 provides a sensitivity
288 analysis on the value of the solar electricity, which is currently under intense debate in the electrical
289 industry. PV is inherently distributed so using the centralized coal value of electricity of \$0.03/kWhr is
290 misleadingly pessimistic. In most of the U.S. PV is currently net metered making the values between
291 \$0.06-0.12/kWhr more realistic. As can be seen in Table 2, all of these values actually have a net
292 economic benefit for saving lives from only the value of electricity. There has also been a strong case
293 made [59] that net metering actually represents a subsidy to electric utilities as the value of solar can be
294 higher (e.g. \$0.14/kWhr in Minnesota). When looking at the potential for isolated communities to
295 adopt solar the current high costs of electricity turn the potential economic savings per life save truly
296 substantial. As technology has progressed to such a point that PV, battery and cogen units can displace
297 the use of the grid in even the most extreme circumstances [83-86], these levels of savings are possible
298 for the small populations living in such regions [60]. The use of PV to offset coal-fired electricity
299 compares exceptionally favorably to more conventional forms of health policy interventions, the best of
300 which (e.g. helping children in developing nations [87]) still costs a few thousand per life rather than
301 conserving money.

302 The results clearly show, premature deaths due to anthropogenic effects (coal combustion and
303 pollution) can be mitigated through anthropogenic efforts (PV electrical energy conversion). Policies
304 can be developed at many scales (international, federal, state, and local levels) to contribute to the
305 concerted climate change mitigation efforts. There are several policy interventions that could accelerate
306 PV adoption: 1) Effective renewable portfolio standards (RPS) programs [88] and Mandatory Green
307 Power Option (MGPO) [89] can be implemented at the state level. As air pollution is not limited to
308 state boundaries, as is shown in Figure 1, requiring states to design RPS programs would decrease
309 emissions from electrical generation. Federal agencies, such as the EPA, can strengthen particle
310 pollution standards, which can indirectly lead the electrical industry to adopt renewable energy
311 generation systems [90, 91]. An alternative strategy includes instituting state taxes or carbon trading
312 mechanisms [92, 93] on coal usage. States and industries that continue coal usage would pay higher
313 taxes to internalize environmental and health effects. EPA regulations such as Mercury and Air Toxics
314 Standards, are responsible for the decommissioning of 72 GW of coal electrical generating capacity
315 [94]; this number is expected to rise by 2020. On the other hand, increasing federal incentives for solar
316 PV will likely result in a rapid transition to cleaner energy generation. It is important to note that a
317 portfolio of these policy implementations will be more effective in reducing emissions and promoting
318 renewables than any single policy or program [90]. In the context of mortality in the U.S., exploring
319 and adapting wartime mobilization strategies [95] to a national solar PV electrical transition may
320 provide enough emission mitigation to slow anthropogenic climate change effects.

321 Finally, this study has only explored the impact of coal-fired electricity conversion to solar PV
322 on mortality. However, current air pollution costs also occur in medical costs and lost productivity. In
323 2010, OECD nations spent roughly \$1.7 trillion in attempts to combat and treat effects from outdoor air
324 pollution [96]. The U.S. spends roughly \$185 billion per year on coal emission effects; these represent
325 only health related costs [7]. California alone spent \$193 million in hospital care in 2007 due to air

326 pollution effects [97]. It has long been established that energy policy creates horrendous public health
327 problems and injustices [98], and this study makes clear large scale PV deployment to eliminate coal
328 could help alleviate this historical problem. Future work can help quantify the values of these other
329 effects from a transition from coal to solar based electrical generation.
330

331 5. Conclusions

332
333 The results of this study showed a clear geospatial correlation between coal fired power plants
334 and mortality from air pollution in the U.S. at the state level. To reduce these deaths coal-fired
335 electricity must be eliminated and the results showed that 51,999 American lives could be saved per
336 year by transitioning from coal to PV-powered electrical generation in the U.S. To accomplish this,
337 755GW of U.S. PV are needed and the first costs for such a national array are \$1.45 trillion. Over the
338 25 year warranty on the PV modules the first cost per life saved is approximately \$1.1 million, which is
339 comparable to the value of a human life used in other studies. However, as the solar electricity has
340 value, the cost per life for offsetting coal with PV actually saved money as well, in some cases several
341 million dollars per life. It is concluded that it is profitable to save lives in the U.S. with the substitution
342 of coal-fired electricity with solar power and that the conversion is a substantial health and
343 environmental benefit. Evolving the U.S. energy system utilizing clean, alternative technology will
344 allow the U.S. to prevent thousands of premature deaths along with becoming a global leader in
345 renewable technology adoption.
346

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581
582 **Figure Captions**

583
584 Figure 1. Coal fired
585 electricity facilities lo-
586 cated in the U.S. and the
587 annual mortality due to
588 coal emissions per
589 100,000 people in each
590 U.S. state.

