A Study of Carbon Emissions and Energy Consumption of Solar Power Generation in Phoenix, Arizona

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Abstract

The emissions of solar power generation have been extensively researched in the past three decades (NREL, 2021b). Meanwhile, the solar power generation (especially rooftop solar systems) in the U.S. and across the world has been rising, a trend that is expected to continue at a much faster rate in the next several decades. As this trend continues, the issue of carbon neutrality of solar power becomes even more important, especially because the catastrophic effects of climate change continue to intensify.

Our model has three components: (a) lifetime power generation model, (b) energy intensity model for a solar panel including manufacturing, transportation, installation, operation, and maintenance, and (c) emission model based on several factors including irradiation power density of the installation site, the fuel mixture used in various processes in manufacturing steps, and several other variables.

Our preliminary results show that a 400-W solar panel operating in Phoenix, Arizona takes an input energy of 1,423.34 kWh and produces 21,411.81 kWh in its 25-year operating life, which corresponds to an average annual generation of 856.47 kWh and an energy payback period of 1.66 years. Furthermore, the energy intensity of this panel is 66.47 Wh/kWh. More importantly, the emission intensity of this panel is either 27.41, 36.37, or 40.88 g-CO_2/kWh depending on whether it is manufactured in the U.S., Europe, and China, respectively.

Keywords: Emission intensity, input energy, solar power generation, carbon footprint of photovoltaics, solar panel manufacturing

Life Cycle Assessment (LCA) Model

We incorporated the energy input and emissions of 19 processes involved in the life cycle assessment (LCA) of solar panels. We partitioned these processes into three main components: (1) manufacturing, (2) transportation, and (3) installation at the consumer site, as shown in Fig. 1. Our LCA model has three components: (a) lifetime energy production model, (b) energy intensity model for a 400-W solar panel including raw material, manufacturing, transportation, installation, operation, and maintenance, and (c) emission model based on several factors including irradiation power density of the installation site, fuel mixture used in various processes in manufacturing steps, and several other variables.

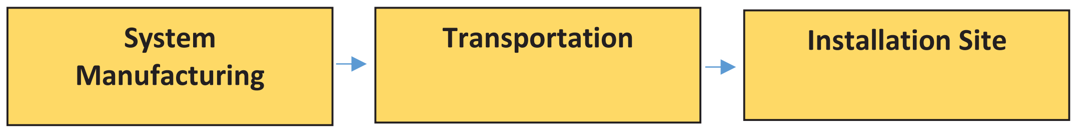

Fig. 1. Overall model incorporating emissions from three main components.

1.1. Lifetime Energy Production Model:

The annual solar irradiation energy is given by Eq. 1:

$$E_{irr} = 365 * S_{ph} * A_p \qquad Eq. (1)$$

where

E_{irr} = annual irradiation energy received by the panel (kWh),

S_{ph}= solar peak hours of the location (6.5 kWh/m^2/day in Phoenix, AZ), and

A_p = area of the panel (m^2).

The area of the panel is given by Eq 2:

$$A_p = \frac{P_p}{A_{pd}} \qquad Eq. (2)$$

where

P_p = DC power rating of the panel (400 W in this model), and

A_{pd}= panel area power density of REC Alpha Pure Series (216 W/m^2) (REC, 2024).

The area of the 400 W is 1.85 m^2. The generated DC electricity energy by the panel is given by Eq. 3:

$$E_{genDC} = \eta * E_{irr} \qquad Eq. (3)$$

where

E_{genDC}= annual DC electricity generated by the panel, (kWh) and

η = net conversion efficiency of the panel (varies throughout the life of the panel).

The temperature and aging degradation of the panel are incorporated in the model as given by Eq 4:

$$\eta = \eta_0 [\ a_{dc1} - (n_j - 1)\ a_{dc}] \qquad Eq. (4)$$

where

η_0= conversion efficiency in year 0 (21.6%),

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n_j = number of years the panel has been in operation, (years j = 1 to 25),

a_{dc1} = aging degradation coefficient of the panel in year 1 (98%)

a_{dc} = aging degradation coefficient of the panel in years 2 through 25 (-0.25%/$year$ after year 1)

And finally, the annual AC electricity produced by the panel in years j = 1 to 25 is given by Eq. 5:

$$E_{genACj} = \eta_{DCAC} * E_{genDC} \qquad Eq. (5)$$

where

E_{genACj} = annual AC electricity generated (kWh) in years j = 1 to 25,

η_{DCAC} = DC to AC inverter efficiency (95%),

The lifetime energy production will then be given by:

$$Lifetime\ Energy\ Produced = \left(\sum_{j=1}^{25} E_{genACj} \right) \qquad Eq. (6)$$

1.2. Input Energy and Energy Intensity Model

Our model takes into account the contributions of 19 processes to the total energy required to manufacture, transport, install, and dispose of a 400-W solar panel. The required energy (also referred to as embodied energy) in the life cycle of the panel from starting raw materials to its final disposal is given by Eq. 7:

$$E = E_0 + E_1 + E_2 + E_3 + E_{BOM} + E_4 + E_5 + E_{AL} + E_{GL} + E_{BOP} + E_{BOS} + E_{BOF} + E_{INV} + E_{TRANW} + E_{TRANL} + E_{INST} + E_{BOI} + E_{OPM} + E_{DD} \qquad Eq. (7)$$

where (all energy inputs are in kWh)

E = total input energy of the 400-W system,

E_0 = input energy of metallurgical grade silicon (MG-Si, 9N),

E_1 = input energy of trichlorosilane (TCS, 11N),

E_2 = input energy of chemical vapor deposition (CVD),

E_3 = input energy of monocrystalline wafer (ingot formation, cropping, slicing, and cleaning),

E_{BOM} = input energy of balance of materials (chemicals, mostly acids)

E_4 = input energy of cell conversion (n-type diffusion, emitter formation, silicon oxide, aluminum oxide, anti-reflective coating, ohmic contacts, fingers, and bus bars), (plus 7% for unusable rejects)

E_5 = input energy of panel assembly,

E_{AL} = input energy of aluminum frame,

E_{GL} = input energy of glass,

E_{BOP} = input energy of balance of panel assembly (automatic loading of glass panels, soldering, pates, testing),

E_{BOS} = input energy of balance of system (electrical components, panel wires and connectors)

E_{BOF} = input energy of balance of finished product (preparation, packaging, storage)

E_{INV} = input energy of inverter,

E_{TRANW} = input energy of transportation (over water) of the system to the U.S.,

E_{TRANL} = input energy of transportation (over land) to the system to installation site,

E_{INST} = input energy of installation (site preparation, tools),

E_{BOI} = input energy of balance of installation (wires, junction boxes, connectors),

E_{OPM} = input energy of operation and maintenance, and

E_{DD} = input energy of decommissioning and disposal.

The numerical values of the above input energies are calculated based on the data published by a large number of researchers, most notably at the National Renewable Energy Laboratory (NREL). The original data and the values calculated for a 400-W system are given in Tables 1, 2, and 3. The sources for the raw data shown in these tables are (NREL, 2019 a, b, c, d) (NREL, 2021a) and others. For a complete list of references for raw data used in our model, see (Khoie et. al. 2024).

Table 1: Energy input of 6 processes in the fabrication of wafers used in a 400-W solar panel. The panel consists of 66 wafers (132 half-cut), each with a 17 g weight.

Major Process	Symbol	Sub - Process	Raw data reported	Input energy kWh/wafer	Input energy for 400-W panel (kWh)
A) MG-Si	E_0 Total (A)	Metal Grade Silicon Purity 8N to 9N	1250 MJ/kg	5.9	**389.33**
B) Wafer	E_1	Trichlorosilane (TCS) 11N	15 kWh/kg	0.255	16.83

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	E_2	Siemens CVD	30 kwh/kg	0.51	33.66
	E_3	Ingot		0.76	49.50
	E_{BOM}	Balance of materials		1.04	67.04
	E_4	Cell conversion (+7%)		0.28	18.48
	Total (B)	**Wafer Production**			**185.51**

Table 2: Energy input of 7 processes in the manufacturing of a 400-W solar panel using 66 wafers.

Major Process	Symbol	Sub - Process	Raw data reported	Input energy kWh /panel	Input energy of 400-W panel (kWh)
C) Panel	E_5	Panel assembly		0.42	27.72
	E_{AL}	Aluminum frame	17 kWh/kg	2.05 kg/panel	34.85
	E_{GL}	Glass layers	1.7 kWh/kg	16.4 kg/panel	27.88
	Total (C)	**Panel Production**			**90.45**
	Total (B+C)	**Wafers and Panel**			**275.96**
	E_{BOP} **Total (BOP)**	Balance of electrical energy of wafers and panel	19% of (B+C)		**52.43**
D) Inverter	E_{INV} **Total (D)**	Inverter	59 % of (B+C)		**193.75**
E) System	**Total (E)**	**Sum of (A+B+C+BOP+D)**			**911.73**

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F) **BOS**	E_{BOS}	Balance of system	10% of (E)		91.17
G) Ready to ship	E_{BOF}	Packaging, storage, etc.	5% of (E)		45.59
H) Out the factory	**Total**				**1048.49**

Table 3. Energy input of the remaining six processes, including transportation of a 400-W panel to the installation site, installation, operation, and maintenance, decommissioning and disposition.

Major Process	Symbol	Sub - Process	Raw data reported	Input energy of a 400-W panel kWh
I) Shipping	E_{TRANW}	Transportation over water (12,000 km)	10 gCO2/Tkm	4.81
	E_{TRANL}	Transportation over land (600 km)	100 gCO2/Tkm	3.07
J) Installation	E_{INST}	System Installation	2.5% of (H)	26.21
	E_{BOI}	Balance of Installation	2.5% of (H)	26.21
K) Operation and Maintenance	E_{OPM}	Inverter	20% of (H)	209.69
L) Disposal	E_{DD}	Decommissioning and disposal	10% of (H)	104.85
Total LCA	**Total**	**Sum of (H thru L)**		**1423.34**

1.3. Emissions Intensity Model

The energy supply in the manufacturing, installation, operation, and decommissioning of a solar panel is 80% electricity, and most of the remaining 20% is non-electricity sources, which are mostly natural gas (IEA, 2022). To accurately model the emissions of a solar panel, one must consider each and every one of the 19 processes (in Eq. 7)

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and determine the fuel mixes used in these processes, a task that is extremely involved. A more reasonable approach is to separate the processes into three groups: (1) the processes that require mostly electricity energy, ($E_{ELEC-INTENSE}$), (2) the processes that use mostly non-electricity energy sources ($E_{NON-ELEC-INTENSE}$) and (3) the transportation processes (E_{TRANS}). These three groups of energy sources are given by Eqs. 8, 9, and 10, respectively:

$$E_{ELEC-INTENSE} = E_1 + E_2 + E_3 + E_4 + E_5 + E_{BOP} + E_{BOS} + E_{BOF} + E_{INV} + E_{INST} + E_{BOI} + E_{OPM} + E_{DD} \qquad Eq.(8)$$

$$E_{NON-ELEC-INTENSE} = E_0 + E_{BOM} + E_{AL} + E_{GL} \qquad Eq.(9)$$

$$E_{TRANS} = E_{TRANW} + E_{TRANL} \qquad Eq.(10)$$

The resulting emissions are then calculated using Eq. 9:

$$C_{O2} = E_{ELEC-INTENSE} * C_{ELEC-INTENSE} + E_{NON-ELEC-INTENSE} * C_{NON-ELEC\_INTENSE} + E_{TRANS} * C_{TRANS} \qquad Eq.(9)$$

where (all energy inputs are in kWh)

C_{O2} = total emissions (g-CO_2),

$E_{ELEC\_INTENSE}$ = total energy of processes that are electricity intensive (kWh),

$C_{ELEC-INTENSE}$ = emissions coefficient of $E_{ELEC\_INTENSE}$ energy (g-CO_2/kWh),

$E_{NON-ELEC-INTENSE}$ = total energy of processes that are non-electricity-intensive (kWh),

$C_{NON-ELEC-INTENSE}$ = emissions coefficient of $E_{NON-ELEC-INTENSE}$ energy (g-CO_2/kWh),

E_{TRANS} = total transportation energy (kWh),

C_{TRANS} = emissions coefficient of transportation energy (g-CO_2/kWh),

The worldwide energy used in the manufacturing, installation, operation and decommissioning of a solar panel ($E_{ELEC-INTENSE}$) is 80% electricity with the remaining 20% non-electricity sources mainly natural gas (IEA 2022). The $E_{NON-ELEC-INTENSE}$ energy sources, vary from one process to another, but are very close to 50% electricity and 50% natural gas. For E_{TRANS} the transportation fuels are heavy fuel oil (HFO) for cargo ships and gasoline for trucks.

We simulated the emission intensity of the 400W solar panel for various scenarios including panels that are made in the U.S., Europe, China, based on the fuel mix used in these regions for electricity generation as tabulated in Table 4.

Table 4. Fuel mixes used in electricity generation in the U.S., Europe, and China. For comparison, the average values of the world are also listed. Other sources are nuclear, hydro, and renewables.

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	U.S.	Europe	China	World
Coal %	19.5	13.1	63.0	35.7
Oil %	0.5	30.5	1.0	3.0
Natural Gas %	39.9	26.7	3.0	22.5
Other %	40.1	29.7	33.0	38.8
Sum %	100%	100%	100%	100%
Source	(U.S. EIA 2023a) (U.S. EIA 2023b)	(IEA 2021)	(U.S. EIA 2021)	(OWID 2020) (IEA 2019)

Using the information provided by the U.S. Energy Information agency (U.S. EIA, 2023c) the U.S. electricity generation emission coefficients of coal, natural gas, and petroleum are 1044 g CO_2/kWh, 440 g CO_2/kWh, and 1080 g CO_2/kWh, respectively. The average emission coefficient for all sources other than the above (nuclear, hydro, and renewables) is about 25 g CO_2/kWh (U.S. EIA, 2023c).

2. Results

The sweet spot of the U.S. for solar electricity generation is its Southwest region. We chose the Phoenix area as it is home to 4.95 million people (Statista, 2023). The Phoenix area has a 6.5 kWh/m^2/day solar peak hour resulting in 21,411.81 kWh of AC electricity over 25 years of operation from the 400-W solar panel which amounts to an average annual production of 856.47 kWh. With 1423.34 kWh of input energy (Table 3), the panel's energy payback is 1.66 years. The energy intensity of this panel is 1,423.34 kWh/21,411.81 kWh, which is 66.47 Wh/kWh.

The input energies of the three groups of processes add up to 1,423,34 kWh as shown in Table 5, of which 976.56 kWh is electricity (mostly used in manufacturing processes), 438.90 kWh from natural gas (mostly used in the production of metal-grade silicon, aluminum frame and glass), and 7.88 kWh from oil used in transportation.

Table 5: Input energy of the three groups of processes, $E_{ELEC-INTENSE}$, $E_{NON-ELEC-INTENSE}$, and E_{TRANS}. All numbers are in kWh.

Process Group	Electricity	Natural Gas	Oil	Total of Group
$E_{ELEC-INTENSE}$ Electricity-Intense Group	716.88	179.22	0.00	896.10
$E_{Non-ELEC-INTENSE}$ Non-Electricity-Intense Group	259.68	259.68	0.00	519.35

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E_{TRANS} Transportation Group	0.00	0.00	7.88	7.88
Total (kWh)	976.56	438.90	7.88	**1423.34**

The total electricity of 976.56 kWh is produced from four different sources (fuel mixes) consisting of coal, oil, natural gas, and other sources which include, nuclear, hydro, and renewables including wind and solar. Table 6 shows the contribution of each source to the total electricity based on fuel mixes used in the U.S., Europe, and China. The resulting emissions for electricity used in the processes are shown in Table 7.

Table 6. Amount of electricity generated from each of four fuel types in the U.S., Europe, and China. All numbers are in kWh.

Sources of Electricity Generation	U.S.	Europe	China
Electricity from Coal	190.43	127.93	615.23
Electricity from Oil	4.88	297.85	9.77
Electricity from Natural Gas	389.65	260.74	29.30
Electricity from Other Sources	391.60	290.04	322.26

Table 7. Emissions of electricity from each fuel type used in the U.S., Europe, and China.

Emissions	U.S.	Europe	China
Electricity from Coal (g CO_2)	198,808	133,558	642,303
Electricity from Oil (g CO_2)	5,273	321,679	10,547
Electricity from NG (g CO_2)	171,445	114,726	12,891
Electricity from other (g CO_2)	9,790	7,251	8,057
Total Electricity Emission (g CO_2)	385,316	577,214	673,797

Adding all emissions from all sources, (shown in Table 8), the total emissions of a 400-W panels are 586,941 g CO_2 and 778,839 g CO_2, if it is manufactured in the U.S. or Europe, respectively. However, the same panel, cradle to grave, produces 875,422 g-CO_2 if it is made in China. With a lifetime electricity generation of 21,411.81 kWh, this 400-W panel has carbon emission intensity of 27.41, 36.37, and 40.88 g CO_2 /kWh if it is made in the U.S., Europe, or China, respectively.

Table 8: Total emissions from various sources used in the U.S., Europe, and China.

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Emissions	U.S.	Europe	China
Total Electricity (g CO_2)	385,316	577,214	673,797
Total Natural Gas (g CO_2)	193,115	193,115	193,115
Total Oil (g CO_2)	8,510	8,510	8,510
Total All groups (g CO_2)	586,941	778,839	875,422
Emission Intensity (g CO_2/kWh)	**27.41**	**36.37**	**40.88**

3. Conclusion

A 400-W solar panel operating in one of the sweet spots of solar power generation in the U.S., namely Phoenix, Arizona, takes an input energy of 1,423.34 kWh and produces 21,411.81 kWh in its 25-year operating life. The energy intensity of this panel is therefore 66.47 Wh/kWh (=1,423.34 kWh/21,411.81 kWh) and with an average annual production of 856.47 (=21,411.81 kWh/25 year), it takes 1.66 years (=1,423.34 kWh/856.47 kWh per year) to give its input energy back.

Finally, the emission intensity of this panel (total emissions in g CO_2 / lifetime generation in kWh) is 27.41, 36.37, and 40.88 g CO_2/kWh depending on whether it is manufactured in the U.S., Europe, or China, respectively. Our results, for both energy intensity and emission intensity, while well within the range of harmonized results reported by NREL (2021a), are on the lower side of the scale. These underestimations have two main reasons: (1) the solar panel studied here (as are most rooftop panels available in the market today) are now about 7% more efficient (~21% in 2024) than they were then (~14% in 2012), and (2) recent advances in manufacturing of solar panels have resulted in lower input energy of various processes.

Conflict of Interest

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