Analyzing Optimal Renewable Energy Portfolio for Electricity Generation in Arizona and Texas with Lowest Carbon Emissions

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Abstract

In this paper, we present an optimization algorithm for determining the wind-solar portfolio for electricity generation with minimum emissions in two specific locations in the U.S., Texas and Arizona. Our model assumes a 1% annual increase in electricity demand as well as a 12% increase in the population over the next 25 years. The difference between the 2050 electricity demand and existing generation by nuclear, water, solar, and wind (which is currently being generated from fossil fuels) will be replaced by a solar-wind portfolio which will result in the lowest emissions. Our results show that Maricopa County will achieve its lowest emissions per capita in 2050, when its renewable electricity is produced with 100% solar and 0% wind, which will result in 402 kg CO_2/person. Amarillo will be able to reduce its per capita emissions to as low as 277 kg CO_2/person with a renewable portfolio consisting of 100% wind and 0% solar.

Keywords: emission intensity of solar power, emission intensity of wind power, optimization of electricity generation by wind and solar energies, lowest renewable emissions

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1. Introduction

In 2022, the world consumed 25,530 billion kWh of electricity, of which 4,070 billion kWh (about 15.9%) was used in the United States (Statista 2023a; U.S. EIA 2023). It has been projected that by 2050, U.S. electricity consumption will reach 5,178 billion kWh which is about a 27% increase in the next 27 years, roughly 1% per year. In the next three decades, the world's electricity demand is expected to increase at a much higher rate of 3% per year (Enerdata 2023; Statista 2023b). Furthermore, it is estimated that about two thirds of the world's electricity generation in 2050 will be from nuclear and renewables, with solar and wind showing the highest levels of growth (IER 2023). Unfortunately, these projections still leave about a 30% share of coal and natural gas in the world's electricity portfolio in 2050.

The U.S. National Oceanic and Atmospheric Administration (NOAA) indicated in its 2022 report that while emission-reduction strategies are required in all energy sectors, there is a growing interest in removing greenhouse gases already in the atmosphere (NOAA 2022). The report identifies 11 removal strategies including several biological methods of removing carbon from the oceans and the atmosphere (NOAA 2023). The continued use of coal and natural gas in the world's electricity generation through 2050 – during the 25-year transition period –- flies in the face of NOAA's recommendation for carbon removal. Furthermore, as the world transitions to a massive amount of electricity generation by solar power and wind power in the next 25 years, the issue of the carbon footprint of these two renewable sources becomes increasingly more important.

The United States has truly abundant solar and wind resources, as shown in Figures 1 and 2, respectively. However, there are great variations in the amounts of these resources from one location to another. While the Southwest of the U.S. enjoys significant solar irradiance (solar peak hours in 6 to 7 kWh/m^2/day, the Northeast of the U.S. receives about 4 kWh/m^2/day of sun energy. Similarly, while the sustained average wind speeds of 9 to 10 m/s (at 30 meters above the surface) are abundant in the U.S. Midwest region, the sustained wind speeds in the Southeast of the U.S. are in the range of 4 to 5 m/s and (NREL 2018; NREL 2023).

We previously investigated the emission intensity of wind power generation in one of the sweet spots of wind energy in the U.S., the panhandle of Texas (Khoie 2021). Our results showed that a 1.3-MW Nordex windmill operating in Amarillo, Texas produced 14.45 g CO_2/kWh. More recently, we developed an LCA model for analyzing the emissions of solar power generation in one of the sweet spots of solar energy in the U.S., Phoenix, Arizona (Khoie, 2024a). The results of our model showed that the emission intensity (total emissions in g CO_2 /lifetime generation in kWh) of solar power

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generation was 27.41, 36.37, and 40.88 g CO_2 /kWh depending on whether the solar panels are manufactured in the U.S., Europe, or China.

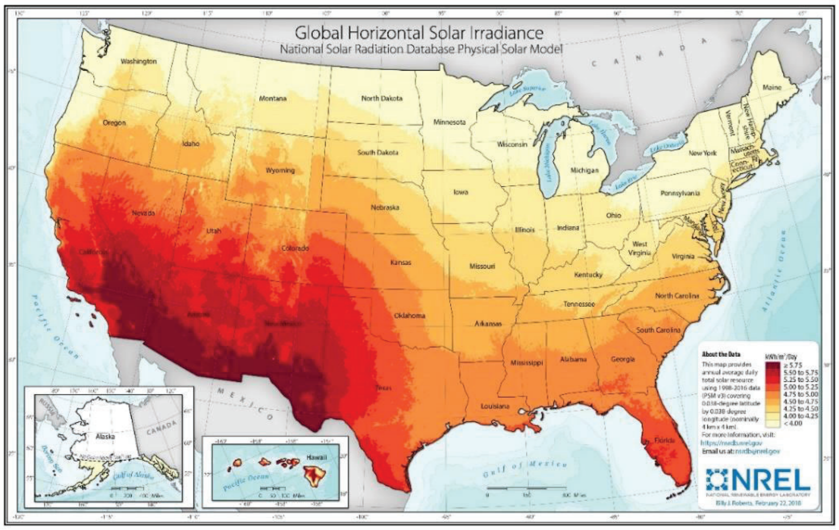

Fig. 1. The U.S. solar irradiance map (NREL 2018).

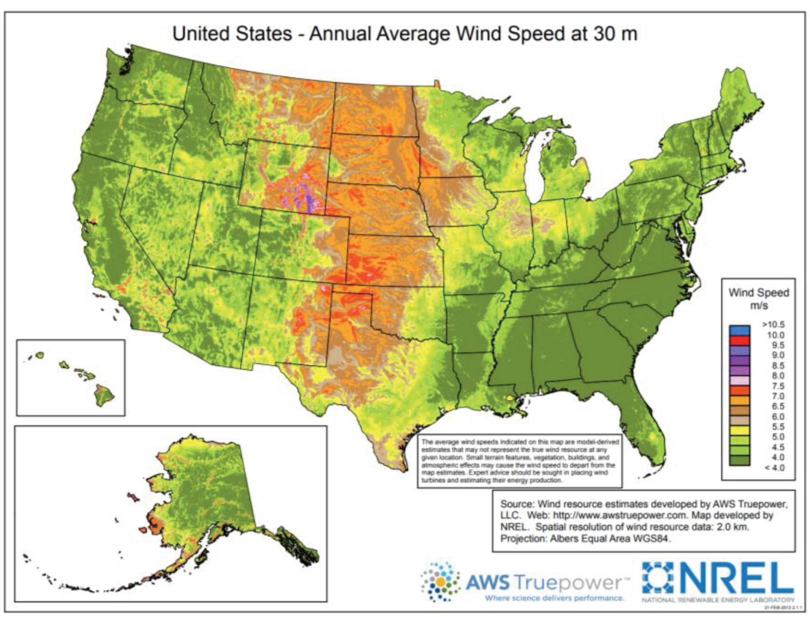

Fig. 2. The U.S. annual average wind speed at 30-meter elevation (U.S. EERE, 2024).

respectively. We have expanded our solar emissions model with additional details and the results are reported elsewhere (Khoie, 2024b).

2. Optimization Model

This paper aims to develop a model to produce strategies for the implementation of wind and solar power in various locations in the U.S. based on *local* variables as shown in Fig. 3 and as follows:

(1) Determine the current and projected electricity need of the location.
(2) Subtract the available existing renewable energy, nuclear energy, and hydropower.
(3) Produce various solar-wind portfolios based on the amount of wind energy and solar irradiation available.
(4) Determine the carbon emissions of each solar-wind portfolio using the emissions models we previously developed for solar and wind (Khoie, 2024b; Khoie, 2021).
(5) Search for the optimal solar-wind portfolio for that location which results in lowest possible emissions.

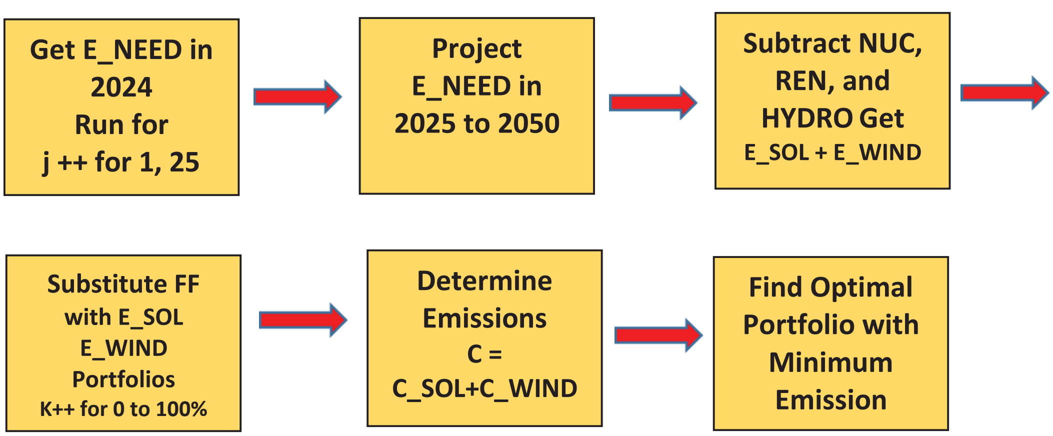

Fig. 3. Flow chart of the optimization model.

The optimal renewable electricity portfolio in 2050 is then determined as follows:

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- Determine the population growth in 2050 by adding 12% to the current population (U.S. CBO, 2024): $N_{pop-2050} = 1.12 * N_{pop-2024}$.
- Start with current (2024) total annual generation and determine the electricity demand in 2050 by adding 1% per year: $E_{total-gen-2050} = 1.25 * E_{total-gen-2024}$.
- Determine the amount of current annual generation by renewables; add existing nuclear, water, solar, and wind generation from the total current generation: $E_{renewable-gen-2024} = E_{nuclear-gen-2024} + E_{water-gen-2024} + E_{solar-gen-2024} + E_{wind-gen-2024}$.
- Determine the amount of renewable generation needed in 2050; subtract the existing renewable generation from the total generation in 2050: $E_{renewable-gen-2050} = E_{total-gen-2050} - E_{renewable-gen-2024}$. This is the amount of renewable generation that is needed to be installed by 2050.
- Start with 0% solar and 100% wind combination and evaluate the emissions of the resulting renewable portfolio. Repeat this process 25 times, adding 4% solar while reducing wind by 4% each time.
- Determine the per capita emissions of each portfolio by dividing the total emissions of each portfolio (including the emissions of existing renewables in 2024) by the population in 2050: $C_{per-capita-2050} = C_{total-2050}/N_{pop-2050}$
- Determine the portfolio that results in the lowest per capita emissions.

3. Results

The lifetime emissions of the 1.3-MW Nordex N-60 are 1,870 Mg CO_2. With 161,808,798 kWh generated in its 25-year lifespan, the emission intensity of this windmill is 11.56 g CO_2/kWh when operating in Amarillo, Texas (Khoie, 2021). However, this windmill has a significantly higher emission intensity of 77.59 g CO_2/kWh when operating in Maricopa County due to a drop in average wind speed (from 9 m/s in Amarillo to 5.6 m/s in Maricopa). Using China's electricity portfolio (which is close to those of Singapore's, where the panels are made) the emission intensity of the REC Alpha Series 400-W panels (REC 2024) is 40.88 g CO_2/kWh for Maricopa County, and 45.82 g CO_2/kWh for Amarillo. The above data are tabulated in Table 1.

Table 1. Average wind speed and solar peak hours in Mariposa County, and Amarillo, along with emission intensities of wind, solar, and nuclear power generations in these locations

	Maricopa County, Arizona	Amarillo, Texas	Sources
Average Wind Speed (m/s)	5.6	9	(U.S. EERE, 2024) (NREL, 2023)
Wind Emissions (g CO_2/kWh)	77.59	11.56	

Average Solar Peak Hours (kWh/m^2/day)	6.5	5.8	(NREL 2018)
China-Made Solar Panel Emissions (g CO_2/kWh)	40.88	45.82	
U.S.-Made Solar Panel Emissions (g CO_2/kWh)	27.41	30.72	
Nuclear Emissions (g CO_2/kWh)	12.0	12.0	(WNA 2024)

With the emission intensities given in Table 1 and the current 2024 data on population, annual generation, fuel mix, and emissions of electricity generation from each fuel in Maricopa County and Amarillo, we run 25 simulations based on the algorithm described above. The results are shown in Fig. 4.

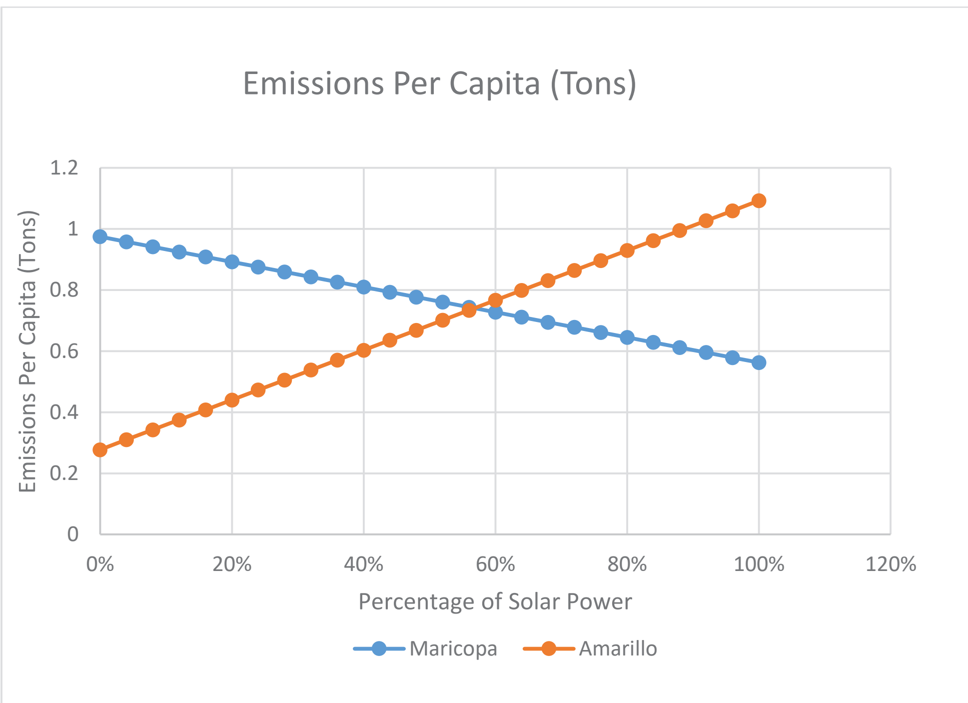

Fig. 4. The results of simulations for Maricopa County and Amarillo. The horizontal axis is the percentage of solar power in the portfolio.

Figure 4 shows that for Maricopa County, a 0% solar–100% wind portfolio results in 975 kg CO_2/person/year, whereas a 100% solar–0% wind portfolio produces 563 kg CO_2/person/year. This is because while solar peak hours in Maricopa County are 6.5

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kWh/m^2/day (near ideal condition), the average wind speed is only 5.6 m/s, which is rather low for the massive amount of wind power generation.

In contrast, for Amarillo, a 0% solar–100% wind portfolio has significantly less emissions, 277 kg CO_2/person/year, compared to 1093 kg CO_2/person/year for a 100% solar–0% wind portfolio. Again, this is because wind speed of 9 m/s makes Amarillo an ideal location for wind power generation.

It should be noted that although available solar peak hour in Amarillo is 5.8 kWh/m^2/day which is much higher than many locations in the U.S., but there is no combination of solar-wind generation that will result in lower emissions than the 0% solar–100% wind combination.

Table 2 lists the details of the results of our optimization model for Mariposa County and Amarillo. In this table, we list the population, annual generation, and emissions for these two locations in the year 2050, and for comparison, we also list the 2024 data.

Table 2: Population, annual generation, and emissions of Mariposa County and Amarillo in the years 2024 (current portfolio including fossil fuels) and 2050 (optimal portfolio without fossil fuels)

	Maricopa County, Arizona in 2024	Maricopa County, Arizona in 2050	Amarillo Texas in 2024	Amarillo Texas in 2050
Population (12% increase by 2050) (U.S. CBO 2024)	4,950,000	5,544,000	202,000	226,240
Total Annual Generation (GWh) (1% annual increase thru 2050)	80,076	100,896	4,305	5,424
Annual Generation Per Capita (kWh/person)	16,176	18,199	21,287	23,974
Annual Generation from Coal (GWh)	0	0	3,490	0
Annual Generation from Natural Gas (GWh)	41,360	0	775	0
Annual Generation from Other Fossil Fuels (GWh)	20	0	0	0
Total Annual Generation from Fossil Fuels (GWh)	41,380	0	4,265	0
Total Annual	18,220,000	0	3,984,560	0

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Emissions from Fossil Fuels (Tons)				
Annual Generation from Nuclear (GWh)	34,510	34,510	0	0
Annual Generation from Water (GWh)	286	286	0	0
Annual Generation from Wind (GWh)	0	0	40	5,424
Annual Generation from Solar (GWh)	3,900	66,100	0	0
Total Annual Generation from Renewables + Water + Nuclear (GWh)	38,696	100,896	40	5,424
Total Annual Emissions from Renewables + Water + Nuclear (Tons)	576,984	3,119,710	462	62,705
Total All Emissions (Tons)	18,796,984	3,119,710	3,985,022	62,705
Annual Emissions Per Capita (Tons/person)	3.80	0.563	19.73	0.277
% Reduction in Per Capita Emissions		85.2%		98.6%

The highlights of the results shown in Table 2 are:

- Amarillo, with 19.73 tons/person/year in 2024, has very high per capita emissions, due to its heavy reliance on coal power generation without any nuclear or hydropower generation and its minimal use of wind power (40 GWh of wind).
- Maricopa County, with 3.80 tons/person/year in 2024 has significantly lower per capita emissions in 2024 because of its reliance on nuclear power (34,510 GWh) and solar power (3,900 GWh).
- Amarillo's optimal electricity portfolio in 2050 will be 100% wind power, which will result in per capita emissions of only 277 kg CO_2/person/year. This is a significant drop (98.6%) in its emission from 2024 levels which is entirely due to the low emission intensity of wind in Amarillo, one of the sweet spots of wind energy in the U.S.
- Maricopa County's optimal electricity in 2050 would be a mix of nuclear power (34,510 GWh) and solar power (66,100 GWh) which gives it 563 kg-CO_2/person/year per capita in emissions. Although this would be a significant drop of 85.2% from its 2024 levels, it would remain much higher than that of

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Amarillo. This is due to the relatively high emission intensity of solar power generation in Maricopa County although it is an ideal location for solar energy.

4. Conclusion

The choice of the two locations for this study, Maricopa County and Amarillo, was made based on their contrasting solar and wind potentials. This choice resulted in each location having either 100% solar or 100% wind as its optimal renewable portfolio. Our results show that electricity generation with lowest possible emissions requires consideration of (1) emission intensities of solar and wind power generation based on the fuel mix used at the manufacturing site, (2) emission intensities of solar and wind power at the generation site, and (3) the availability of solar and wind resources at the generation site. For Amarillo, Texas, a sweet spot for wind power generation, the lowest renewable emissions are achieved by using 100% wind power in its 2050 renewable electricity portfolio, whereas for Maricopa County, a sweet spot for solar power generation, 100% solar power results in lowest emissions. While these results were expected, our model establishes the validity of such expectations.

Another important takeaway from our results is that for locations with high percentages of solar power in their renewable electricity portfolios, solar panels that are made in the U.S. will have significantly lower emissions, as shown in Figure 5. Solar panels made in China have 563 kg/person emissions, while solar panels made in the U.S. produce 402 kg/person, a 29% decrease in per capita emissions.

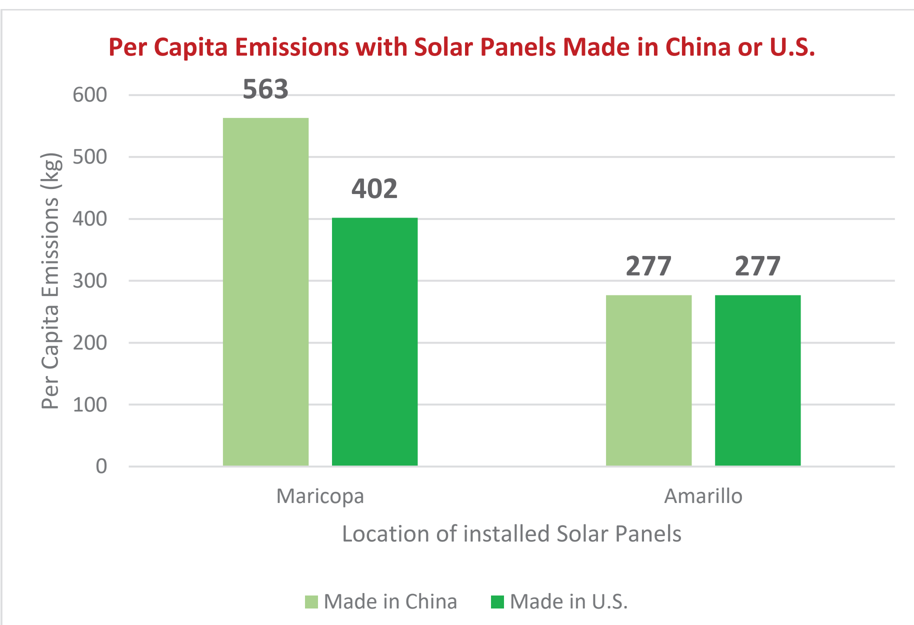

Fig. 5. For locations such as Maricopa County, Arizona, installing U.S. made solar panels reduces per capita emissions by 29 percent.

5. Limitations of Our Models and Future Refinements

For limitations of our models for emission intensities of solar power generation see Khoie (2024a). For wind power generation see Khoie (2021). Additional limitations of the model presented here are:

(1) The small difference in contribution of emissions due to land transportation of the solar panels to the two locations was ignored.
(2) In calculating the population of each location in 2050, we used the 12% projected population growth of the U.S. and ignored local variations as well as possible migration among various locations (U.S. CBO, 2024).
(3) Using a 1.3-MW windmill to power 260 homes (average of 5 kW per home) requires power distribution systems which will result not only in losses but also create additional emissions of the parts and components of the system. Our model does not take these into account.
(4) The solar power generation used in our model is based on rooftop installation of 400-W panels. Studies have shown that the emissions can be reduced using utility-scale solar power generation.

Our future work will include incorporating the above in our emission models to more accurately determine the optimal portfolios for these and other locations throughout the U.S. (Khoie, 2024c).

Conflict of Interest

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