MECH0032 - New and Renewable Energy Systems

An Analysis of the Past and Future Global Electricity Landscape and Photovoltaic Solar Design Study

Candidate number: KHQQ0

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Executive Summary

Climate change is causing increased global pressure to transition to sustainable methods of electricity generation in order to reduce greenhouse gas (GHG) emissions. This report considers three topics pertaining to this transition. The first topic considers global trends in electricity generation that took place between the years 2012 and 2022. The second topic considers predicted changes in demand for electricity between the years 2023 and 2050. The third topic is a design study of a medium-sized solar PV (SPV) plant, considering its location, layout, environmental impacts, and financial feasibility.

The first topic, which considers trends in electrical power, demonstrates the changing energy landscape that has taken place over the last decade. GHG emissions associated with electricity production comprises roughly a quarter of total global emissions (1). Fossil fuels, including oil, natural gas, and coal, are wholly responsible for these electricity-associated emissions, and currently comprise more than half of the global electricity mix, especially in developing countries. This is changing however, as policies and lowering costs of renewables have led to rapid growth in electricity production from renewable sources. In the last decade, electricity production by solar and wind have grown especially rapidly. While overall electricity generated from fossil fuels has increased, their share of the electricity mix is decreasing. Nuclear and hydro, while growing in production, are also declining in their share of the mix, as a greater preference for solar and wind has been demonstrated.

The second topic to be discussed is predicted changes in demand for electricity between the years 2023 and 2050. The *World Energy Outlook 2023* outlines three possible scenarios for humanity's response to climate change, from which electricity demand can then be predicted. In the first scenario, where humanity abides by its current policies, demand for electricity rises in a largely linear fashion, continuing the trend seen in the last decade for an 80% increase by 2050. The second scenario, where humanity meets all national energy and climate targets, sees a steep increase in electricity demand starting in the early 2030s for an overall increase of 125%. In the last scenario, where humanity achieves net-zero emissions by 2050, ramping up starts as early as the late 2020s and results in an overall increase of over 150%. This increase in demand is largely driven by growth in the electric transportation sector, increasing by a factor of up to 20x depending on the scenario. In each of the scenarios, demand is primarily met by SPV and wind.

The third topic is a design study of a 10.9 MW SPV plant producing 15 GWh/year in Shirley, Massachusetts, USA. In the design portion, the location, module type and model, energy output, and spacing and layout of the plant are discussed and determined. Using PVWatts, 19500 fixed-tilt modules at 32.5° taking around 39 acres of land were determined to be suitable for the energy requirement. Total system losses were found to be 14%. Upon designing the plant itself, several additional relevant questions are considered. Intermittency associated with solar energy can be addressed through a Battery Energy Storage System (BEES). The environmental impact of the farm is minimal thanks to considerations made when selecting the location, however, visual concerns are still relevant. Impact of global warming on the farm can be either beneficial or harmful, as increased temperatures could raise average ambient temperatures closer to the optimal range for solar panels, whereas increased cloud cover and weather volatility could prove detrimental. Lastly, a LCOE (Leveled Cost of Electricity) analysis determines that the farm is financially viable over a 15-year period.

Section 1 - Trends in Electrical Power

This section considers historical trends that took place with electrical power between the years 2013 and 2022. Figure 1 is an area chart from which several observations can be drawn. Data from the years 2013 and 2022 was used to construct Table 1 to look at the change in further detail.

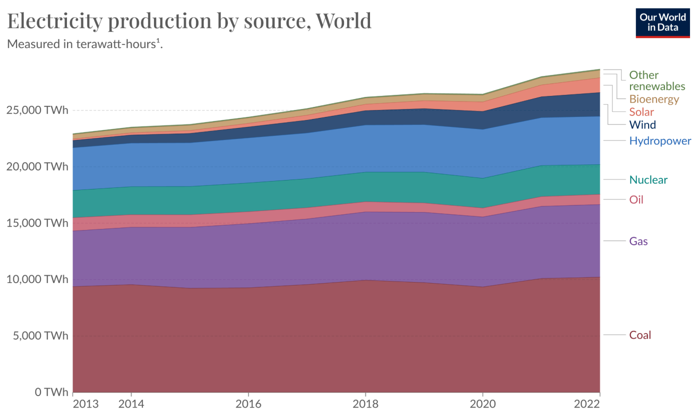


Figure 1: Global electricity production by Source, 2013-2022 (2)

Figure 1 provides a good overview of the trends in electricity production that have taken place from 2013 to 2022. The first observation is that overall electricity production increased. Upon closer examination, one can see that coal, oil, nuclear, and hydro stayed relatively constant, gas made modest gains, and the largest gains were seen in wind, solar, bioenergy, and other renewables.

Table 1: Electricity Production and Contribution in 2013 and 2022 (2)

	2013 Prod. (TWh), Contribution (%)	**2022 Prod. (TWh), Contribution (%)**	**Change in Prod. (%)**	**Change in Contribution (%)**
Solar	132, 0.6%	1310, 4.6%	+894%	+694%
Wind	641, 2.8%	2098, 7.3%	+227%	+162%
Hydro	3781, 16.5%	4289, 15.0%	+13%	-9%
Nuclear	2424, 10.6%	2632, 9.2%	+9%	-13%
Gas	4931, 21.5%	6444, 22.5%	+31%	+5%
Oil	1180, 5.2%	904, 3.2%	-23%	-39%
Coal	9374, 40.9%	10212, 35.6%	+9%	-13%
Total	22931, 100%	28661, 100%	+25%	N/A

Table 1 provides a breakdown of global electricity production and contribution (share of the mix) in 2013 and 2022 by each of the major electricity sources, as well as the corresponding percent changes in production and contribution for each of the sources between 2022 and 2023. Two trends can be observed: changes in overall electricity production and changes in contribution to the overall electricity mix. This distinction is made because, while the total production of a source can be increasing over a given time period, its share of the mix can be decreasing.

Changes in production by source are provided by the fourth column in the table. Since total demand for electricity increased by 25% from 2013 to 2022 (last row of column four), it makes sense that almost all of the sources including fossil fuels increased in production, since decreasing production of undesirable sources is difficult when total demand is rising. There are, however, more significant percentage increases in production attributed to solar (+894%), wind (+227%), hydro (+13%), and gas (+31%) compared to nuclear (+9%), oil (which actually decreased by 23%), and coal (+9%). The largest gains were in solar and wind, as these are relatively newer technologies and have been prioritized in policy over the last decade. Out of the three renewables solar, wind, and hydro, solar especially saw the greatest gains.

Changes in share of, or contribution to, the electricity mix are provided by the fifth column. This column shows again that solar and wind have been the dominant electricity sources over the last decade in terms of growth - not only are solar and wind increasing in total production, they are also increasing in their share of the electricity mix. Conversely, although production increased for hydro, nuclear, and coal, their shares of the mix decreased. The share of gas increased, though very marginally compared to the increases in solar and wind.

Looking ahead, the trends observed in both columns support the conclusion that solar and wind, with solar to a greater degree, are the renewable electricity generation sources that have the greatest potential to displace fossil fuels as humanity seeks to decarbonize towards 2050. This is indeed corroborated by the findings in Section 2.

Section 2 - Predicted Changes in Demand

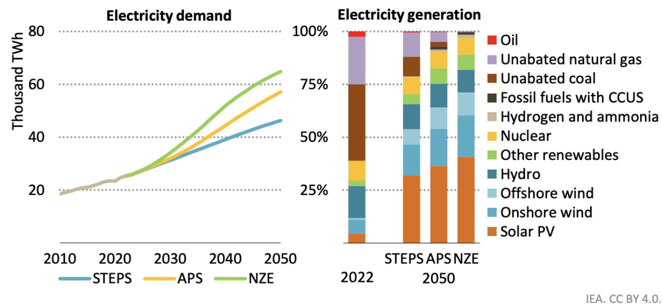
This section considers predictions of how global demand for electricity will change between the years 2023 and 2050.

By 2050, one can anticipate a significant increase in electricity demand globally, particularly driven by the electrification of the transport sector and increased domestic consumption due to electrification and technological advancements. However, the rate of increase will be influenced by the pace of efficiency improvements, the speed of the transition to renewable energy sources, and the effectiveness of policies aimed at curbing overall energy consumption. This variance in the possibilities is why many energy/climate models have outlined multiple scenarios differing on the aggressiveness with which humanity takes action towards climate change. This report specifically considers the International Energy Agency (IEA)'s *World Energy Outlook (WEO) 2023*, an authoritative source for analysis and projections of the global energy landscape.

WEO outlines three scenarios that model how the landscape of global energy will change from now to 2050: The Stated Policies Scenario (STEPS), The Announced Pledges Scenario (APS), and Net Zero Emissions (NZE). As the names imply, STEPS "provides an outlook based on the latest policy settings", APS "assumes all national energy and climate targets made by governments are met in full and on time", and NZE is the best-case scenario of global net-zero emissions and global warming limited to 1.5 °C.

Figure 2 has two charts, one that shows changes in electricity demand between 2022 and 2050 (differences in data between 2022 and 2023 are negligible), and one that shows the sources that comprised and will comprise the electricity mix in 2022 and 2050, respectively.

According to the left chart, electricity demand will rise between roughly 80%, 125%, and over 150% by 2050 according to the STEPS, APS, and NZE scenarios, respectively. STEPS largely follows the linear trend established in the 2010s while the APS and NZE deviate from the trend, with the NZE deviating more significantly and sooner. The increase in demand is largely driven by emerging markets and developing economies. Electricity demand in China in particular is predicted to be more than twice as much as any other country by 2050. Likewise, high annual growth in electricity demand in India places it behind only China and the US. In general, increased global energy/electricity demand stems from population growth, economic development, and rising living standards.



Electricity demand rises over 80% to more than 150% by 2050 across scenarios and is met increasingly by low-emissions sources at the expense of unabated coal and natural gas

Figure 2: Global electricity demand, 2010-2050, and generation mix by scenario, 2022-2050 (3)

Looking at the right chart, it becomes clear that SPV will become the dominant electricity generation source regardless of scenario. Offshore and onshore wind combined are the second largest energy source. These findings align with the observations made in Section 1, which showed the astronomical present-day growth in SPV and wind.

Figure 3 shows electricity demand broken down by sector and region. For the purposes of addressing how changes to domestic consumption and transport will contribute to the increase in demand, the "By sector" chart is the focus for analysis.

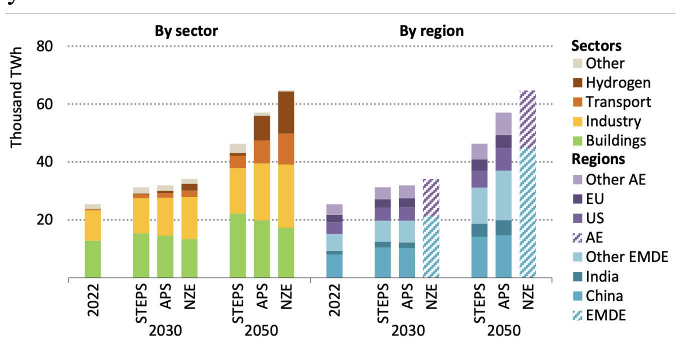


Figure 3: Electricity demand by sector and region, and by scenario (3)

In 2022, electricity demand was mainly due to consumption from the industrial and building sectors. Transport, including cars, trucks, ships and planes, is largely absent as a consumer of electricity as it is dominated by oil consumption. By 2050 an increase in global demand for electricity in all sectors and scenarios can be seen. One big shift is that transport will become a far greater consumer of electricity due primarily to a boom in EVs. Presently, EVs are a proven technology and thus have a clear path to mass-market adoption. Electric trucks exist in limited amounts while electric ships and planes are still a novel technology, so they will contribute less to future demand of electricity. In the APS and NZE, a significant increase in electricity consumption to produce hydrogen through electrolysis will occur, representing a more profound shift away from present-day policy.

Buildings remain the largest consumers of electricity through to 2050 in the STEPS and APS, driven by an increase in demand for appliances, space cooling and heating, and heat pumps. In the NZE, improved energy efficiency reduces growth in the building sector's demand for electricity. Industry becomes the second-largest consumer of electricity for the STEPS and APS and the largest for the NZE, as industrial electric motors see increased adoption.

Section 3 - Solar Farm Design

This section considers the design of a hypothetical 10.9 MW SPV farm for the purpose of generating 15 GWh/year of electricity in Massachusetts, United States. The section is split into five parts – Part a describes the design itself, Part b addresses how the effects of intermittency associated with SPV can be mitigated, Part c assesses the environmental impact of the plant, Part d considers how the plant may be impacted by global warming, and Part e is a financial analysis of the operation.

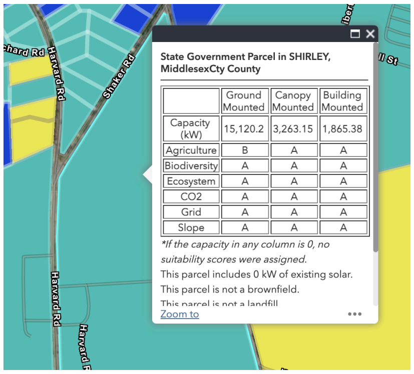
Part a - Design

Location

The first step when it comes to designing a solar plant is choosing the location, as it plays an important role in the performance and feasibility of the plant. Massachusetts was chosen as the author of this report is familiar with it, it is a very climate-friendly state and hub of renewable energy technology in the US (4), is densely populated which provides a unique challenge (5), and is overall a less conventional location than other sunnier states, making for a more interesting analysis.

In order to refine the location further and choose the plant size, a study conducted by the Massachusetts Department of Energy Resources (DOER) that analyzed the potential of every tax plot of land in the state to be a location for solar siting was considered. It assessed every plot based on six criteria - Agriculture, Biodiversity, Ecosystem, CO2, Grid, and Slope. Agriculture, Biodiversity, Ecosystem, and CO2 consider the negative impacts constructing the plant would have on those respective metrics, while Grid and Slope consider the ease with which the plant can be connected to the grid and whether the ground is sufficiently level, respectively.

A plot was chosen in Shirley, MA with capacity roughly suited to the 15 GWh/year requirement that scored the highest in all criteria except Agriculture, which it had a moderate score for (Figure 4). The plot is an ideal location for many reasons. It is an open, undeveloped, flat piece of land, far from any wildlife. The fact that it is undeveloped means it will be cheaper, easier, and less environmentally harmful to install panels there. Since it is open, shading from trees or other obstructions won't be an issue. Connecting the panels to the grid will also be very easy, as shown by Figure 5. The colored line is a 3-phase line and the nearest substation is only a mile away.



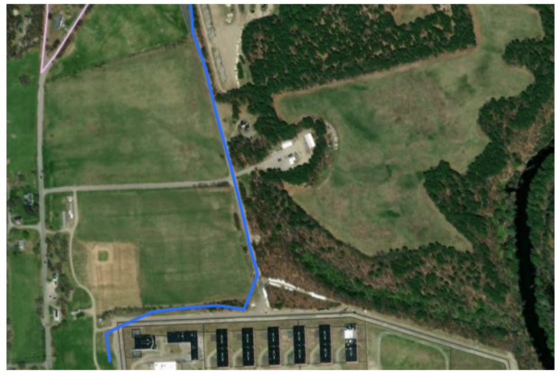


Figure 4: Suitability of chosen plot for solar (6)
Figure 5: Satellite image showing adjacent 3-phase line (7)

The plot scored a B for Agriculture, which is unfortunately the case for many ground-mounted solar systems as the land requirements for agriculture are often similar to the requirements for solar farms.

Module Type and Model

Upon considering monocrystalline, polycrystalline, thin-film, and bifacial solar cells, the optimal type for this project was determined to be monocrystalline bifacial cells. This is due to their high energy and space efficiency, durability, and great performance across varied temperatures. Since this project is located in Massachusetts, the third most densely populated state in the US (5), space efficiency is of paramount importance. Monocrystalline bifacial cells produce more energy for a given area of land, and are thus optimal in this respect. Massachusetts is a state with hot, humid summers and cold, snowy winters (8), so withstanding the elements and varied temperatures demands high durability and temperature resilience. The property of panels being bifacial allows them to absorb light from underneath, which is suitable for ground-mounted panels, further improving space efficiency and long-term return (9). Though they are costlier than other types of PV cells, for the reasons described above they are the optimal choice for this particular application and to maximize long-term returns.

The specific manufacturer and model chosen for this project is the Longi 560W Hi-MO 5. Longi is the world's largest manufacturer of monocrystalline panels, and their 560W Hi-MO 5 is especially suitable for ground-mounted, utility-scale solar applications.

Calculations

For the calculations, PVWatts by the National Renewable Energy Laboratory (NREL) was used as it is free, trustworthy, and accurate, especially in the United States. The settings inputted into the calculator will now be considered. Specific location was already determined in Location.

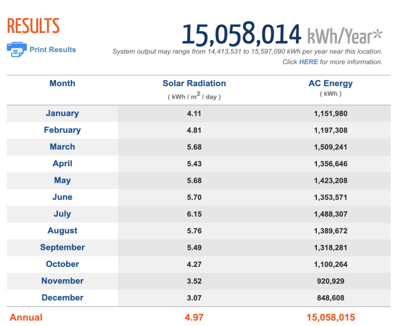
Module Type was set to "Premium", which corresponds to an efficiency of 21%, slightly less than the 21.7% rated max efficiency of the module being used (10).

Next is System Losses, which represent various ways energy can be lost that are not captured by the baseline efficiency value. Soiling was reduced from 2% to 1%, as the site is located in suburban Massachusetts, which has very clean air, frequent rain, and experiences little dust and pollution (8,11).

Shading was reduced from 3% to 1%, as the site is an open field and spacing will be designed to minimize shading. Snow was increased from zero to 1%, as snow is significant in Massachusetts, although it should slide off relatively easily due to the tilt angles used in this project. Wiring was increased from 2% to 3% to take into account potential transformer losses. Lastly, age was increased from zero to 1% to consider any other minor degradations resulting in lowered efficiency over time. Light-induced degradation was kept at 1.5%, in-line with the manufacturer quoted <2% (10). Limited and inconsistent values for availability factor were found online, as it seems to be a seldom-tracked value for SPV. "Reliability" didn't return results on Google for a quantitative number, but more-so the vague qualitative measure of whether a system is deemed to operate consistently over a long period of time. One peer-reviewed article found the availability factor to be roughly between 92.5% and 95.5%, or availability losses from 4.5-7.5% (12). Since this study was conducted in India, using data over 8 years old, and less efficient polycrystalline cells, it can be assumed that the default availability loss factor of 3% is reasonable. With all other losses left to default values, total system losses are 14.06%.

Advanced parameters were left to default, except Bifacial, which was set to Yes. One of the advanced parameters takes into account inverter efficiency, which is set to 96% – reasonable for high-performance inverters. Azimuth angle was left default (180°), which is optimal for SPV in the northern hemisphere.

This left the parameters for system size, array type, and tilt. Although single-axis arrays may be more financially viable over the long run (13), fixed arrays are preferable in Massachusetts due to the risk of storms and extreme weather events damaging moving components (14), which will only be exacerbated by climate change (see Part d - Impact of Global Warming). Tilt was determined through an online calculator that considered the location of the site (15). Further testing with PVWatts gave an optimal tilt of **32.5°**. Setting half of the modules to 47.5° tilt for winter and to 17.5° tilt for summer was also tested, though was found to yield less total energy over a year than setting all modules to 32.5°. The last parameter was the system size itself. Through trial and error it was determined that a system size of **10920 kW,** or **19500** 560W modules produces slightly over **15 GWh/year** on average (Figure 6).


RESULTS

Print Results

15,058,014 kWh/Year*

System output may range from 14,413,531 to 15,597,090 kWh per year near this location.
Click HERE for more information.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)
January	4.11	1,151,980
February	4.81	1,197,308
March	5.68	1,509,241
April	5.43	1,356,646
May	5.68	1,423,208
June	5.70	1,353,571
July	6.15	1,488,307
August	5.76	1,389,672
September	5.49	1,318,281
October	4.27	1,100,264
November	3.52	920,929
December	3.07	848,608
Annual	4.97	15,058,015

Figure 6: Results of PVWatts Calculation (16)

Spacing and Layout

Assuming a configuration that's double-stacked to reduce number of racking frames necessary, with portrait orientation for simplicity, the equation to determine the minimum spacing between rows of the panels can be used:

Minimum spacing = $D_1 + D_2 = L\,cos\,\alpha + H\,cot\,\beta$,

$L = 2 * length\,of\,single\,module = 2 * 2.28 = 4.56\,m$, $\alpha = tilt\,angle = 32.5°$,

$H = L\,sin\,\alpha = 2.278 * sin\,(32.5) = 2.45\,m$,

$\beta = \theta - 23.5 = (90 - latitude) - 23.5 = 90 - 42.5 - 23.5 = 24°$,

Minimum spacing $= 4.56 * cos\,(32.5) + 2.45 * cot\,(24) = 9.34\,m$

In order to avoid shading at early and late times during the winter and allow access for maintenance, this value will be increased by a further 3.66, bringing the spacing between panels to **13 m.** The plot can be divided into four sections A-D in order to accommodate the panels (Figure 7).

Figure 7: Different sections of solar farm (17)

Using a distance calculator (18), Section A was determined to have dimensions 322x195 m. Given that the width of the modules is 1.134 m, and adding a 10 mm gap to accommodate expansion of the module frame (19), 322/1.144 = 281 panels or 562 modules can fit in a row. Given a spacing of 13 m between rows, 195/13 = 15 rows can fit in this section. This gives a total of 15 * 562 = 7306 modules.

Executing the same calculations for sections B and C, 3542 and 4368 modules were determined to be able to fit in sections B and C, respectively. The remaining 4284 modules needed to reach 19500 total modules were then determined able to fit in section D. The total area taken up by the four sections is **158263 m^2.**

Part b - Intermittency

The problem of intermittency is inherent with SPV, as it can only generate power during the day. Though it is currently not an issue in Massachusetts that solar power is in danger of being wasted, because renewables in this area aren't yet close to meeting entire demand at any time of day, it could be a problem in the future when SPV expands and there's excess energy produced during the day.

Thus, either to provide a baseload of clean solar power throughout day and night, or to address future concerns when fossil fuels are completely de-phased, a system that stores energy is needed. The first obvious solution is a Battery Energy Storage System (BESS). Simply put, this would be a large-scale battery storage system that stores energy made during the day to be used during periods of low sunlight or at night. The BESS can also be used to smooth out the energy output of the solar farm during the day, since solar output is less in the mornings and late afternoons.

A practical example of this is Gateway Energy Storage in southern California, a 250 MWh lithium-ion BESS and currently the largest battery in the world (20). The system stores solar energy collected during the day to be used for peak demand at night.

Part c - Environmental Impact

Fortunately, the overall environmental impact of the solar farm is minimal, which is one of the reasons the site was chosen. The plot is far from wildlife and vulnerable ecosystems, and the land is already flat except for section D, meaning disturbance of wildlife/biodiversity and ecosystems would be minimal. One concern is the panels causing bird deaths (21), though the total number of birds killed by this effect is minimal. Since PV panels don't generate any noise, the only noise would be from the inverters and power equipment, which, if placed far from the few housing structures observable from google earth, such as the top right of section A, would not pose an issue. Though not impacting the "environment", solar panels can alter the visual landscape, which may be a concern for nearby residents. This can be addressed by installing vegetative buffers around the site, improving ground-level aesthetics.

Since solar panels consume no "fuel", environmental impacts resulting from the plant's operation are minimal, and in fact should be net-positive, considering they result in lower concentrations of CO_2 and other harmful gases in the atmosphere.

According to the EPA, by 2030 the "US is expected to have as much as one million tons of solar panel waste" (22). Solar panels contain hazardous minerals such as lead and cadmium, which if not disposed of or handled properly can have the potential for environmental contamination by leaching into the soil and groundwater. Recycling and proper waste management practices can significantly reduce the plant's environmental impact and minimize waste during decommissioning.

Part d - Impact of Global Warming

Though it is difficult to fully predict the effect of global warming on solar energy, there are several possibilities, each with the potential of improving or worsening the performance of SPV. Since the United States is a large country, changes mainly in the context of Massachusetts are considered.

The first effect is rising temperatures. The current yearly average temperature in a city nearby to the project is ~9.5 °C (23), far below the optimal temperature range for SPV of 20-25 °C (10), meaning global warming would likely result in an improvement in performance of this plant. In addition, average temperatures in winter are expected to increase more than average temperatures in summer in Massachusetts (24), meaning efficiency gained in the winter will outweigh efficiency lost in the summer.

A negative effect would be increased weather volatility. Massachusetts is already prone to extreme weather events, and global warming is expected to exacerbate this. Storms and heavy precipitation are expected to increase in frequency and intensity and hurricanes are predicted to reach further north than they have historically (25). These can cause physical damage to panels and supporting infrastructure, leading to increased maintenance costs and downtime. This is a main reason why fixed panels, which are more robust than solar trackers, were chosen for this project.

Another potential effect is changes in solar irradiance. Global warming could lead to changes in cloud cover and atmospheric conditions that might increase or decrease the amount of solar irradiance, leading to a corresponding increase or decrease in solar energy extraction (26).

Part e - Financial Analysis

In order to determine if the plant is financially viable over a 15-year life span, the Levelized Cost of Renewable Electricity ($LCOE_R$) for the plant and Levelized Cost of Utility Electricity ($LCOE_U$) for local utility electricity can be determined using an NREL calculator and subsequently compared. If the $LCOE_R$ is less than the $LCOE_U$, the plant is predicted to be financially viable. To clarify, $ means USD.

Massachusetts has the Solar Massachusetts Renewable Target (SMART) Program, which subsidizes solar development. According to data on solar projects installed through the SMART program from 2018-2022, the total development and installation cost of large (>= 1 MW) ground-mounted projects in Massachusetts is estimated to be $2.31 per W_{DC} (6). For 10.9 MW_{DC}, this comes out to $25.2 million.

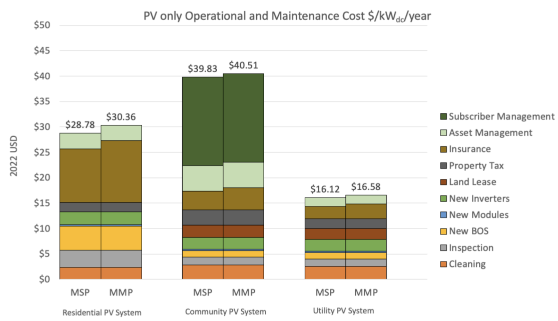


Figure 8: O&M costs of solar installations by type (27)

Operational and maintenance costs can be determined from NREL benchmarks (Figure 8). Although this project's capacity is far below the capacity used to define a utility-scale system (100 MW_{DC}), it does not involve a subscriber management system like the community solar system, so a cost reasonably higher than the Modeled Market Price (MMP) for a utility system can be assumed, $20 / kW_{DC} / year. The average price of utility-purchased electricity in Massachusetts in 2023 was $0.182/kWh (28). Finally, using a standard real discount rate of 3% (29) to factor in the time value of money and a capacity factor of 24.5% (30), these values can be plugged into the NREL calculator to arrive at the two LCOEs.

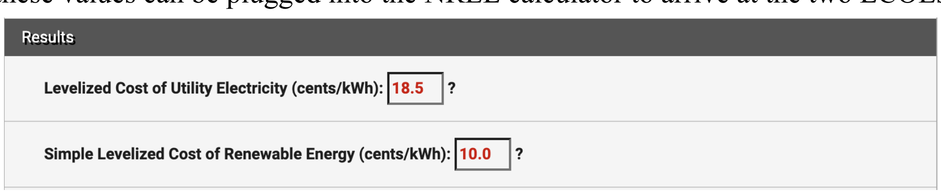


Figure 9: LCOE calculator results (31)

Therefore, the plant can be expected to make a profit of roughly (0.185-0.10 $/kWh)($15.06*10^6$ kWh/year * 15 years) = **$19.2 million** over a 15-year life span.

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