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CORN ETHANOL VS. SOLAR
LAND USE COMPARISON

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HIGHLIGHTS

Wisconsin already uses over 1,000,000 acres of agricultural land for energy production in the form of corn used to produce ethanol.

Ethanol is a much less efficient form of energy production compared to solar photovoltaics (PV).

Using Energy Return on Investment (EROI) as a metric, solar PV is around 8 EROI while corn-derived ethanol is approximately 1.2 EROI. Using this metric, 88% of the energy generated by solar PV goes to society, while 12% is offset by production requirements.

In contrast, 20% of the energy generated by corn ethanol goes to society, while 80% is offset by production requirements.

Assuming average EROI, net energy production per acre is 100-125x greater for solar PV than for corn-based ethanol

Looking at land-use efficiency, corn-derived ethanol used to power internal combustion engines requires about 85x (range: 63-197x) as much land to power the same number of transportation miles as solar PV powering electric vehicles.

Even if the ethanol is converted to electricity to power more efficient electric vehicles, corn ethanol still requires 32x the amount of land to power the same number of vehicle miles.

Wisconsin's one million acres of corn for ethanol can power 10 billion vehicle miles travelled annually with internal combustion engines or 23 billion electric vehicle miles annually. If replaced with solar PV, those 1 million acres could generate enough electricity to power 804 billion electric vehicle miles annually.

This translates to 1 million acres of corn ethanol powering annual travel of 700,000 internal combustion engine passenger cars or 2 million electric vehicles. The same area of solar PV could power the annual travel of 60 million electric vehicles.

Looking at total energy generation from corn to account for useful by-products of ethanol production used as animal feed, solar PV generates 14-17 times more gross energy per acre than corn produces.

Technological advances provide substantial scope for increased land use efficiency from solar PV: energy density (MWh per acre) has increased 25-33% from 2011-2019.

To meet Wisconsin's carbon-free goals, 240,000-285,000 acres will be needed for solar PV with today's technology. This amounts to 1.7-2.0% of agricultural land in the state and less than 1/3 of the land currently being used to grow corn for ethanol.

INTRODUCTION

One of the concerns about utility-scale solar development is the amount of land needed for these large solar facilities, which are commonly placed on agricultural land. The Wisconsin Clean Energy Plan (**1**) estimates that Wisconsin will need approximately 35 million MWh of utility-scale solar PV generation by 2050 to meet its carbon free goal. Using a solar capacity factor of 16.5% for Wisconsin (**2**), 35 million MWh would require 24.2 GW (**3**) of utility-scale solar capacity. Similarly, a recent Evolved Energy Research report estimated that Wisconsin would need 28.5 GW of utility-scale solar capacity to achieve 100% clean energy in the state. (**4**)

Conservatively assuming that about 10 acres (this includes accessory buildings, access roads and areas around the solar arrays) is needed per MW of utility scale solar (**5**), between 240,000 and 285,000 acres of land will thus be needed for utility-scale solar facilities in order to meet Wisconsin's carbon-free goals. This represents 1.7-2.0% of all farmlands in Wisconsin and 2.6-3.1% of all harvested cropland in the state. (**6**)

In Wisconsin, one million acres of agricultural land is already used to harvest energy in the form of corn grown for ethanol, accounting for a quarter of all corn planted in the state. (**7**)

Ethanol is an alcohol formed through the fermentation of sugars in corn grain. Ethanol is blended with gasoline in order to meet Clean Air Act requirements for making transportation fuel cleaner burning and to comply with the Renewable Fuel Standard, which requires certain volumes of renewable fuel replace petroleum-based fuel.

This existing use of land to generate energy leads to the question of what is a more efficient land use from an energy production standpoint: harvesting energy from growing corn for ethanol or from solar panels. Here, we look at several ethanol and solar comparisons: vehicle miles powered per acre, energy return on investment, and total energy production.

1. https://osce.wi.gov/pages/cleanenergyplan.aspx

2. Table 4-44 in: https://www.epa.gov/power-sector-modeling/documentation-epas-power-sector-modeling-platform-v6

3. 8760 hours per year* 0.165 = 1445.4 MWh per 1 MW; 35,000,000 MWh/1445.4 MWh per MW = 24,214 MW

4. https://gridlab.org/wp-content/uploads/2022/10/Evolved-Energy-Research_100-percent-in-Wisconsin_Published.pdf

5. Great Plains Institute estimates 10 acres per MW (https://betterenergy.org/blog/the-true-land-footprint-of-solar-energy/) and internal analysis of existing and planned solar developments as of July 2020 finding ~9 acres per MW.

6. USDA 2017 Census of Agriculture reports 14,318,630 acres of farmland and 9,234,611 acres of harvested cropland in Wisconsin. Available at < https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_State_Level/Wisconsin/st55_1_0009_0010.pdf>

7. "Ethanol - Wisconsin Corn." Wisconsin Corn -. Accessed October 26, 2022. https://wicorn.org/ethanol.

VEHICLE MILES POWERED

One metric used to evaluate relative efficiency is comparing the similar end uses of the two energy generation pathways. We found two peer-reviewed studies and several non-peer-reviewed studies conducting this comparison.

Geyer et al. (2013) (**8**) provided all equations for its calculations, allowing us to insert Wisconsin-specific values for typical annual solar radiation and corn yield. Comparisons are summarized in Table 1 and all calculations are shown in **Appendix 1**.*

Table 1. Sun-to-wheels comparison for ethanol and solar panels to power internal combustion vehicles (ICV) and battery electric vehicles (EV) from Geyer et al. 2013. For the solar calculations we used a typical average annual solar radiation in WI of 4.5 kWh per day per square meter.[9] For the corn ethanol calculations, we used the Wisconsin average corn yield in 2021 of 180 bushels per acre.[10] Where indicated, we also show calculations to account for increased efficiencies with subsequent technological advances in solar panels. Detailed calculations found in the Appendix.

Type of energy	ICV Miles Powered per Acre	EV Miles Powered per Acre
Corn Ethanol[a]	9,373	23,282
Switchgrass Ethanol	10,742	27,163
Solar (CdTe) 2010	n/a	1,399,989
Solar (mono-Si) 2010[b]	n/a	2,177,760
Solar (CdTe) 2022[c]	n/a	2,799,977
Solar (mono-Si) 2022[c]	n/a	3,111,086

[a] Using the maximum county-level corn yield of 210 bushels per acre, these values are 10,935 and 27,163 respectively
[b] Original study was conducted using cadmium telluride (CdTe) panels with 9% efficiency, this value is adjusted for mono silicon (mono-Si) panels with 14% efficiency which were the minority in 2010.
[c] These two values have been added for standard efficiencies of CdTe and mono-Si in common use today, 18%[11] and 20%[12] respectively. Silicon is now the dominant type of panel, but CdTe has advanced too.

8. Geyer et al. 2013. Spatially-explicit life cycle assessment of sun-to-wheels transportation pathways in the U.S. Environmental Science & Technology 47: 1170-1176

9. NREL. 2018. Direct normal solar irradiance. Available at: < https://www.nrel.gov/gis/assets/images/solar-annual-dni-2018-01.jpg>

10. United States Department of Agriculture National Agricultural Statistics Service. 2022. Wisconsin Ag News- 2021 Corn County Estimates. Available at: < https://www.nass.usda.gov/Statistics_by_State/Wisconsin/Publications/County_Estimates/2022/WI-CtyEst-Corn-02-22.pdf>

11. “Cadmium Telluride.” Energy.gov. Solar Energy Technologies Office. Accessed October 27, 2022. https://www.energy.gov/eere/solar/cadmium-telluride.

12. Ballif et al. 2022. Status and perspectives of crystalline silicon photovoltaics in research and industry. Nature Reviews Materials 7: 597-616

* **Appendix available online, see page 9**

The second peer-reviewed article, by Pontau et al. (**13**), report a 20-fold increase in land use efficiency between solar PV (~ 169,000 miles per acre) and corn ethanol (~8,000 miles per acre). However, we note that Pontau's solar PV calculation assumes that that solar panels account for only 20% of the facility's total footprint, and that Geyer et al.'s calculations appear to only use panel surface area, not total facility footprint. Pontau's 20% assumption is likely a low estimate based on reported direct vs. total land footprint calculations. (**14**)

If we assume that solar panel surface area is 60% of a facility's total surface area (lower end of calculations from Ong et al. 2013), Geyer's calculations are reduced to 839,993 miles per acre from solar PV, about 90 times the miles per acre of corn ethanol. Likewise, adjusting Pontau's calculations results in 505,858 miles per acre PV solar, 63 times the miles per acre of corn ethanol used to power internal combustion engines. Other, non-peer reviewed analyses come to similar conclusions **(Table 2)**.

Table 2. Summary of non-peer reviewed analyses comparing the land use efficiency of solar PV vs. ethanol to power electric vehicle (EV) or internal combustion vehicle (ICV) transportation. Source of ethanol noted in parentheses.

Source	Increased Land Use Efficiency	EV miles per acre solar PV	ICV miles per acre of ethanol	Location
Nussey 2021[15]	73x	710,250	9,691 (corn)	Iowa
Smith 2022[16]	73x	900,000	12,382 (corn)	Iowa
Weaver 2022[17]	197x	1,300,000	6,600 (corn)	United States
Carbon Brief 2022[18]	48-112x	654,000	5,785 (wheat) 13,300 (sugar beet)	United Kingdom
RENEW Wisconsin[19]	65x	715,000	11,000 (corn)	Not reported

13. Pontau et al. 2015. Assessing land-use impacts by clean vehicle systems. Resources, conservation and Recycling 95: 112-119

14. Ong et al. 2013. Land-Use requirements for solar power plants in the United States. NREL Technical Report NREL/TP-6A20-56290

15. Nussey B. 2021. Making ethanol from corn is the least efficient use of farmland.< https://www.freeingenergy.com/replace-farmland-farm-corn-ethanol-solar-panels/>

16. Smith A. 2022. Should farmers plant solar panels or corn? < https://asmith.ucdavis.edu/news/which-better-crop-corn-or-solar-panels>

17. Weaver JF. 2022. Solar+food in ethanol fields could fully power the United States. < https://pv-magazine-usa.com/2022/03/10/solarfood-in-ethanol-fields-could-fully-power-the-united-states/>

18. CarbonBrief. 2022. Factcheck: is solar power a 'threat' to UK farmland? < https://www.carbonbrief.org/factcheck-is-solar-power-a-threat-to-uk-farmland/>

19. https://www.renewwisconsin.org/solar-and-agricultural-land-use/

Averaging these values results in solar PV powering 803,586 electric vehicle miles per acre compared to 9,523 miles internal combustion vehicle miles per acre from corn ethanol. This is an 84x increase in land use efficiency. If the 1 million acres of corn grown for ethanol in WI were replaced with solar PV, this would power 804 billion vehicle miles compared to 9.5 billion miles from corn ethanol.

Electric vehicles are far more efficient than ICVs, which contributes to this gap. However, even if the ethanol was converted to electricity to power electric vehicles, solar PV would still power 30x more vehicle miles (804 billion miles vs. 23-27 billion miles powered by 1 million acres).

Furthermore, as shown in Table 1, technological advances can make solar PV even more efficient while there is much less limited scope for efficiency improvements from corn or switchgrass ethanol. The latter are fundamentally limited in large part by the efficiency of photosynthesis, although continued productivity increases will increase corn ethanol efficiency. Indeed, a recent analysis found that the energy density of solar PV has increased 25-33% from 2011-2019, underscoring how the theoretical scope for improvement is being realized. (**20**)

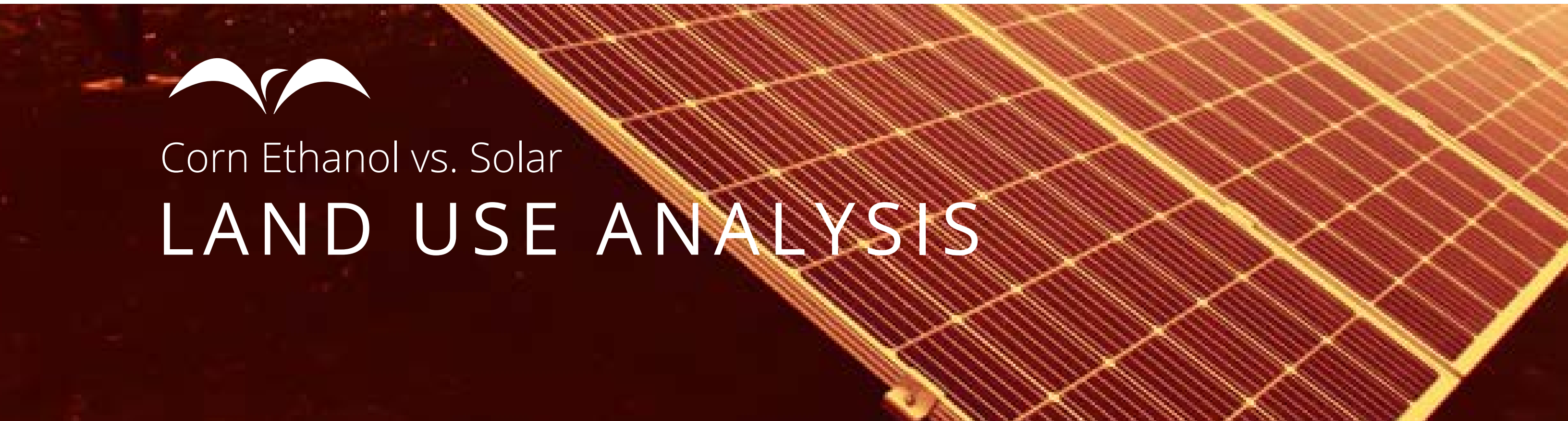
20. Bolinger & Bolinger. 2022. Land requirements for utility-scale PV: an empirical update on power and energy density. IEEE Journal of Photovoltaics 12: 589-594

ENERGY RETURN ON INVESTMENT

However, one must also consider how much input is required to obtain these energetic outputs. Corn needs to be grown, harvested and processed into ethanol, all of which requires energetic inputs. Likewise, solar panels need to be manufactured and installed. One metric used to evaluate this is called "Energy Return on Investment," or EROI. This metric is the ratio of the energy generated to the energy input required.

EROI is a unitless value which serves as a metric for comparing and analyzing different energy resources. It is calculated by dividing the energy gained from the energy source by the sum of energy inputs necessary for its creation: EROI = energy gained/energy required. If the energy returned is greater than 1, it is a net energy gain. If this value is below 1, then the energy resource is a sink. These inputs include things such as fuel for biorefineries or the installation of solar. It does not include the energy inputs necessary for its use, such as distribution and storage.

Disagreements on what to include in the inputs is one of the main reasons for differing estimates. EROI estimates can vary substantially, and one of the challenges with calculating the EROIs of biofuels and solar comes from the assignment of its system boundaries. These boundaries define what is and what is not included in calculating EROI, such as deciding what various energy costs expended along the supply chain should be included as inputs, and to what degree.



Across different production processes these costs can take many forms, such as the energy expended for the extraction of silicon used in panels or fuel cost for a biorefinery. The boundaries of an EROI analysis of ethanol are typically set "at the farm gate," meaning calculation ends once the product is produced. Generally, the expansion of system boundaries leads to a lower overall EROI.

It is important to note that EROI's energy efficiency relationship is not linear (i.e. an EROI of 10 is not 10x more efficient than an EROI of 1, **Figure 1**). Another way to contextualize EROI is by looking at the net energy gain from an energy source as a percentage that is delivered to society. For example, 1 liter of a fuel with an EROI of 100 delivers 99% of that fuel to society [(EROI – 1)/EROI) x 100 = 99] while only 1% is used to generate this fuel. In comparison, 1 liter of fuel with an EROI of 2:1 delivers 50% of that fuel to society.

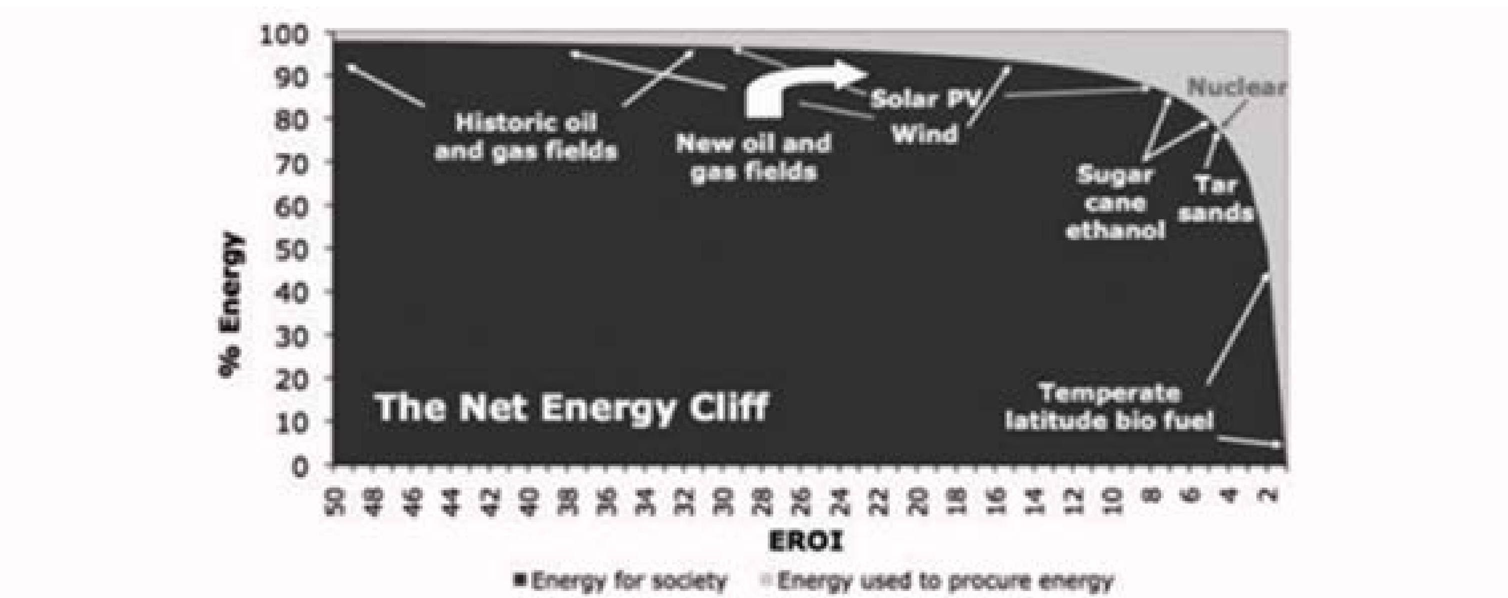


Figure 1. Net Energy Cliff, excerpted from Murphy et al. 2010. (**21**) Original figure legend: "The 'Net Energy Cliff.' As EROI approaches 1:1 the ratio of the energy gained (dark gray) to the energy used (light gray) from various energy sources decreases exponentially."

21. Murphy and Hall. 2010. Year in review: EROI or energy return on (energy) invested. Annals of the New York Academy of Sciences 1185: 102-118.

Table 3 summarizes EROI estimates for solar and ethanol production. As discussed above EROI estimates will vary depending on the researchers, but most important is the general trend in EROI between energy sources. These are corn ethanol, switchgrass ethanol, and solar, three renewables that farmers are choosing from.

Table 3. EROIs reported for solar and ethanol production. Mean value and/or range of values are presented. References to the sources are provided at the end of the report.

Solar	Corn Ethanol	Switchgrass Ethanol
3.75-10.0 (Hall et al. 2008)	1.36 (0.84-1.62) (Hammerschlag 2006)	4.06 (0.69-6.6) (Hammerschlag 2006)
6.56 (6-12) (Kubiszeweski et al. 2009)	1.3 (0.6-1.6) (Murphy & Hall 2010)	9.26 (0.72-17.8) (Hall et al. 2011)
6.8 (Murphy & Hall 2010)	1.28 (0.82-1.73) (Hall et al. 2011)	4.16 (Zanetti et al. 2019)
3.8-4.0 (Weissbach et al. 2013)	1.01 (0.64-1.18) (Murphy et al. 2011)	
~10 (Hall et al. 2014)	1.01-1.07 (Murphy et al. 2016)	
11.6 (8.7-34.2) (Bhanderi et al. 2014)	0.67 (Wang & Cheng 2018)	
9.1-9.7 (Raugei et al. 2017)	1.0 (0.94-1.04) (Chibroga et al. 2020)	
21-22 (northern climate) (Fthenakis et al. 2021)	1.0 (Murphy et al. 2022)	
10 (5-75) (Murphy et al. 2022)		

As shown in Table 3, EROI for corn ethanol is typically around 1.2:1. These numbers suggest that corn ethanol is barely breaking even, and at worst requiring more energetic input than it produces. At an EROI of 1.2: 1, 80% of the total energetic output is offset by the input requirements, resulting in a net energetic return of 20%. Even optimistically using an EROI of 2:1 for corn ethanol, half of the total energetic output is offset by input requirements.

Published EROI estimates for solar range from 3.75:1 to >50:1, typically around 8:1. This indicates that only 12% of solar energetic production is offset by input requirements, resulting in a net energetic return of 88%. Thus, when accounting for inputs, the net energy production of solar is 100-125 times that of corn ethanol.

The EROI of corn ethanol is sometimes estimated to fall below 1, the bare minimum for positive returns on investment. This means that corn ethanol is, by some estimates, a net energy sink. Estimates for positive returns show the amount gained is marginal compared to the energy costs. Even some of its more favorable estimates do not place its EROI above 2, making it a particularly low returning energy source compared to many others in use, including competing renewables.

Hydroelectric power performs the best, with an EROI of > 40, wind is behind that with an EROI of ~20, and geothermal has an EROI of ~9 (**22**) EROI estimates for switchgrass ethanol are higher than for corn ethanol but have wide ranges of estimated values (Table 3).

This variability is because investigators disagree on the viability of burning switchgrass waste to fuel the biorefineries that produce ethanol. Switchgrass is a cellulosic ethanol source, so its refining leaves behind cellulosic waste.

Many paper mills already process cellulosic waste and use it for fuel, so some argue that it would also be viable to burn the cellulosic waste from switchgrass production. However, others contend that the waste from switchgrass ethanol will not have the same utility.

22. Hall CAS, Lambert JG, Balogh SB. 2014. EROI of Different Fuels and the Implications for Society. Energy Policy 64: 141–52

A corn ethanol processing plant in Iowa
Photo: Lynn Grae - Getty Images

TOTAL ENERGY PRODUCTION

Only looking at the final ethanol fuel ignores an energetic pathway of societal value from ethanol production that needs to be considered when comparing land use efficiency. Coproducts of ethanol production (e.g., distillers grains and corn gluten meal) are used as livestock feed.

To account for this, we can look at the total amount of energy, regardless of how it is used, generated by solar panels compared to the total energy accumulated in corn, assuming it all gets used. Using average and maximum 2021 corn yields in Wisconsin (180-210 bushels per acre) (**23**) and conservative solar electricity generation rates in Wisconsin (300-325 MWh per acre) (**24**). solar panels still generate 14-17 times more gross energy per acre than corn produces.

However, animals are not 100% efficient at converting feed to meat or milk used by humans and so some of the gross energy in corn is lost in conversion to livestock product. When explicitly accounting for the energy available to humans from distillers' grains used to feed livestock, the combined energy of ethanol and beef produced from distillers' grains from one acre of corn grown for ethanol is 22-28 times less than energy produced from an acre of solar PV. Animals are more efficient at turning feed energy into dairy products: the combined energy of ethanol and dairy product produced from distillers' grains from one acre of corn is 18-23 times less than energy produced from an acre of solar PV.

Many paper mills already process cellulosic waste and use it for fuel, so some argue that it would also be viable to burn the cellulosic waste from switchgrass production. However, others contend that the waste from switchgrass ethanol will not have the same utility.

CONCLUSION

In sum, while there is no perfect comparison of the land use efficiency of harvesting energy via corn-based ethanol versus generating energy via solar panels, all the metrics described above demonstrate that solar is far more efficient at generating energy. This comparative land use efficiency should be considered alongside other environmental considerations such as the water pollution (**25**) and potential increase in greenhouse gas emissions (**26**) that accompany corn ethanol production.

23. United States Department of Agriculture National Agricultural Statistics Service. 2022. Wisconsin Ag News- 2021 Corn County Estimates. Average 2021 yield was 180 bushels per acre. Maximum county yield was 210 bushels per acre in Lafayette county. Available at: <https://www.nass.usda.gov/Statistics_by_State/Wisconsin/Publications/County_Estimates/2022/WI-CtyEst-Corn-02-22.pdf>

24. Bolinger and Bolinger (2022) report a 25th percentile of solar PV energy density of ~325 MWh per year per acre. Similarly, CPCN Applications for Koshkonong and High Noon projects state anticipated annual outputs of 500,000-700,000 MWh for ~2,000 acre facilities, translating into ~300 MWh per year per acre.

25. Donner SD and Kucharik CJ. 2008. Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. Proceedings of the National Academy of Sciences USA 105: 4513-4518

26. Lark TJ, Hendricks NP, Smith A, Gibbs HK. 2022. Environmental outcomes of the US Renewable Fuel Standard. Proceedings of the National Academy of Sciences USA 119: e2101084119

SOURCES

TABLE 1 SOURCES

IBhandari, KP, Collier JM, Ellingson RJ, Apul DS. 2015. Energy Payback Time (EPBT) and Energy Return on Energy Invested (EROI) of Solar Photovoltaic Systems: A Systematic Review and Meta-Analysis. Renewable and Sustainable Energy Reviews 47: 133–141. https://doi.org/10.1016/j.rser.2015.02.057.

Chiriboga, G, De La Rosa A, Molina C, Velarde S, Carvajal C G. 2020. Energy Return on Investment (EROI) and Life Cycle Analysis (LCA) of Biofuels in Ecuador. Heliyon 6: e04213. https://doi.org/10.1016/j.heliyon.2020.e04213.

Fthenakis V and Leccisi E. 2021. Updated Sustainability Status of Crystalline Silicon-based Photovoltaic Systems: Life-cycle Energy and Environmental Impact Reduction Trends.” Progress in Photovoltaics: Research and Applications 29: 1068–77. https://doi.org/10.1002/pip.3441.

Hall CAS, Powers R, Schoenberg W. 2008. Peak Oil, EROI, Investments and the Economy in an Uncertain Future. In: Biofuels, Solar and Wind as Renewable Energy Systems, edited by David Pimentel, 109–32. Dordrecht: Springer Netherlands https://doi.org/10.1007/978-1-4020-8654-0_5.

Hall CAS, Dale BE, Pimentel D. 2011. Seeking to Understand the Reasons for Different Energy Return on Investment (EROI) Estimates for Biofuels. Sustainability 3: 2413–32. https://doi.org/10.3390/su3122413.

Hall CAS, Lambert JG, Balogh SB. 2014. EROI of Different Fuels and the Implications for Society. Energy Policy 64: 141–52. https://doi.org/10.1016/j.enpol.2013.05.049.
Hammerschlag R. 2006. Ethanol's energy return on investment: a survey of the literature 1990-present. Environmental Science & Technology 40: 1744-1750.

Murphy DJ and Hall CAS. 2010. Year in Review-EROI or Energy Return on (Energy) Invested. Annals of the New York Academy of Sciences 1185: 102–118. https://doi.org/10.1111/j.1749-6632.2009.05282.x.

Murphy DJ, Hall CAS, Dale M, Cleveland C. 2011. Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels. Sustainability 3: 1888–1907. https://doi.org/10.3390/su3101888.

Murphy D, Carbajales-Dale M, Moeller D. 2016. Comparing Apples to Apples: Why the Net Energy Analysis Community Needs to Adopt the Life-Cycle Analysis Framework. Energies 9: 917. https://doi.org/10.3390/en9110917.

Murphy DJ, Raugei M, Carbajales-Dale M, Estrada BR. 2022. Energy return on investment of major energy carriers: review and harmonization. Sustainability 14: 7098.

Raugei M, Sgouridis S, Murphy D, et al. 2017. Energy Return on Energy Invested (ERoEI) for Photovoltaic Solar Systems in Regions of Moderate Insolation: A Comprehensive Response.” Energy Policy 102: 377–384. https://doi.org/10.1016/j.enpol.2016.12.042.

Wang Yu and Cheng M-H. 2018. Greenhouse Gas Emissions Embedded in US-China Fuel Ethanol Trade: A Comparative Well-to-Wheel Estimate. Journal of Cleaner Production 183: 653–61. https://doi.org/10.1016/j.jclepro.2018.02.080.

Weissbach, D, Ruprecht G, Huke A, Czerski K, Gottlieb S, Hussein A. 2013. Energy intensities, EROIs energy returned on invested), and energy payback times of electricity generating power plants. Energy 15: 210-221. https://doi.org/10.1016/j.energy.2013.01.029

Zanetti F, Scordia D, Calcagno S, Acciai M, Grasso A, Cosentino SL, Monti A. 2019. Trade-off between Harvest Date and Lignocellulosic Crop Choice for Advanced Biofuel Production in the Mediterranean Area. Industrial Crops and Products 138: 111439. https://doi.org/10.1016/j.indcrop.2019.06.002.

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