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Application of Data Analysis and Visualization Tools for U.S. Renewable Solar Energy Generation, Its Sustainability Benefits, and Teaching In Engineering Curriculum

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Abstract

The advancement of Data Analysis technologies with visualization has gained significant ground in the industries and they are also gaining ground in higher education curriculum. This research will focus on the application of these techniques to the energy industry – in particular, solar renewable energy generation in all the States in the United States (US). One strong opposing action against the progression of climate change is the use of renewable energy.

The objective of the research is to develop a case study on renewable solar energy and its impact on abating or preventing CO_2 emissions to help reduce the severe impacts of climate change in the United States and demonstrate how it supports the 3Es of sustainability at the same time. This research paper will specifically explore the past production of solar energy in all the states in the US, and with the use of data analysis tools will predict the production to the year 2030. The reduction of CO_2 emissions with the use of renewable solar energy is in direct support of the three elements of sustainability, namely the 3Es: Environment, Economics, and Equity (or social justice). This research will quantify the past benefits already realized in all these three areas for solar energy, and project them up to 2030.

Cluster analysis technique will be applied to solar generation across all US States to identify group(s) at distinct levels of production. This can help States to follow the leading State(s) policy and process to increase their solar generation and thus help manage climate change. Solar energy generation challenges and recycling issues of solar equipment will also be addressed.

This case study approach will fill a gap that currently exists in engineering education when it comes to exploring renewable energy and its sustainability benefits with modern data analysis tools. This research will use publicly available data sources (e.g., NREL, EIA), ubiquitous Excel, and open-source data analytics and prediction tool Orange (for K-Means clustering analysis), so this type of case study approach could be taught and engage engineering students without any barrier. For highly effective visualization, the use of Tableau is also demonstrated.

Introduction

The demand for energy consumption in the world is growing at an annual rate of close to 2% per year (Welker, A., et al., 2022)) and that translates to about 3,598 Twh in 2022. In the United States (US), the energy consumption growth rate is 2.6% which translates to about 106 Gwh in 2022 (EIA, US Electricity Overview, 2023). The US energy generation sources in 2022 (US Primary Energy Source, 2022) are shown in Figure 1.

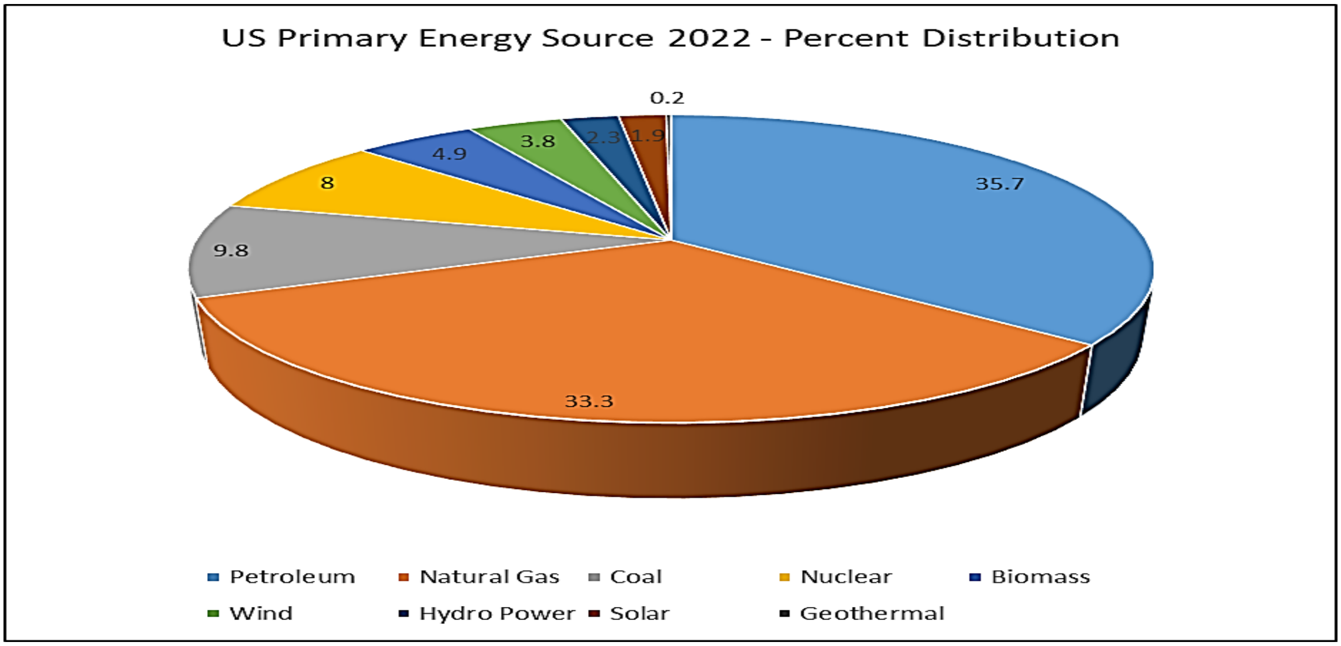

Figure 1 US Energy Source Distribution (Source EIA)

Fossil fuels (Petroleum, Natural Gas, and coal) make up 78.8% of the total energy source in the US. Petroleum is the largest source and solar is the lowest. Renewable sources add up to 13.1% (Solar at 1.9%). It has been a fact that these non-renewable sources of fossil fuels burning are one of the main causes for the release of Green House Gases (GHG, mainly CO_2) impacting climate change (IPCC Climate Change Report, 2023). The renewable energy generation process creates no GHG and is being pursued by the US government to be the future of energy generation. Solar energy is used for electricity and heating. In a recent bill passed in the US, the goal is to be carbon neutral by 2050 (Infrastructure Bill, 2021).

This research will focus on and address renewable solar energy generation in the US - past, present, and future, in three main topic areas as shown below:

- Data Analysis: Perform data analysis on US Solar Energy generation in all 50 states (1990-2022) and forecast/predict the generation from 2023 to 2030. Publicly available data set(s) will be used for the analysis.
- Sustainability Benefits: Identify the benefits of the growth of solar from the three main aspects of sustainability – the 3 Es, namely, Environment, Economics, and Equity (or social) and relate these benefits to the United Nations' 2030 Sustainable Development Goals (SDG).

- Teaching in Engineering Curriculum: Identify the importance of introducing sustainability education in engineering curriculum (e.g., Engineering Management, Civil Engineering) and demonstrate the use of different tools for data analysis with visualization in higher education. In this research paper, Solar energy generation is explored as the case study for teaching.

This research will identify the benefits that have already been realized with solar generation in the US (data available starting in 1990). The research will also explore the concerns regarding the recycling of solar panels and potential solutions.

US Solar Energy Generation – Past and Current Trends

Humankind has an exceptionally long history of using solar energy. Modern solar electricity generation using semiconductor technology started with the research breakthrough in Bell Lab in 1954 (Solar Timeline, n.d.). The advancement in semiconductor technology gave rise to the use of solar photovoltaic arrays (precursor to modern-day solar panels, was used in Explorer VI satellite launched in 1959).

The US Energy Information Administration (EIA) has been collecting and publishing data on the electricity generation history from all the states in the US since 1990. The latest complete report and dataset is for the year 2022 (US States Electricity Historical Data, 2023) and this dataset was primarily used to identify for all states (including DC) solar generation over the years 1990 to 2022. The data also identifies up to six different producers of solar electricity. In the 90s, there were only a couple of states generating and reporting on solar electricity generation – primarily, CA and TX. The data for the years 2000 and 2010 shows more states joining. Most all states reported solar generation starting in 2018 and these are the years with significant data. Figure 2 below shows the US Total generation (see Appendix 1 for all the States). The chart shows a strong correlation of the data with a high R^2 value of 0.93 which confirms the validity of choosing the right data for analysis (as noted, the solar generation values in the 90s and 2000 were insignificant). Significant growth was noticed over five years (2018 – 2020) and they form a good basis for forecasting/predicting the growth for the future years 2023 – 2030 (described in a later section).

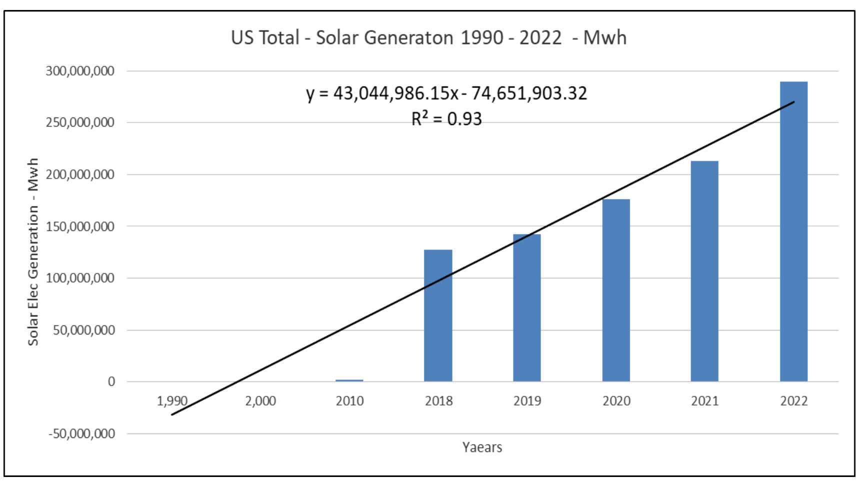

Figure 2 - US Total Electricity Generation 1990 - 2022

Figure 3 below shows the top 10 states solar generation with CA leading close to 80 million Mwh for 2022, and Texas around 44 Mwh (about 42% lower). The main takeaway from Figure 3 is that there is a huge variation in the solar generation capacity and the last State of SC's 2022 generation is 4.8 Mwh. Although there has been a big push to go solar from the Federal government since 2005 (Energy Policy Act, 2005), it is clear that there is huge variation in embracing solar generation across the States.

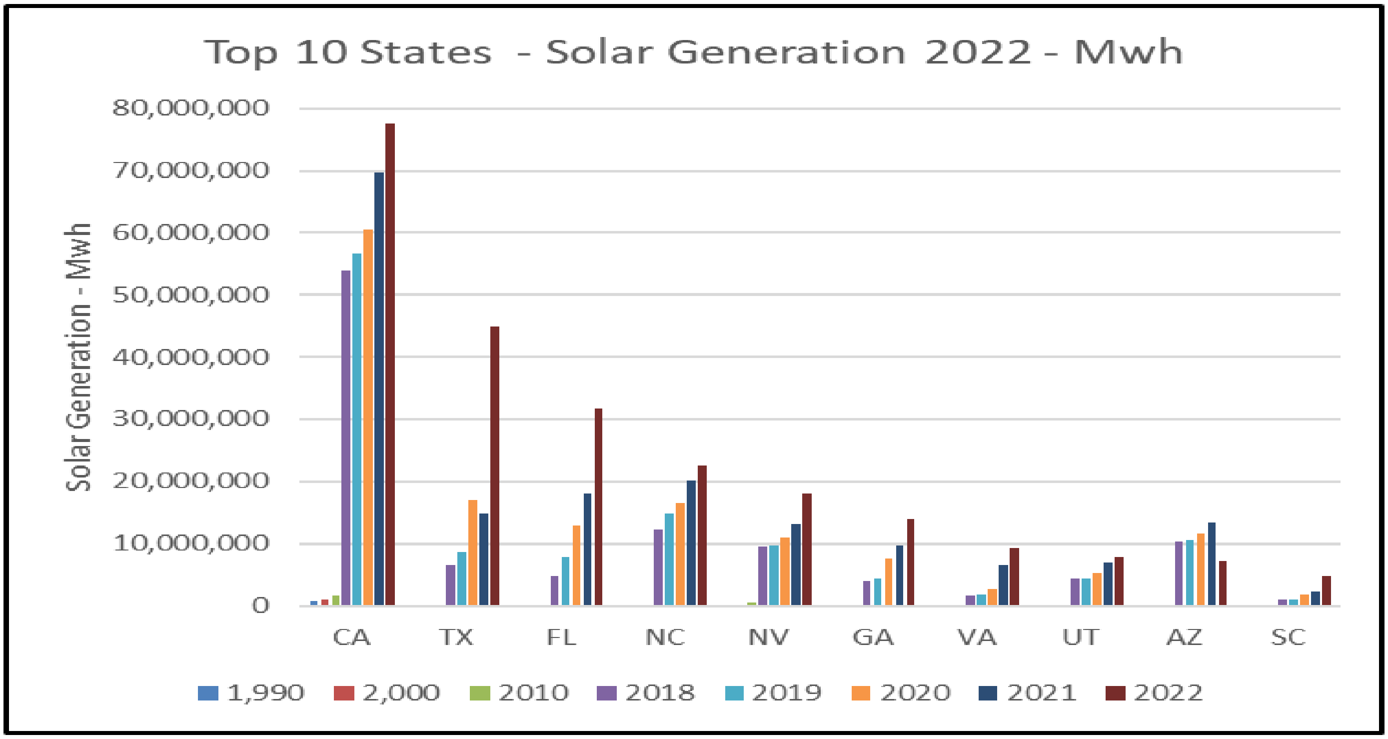

Figure 3 Solar Generation - Top 10 US States

It is to be noted that the price per installed watt of solar energy generation has come down drastically. Per a report from the National Renewable Energy Laboratory (NREL) report, there has been a 71.6% reduction in the cost of solar systems, and the cost of the module has reduced from $2.50 to around $1 per watt (Solar Price Declines per Watt. 2021). This lower price is due to the semiconductor technology improvements, and this is available to all the States in the US.

In addition, each State had the independence to create their own renewable energy policies and in particular for solar energy production. As seen in Figure 3, CA is ahead of any other state and the highlights of its renewable energy policy are as follows:

- CA has an Energy Commission that was established in 1975, oversees the creation and implementation of energy policy, and renewable energy is a key part of the State's policy (CA Energy Commission, n.d.). With their focus on Solar, CA has set policies to strongly encourage the adoption of solar for end customers and utilities.
- The overall CA renewable energy generation policy details are as follows:

- CA's aggressive goal is to be 100% clean electricity by 2045 and mandates their utilities (Renewables Portfolio Standard or RPS law) to source higher percentage of electricity from renewables (in 2020, it was 34.5% exceeding the goal of 33%; 60% by 2030 per Senate Bill SB 100 (Berkeley Law, 2002)).
- CA offers rebates, additional tax credits (through Utilities), and Net Energy Metering (NEM) programs (to the end customer)[1].
- CA State 2020 mandate is for solar energy source installation for all new construction of single-family homes, townhomes, and low-rise multi-family homes (CA Solar Mandate. 2020)
- Other aspects that help CA include the state having plenty of sunlight (estimated at 284 days in a year) that helps solar generation. The State also has large desert land where currently a solar farm is in operation and others are planned to produce 550 megawatts (Nextera Energy, 2011). CA also has encouraged community solar farms which benefits homeowners to use solar energy without solar panels on their roofs (Livermore Community Solar, 2020). CA's solar generation in 2022 accounts for 26.8% of the total Solar generation in the US, and accounts for 24.1% of the CA's own total electricity demand.

There could be many reasons why other States have not been able to reach higher levels of solar generation. One reason certainly will be the State's physical location not too conducive to sunlight like CA is. NREL has published data that provides average annual daily solar energy resource available for all 50 states (Solar Resource Maps and Data, n.d.). This data can be especially useful for a State's solar policy setting and priority. In cold winters states, use and application of passive solar techniques can be strongly recommended. Other reasons include political (lack of state level aggressive policies), resistance from the utility companies, lack of additional rebates and tax credits. One other key element could be that the public might need more solar energy generation (and use) awareness through effective public education. It could also be financial (upfront cost and lack of financing resources).

US Solar Energy Forecasting (2023 – 2030) and State-Level K-Means Clustering Data Analysis

The current solar generation trend in the US States was discussed with charts. US Solar generation data was available for 33 years and a significant increase in solar generation trend was noticed starting in 2018 in 46 States (the following states had zero: AK, ND, NH, WV, and DC). This section will look at the future of solar generation based on significant data from the past and analyze the State data. With teaching in mind, three different tools will be used to cover three distinct aspects of the full data – past and projected or forecasted future solar generation, analysis and visualization. Excel will be for forecasting future years. K-Means clustering analysis will be done with the Orange data mining and analysis too. Tableau will be used to

[1] In 2023 CA introduced NEM 3.0 where the end customers get reduced net metering benefits. With the steep fall in installations, CA is revisiting this decision. https://www.energysage.com/blog/net-metering-3-0/

demonstrate visualization of the solar generation data. Demonstrating various aspects of data analysis using different tools exposes the students to perceive their advantages.

Solar Generation Forecasting with Excel

As noted above, solar generation data from EIA was available from 1990-2022 for all the states in the US (part of States' reporting requirement to the US Energy Department). Most States did not have any solar generation report at all in the 90s except for CA, TX, and a few others. Reporting got better after 2000 with more States participating and the real change and quick ramping of solar generation really started in 2018 and showed rapid increases each year to 2022.

One of the objectives here is to forecast solar generation for the US States to 2030 to be in line with the big UN's Sustainable Development Goals (SDG) 2030. This will help analyze the sustainability aspects of solar generation and relate it to UN SDGs. The SDG's goals directly support the 3Es of sustainability. This aspect will expose and directly connect the students to sustainability.

After reviewing and testing various forecasting methods (e.g., average, exponential, aggregate average) Excel's liner forecasting function (also referred to as Regression Linear Forecasting) was used to forecast solar generation starting with 2023 and using the last five years of actual (and highly significant) solar generation data. Every succeeding year forecasting used the last five years of data. Figure 4 shows the forecasted generation with an R2 value of 0.9916.

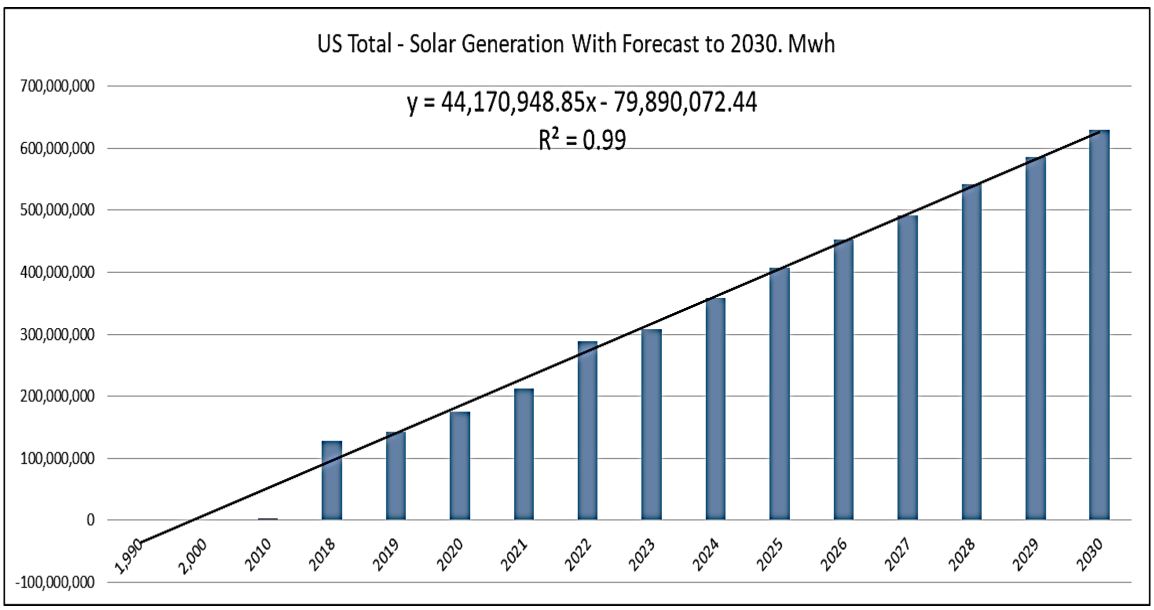

Figure 4 – US total solar Generation Forecast to 2030.

K-Means Clustering Analysis with Orange Data Mining and Analysis Tool

K-Means Clustering is an unsupervised machine learning algorithm that identifies and groups similar data points (i.e., patterns) in a dataset based on centroids (K-Means Clustering Algorithm, n.d.). Users can set the number of clusters in a tool (e.g. Orange; https://orangedatamining.com/, n.d.) and change them to observe the cluster member (and pattern) changes to get to an optimal group as necessary (Jeffery D Comm, et all, Business Analytics. 2024). Cluster members will tend to have similar attributes. This clustering technique is becoming well known for its simplicity of use with centroids for grouping observations from a dataset. A measure of cluster cohesion (or separation) is called Silhouette, varying from +1(members have strong similar attributes, close to each other) to -1 (just the opposite of +1, members with poor attributes, a member may belong to another cluster or group).

Orange is a Data Mining and Analysis tool is an open source tool and has extensive data analysis capabilities. The tool is used in higher education to teach data mining and analysis and has all the features that one can expect from a data analysis tool. It is a user-friendly tool with plenty of online videos and other help with documentation. Orange tool uses widgets for distinct functions. Orange's basic widget configuration for k-Means clustering data analysis is shown in Appendix 1.

In this research, Orange is used for k-means clustering on the US 50 States (plus DC) solar generation dataset (same data set used for forecasting discussed earlier). In this clustering, one will observe how the different States might be grouped together based on their solar generation capacity. This can give rise to recommendations for some State groups with lower solar capacity to join those with high capacity. One can also discuss some common attributes applicable to a given cluster.

In the dataset, solar generation, past and future forecasting, were done at each State level. The US Total charts shown earlier were a summation of all States' generations. The dataset was used in Orange to run several numbers of clusters. For discussion in this research, the Orange tool runs from two clusters, namely 4 and 5, which were found to be optimal, and they will be presented and discussed here. The Silhouette value for each of the two clusters is also presented.

Figure 5 shows Orange's graphical output of K-Means clustering, 4 clusters (or groups) for all the solar generation capacity of all the States and DC (the states are identified with 2 letters).

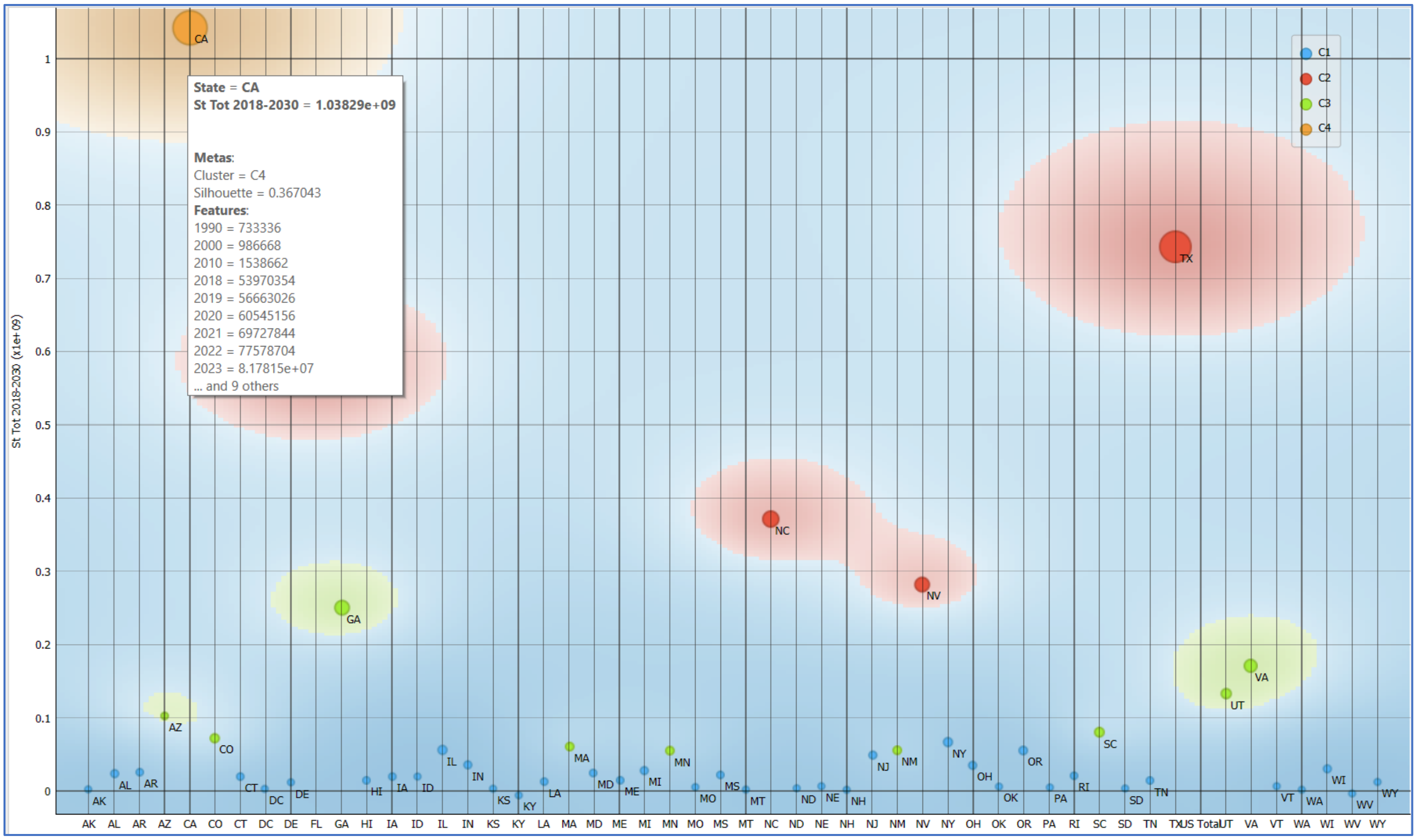

Figure 5 US States Solar Generation Clusters - Orange tool's Output for 4 Clusters

The four clusters have the following States as noted in Figure 5, see below. The Y-axis is the solar generation total from 2018-2023 in Mwh (most significant years).

Cluster 4 - C4 = CA
Cluster 3 - C3 = AZ, CO, GA, MA, MN, NM, SC, UT, VA
Cluster 2 - C2 = FL, NC, NV, TX
Cluster 1 - C1 = ALL OTHERS

The silhouette coefficient measure for all clusters was positive, in the range of 0.7 – 0.75 for the Cluster 1 to 3 states, and 0.36 for Cluster 4 State, namely CA. This indicates clearly that CA is an outlier, as seen in Figure 5. All the others were in between. The silhouette coefficient indicates a reasonable or optimal clustering.

A couple of key takeaways from the clustering chart. First about the cluster 1 States (blue color-coded), the lowest is zero and NY being the highest in solar generation. Given the current Federal Government mandate for reaching net-Zero by 2050, there needs to be some serious actions put in place to increase solar generation in these states. Given sunlight is a factor in generation, the States seriously need to take some actions to update and upgrade their solar policies. The states of CO and UT in cluster C3 with their sunlight limitation demonstrate strength in solar generation. There is something to be learned from their policies. Other potential limitations discussed earlier might apply to some of the states (e.g., resistance from utility companies) and they may be more difficult to overcome. By not implementing policies that foster renewable energy generation, some states would lose federal funding from the Infrastructure Bill.

Another k-means chart for 5 clusters is in Appendix 1.

Visualization of Solar Generation with Tableau.

Tableau tool provides for powerful visualization of data and the tool will be used to show US States' solar generation in different formats (Tableau - Important Features, 2022). Two key visualization features will be used here.

Figure 6 below uses the pre-installed Geo map data feature for the US States to display the US map with its States and the solar generation data within each state. By hovering over a state, one can also view the real value of the data. In Figure B6, the data is shown for CA.

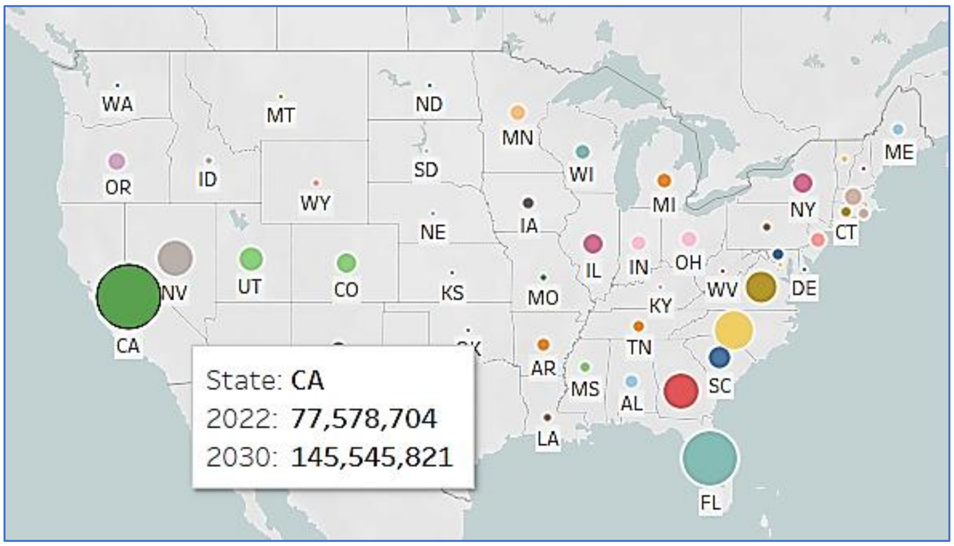

Figure 6 Tableau's US Geo Map with Solar Generation data

From the above US Geo map, one can immediately notice the physical location of a state and thus the sunlight's influence on solar generation (AK and HI are not shown to keep the size of the map smaller). One can expect more solar generation from the western and southern states. As noted in earlier discussions, solar generation depends on state policies and other incentives (in addition to the sunlight) which vary among the States.

Figure 7 shows another Tableau visualization chart called the Bubble chart. One can quickly visualize the size of the solar generation data. One can hover over any state and can see the associated data – here it is shown for SC. The bigger States are immediately noticeable and so are the smaller ones.

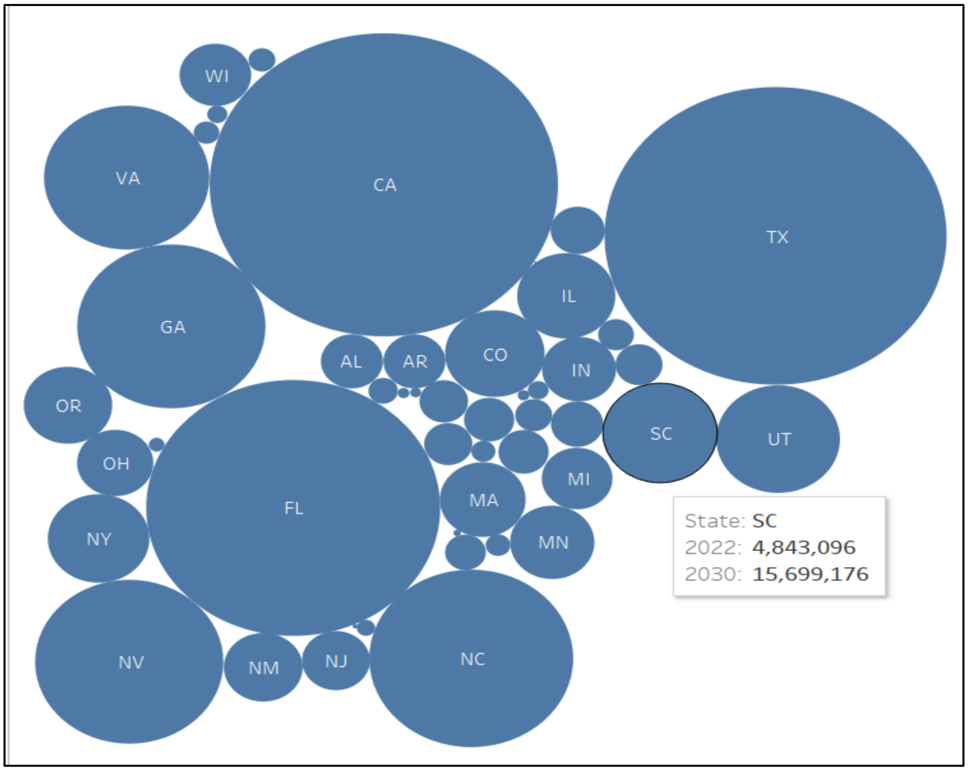

Figure 7 Bubble Chart showing Solar Generation (2030).

As noted earlier, three tools are discussed here to expose the students to different types of tools in their curriculum. One has to subscribe or buy Excel or Tableau, and Orange is free open source. Tableau provides all the capabilities demonstrated in the other two tools, but it is also an expensive tool[2].- Here one can change visualization options dynamically without having to reload datasets (e.g., Tableau by default knows all the world region data to do Geo Maps).

With the fast-changing technology, industries are demanding data analysis skill(s) from their employees. Teaching the use of three tools with a case study to engineering students as demonstrated here, can help meet that demand. The approach taken in this case-study research is to bring home the two key areas to engineering students – the knowledge and importance of sustainability, and the tools to do data analyses with visualization.

Costs and Challenges of Solar Energy

Solar energy is the fastest growing renewable energy, as noted earlier, and is the focus in this research paper recognizing several benefits. The huge decline in the cost of solar panel production along with improved technology, federal and state incentives has benefited large deployments of home and business rooftop solar installation. The environmental, economic and equity benefits will be discussed in detail with quantification in sections below.

[2] There is a Tableau Public free version with perhaps limited capabilities that can be explored for student learning. https://public.tableau.com/app/discover

The maintenance of an installed and working solar system is relatively negligible compared to any fossil fuel energy plant since there are no moving parts and replacement of panels is easy. Solar systems are generally guaranteed for twenty-five of service, the rate of production is also generally guaranteed by the installation company and if they fail, the installation company pays the difference to a home roof solar system (Yeager, 2009.). The solar farm panels need to be cleaned depending on their location (e.g., desert dust). The inverters are generally guaranteed for 7 -10 years, and one can buy an option during installation to replace them at no cost to the owner. US National Laboratories have documented best practices for the Operation and Maintenance (O&M) of Photovoltaic Systems and it provides recommendations for effective O&M services with lower costs (National Renewable Energy Laboratory, Photovoltaic Systems Best Practices, 2018). There are no moving parts in the solar energy generation system which makes O&M simpler and less expensive than fossil fuel plants (e.g., coal power plant).

Challenges for solar energy generation:

- High initial cost. This is a challenge for the lower income households as well as for utilities. CA state provides for solar system installations at no cost to low-income households (Low-Income Weatherization Program, n.d.).
- Solar Farms need a large land area that might impact on local wildlife, and some consider it to be aesthetically unattractive.
- Currently there are no policies as to the recycling of the panels after their lifetime and this can cause a huge environmental problem since the panels contain toxic chemicals (e.g., lead, cadmium). This will be discussed later in this paper.
- Solar generation is only when the sun is shining, thus dormant about half the time. The remediation for this is to store the excess energy during the production period.
- During cloudy days, the efficiency of solar panels drops to about 15-20% (Solar Panels and Cloudy Days, n.d.).

Renewable Energy Impacts on UN’s 2030 Sustainability Development Goals(SDG)

The United Nations (UN) has played a key role in the current thought processes and actions relating to sustainability. UN’s 1987 report titled "Our Common Future” under the Chair of Gro Harlem Brundtland, laid the foundation for most all sustainability activities today (Our Common Future, 1987). The key objective of the report was to identify global environmental issues and alert the world population to climate change. The report also defined sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their needs. The modern interpretation and implementation areas of sustainable development are, Environment, Economics, and Equity (or social), normally referred to as the 3Es. The 2012 UN’s Sustainable Development conference in Rio de Janeiro generated the Sustainable Development Goals (SDG) 2030 to meet the challenges of the 3Es. The UN set seventeen 2030 SDGs that are deeply interconnected through synergies and trade-offs (UN 20230 Sustainable Development Goals, 2012; Independent Group of Scientists, 2023).

Based on the current state of knowledge embodied in international scientific reports, UN flagship reports, and selected scientific papers, some SDGs are multipliers of trade-offs, others are just buffers and few are multipliers of benefits. Focusing directly on SDG 2 (zero hunger) and SDG 8 (economic growth) is risky because they can function as multipliers of trade-offs; SDG 1 (poverty), SDG 3 (health), SDG 5 (gender), and SDG 10 (inequality) are predominantly systemic buffers that have no multiplier effect on other goals (Pham-Truffert 2020). SDGs 6 (clean water and sanitation), 7 (affordable clean energy), and 13 (climate action) are among the most synergistic goals and are associated as drivers of sustainable progress (Independent Group of Scientists, 2023). In particular, the seventh SDG, affordable and clean energy, has strong multiplier effects on SDG1 (no poverty), SDG2 (zero hunger), SDG3 (good health), SDG6 (clean water and sanitation), and SDG13 (climate action). It also has positive effects on SDG4 (quality education), SDG5 (gender equality), SDG9 (industry innovation, infrastructure), and SDG11 (sustainable cities and communities) (Pham-Truffert 2020). For these reasons, SDG7, affordable and clean energy, is a good policy choice to achieve sustainability.

Our focus here is to explore the 3Es of renewable solar energy sources in the US. The outcome of the seventh goal impacts other SDGs as well in a positive manner. Each of the 3Es will be elaborated individually in the sections below.

Quantified 3Es Benefit Analyses of Solar Energy

In this section the 3Es benefits, namely, Environment, Economics, and Equity (or Social) of Solar energy generation will be discussed with quantification of the supporting data. The key here to note is that these benefits have already been realized and recognized.

Environment

Science has established beyond any doubt that the planet Earth is warming up due to the greenhouse effect caused by GHG gases, mainly CO2 (IPCC Climate Change Report, 2023; Climate Change, 2023). The CO2 atmospheric concentration has gone from about 275 parts per million (ppm) to the current level of 421.78 ppm (Latest CO2 Reading, 2023). The trapped CO2 along with other gases from the burning of fossil fuels is affecting human health and the planet's ecosystem (greenhouse effect).

Here the focus will be to address and quantify the amount of GHG prevented (or abated) due to solar energy generation (shown in Figures 2 and 3 above). National Renewable Energy Laboratory (NREL) documents three main GHGs that are emitted from fossil fuel power plants, namely, CO2, SO2, and NO for every Mwh energy generated from fossil fuel plants (Appendix 1, U.S. Energy Information Administration Dataset). Figure 8 shows the overall GHG gases prevented due to solar generation over the years. The abatement of GHG will continue as the US reduces the use of fossil fuels.

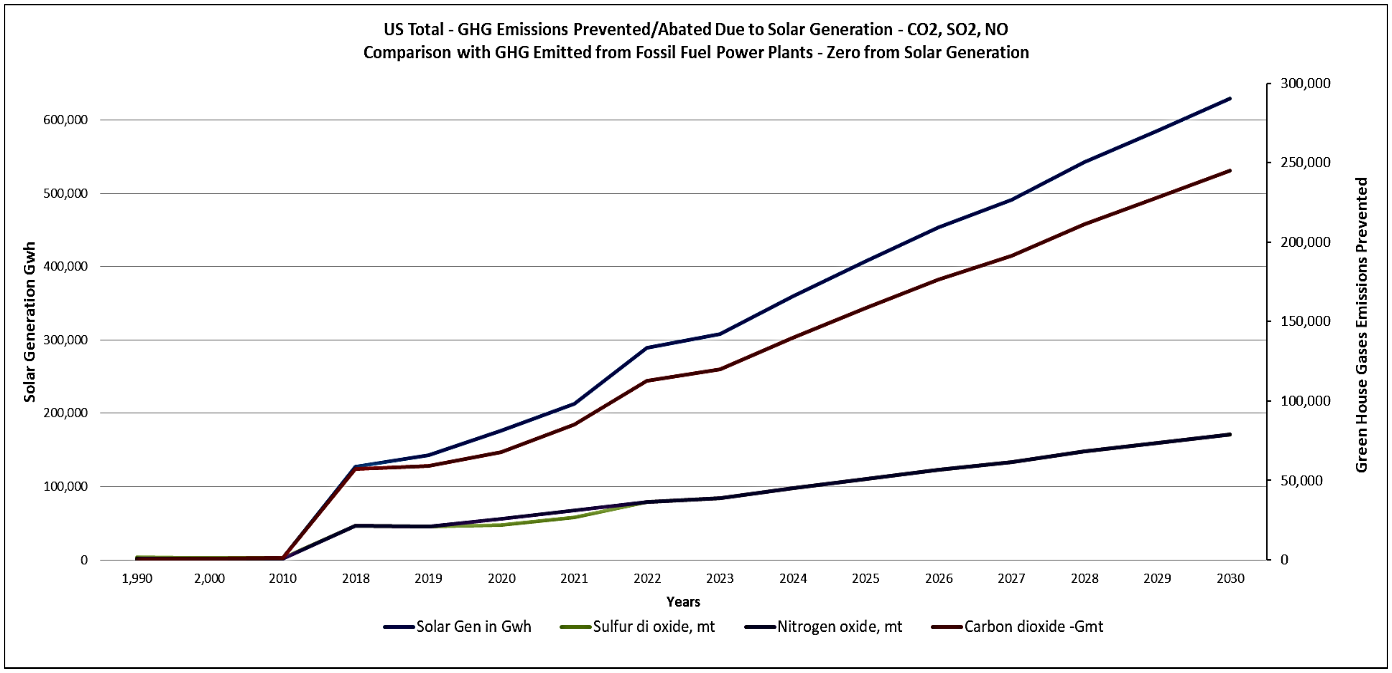

Figure 8 GHG Prevented Due to Solar Generation

The GHG emissions impact beyond the environment has also been researched and documented. A long-term sustainable remediation price tag is estimated to be in the range of $51 to $185 per ton of CO2 emitted into the atmosphere (Manke, K., 2022). Solar generation over the last twenty years has already demonstrated huge remediation savings for the US. Assuming an average cost of $118 for remediation, the US has already saved over $24B just for the CO2 emission prevented in 2022. The CO2 emission into the atmosphere will continue to increase although the rate of increase may be lower in the coming years due to countries slowly moving away from fossil fuels. Thus, the negative impact on the earth's ecosystem and human life will continue for years (e.g., on oceans, rivers, lakes, freshwater supply, land, wildlife, and human mortality) and remediation will become necessary.

The surge in fully electric vehicles (zero CO2 emissions) and chargeable hybrids (emissions only when the gasoline engine runs – minimal CO2 emissions) are big users of electrical energy. One Mwh of solar energy used in an electric vehicle(s) is estimated to be equivalent to 4,000 miles of a gasoline car(s) not driven. With an estimate of one pound of CO2 emitted per mile driven by a gasoline engine, this is equivalent of abating 2 metric tons of CO2 into the atmosphere with electric vehicle. In an electric vehicle, 77% of the electrical energy goes to power the wheels while gasoline vehicles convert only about 12% - 30% of gasoline energy to power the wheels (All-Electric Vehicles, n.d.). There are other benefits of driving an all-electric vehicle (or chargeable hybrid) – less noise, less maintenance cost, better acceleration, and no CO2 emissions while idling during city traffic red lights. It is to be noted that much of the power generated in the US today for charging the EVs still comes from fossil fuel power plants (coal and gas). But the benefit still is that the electric vehicles do not use fossil fuels to operate – still a big environmental benefit.

Economics

The economic benefits of solar energy can be grouped into four categories:

Job Creation: It is estimated there are 250,000 – 260,000 workers in the solar energy industry in the country and it will grow 63% from 2020 to 2029, with 400,000 solar jobs by 2030 (Energy5 2024; IREC 2023; SEIA 2017, 2018, 2021). These jobs include R&D, engineering, manufacturing, installation, maintenance, marketing, and sales, some of them skill-intensive and most of them well-paid. The number of jobs created by MWh of solar energy varies depending on the scale of the project and its location. Residential solar projects could create 26.6 jobs per MW while utility-scale solar may generate just 2.1 jobs per MW (FreeingEnergy, 2021). On average, the Solar Energy Industries Association claims that every 1 MW of installed solar system creates 5.7 direct and indirect jobs.

Cost Reduction: Renewable energy costs have been steadily declining in recent years, making them increasingly competitive with fossil fuels. In general, there has been a 64%, 69%, and 82% reduction in the cost of residential, commercial-rooftop, and utility-scale PV systems since 2010, respectively (Feldman et al, 2021). This trend is expected to continue, with the Levelized Cost of Energy (LCOE) for utility-scale solar projects projected to reach $0.03 per kilowatt-hour by 2030 (Feldman, et al, 2021). In fact, the LCOE for solar is now lower than for coal and/or natural gas in California, Texas, and Illinois. Florida, New York, and Hawaii (EIA 2022). The national average LCOE for solar is expected to reach parity with traditional energy sources in the near future because the LCOE for solar continues to fall.

Energy Security: While it is not directly quantifiable, the increment of solar energy reduces dependence on imported fossil fuels from Middle Eastern countries and acts as an argument to reduce geopolitical tensions. Internally, California, Texas, Florida, Arizona, and North Carolina lead the country in solar generation due to high sun exposure, favorable regulations, and infrastructure investments (SolarSME 2023; Ritchie 2023; Choose Energy 2023). The development of solar farms along with wind farms could increase grid resilience and provide backup power during outages.

Reduced Healthcare Costs: Air pollution from fossil fuels causes respiratory illnesses such as bronchitis, asthma, and emphysema due to carbon dioxide, nitrogen, and sulfur oxides, as well as particulate matter pollution, leading to significant healthcare costs. Shindell (2016) found that clean energy policies in the U.S. could prevent about 175,000 premature deaths by 2030, with about 22,000 fewer annually thereafter. He estimated these health benefits have a monetary value of about US$250 billion per year between 2016 and 2030. It was also found in the literature that regions in the eastern half of the US generally had higher health benefits and higher total benefits than regions in the western half because of the higher proportion of coal displaced there (Buonocore et al, 2015). For both solar PV types, utility-scale and rooftop, the Great Lakes/Mid-Atlantic regions had the highest benefits per MWh and the lowest were in California, Southwest, and Rocky Mountains by a factor of four (Buonocore et al, 2019). The transition to renewable energy can significantly reduce these costs by improving air quality.

Research has also shown that there is a positive correlation between GPD and energy consumption in a country (GDP and Energy, L Topolewski, 2021). With affordable and easy access to solar energy, the impact on a country's GDP can be expected to be positive.

Equity (or Social Justice)

UN's 2030 SDG report recognizes societal equity and the specific topics under Equity and how solar energy generation and access to it supports the UN's core principles that include fairness and justice and addressing inequalities.

Social and societal impact can be a part of the curriculum when teaching sustainability to engineering management students (Forbes et al., 2022). Social touchpoints span disparities, engagement, job equity, culture, education, and shaping policies. By focusing on environmental, societal, and governmental topic areas, students can broaden the scope of impact for projects beyond the immediate stakeholders, organizations, and the direct community. This broad view provides a long-term perspective across observable impacts and beyond, including the more significant societal concerns (Ding & Beh, 2022).

Some of the highlights that are possible include understanding access disparities. Engineering students can explore how access to solar technologies allows their projects, organizations, and communities to begin to transform through renewable energies (Ding & Beh, 2022). This conscious effort to include solar energy as an example of renewables and sustainability gives a specific practical application that students can consider, calculate, and measure regarding societal impact (Ehsanullah et al., 2021). The practical application brings the concept of access disparities to the forefront of the teaching and learning process and broadens the arguments and discussions considered in decision-making.

Other touch points related to societal issues include affordability, engagement, and job equity. These elements demonstrate to the engineering student the side effects often experienced through sustainable and renewable decisions. These include socioeconomic considerations within a particular community and financial access to renewable resources. Geographically, this could consist of elements within the supply chain that encourage or prohibit access to solar energy as a renewable concept (Ehsanullah et al., 2021).

Community engagement speaks to the possibility of historical and future projects being supported by or challenged by a direct or indirect community looking to consider the long-term impacts of engineering decisions. Community engagement includes projects informing the community of potential changes in sustainable practices incorporating renewables and elements to better participate in environmental stewardship (Djoundourian, 2011). These engagements can extend to collaborating with community organizations at the local, state, or government levels to serve the nation better.

Job equity refers to providing equality of opportunity by engaging in sustainable practices for long-term societal betterment. These factors, concerns, or decisions allow the engineering student to assess the impact across time and region for sustainable choices and particular engineering projects. Some deciding factors that could better inform a project would be the long-term societal effects on existing and potential jobs within a region or society (Kim & Go, 2020).

Finally, health impacts and regulatory policies are significant in engineering projects. Understanding sustainability, specifically through solar energy renewables, allows a specific example of potential health impacts through cleaner sources of direct or indirect power requirements. Health impacts demonstrate the organization's understanding of possible renewable technologies, existing power resources, and the cost-benefit of moving towards more sustainable and long-term resources (Hu et al., 2021). Regulatory policies must be researched and included in the decision-making project for four engineering students, as the potential for real-world challenges and compliance is very much a part of projects with touchpoints to health and sustainability. Policies often come with requirements that have associated benefits as well as costs, and students learn to account for these components in the solar energy examples.

Although it is out of scope for this research, past research has clearly shown that the world population growth rate and the per capita energy consumption have an inverse correlation (Sheffield J., 1998). In other words, as the energy consumption per capita increases, the population annual growth rate decreases, and is especially true for developing nations. Additional quantification relating to equity were also addressed above in economic impacts of solar energy generation.

Recycling Concerns With Solar Energy Generation Equipment

There are no federal regulations regarding the end-of-life disposal (EOL) of solar generating equipment, mainly solar panels, in the US. Some of the installations done in the 90s are already in the EOL cycle and it is unclear how they are being disposed of. In CA alone, it is estimated that there are about 1.2 million rooftop solar installations, and the largest solar photovoltaic farm has over eight million solar panels (Desert Sunlight Solar Farm, 2011.). In the US, based on a 25-30 year EOL for solar Photovoltaic (PV) modules could total one million metric tons (Mt) by 2030 and 10 Mt by 2050. This gives an idea of the potential problem facing the industry with no EOL disposal policies or standards. According to NREL's survey, only four states in the US, namely, CA, WA, NJ, NC, have recently enacted laws addressing PV module recycling at their EOL (Curtis, T. L., et al, 2021).

In the 2020s, most PV Module contain a combination of the following minerals, including rare earth elements (Minerals in Solar Panels, 2020), whose recovery and reuse directly supports the 3Es.

- Minerals: Aluminum, Cadmium, Copper, Gallium, Indium, Nickle, Silver, Lead, Zinc
- Chemicals: Fluorine and Antimony Oxide compounds, Ethylene Vinyl Acetate, Adhesives, sealants, cleaning agents. Dumping them as waste in landfills will pollute the ground water.

Table 1 below from the NREL report on PV module recycling survey presents the Drivers for PV Module Recycling and the responsible actors.

Table 1 Drivers for PV Module Recycling (Curtis, T. L., et al, 2021)

Economic Drivers	Potential Benefits	Actor(s)
Cost savings and increased profits	Recycling and resource recovery can reduce manufacturing costs and create additional revenue streams and tax benefits	Manufacturer, PV Owner, O&M
Enhanced competitiveness	Recycling and resource recovery can increase a business's "green" or "environmentally responsible" image and increase consumer trust	Manufacturer, PV Owner, O&M, Installers, End User
New and expanded market and employment opportunities	Recycling-based resource recovery presents opportunities for new and expanded markets and job creation	Manufacturer, PV Owner, O&M, Installer, Recycler, Government
Environmental Drivers	**Potential Benefits**	**Actor(s)**
Reduced negative environmental impacts	Recycling can reduce waste, greenhouse gases, and other environmental, and the total energy required to mine, transport, refine and manufacture PV modules	Manufacturer, PV Owner, O&M, Installer, Recycler, Government
Reduced resource constraints	Recycling-based resource recovery can conserve high-value materials, prevent resource constraints, reduce raw material import demand, and reduce supply chain concerns	Manufacturer, Government

The full scope of examining the PV module recyclable subject is beyond the scope of this research. It is clear from forecasts discussed earlier that if unchecked with proper polices on requirements and standards for recycling PV modules, US could have another huge problem similar the chemical dumps being addressed by Environmental Protection Agency (EPA) and mostly being paid for by the US taxpayers for cleanup. In Europe, ISO Standard 14001 Environmental Management Systems (2015) has already included some parts of the PV recycling in its environmental performance requirements.

Effective policies and methods to recycle solar generation equipment and circular economy include the following:

- Both Federal and State governments should take steps now to address this issue. This can include the development of innovative technologies for effective recycling of this new and emerging industry. A special branch within EPA could be set up to manage this solar equipment recycling and prevent future dump sites that may become big risks for ground water and environment.
- Aluminum metal refining takes more energy than steel, manufacturers of solar panels should be designing standard size panels and for reuse, thus reducing energy consumption for the solar equipment. They also should be charged with the responsibility of taking the panels back on their EOL and re-introduce them in their new manufacturing. This practice is already being enforced in Europe (Europe's WEEE Directive, 2021).
- Recovering the rare minerals will help reduce unnecessary mining for these metals in poor countries in Africa and other countries including China.
- Provide incentives for recycling.

Solar Generation and its related Sustainability Benefits in Engineering Education with Data Analysis and Visualization tools

Students' perception of sustainability within the engineering management program relies largely on personal experience and more educational background (Aginako & Guraya, 2021). In a modern context, this can lead to a well-informed graduate student with a basic understanding of balancing resources and the societal impacts of environmental decisions. However, there can be significant room available to inform further an overall understanding of the environmental, governmental, and societal impacts of engineering decisions. By providing case studies with practical applications, graduate students in engineering can build on previous foundations and expand sustainability concepts to balance engineering decisions and professional perspectives with environmental insights properly (Sánchez-Carracedo et al., 2020).

A case study methodology, in conjunction with an introduction to tools, techniques, and procedures for analysis and decision-making, is one of the critical ways practical labs and hands-on experience can be facilitated (Desha et al., 2007). Creating a toolset for educational and professional environments requires utilizing principles related to force sustainability and analytical tools that are specifically matched with data analysis. To demonstrate and facilitate the engineering management student experience, the researchers utilized foundational tools like Excel, tableau, and Orange and sophisticated experiments using IBM Watson.

Excel serves as a significant touch point for graduate students in analyzing data on sustainability concepts. It also offers a platform for statistical viewpoints and a practical bridge to decision-making. Engineering management students could understand and anticipate the potential implications of actions on environmental elements surrounding practical engineering challenges through trend analysis and descriptive statistics. Solar energy output and a state-by-state analysis of the potential for renewable energy sources in the United States provided the essential data for the initial case study, allowing for interpolating and extrapolating data from real-world examples (Aginako & Guraya, 2021). Using the Excel toolset, students could see the statistical outcomes and forecasts using regression, which allowed them to visualize the potential benefits and challenges of various decisions. Students could also dynamically evaluate the impact of specific resource decisions and engineering problems.

The following step is for students to utilize advanced data analysis tools to comprehend the impact of solar energy production and decisions regarding renewable resources. Orange, which enables advanced visualization of regional impacts, and cluster analysis, which enables students to appropriately categorize decisions and outcomes, are both examples of these tools. To be more specific, students can be tasked with visualizing the right categorization of investments, resource balance, and prospective return on investment, as well as localizing solar energy decisions and outputs for distinct locations within the United States. Students are provided with the opportunity to perform an impact analysis in the most effective manner possible by utilizing this type of cost-benefit analysis, which makes use of advanced visualization tools. This allows students to comprehend the implications of addressing organizational concerns in a way balanced with governmental regulations and healthy societal policies (Forbes et al., 2022).

Finally, students can also explore advanced data analysis through artificial intelligence prediction, where multidimensional data sets reveal potential patterns of consequence. To be more specific, datasets and sustainability that are centered on renewable energies and solar output could reveal potential business impact through the lens of societal and governmental touchpoints, while also enabling the simulation of multiple decisions within an engineering solution. The students can see the difference between a plain analysis for business impact and the strength of scenario analysis created by machine learning algorithms by this sort of forecasting through exploration. At an advanced level students can realize that artificial intelligence, visualization, and quantitative decision-making make it possible to have a wider range of tools and can reveal relationships between inputs and outputs that have significant effects on the environment, government, and societal outcomes (Huang et al., 2020).

Conclusions

This case study approach to research solar energy's past, present and future with data analysis tools, visualization, and relating it to sustainability elements, is a holistic approach to engage engineering students. Renewable energy papers generally tend to look ahead. It is important to review the past solar energy generation story and the benefits already realized in a quantitative manner, as demonstrated in this research case study. The future solar generation (and 3Es benefits) was also forecasted up to 2030. Sustainability 3Es subject-material is not something engineering students are exposed to or taught as a part of the curriculum. This is important since any and all future jobs will have sustainability components including engineering jobs.

This research demonstrated key engineering approaches of analyzing the past, present and forecasting the future, use of data analysis tools for better understanding US solar energy generation for all States and using K-means clustering for appropriate groupings of States. Thus poor performing states can learn from those leading in solar generation. The benefits of solar already realized (and the future benefits to 2030) were also discussed under the 3Es of sustainability with all applicable quantifications. The paper has been structured with student learning in mind with key charts in the main body and additional charts in the Appendix. Three different analytic tools were demonstrated: Excel for forecasting, open source Orange for K-Means clustering of US States' solar generation data, and Tableau for better visualization, thus exposing students to different tools. This approach will help the students to be ready with skills needed by modern industry. Application of data analysis tools to energy generation (including 3Es benefits) can be extended globally for all the renewable energy sources.

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Appendix 1 US Solar Energy Historical Data Sources and Additional Data Analysis Charts

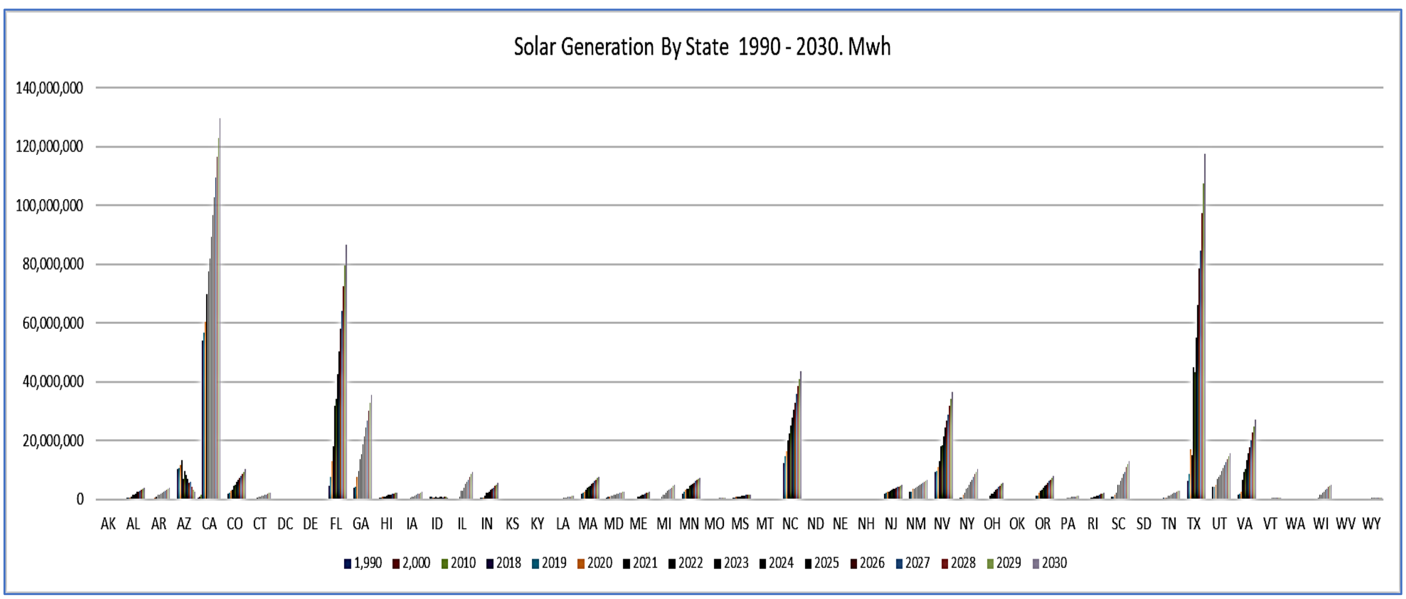
1. Data Sources

Electricity Historical State Data website hosted by U.S. Energy Information Administration
https://www.eia.gov/electricity/data/state/

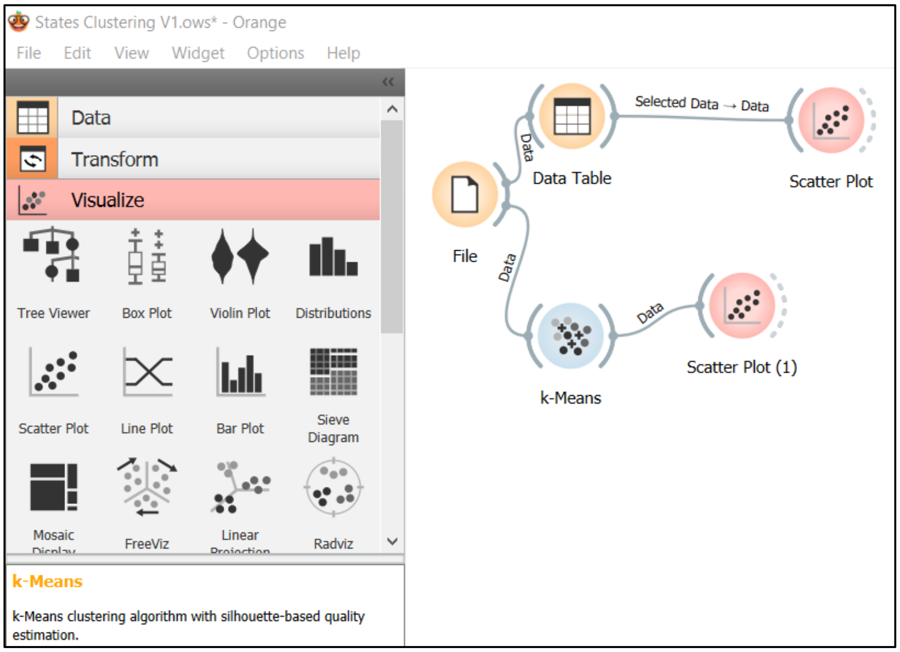
The screenshot below the website shows all the different reports and Excel files. Most all the information on US States electricity history by States was from this website, specifically using the real data from 1990 – 2022 (final report).

EIA-860 Annual Electric Generator Report (released: 9/20/2023)		format
1990–2022	Existing Nameplate and Net Summer Capacity by Energy Source, Producer Type and State (EIA-860)[1, 3]	XLS
2023–2027	Proposed Nameplate and Net Summer Capacity by Year, Energy Source, and State (EIA-860)[1]	XLS
EIA-923 Power Plant Operations Report (released: 11/28/2023)		format
1990–2022	Net Generation by State by Type of Producer by Energy Source (EIA-906, EIA-920, and EIA-923)[1]	XLS
1990–2022	Fossil Fuel Consumption for Electricity Generation by Year, Industry Type and State (EIA-906, EIA-920, and EIA-923)[2]	XLS
1990–2022	U.S. Electric Power Industry Estimated Emissions by State (EIA-767, EIA-906, EIA-920, and EIA-923)[4] **Final 2022 data released on November 1, 2023**	XLS
2001–present	Net Generation by State by Type of Producer by Energy Source[1]	XLS
2001–present	Fossil Fuel Consumption for Electricity Generation by Year, Industry Type and State[2]	XLS

2. Chart Showing the Total Solar Generation for all US States including the projections for 2023 to 2030.



3. Orange's Widgets configuration for k-Means clustering Data Analysis



4. K-Means Clustering – 5 Clusters. All Silhouette numbers were also positive here.