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Lifecycle and Avoided Emissions of Solar Technologies

Careful lifecycle analysis combined with displaced emissions analysis can result in meaningful insight to guide renewable project selection.

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ABOUT WATTTIME

WattTime is a 501(c)3 nonprofit with a software tech startup DNA, dedicated to giving everyone everywhere the power to choose clean energy. We invented Automated Emissions Reduction (AER), which allows IoT devices—smart thermostats, battery energy storage, electric vehicles, and more—as well as the utilities and people that use them, to effortlessly reduce emissions from energy, when and where they happen. AER works by deploying cutting-edge insights and algorithms, coupled with machine learning, to shift the timing of flexible electricity use to sync with times of cleaner energy and avoid times of dirtier energy. We conduct ongoing research collaborations into the algorithms and analyses that make AER possible, advocate for the spread of AER, and assist organizations in adopting the technology by selling solutions that make it easy for anyone to achieve emissions reductions without compromising cost and user experience. WattTime was founded by PhD students at the University of California, Berkeley, and in 2017 became a subsidiary of Rocky Mountain Institute.

For more information, visit <https://WattTime.org>.

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Executive Summary

Geographic location plays the largest role in determining the net emissions impact of a solar photovoltaic (PV) project, but the generation technology (i.e., type of PV) can also impact a project's overall emissions reduction. The cleaner a grid gets, the more important embodied emissions of the chosen PV technology becomes.

Using avoided emissions analysis combined with lifecycle analysis can be a valuable tool to determine the net emissions benefit of a project. These analyses can both identify *where* a project will have the greatest emissions-reduction impact as well as *what* PV technology will cause the least lifecycle emissions during production and deployment. Combined, this information can identify projects that result in the greatest possible emissions reductions.

For example, PV technologies with low lifecycle CO₂ emissions deployed in carbon-intensive electricity grids can result in a net CO₂ payback time of less than one year, as in the case of CdTe PV deployed in North

Carolina. In contrast, PV technologies with higher lifecycle CO₂ emissions deployed in low-carbon electricity grids can result in a net CO₂ payback time of greater than ten years, in the case of silicon PV deployed in France.

When engaging in renewable energy purchasing, organizations can use avoided emissions analysis combined with careful lifecycle analysis to gain meaningful insight into to guide renewable project selection. The grid region where the project is located is the primary driver of total emissions-reduction potential, but embodied lifecycle emissions also plays a role.

The contribution of PV technology lifecycle emissions to solar project net emissions reduction potential is particularly important in low-carbon grids, which are expected to become more common as more renewables are deployed globally.

Introduction

The amount of environmental benefit from a new renewable energy project primarily depends on the amount of conventional energy it displaces (i.e., fossil-fueled thermal generation). The amount of carbon emissions that a renewable energy project displaces per megawatt-hour (MWh) of generation can vary greatly based on factors such as which power grid the project is located in and the generation profile of the project.

While renewable projects reduce emissions by displacing fossil generators on the grid, a new project also comes with embodied emissions caused by manufacturing and deployment. By comparing the embodied emissions of a project with the emissions it displaces in operation in the assessment of a project, we can begin to understand the full impact of investment in a new project.

To understand the total impact of a solar project, in this report WattTime looks at the lifecycle emissions of different photovoltaic (PV) generation technologies compared to the emissions displaced by the same generators during operation to determine net emissions impact.

The analysis includes the four most common PV technologies including monocrystalline, multicrystalline silicon, copper indium gallium diselenide (CIGS), and cadmium telluride (CdTe). Projects in three regions,

France, North Carolina, and California, where the displaced emissions vary significantly were selected to provide a representative spectrum of potential impact. A ten megawatt (MW_{AC}) system was modeled as it is representative of the mean size of ground-mount PV systems being installed.ⁱ

Project location and type of PV generation technology determines net emissions

WattTime conducted a location-specific avoided emissions analysis and lifecycle emissions assessment of the four different $10 MW_{AC}$ photovoltaic generation technologies in three regions across a typical 25-year lifespan. WattTime's analysis reveals variation in emissions across the different projects based on both technology and location.

See Table 1 and Figure 1 for a summary of the results of the analysis, including total lifespan net emissions reduction as well as the emissions reduction per MWh. Because the projects both generate different quantities of electricity and displace different quantities of emissions due to their location, WattTime also normalized the displaced emissions per MWh to allow projects to be more easily compared.

ⁱ <https://www.seia.org/research-resources/major-solar-projects-list>

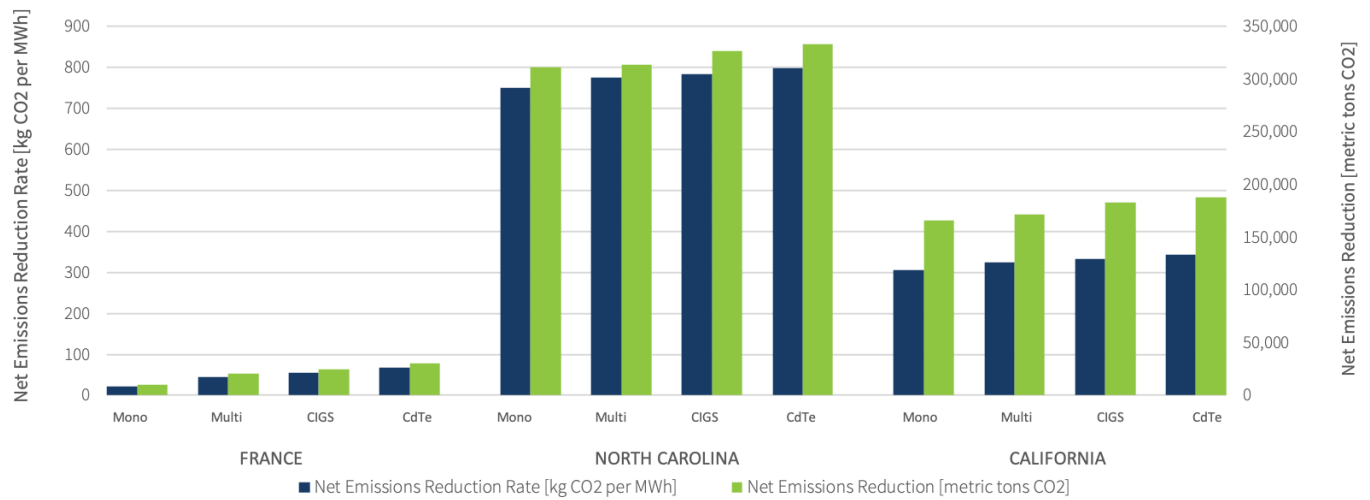
TABLE 1

Net emissions reduction rate and overall project lifetime net emissions reduction total

Photovoltaic Generation Technology	France		North Carolina		California	
	Net Emissions Reduction Rate (kg CO ₂ /MWh)	Net Emissions Reduction (metric tons CO ₂)	Net Emissions Reduction Rate (kg CO ₂ /MWh)	Net Emissions Reduction (metric tons CO ₂)	Net Emissions Reduction Rate (kg CO ₂ /MWh)	Net Emissions Reduction (metric tons CO ₂)
Monocrystalline	22.6	10,271	749.3	310,983	305.2	166,220
Multicrystalline	45.9	20,293	774.9	313,568	324.5	171,500
CIGS	54.6	25,107	784.3	326,951	332.2	183,200
CdTe	67.6	30,587	799.0	333,043	343.2	187,856

FIGURE 1

Net emissions reduction rate and overall project lifetime net emissions reduction total



This analysis looks at two primary factors that drive the net emissions reduction of a project: the generation technology and the location where the generator is sited.

The most substantial difference in avoided emissions rates can be seen when comparing projects between regions. Projects in North Carolina displace nearly fifteen times more emissions than projects located in France. This can be seen in the total displaced emissions rate in Figure 1. This is driven by the difference in fossil resources displaced by each megawatt hour of generation in each location. For example, the marginal generators in France are primarily low carbon, so a new project primarily displaces other low emissions resources. In California, the marginal generator mostly consumes natural gas and is occasionally renewable, so that the displaced emissions are higher than France, but still relatively low. In North Carolina the marginal generator is either coal or natural gas, causing a new renewable generator to push off much dirtier generation and reduce substantially more emissions than in either France or California.

Generation technology also determines the emissions caused by a project. Comparing different technologies within a single region shows that the lifecycle emissions vary based on the PV generation technology employed. Silicon technologies, especially monocrystalline, include greater emissions due to the material and manufacturing requirements, while thin film technologies cause lower emissions, which is reflected in the total higher net emissions reduction.

When emissions from the manufacture and deployment are compared, the net emissions reduction of a project can be determined. The results show where the greatest emissions reductions can be achieved when taking into consideration the net emissions reduction of a project. When engaging in renewable energy purchasing, organizations should consider both the embodied emissions of the technology as well as the region where the generator is being installed in order to maximize the total emissions reductions. Careful lifecycle analysis combined with displaced emissions analysis can result in meaningful insight to guide renewable project selection.



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Assumptions and Methodology

UNDERSTANDING LIFECYCLE ANALYSIS

Solar panels take considerable resources and energy to manufacture, in addition to transporting and deploying these technologies. To assess this impact, a lifecycle analysis is used to assess the emissions of every step of producing a panel from the raw material extraction through the end of life. The lifecycle analysis framework defines the methods for the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its lifecycle, from the extraction of resources and the production of raw materials, to product manufacturing, transportation/distribution, use and re-use, maintenance, and recycling and/or disposal.

Generally, ISO 14040/14044 defines the goal of and lifecycle analysis and how to set the scope, including functional unit, system boundary, and reference flow of the analysis under consideration. A lifecycle analysis relies on an inventory of inputs including energy, water, infrastructure, raw materials, packaging, transport, disposal, and emissions with documented data quality. This information is used to assess the impact of a system or unit with related uncertainty.

The lifecycle methodology for PV technologies are defined in the IEA PVPS Task 12 LCA methodology guidelinesⁱⁱ for PV and defines a set of required information:

- PV technology (single and multi-crystalline silicon, CdTe, CIS, micromorphous silicon)
- Type of system (e.g., roof-top, ground-mount, fixed-tilt or tracker)
- Module-rated efficiency and degradation rate;
- System lifetime
- Location of installation
- Annual irradiation,
- Expected annual electricity production with the given orientation and inclination or system's performance ratio

While lifecycle analyses can include many different impact categories, given the role PV is expected to play in the world's clean energy transition, this report focuses on global warming potential.

ⁱⁱ <http://iea-pvps.org/index.php?id=414>

UNDERSTANDING DISPLACED EMISSIONS

A renewable energy project reduces greenhouse gas emissions by displacing another source of generation. Adding one megawatt-hour of electricity from a renewable energy project to a power grid at a specific time and place displaces whatever power plant(s) would have otherwise produced power at that time. These are known as the marginal power plant(s). The specific properties of the displaced power plant(s), including efficiency and fuel type, determine the amount of avoided emissions.

Because the marginal plant varies greatly by both time of day, season, and location, adding a renewable energy project to an electric grid results in significantly different reductions in emissions depending on the siting and generation profile (that is, the timing of the generation) of the renewable energy project. WattTime has developed a scientifically rigorous methodology for determining the emissions of the marginal plant on a real-time, every-five-minute basis for electrical grids throughout the world. These marginal emissions factors form the basis of this avoided emissions calculation.ⁱⁱⁱ

ⁱⁱⁱ <https://www.watttime.org/aer/how-aer-works/>

^{iv} <http://www.iea-pvps.org/index.php?id=463>

METHODOLOGY & ASSUMPTIONS

The lifecycle emissions of the projects under consideration were calculated using ENVI-PV: the International Energy Agency (IEA)^{iv} environmental performance tool for PV systems developed by Mines ParisTech and ADEME based on lifecycle inventories developed by treeze. The following assumptions were used:

- **System Size (DC):** 12 MW
- **Performance Ratio:** 80%
- **System Size (AC):** 10 MW
- **System Life:** 25 years
- **Orientation:** south-facing
- **Inclination:** latitude
- **LCA Method:** Global Warming Potential (GWP) Baseline Model of 100 years (IPCC 2013)
- **Production Regions, where available:**
 - Average Market Europe/US
 - United States
 - China
 - Asia-Pacific
 - Europe
- **Deployment Regions:**
 - Collobrieres, France
 - Hickory, NC (USA) - Duke Energy Carolinas
 - Imperial, CA (USA) - CAISO, SP15

Further assumptions are listed in Table 2.

TABLE 2

PV module specifications

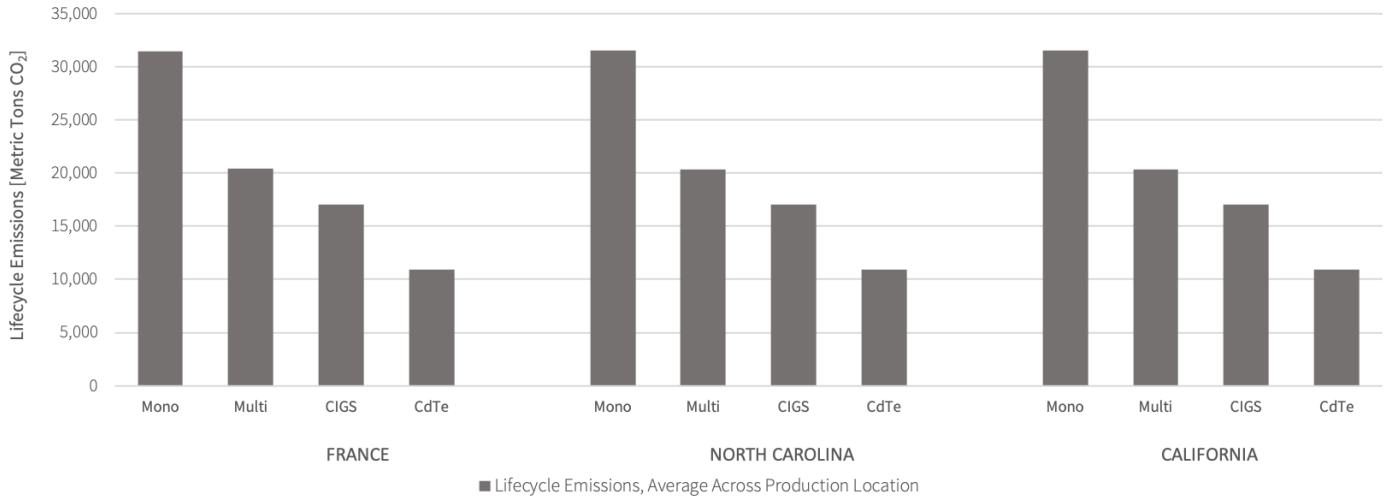
Module Type	Module Name	Module Power
Monocrystalline	Sunpower SPR E19 320	320 W
Multicrystalline	Talesun - TP672P-320	320 W
CIGS	Solar Frontier K185-S	185 W
CdTe	First Solar FS 6390A	390 W

Because the ENVIPV LCA software is only capable of modelling a 570 kW DC system, the results were scaled to a 12 MW DC (10 MW AC) system. The average lifecycle impact of different PV technologies across different production locations in different regions is shown in Figure 2. Because

the displaced emissions of a solar project are not a part of the lifecycle analysis calculation, this report disregards the electricity generation information of the ENVI-PV lifecycle analysis, and WattTime separately calculated the displaced emissions of the projects, as discussed in the next section.

FIGURE 2

Lifecycle emissions by PV technology type and region



The difference in lifecycle emissions between different PV technologies can vary by nearly a factor of three between the least and most emissions intensive technologies. This is driven primarily by the energy and materials intensity of manufacturing the silicon-based panels compared to the thin film technologies.^v The lifecycle or embodied emissions intensity affects the net emissions reduction of an installed system.

The avoided emissions of the projects were calculated using marginal emissions factors developed by WattTime. WattTime’s technology accurately determines time-varying marginal carbon emissions factors for electricity grids around the world at a given time and location. The factors are derived from statistical analysis of which power plants on the local grid were marginal at a given point in time, and the emissions rates of these plants as measured by the U.S. Environmental Protection Agency’s Continuous Emissions Monitoring System (CEMS) and ENTSO-E Transparency Platform. The marginal emissions were calculated for the grid region where the renewable energy projects are located. To create a typical marginal emissions profile, up to three years of historical marginal emissions were used to create a typical daily profile for every hour of each month.

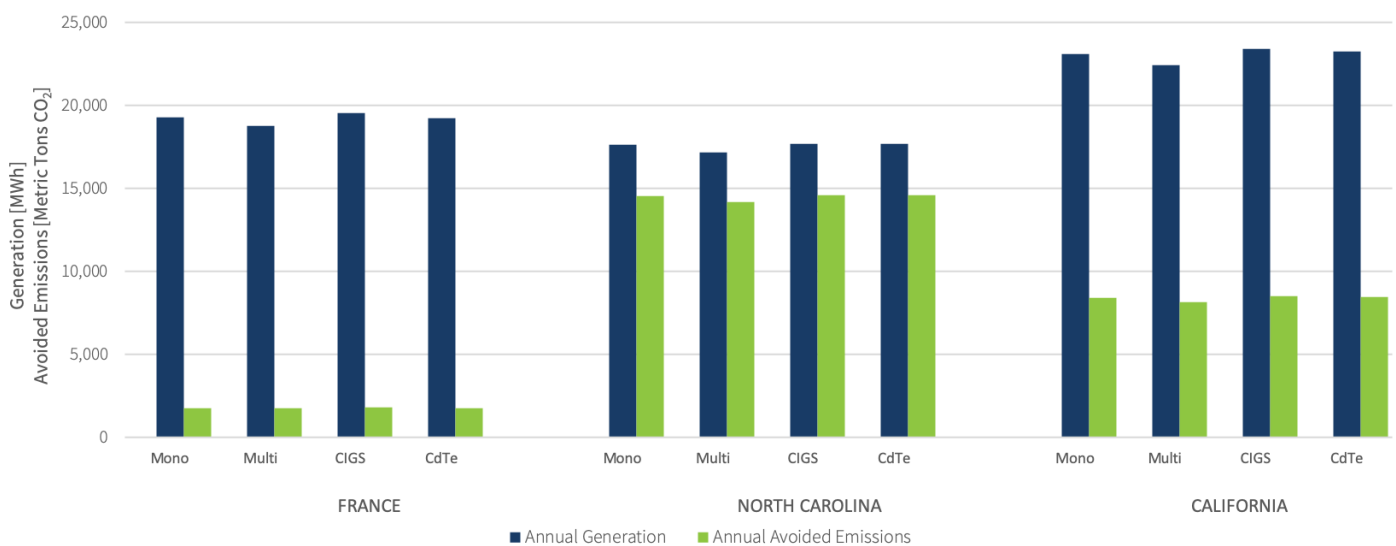
Because actual generation profiles are not available for any of the representative projects, WattTime used simulated data for a typical project located in each region to estimate the avoided emissions. The generation data was estimated using Plant Predict software.^{vi} The same PV system assumptions were used as for the lifecycle analysis. In addition, a 0.5% annual degradation rate was assumed after the first year. The grid regions where the projects are located are identified in the following table.

WattTime combined the hourly generation with the marginal emissions data to determine the total avoided emissions of generation technology in each region. For each hour, the emissions avoided by each project in metric tons of CO₂ are the product of the total generation of the facility in that same hour (in megawatt-hours) and the marginal carbon emissions factor in that hour (in metric tons of CO₂ per megawatt-hour).

Figure 3 shows the total annual generation and total avoided emissions of each PV technology in each location. As can be seen in this chart, while generation is broadly the same in southern France and central North

FIGURE 3

Annual electricity generation & avoided emissions



^v <https://doi.org/10.1016/j.enpol.2019.111234>

^{vi} <https://plantpredict.com/>

Carolina, the emissions displaced by the generation in North Carolina is substantially higher. The solar energy in France displaces other relatively cleaner sources while the generation in North Carolina displaces predominantly coal, so that the same energy generation in North Carolina reduces more than eight times greater emissions. In California, while the total generation is greatest, the displaced emissions fall between France and North Carolina because the displaced resources are a mix of natural gas and renewables. The location of a renewable generator, and thus the generating resources it displaces, directly influences the emissions avoided.

WattTime then compared the emissions caused by the manufacture, transportation and installation of the panels to the emissions reduced through operation to determine the net emissions benefit. A detailed description of these results follows.



Results

Each PV technology displaces a different quantity of emissions because of total generation, where the resource is located, and timing of generation. Furthermore, each PV technology causes different emissions based on the specific manufacturing, transportation, and deployment characteristics. The lifecycle emissions, displaced emissions, and net impact of different types of 10MW systems in different locations are summarized in Table 3. In this table ‘embodied emissions’ refer to the lifecycle emissions or emissions caused by manufacturing, transportation, construction, operational, and end of life while excluding any emissions displacement benefit of the generated electricity. The ‘displaced emissions’ correspond to the emissions reduction resulting from the renewable energy pushed onto the grid and displacing other resources. The ‘net emissions reductions’ show the decreased emissions caused by deploying the generation technology as the difference between the

increase in emissions from the lifecycle and the decrease in emissions due to displaced fossil generators.

All of the systems reduce emissions throughout their 25-year lifespan, but different PV technologies in different regions show widely varying net impacts depending on the emissions intensity of the grid. Overall, systems deployed in North Carolina are substantially more effective at reducing emissions, regardless of the PV technology employed. Overall net emissions reductions vary by less than 7% between different technologies deployed within North Carolina. However, the PV technology selection makes a much larger difference in France where net emissions reduction vary by more than 60%. This is due to embodied emissions remaining nearly the same regardless of deployment region, but displaced emissions differ by more than a factor of eight between North Carolina and France. This pronounces the effect of generation technology selection in regions with lower avoided

TABLE 3

Embodied emissions, displaced emissions, and net emissions reduction totals

Photovoltaic Generation Technology	France			North Carolina			California		
	Embodied Emissions	Displaced Emissions	Net Emissions Reductions	Embodied Emissions	Displaced Emissions	Net Emissions Reductions	Embodied Emissions	Displaced Emissions	Net Emissions Reductions
Monocrystalline	31,411	41,682	10,271	31,495	342,478	310,983	31,495	197,715	166,220
Multicrystalline	20,379	40,672	20,293	20,337	333,904	313,568	20,337	191,836	171,500
CIGS	17,053	42,160	25,107	17,053	344,003	326,951	17,053	200,253	183,200
CdTe	10,947	41,534	30,587	10,947	343,991	333,043	10,947	198,803	187,856

emissions like France and California. In all three regions, thin film PV technologies provide greater net emissions reductions due to their lower embodied emissions.

While Table 3 compares a standard 10MW AC system, Table 4 shows the net emissions reductions of different technologies per megawatt hour of generated energy across the lifespan of a project. This shows the impact of procuring electricity from different technologies on a per megawatt hour basis. The comparison shows similar

results to Table 3, but these metrics may be useful when considering procurement of a fixed quantity of energy.

The total net emissions reduction (metric tons CO₂) and net emissions reduction rate (kg CO₂ per MWh) are shown in Figure 4. While the net emission reductions rate closely tracks the total net emissions reductions, the total net emissions reductions outpace the rate in California because the systems in California produce more electricity on a per megawatt basis, resulting in greater emission reductions.

TABLE 4

Mean net emissions reduction rate by technology and location

Photovoltaic Generation Technology	France	North Carolina	California
Monocrystalline	17.9	744.0	301.2
Multicrystalline	43.6	772.5	322.6
CIGS	54.6	784.3	332.2
CdTe	67.6	799.0	343.2

FIGURE 4

Net emissions reduction rate and overall project lifetime net emissions reduction total

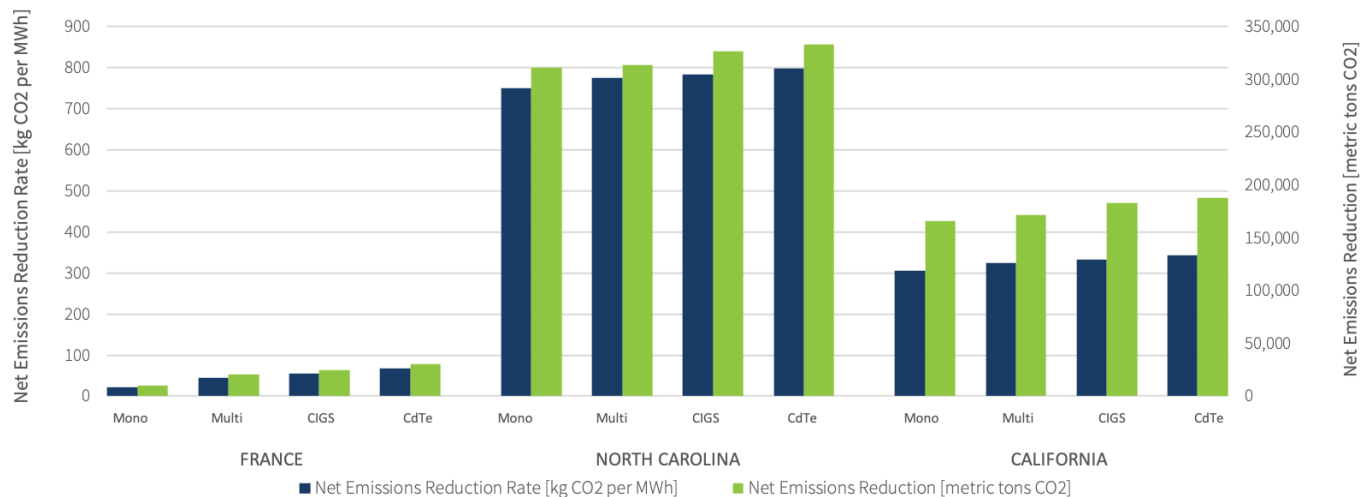


FIGURE 5

Lifetime avoided emissions rate and simple 'CO₂ payback' period

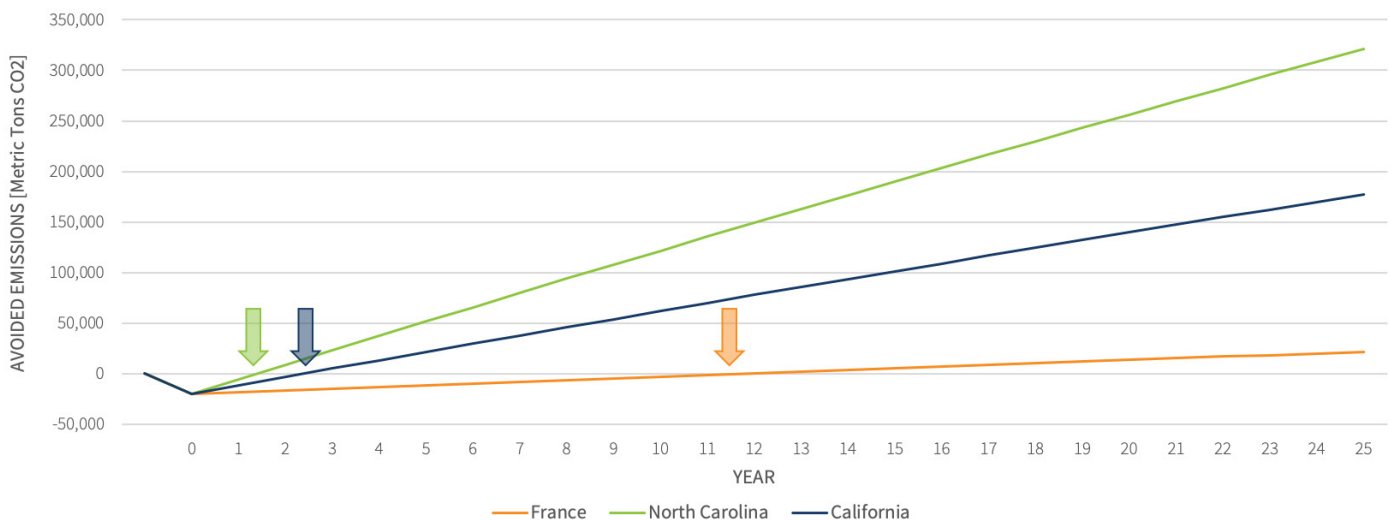
	France				North Carolina				California			
Lifetime Avoided Emissions Rate (metric tons CO ₂ per MWh)	Mono	Multi	CIGS	CdTe	Mono	Multi	CIGS	CdTe	Mono	Multi	CIGS	CdTe
Average Market Europe/US	0.02	0.04	0.05	0.07	0.74	0.77	0.78	0.80	0.30	0.32	0.33	0.34
Production in US	0.02	0.05	0.05	0.07	0.75	0.77	0.78	0.80	0.30	0.32	0.33	0.34
Production in China	0.01	0.04	0.05	0.07	0.74	0.77	0.78	0.80	0.30	0.32	0.33	0.34
Production in Asia-Pacific	0.02	0.05	0.05	0.07	0.75	0.78	0.78	0.80	0.31	0.32	0.33	0.34
Production in Europe	0.04	0.05	0.05	0.07	0.77	0.78	0.78	0.80	0.32	0.33	0.33	0.34
Simple CO ₂ Payback (years)	Mono	Multi	CIGS	CdTe	Mono	Multi	CIGS	CdTe	Mono	Multi	CIGS	CdTe
Average Market Europe/US	19.5	12.8	9.5	6.2	2.4	1.5	1.2	0.7	4.2	2.7	2.0	1.3
Production in US	18.2	11.8	9.5	6.2	2.2	1.4	1.2	0.7	3.8	2.5	2.0	1.3
Production in China	20.7	13.2	9.5	6.2	2.5	1.6	1.2	0.7	4.4	2.8	2.0	1.3
Production in Asia-Pacific	17.5	11.7	9.5	6.2	2.1	1.4	1.2	0.7	3.7	2.5	2.0	1.3
Production in Europe	12.8	9.5	9.5	6.2	1.6	1.2	1.2	0.7	2.7	2.0	2.0	1.3

While region remains the largest driver of emissions reduction along with generation technology, the region where a PV technology is produced does affect the total emissions reduction potential of a project. For example, Monocrystalline silicon PV produced in China and deployed in France takes the longest time to begin reducing emissions beyond its lifecycle emissions, also known as CO₂ payback period. This long payback time is because its net emissions reduction rate is close to zero based on the high lifecycle emissions and low avoided emissions. Monocrystalline silicon PV produced in other regions has lower embodied emissions, so the CO₂ payback period is shorter.

Figure 6 takes a closer look at the CO₂ payback by showing the year over year net emissions reductions. The initial emissions caused by a system are indicated as negative values below the x-axis. As systems cumulatively displace more emissions every year, the net emissions reductions continue to rise. The point at which the line crosses the x-axis is the time at which the system is assumed to have reduced CO₂ emissions by as much as the embodied CO₂ emissions caused in the manufacturing and construction. Figure 6 shows the CO₂ payback period of the average of the PV technologies in different regions. North Carolina and California begin reducing CO₂ emissions on a net basis in less than three years. This is not the case in France, where the breakeven point occurs after 11 years.

FIGURE 6

Net CO₂ emissions reduction in all regions by deployment year averaged across PV technologies. Payback period to net-zero emissions is marked with an arrow.



While Figure 6 shows the average of all the technologies in each region, Figures 7, 8, and 9 show the annual net emissions reduction for each technology in each region. The effect of technology selection is much more pronounced in France as shown in Figure 7. The CO₂ emissions ‘payback’ period varies between 6 and 20 years,

depending on the technology. This effect is much less pronounced in California (Figure 9), where all CO₂ payback periods fall under 4 years, and even less noticeable in North Carolina (Figure 8), where the payback period is less than 2.5 years and as low as half a year for CdTe PV.

FIGURE 7

Net CO₂ emissions reduction in France by PV type. Arrows = payback period to net-zero emissions.

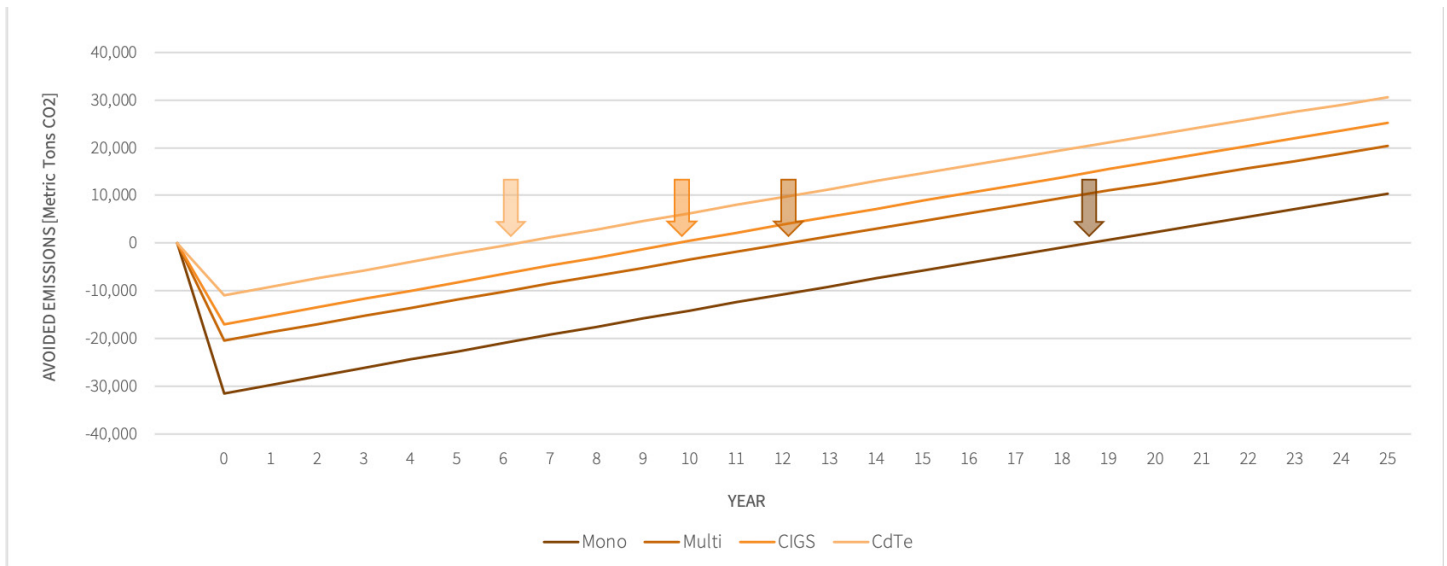


FIGURE 8

Net CO₂ emissions reduction in North Carolina by PV type. Arrows = payback period to net-zero emissions.

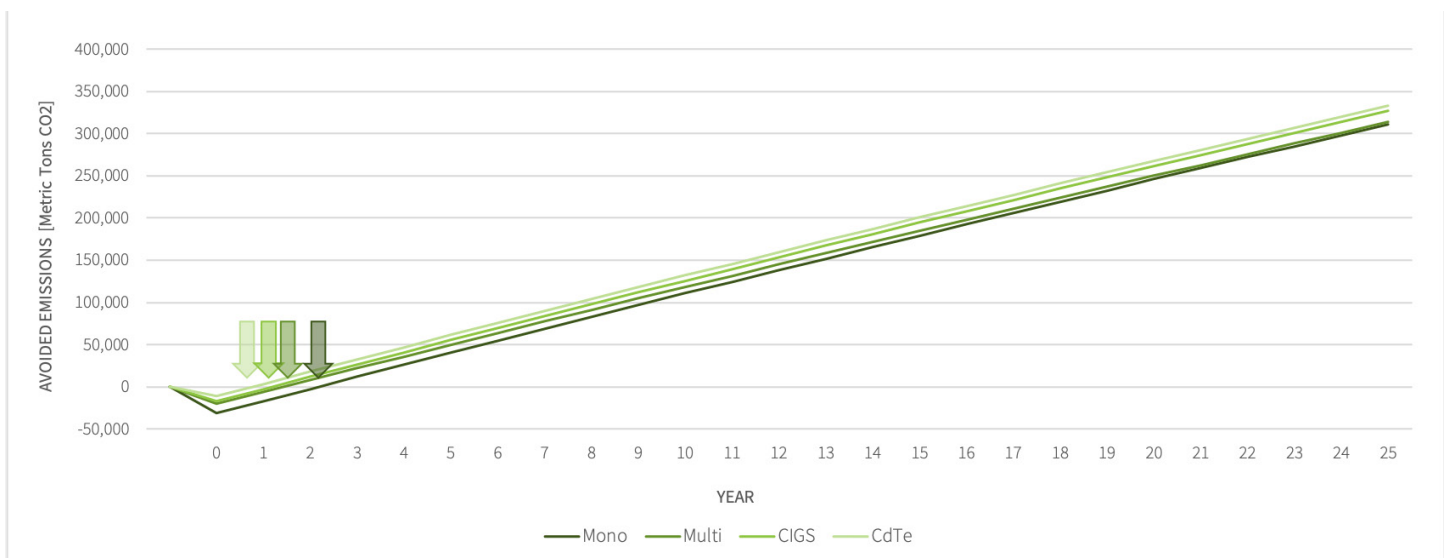
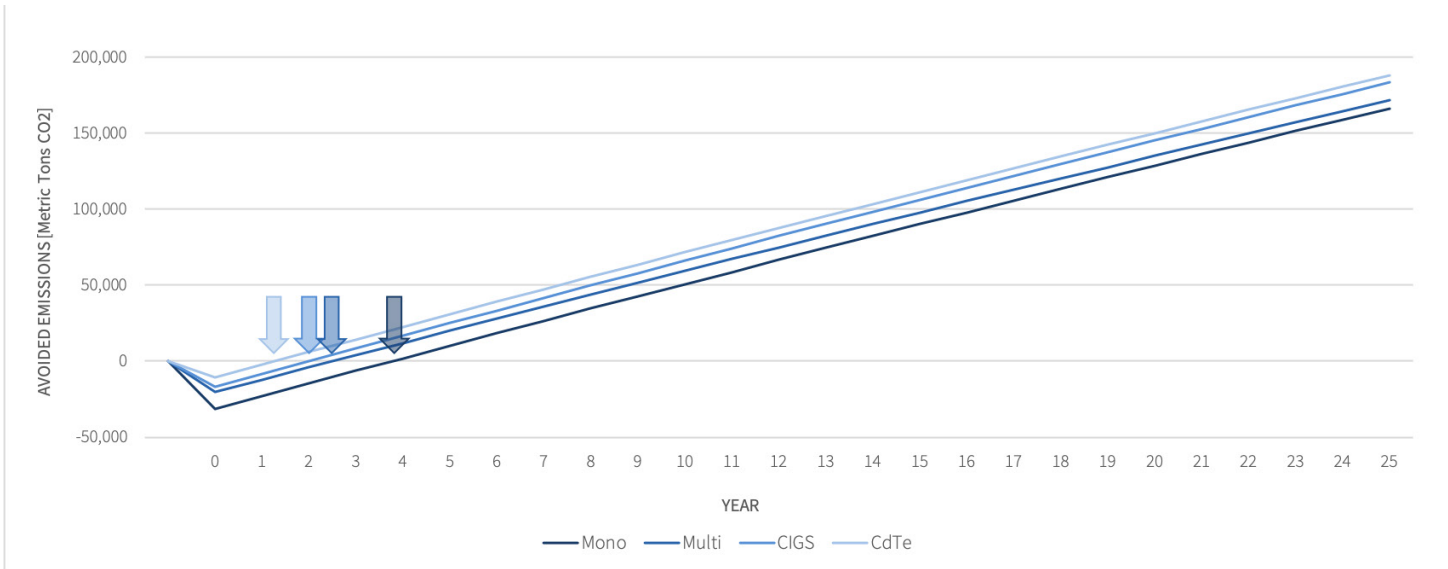


FIGURE 9

Net CO₂ emissions reduction in California by PV type. Arrows = payback period to net-zero emissions.



Conclusion

Overall, project location is the primary driver of the total emissions reduction potential for a solar project, but generation technology is an increasingly important consideration. Using avoided emissions analysis, combined with lifecycle analysis, to determine the net emissions benefit of a project can be a valuable tool in project selection. These analyses can both identify where a project will have the greatest emission reduction impact as well as the technology that will cause the least lifecycle emissions during production and deployment. Combined, this information can lead to projects that result in the greatest possible emissions reductions.

Both developers and purchasers should consider generation technology and location as selection criteria when considering projects for development. As illustrated in the France and California case studies, the contribution of PV technology lifecycle emissions to solar project net emissions reduction potential is particularly important in low-carbon grids which are expected to become more common as more renewables are deployed globally.