Photovoltaic Solar Power: Current Technology, Potential Innovations, and Policy Changes for the Industry

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Abstract:

This paper addresses the concerns and reality of climate change, our future outlook, and one solution that we can invest in in order to address this issue. It shows the current and potential impact of photovoltaic solar cells, starting with a detail of how photovoltaic solar cell technology works. It analyzes the economic cost, quality and performance, and the importance of this technology in terms of its societal and environmental benefit. It explores the potential changes that certain forms of new photovoltaic solar technology can bring to society in order to meet many long-term goals. It then brings together a technological and policy analysis to determine the best solar technology, policy and implementation solutions. Using this determination, it makes specific recommendations for the photovoltaic solar industry moving forward.

1. Introduction:

We face a progression of climate change that is detrimental to our world and threatens to cause a catastrophic global average temperature rise if we do not make changes. If we maintain our current course, the climate will become more varied and unpredictable, and the global average temperature will rise about 4.1 degrees celsius by 2100. This is enough to cause major negative effects on our society. Weather patterns will become less bearable, the ecosystem will suffer, our supply chain will be increasingly damaged and our communities will become less healthy due to low air quality. We are already seeing the beginnings of this trend, so we must act now in order to prevent it from becoming our future.

Many potential solutions have been developed in the forms of renewable energy, carbon capture, sustainable land-use practices and more. I will be exploring an industry with the potential to be a major solution and preventative measure to climate change, the industry of photovoltaic solar cells. Solar cells are one of the most cheap, efficient and reliable renewable energy solutions, but they also have much potential for further development. They are a good alternative to fossil fuels in that they are free of emissions, fully renewable while fossil fuels are finite, and simple and easy in terms of gathering energy when compared to fossil fuels. Despite these benefits, much of the energy market still opts for fossil fuels. There is also room for improvement in terms of solar energy. We must critically analyze factors such as the performance, cost and efficiency of these photovoltaic solar cells and make some changes in order to improve their functionality and create more demand. From a policy standpoint, we need to adopt stronger policies to encourage the use of photovoltaic solar cells. This paper will analyze the current functionality of photovoltaic solar panels as well as potential technological, implementation, and policy improvements.

2. Analysis:

2.1. Functionality:

In order to analyze these factors, we must first understand how a photovoltaic solar cell of current technology works. A solar panel typically contains these layered components shown in Figure A. Each layered component performs a specific function.

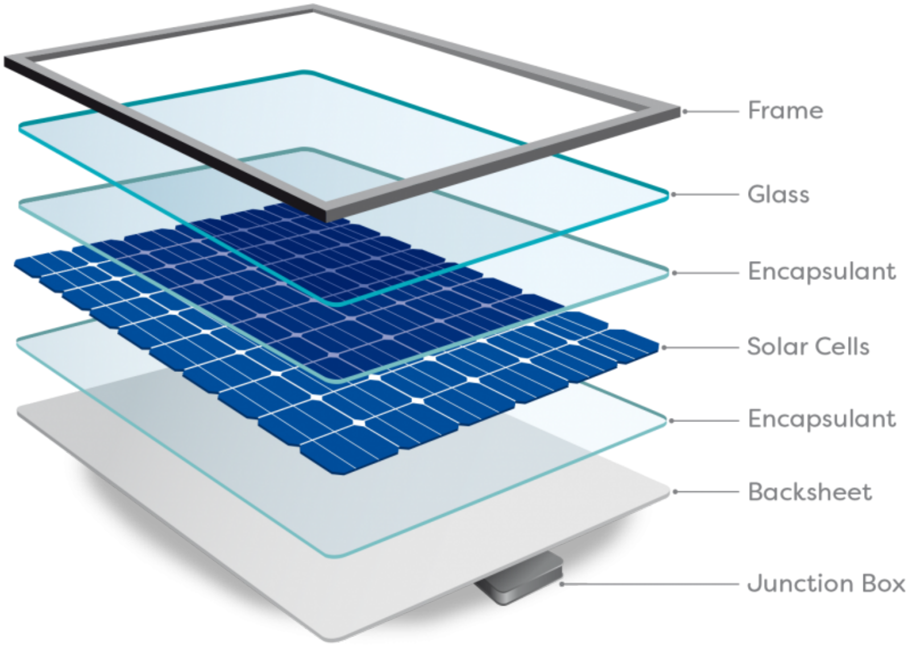


Figure A

1. Frame: Holds solar panel components together
2. Glass: A clear layer that protects the solar cells and all other components below
3. Antireflection coating: Since the silicon solar cells below have high reflectivity, this layer of antireflection coating significantly reduces the amount of sunlight lost to reflection
4. Encapsulant layers: Additional protective layers that prevent outside material such as water or dirt from entering the solar cell layer
5. Solar Cells: The functional layer of the solar panel. This silicon layer of multiple cells converts sunlight into usable electricity. Shown below is the cross section of an individual cell.

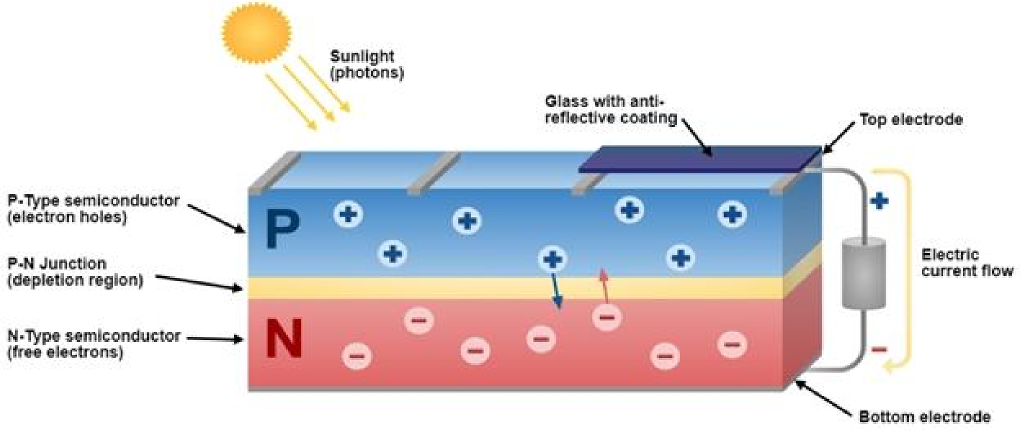


Figure B

When sun rays hit the solar panel and reach the solar cell, Figure B shows how the cell converts the energy to usable electricity. The semiconductor material within the solar cell is divided into two parts. The lower band, or valence band, contains negatively-charged electrons, while the higher band, or conduction band, is an empty band. When the sun's photons hit the cell, the gap between the bands absorbs the photon's energy and excites the electrons in the valence band. The excited electrons move from the valence band to the conduction band. This electron-hole pair reaction leads to an electrical current that is transferred as usable electricity.

6. Backsheet: The bottom layer of the solar panel, a metal sheet that all components rest on
7. Junction box: The box at the back of a solar panel that wires connectors in the solar panel together to create a consolidated electrical output.

Main types of photovoltaic solar cells on the market:

1. Monocrystalline silicon cells - Highest efficiency and highest cost
2. Cast monosilicon cells - High efficiency and lower cost
3. Polycrystalline silicon cells - Lower efficiency and lowest cost

2.2. Performance:

It is important to measure and calculate a few performance factors to determine how beneficial, convenient and effective current photovoltaic solar panels are. This will also gauge how many panels are needed to power certain facilities. We can calculate the power output of a solar panel using average conditions as a benchmark, yet we must also vary the calculations using factors such as sunlight intensity, cloud cover, heat buildup and humidity.

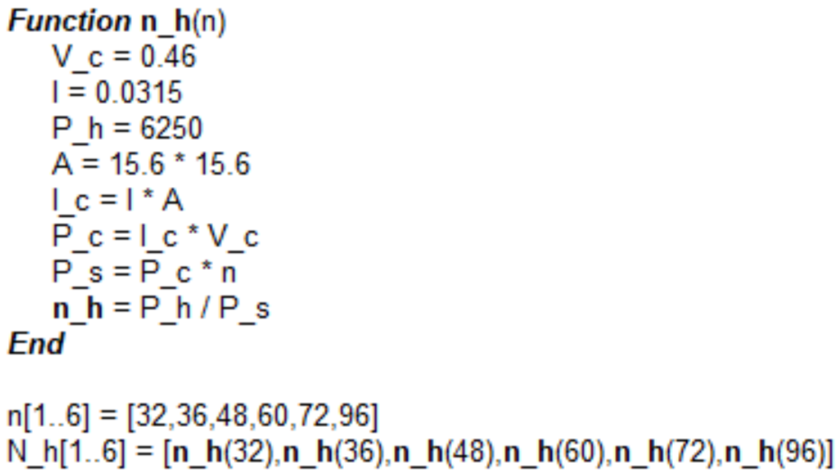
Assumptions:
One solar panel can contain n = 32, 36, 48, 60, 72, or 96 cells depending on the configuration. The typical dimensions of a solar cell are 15.6 x 15.6 cm.

n = number of solar cells per panel
A = area of a solar cell (cm^2)
V_p = solar panel voltage
V_c = 0.46 V = voltage produced per solar cell
P_s = solar panel power
I = 31.5 mA = 0.0315 A = typical current per square centimeter of a solar panel
I_c = current through a solar cell
I_p = current through a solar panel
N_h = number of solar panels needed for the average U.S. house
P_h = 6,250 W = typical power requirement of the average U.S. house

Calculations:
Area of a solar cell: $A = 15.6 \cdot 15.6 = 243.36\ cm^2$
Current through a solar cell: $I_c = I \cdot A$
Power produced by a solar cell: $P_c = I_c \cdot V_c$
Total solar panel power: $P_s = P_c \cdot n$
Number of solar panels needed to power the average house: $N_h = P_h / P_s$

Below is an EES program that uses these formulas and given values to calculate the number of solar panels needed to fulfill the energy needs of the average U.S. home. These initial calculations assume ideal conditions of 24 hour sunlight.

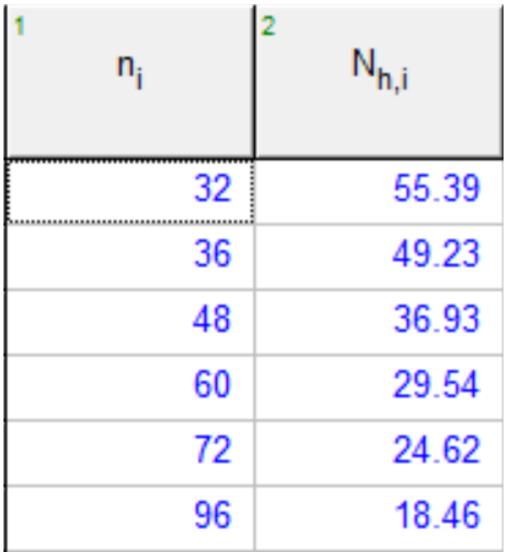
EES Code:



```
Function n_h(n)
    V_c = 0.46
    I = 0.0315
    P_h = 6250
    A = 15.6 * 15.6
    I_c = I * A
    P_c = I_c * V_c
    P_s = P_c * n
    n_h = P_h / P_s
End

n[1..6] = [32,36,48,60,72,96]
N_h[1..6] = [n_h(32),n_h(36),n_h(48),n_h(60),n_h(72),n_h(96)]
```

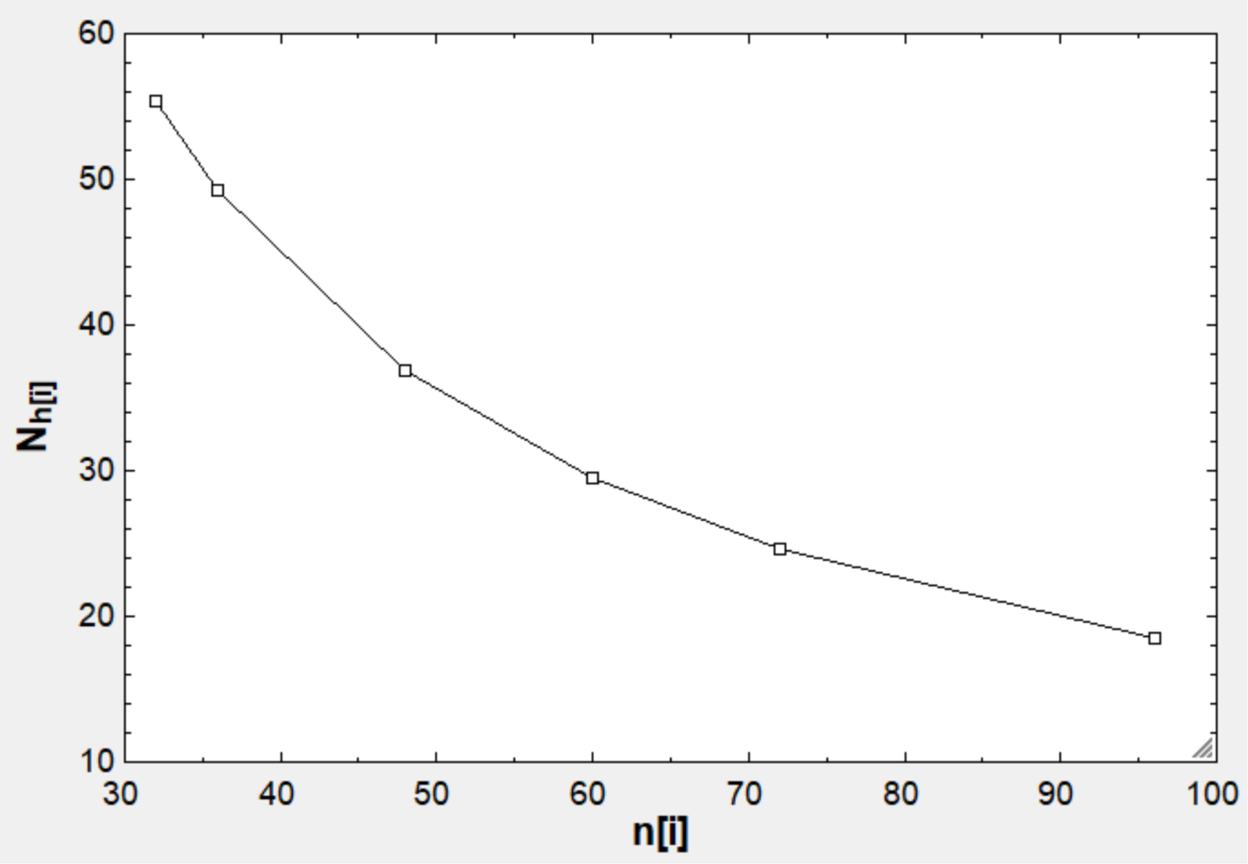
Results Table:



1 n_i	2 $N_{h,i}$
32	55.39
36	49.23
48	36.93
60	29.54
72	24.62
96	18.46

In this table, n represents the number of photovoltaic cells per panel and N_h represents the corresponding number of solar panels you would need to fulfill the energy needs of the average U.S. home.

Photovoltaic Cells per Panel vs Amount of Panels Needed to Power the Average U.S. Home:



These results assume perfect conditions, such as constant sunlight, an average temperature, and no cloud cover. We must, however, consider the limited hours in a day and occasional cloud cover based on geographic region. In adjusting these calculations to account for imperfect conditions, we must first assume the least ideal conditions to form a worst-case scenario. We can assume that the average U.S. home is fitted with a battery storage for energy produced by the solar panels, but we must still assume that more solar panels would be fitted to a U.S. home than our calculations would suggest due to varying conditions and varying energy use.

Here are two main factors that we must consider in terms of the effect they have on our above calculations. My calculations above are an ideal scenario, assuming 24 hour sunlight and no cloud cover as is possible in some regions. These factors below create a worst-case scenario that we will use to alter the above calculations and compare with the ideal scenario.

1. Non-constant sunlight: Sunlight occurs for an average of 12 hours per day, however regions in the northern and southern hemispheres far from the equator can experience days with significantly fewer hours of sunlight during certain seasons. Due to this, photovoltaic solar power becomes inadequate for regions far enough from the equator.

   My above calculations assume 24 hours of sunlight a day, so we must adjust these calculations to assume 12 hour days for an average scenario. As shown below, the final number of solar panels needed for an average U.S. home in this scenario ($N_{h,f}$) will be 2x that of the ideal scenario ($N_{h,i}$) for each amount of solar cells per panel.

   Average scenario: $N_{h,f} = N_{h,i} \bullet (24h / 12h) = \mathbf{2 \bullet N_{h,i}}$

   Let's make an assumption that solar power becomes too costly without enough benefit in regions that experience shorter than 6-hour days during a season. As shown below for a 6-hour daylight scenario, the final number of solar panels needed for an average U.S. home will be 4x that of the ideal scenario for each amount of solar cells per panel.

   Worst-case scenario: $N_{h,f} = N_{h,i} \bullet (24h / 6h) = \mathbf{4 \bullet N_{h,i}}$

2. Periodic cloud cover: The global average cloud cover usually hovers around 0.68, or 68% cloud cover over the surface area of the earth. If we assume this average cloud cover, then the sun is obstructed about 68% of the time during the day.

   Average scenario: $N_{h,f} = N_{h,i} \bullet (1 / (1 - 0.68)) = \mathbf{3.125 \bullet N_{h,i}}$

Among regions that do not experience shorter than 6-hour days, let's assume that the heaviest cloud cover is about 0.75, or 75% cloud coverage.

Worst-case scenario: $N_{h,f} = N_{h,i} \bullet (1 / (1 - 0.75)) = \mathbf{4 \bullet N_{h,i}}$

Both of the factors with average assumptions must be combined to create our average scenario: $N_{h,f} = 2 \bullet 3.125 \bullet N_{h,i} = \mathbf{6.25 \bullet N_{h,i}}$.

Both of the factors with worst-case assumptions must be combined to create our worst-case scenario: $N_{h,f} = 4 \bullet 4 \bullet N_{h,i} = \mathbf{16 \bullet N_{h,i}}$.

Using our calculated data and these adjustments for external factors, we can determine whether or not it is viable for a consumer to fulfill 100% of their energy needs through home solar panels. Using the formulas above, I calculated the amount of solar panels needed to power the average U.S. home given these average and worst-case sets of conditions. I compare these values to those of my initial, ideal conditions calculations.

Number of solar cells per panel (n)	Number of solar panels needed to power the average U.S. home		
	Best conditions (Ideal)	Average conditions	Worst conditions
32	55.39	346.19	886.24
36	49.23	307.69	787.68
48	36.93	230.81	590.88
60	29.54	184.63	472.64
72	24.62	153.88	393.92
96	18.46	115.38	295.36

This table shows the calculated amount of solar panels needed to power the average U.S. home for each of the three sets of conditions I considered. These findings reveal that, although photovoltaic solar panels are a clean, renewable and cheap solution, they are not always the most efficient option for specific conditions. They can be inefficient for a low amount of sunlight per day or high cloud cover.

2.3. Potential Innovations for Photovoltaic Solar Technology:

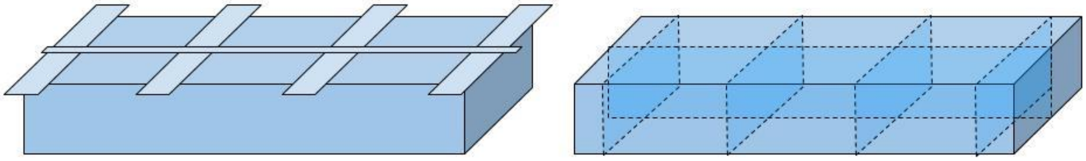
The sun can produce up to 1,000 watts of energy per square meter, or 0.1 watts per square centimeter during peak hours. It averages around 0.05 watts per square centimeter during the day, however. An individual solar cell is 243.36 cm^2 in area, so the sun exerts about 0.05 W • 243.36 = **12.16** watts of power on a solar cell during the day.

As determined by previous analysis, the actual power produced by an industry-standard solar cell is $P_c = I_c \bullet V_c$ = **3.53** watts. Although the sun exerts an average of 12.16 watts of power on a solar cell during the day while the sun is out, the solar cell only turns 3.53 watts of that power into usable power. This means solar cells are quite inefficient and they have a lot of potential for improvement in order to harness more of the sun's energy.

Based on the performance analysis of existing solar technology, we can now explore some possibilities of improving current solar technology in terms of efficiency, cost, convenience, and other factors.

- Smaller photovoltaic cells: The size of a photovoltaic cell has an impact on its efficiency. The larger a cell is, the more resistance the electrons within the cell face when moving, so a smaller cell minimizes this resistance and therefore increases the efficiency of the cell when it is producing power. If we were to develop solar cells smaller than the industry standard of 15.6 x 15.6 centimeters, the cell would be more efficient and harness more of the sun energy discussed above. Smaller solar cells would require more assembly and contribute to a higher manufacturing cost, however the greater efficiency will produce enough extra power to negate the extra cost of manufacturing if the product is used over a long time period. The more energy each panel produces, the fewer panels need to be produced to meet energy needs.

- Electrode placement: Electrodes in industry standard solar panels rest on top of each solar cell in specific locations and completely cover the bottom of each solar cell. These electrodes collect the power produced by the cell and bring it to the junction box. The top electrode is placed on top of the solar cell to minimize the amount of electron resistance from electrons traveling to the electrode. On top of the cell, the electrons have less distance to the electrode, reducing resistance. If the electrons were instead placed vertically, embedded inside the cell, all of the cell's surface area would be exposed to the sun and able to produce electricity. This would increase efficiency by allowing more sun to enter the cell. The electrodes are thin enough that they would not occupy a significant amount of area inside the cell.

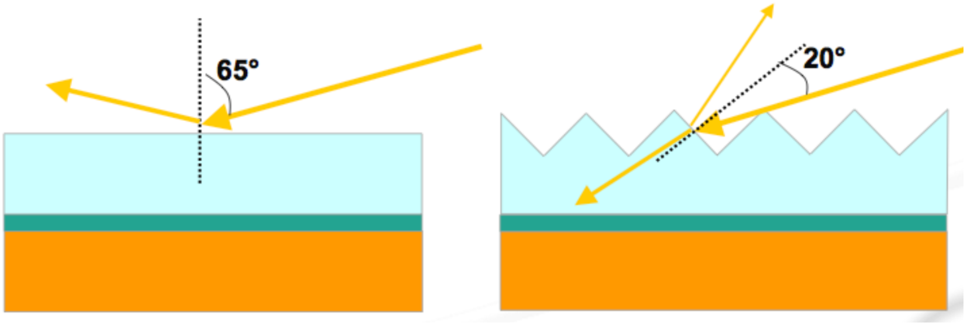


Standard Electrode Placement:

Proposed Electrode Placement:

Figure C

- Light-trapping glass: Standard solar panels use flat glass on the top with an antireflective coating to trap as much light as possible, however light-trapping glass, as pictured below, is more effective at trapping solar radiation than flat glass. This form of glass is slightly more expensive to produce, however using this form of glass with antireflective coating would allow more sunlight to enter the cell and increase efficiency.



Standard solar glass:

Light-trapping glass:

Figure D

2.4. Potential Policy Changes:

In addition to technological innovations, we must also consider changes to current solar policy or else solar technology will not get far due to lack of implementation. Solar technology can become more cheap, efficient and effective thanks to innovation, but it will not be implemented on a large scale soon enough without policy changes. As things stand, current policy does not do much to encourage the use of solar power or other forms of renewable energy. If we continue on our current path, we will experience a 4.1 degree celsius global average temperature increase by 2100. This is enough to cripple our ecosystem, strain our supply chain and destroy our economy. The policies below are some potential changes that local and state governments could implement in order to address this.

- Subsidize solar energy: This policy would give a specific amount of financial support to photovoltaic solar companies and utilities. It would give companies a boost that allows them to produce more solar panels and sell them at a lower price, or otherwise help utilities develop their solar energy production on site and charge lower prices. These outcomes would increase demand for solar power as people begin to choose solar power over other forms of energy for the lower prices.

- Tax fossil fuels and carbon: This policy would place an additional tax on companies who produce fossil fuels and use carbon, particularly those with greater emissions. Doing this would push such companies to increase their prices to compensate for the new tax, reducing demand for fossil fuels in favor of other forms of energy.

- Invest in solar research and development: Solar technology has a lot of potential, and as described above, changes can be made to increase efficiency, decrease cost, and improve energy generation. By investing in solar research and development, we would accelerate the development of greater photovoltaic technology and increase demand as these technologies become more favorable than fossil fuel forms of energy.

- Incentivize electrification: The more technology uses electric power rather than gas or other forms of fuel, the more solar technology is a viable option to power these technologies. No forms of fuel are entirely renewable or clean, so transitioning technology to electric power opens doors for renewable forms of energy to power this technology, particularly solar power.

- Implement solar power for public facilities: Local governments can decide how to power facilities in the public sector. If local governments choose solar power, it has a direct impact on emissions and is a step towards mitigating climate change. If many local governments get on board, we could see a measurable change in our future outlook.

To test the viability of these options, I used EnROADS to measure the impact that each policy lever has on the global average temperature change by 2100. These results are summarized below.

Potential Policy Changes:

Policy Change	**EnROADS Impact on Global Average Temperature by 2100 (Celsius) compared to 4.1**
Subsidize solar energy	3.9
Tax fossil fuels and carbon	3.0
Invest in solar research and development	3.8
Incentivize electrification	4.0
Implement solar power for public facilities	N/A
Combined Policy Scenario Global Average Temperature:	**2.6**

3. Synthesis:

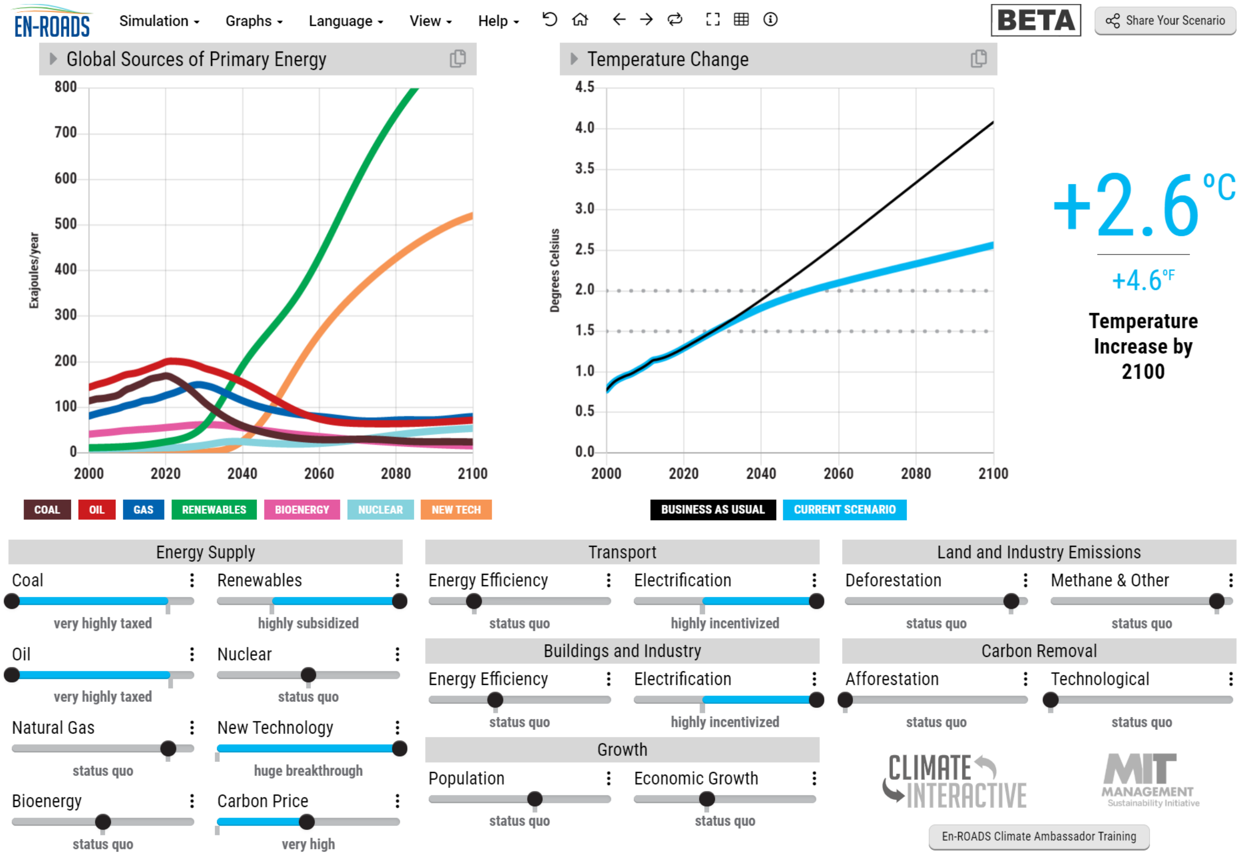
3.1. Best Technology Options:

To improve the efficiency and effectiveness of photovoltaic solar technology, I evaluated three potential changes to solar technology. Smaller photovoltaic cells reduce the amount of resistance electrons face when reaching the electrodes, vertical electrode placement within the cell prevents the electrode from blocking sunlight unlike the industry standard, and Light-trapping glass absorbs more sun radiation than flat glass. Each of these possibilities could yield a benefit in the solar industry. We must ask, however, what the best solution is to prioritize and invest in first. The most important criteria I evaluated in my findings above include energy efficiency, cost, safety, lack of emissions, and renewability among others. Given these findings, I believe that light-trapping glass improves efficiency the most and is the easiest to implement. The other two solutions can also be tested and implemented, however they will require more fundamental changes to the solar cell itself.

3.2. Policy Priorities:

There are many ways to approach solar policy to improve the implementation and use of solar energy. We can implement every policy explored in the analysis above for the best result, as shown in the combined scenario below. Some policies have more of an impact than others, however, so we need to determine what policies to implement first as we cannot implement all policies at once. Our resources are finite and we must find the right balance between implementing these policies quickly enough to reduce the progression of climate change and making sure not to implement all these policies at the same time, which could overwhelm our resources and overwhelm the companies affected. In terms of the most effective policies, taxing fossil fuels and carbon had the greatest impact on our future outlook, so that should be our first priority. From there we can invest more in solar research and development, subsidize renewable energy and incentivize electrification with remaining resources.

Combined scenario in EnROADS:



Energy Supply	Coal	very highly taxed
	Renewables	highly subsidized
	Oil	very highly taxed
	Nuclear	status quo
	Natural Gas	status quo
	New Technology	huge breakthrough
	Bioenergy	status quo
	Carbon Price	very high
Transport	Energy Efficiency	status quo
	Electrification	highly incentivized
Buildings and Industry	Energy Efficiency	status quo
	Electrification	highly incentivized
Growth	Population	status quo
	Economic Growth	status quo
Land and Industry Emissions	Deforestation	status quo
	Methane & Other	status quo
Carbon Removal	Afforestation	status quo
	Technological	status quo

4. Conclusion:

As demonstrated through this paper, our future outlook is grim due to climate change and the damage it threatens to cause. We do not have to give in to this current trend, however, as there are many solutions and possibilities we can implement in order to reduce our emissions and environmental damage. In the photovoltaic solar industry, we must evaluate every possible solution, think critically about what changes we can make, work to inform others, and implement solutions to improve our outlook. This article outlines how to take these actions and apply them specifically to photovoltaic solar technology. In a technological sense, I recommend that photovoltaic solar technology developers reduce the size of solar cells, use light-trapping glass, and reposition the electrodes in solar cells as demonstrated above. I also recommend that local and state governments implement the policy mix that I described in my analysis. With these changes, we can get one step closer to a brighter future and work to ensure that we do not let climate change cause more irreversible damage to our ecosystem and to our society.

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