# The Path to 100%: Palo Alto's Strategy for Renewable Energy

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## Problem Research

Sustainable living has become increasingly important as climate change has caused drastic socioeconomic impacts around the globe. As a focal point of sustainable living, renewable energy is key to reducing carbon footprint, greenhouse gas emissions, and air pollution. Many states have initiated plans to transition to renewable energy generation. In California, the state has established a landmark policy requiring renewable energy and zero-carbon resources to supply 100 percent of electric retail sales to end-use customers by 2045 (Clean Energy States Alliance, n.d.).

In this paper, we focus on evaluating and providing a proposal to transition to 100% renewable energy in the city of Palo Alto, also known as the “Birthplace of Silicon Valley.” Known for its technological innovation and environmental consciousness, it has a population slightly above 66,000. Palo Alto owns, operates, and maintains all its utilities (City of Palo Alto, 2024), making implementing our proposal much more effective with its local control and policy-setting. The city’s long-term contracts for clean energy resources in its portfolio, including solar, wind, hydroelectric generation, and renewable gas from landfills, have allowed Palo Alto to exceed the State’s minimum requirement for delivering eligible renewable energy supplies. Palo Alto’s utility autonomy benefits local residents and businesses with reliable and safe services and competitive utility rates.

Palo Alto has already embarked on significant sustainability initiatives, notably, as of 2021, achieving a reduction in Greenhouse Gas emissions by an estimated 72% since 1990 (City of Palo Alto, 2022). In 2013, the City Council adopted the Carbon Neutral Plan, transitioning to 100% carbon-neutral electricity through renewable and hydroelectric power purchases. With the approval of its comprehensive Sustainability and Climate Action Plan (S/CAP) in 2016, Palo Alto set an ambitious goal to reduce Greenhouse Gas emissions to 80% below 1990 levels by 2030, twenty years ahead of California's statewide goal. In 2017, extending its carbon neutrality efforts, Palo Alto became the first city to provide 100% carbon-neutral natural gas while activating new solar contracts, increasing the city's electricity sourced from solar from 3% in 2015 to 33% in 2017. In 2020, to adapt to changes in California's electric grid and the increase in solar power, Palo Alto updated its Carbon Neutral Plan to use a more precise hourly tracking method for measuring carbon neutrality, ensuring the city's environmental efforts meet the highest standards (City of Palo Alto, 2024).

As we delve into the challenge of transitioning to 100% renewable energy, Palo Alto's past and future sustainability efforts provide a blueprint for action. The city's ongoing dedication to reducing environmental impacts and its forward-looking Sustainability and Climate Action Plan lay the groundwork for our research.

## Local Assessment

Palo Alto’s current renewable energy sources include Wind, Landfill Gas, Solar, Geothermal, and Large Hydroelectric(hydro), which have a cumulative annual energy capacity of a little over 1000 gigawatt-hours (GWH), close to the 1100-1300 GWH annual projected energy demand in 2045. However, most of these renewable energy contracts will expire in the next few years, with Wind contracts expiring in 2028, Landfill Gas contracts phasing out starting in 2026 and ending in 2034, and Geothermal contracts expire in 2036 (CoPA, 2024, p. 61). Therefore, Palo Alto needs a proposal for new energy contracts. We will evaluate various renewable energy sources with consideration of their cost-benefit and environmental impact and create a feasible proposal to transition to 100% renewable energy for the city of Palo Alto in the next 20 years.

According to the City of Palo Alto (2022), solar power constitutes 21.7% of its electricity portfolio, while wind power contributes 4.0%. Biomass and biowaste are responsible for 7.2% of energy production, and small hydroelectric sources, deemed eligible, provide 0.8%. A notable 27.8% is sourced from unspecified power. Despite not being classified as renewable under California's criteria, large-scale hydroelectric power represents 38.3% of the city's energy mix.

Furthermore, Palo Alto aims to achieve significant reductions in greenhouse gas emissions from buildings by improving energy efficiency and design, using performance requirements, and encouraging the electrification of natural gas use in buildings; this includes encouraging the switch to electric heating, cooking, and water heating systems, thereby reducing reliance on fossil fuels and increasing demand for electricity from renewable sources. Furthermore, in continuing to provide carbon-neutral electricity, Palo Alto plans to maintain and enhance its electricity supply from renewable sources. This involves expanding long-term contracts for renewable energy sources such as solar, wind, and hydroelectric power, ensuring the city's electricity needs are met through 100% renewable energy. Palo Alto is looking into offshore wind, enhanced geothermal energy, and solar projects as possible new projects with which they could sign contracts.

## Global Assumptions

1. Technology advances have considerably reduced the cost of renewable energy, and the trend is expected to continue. However, to ensure the consistency and stability of our model, we assume that the unit cost and benefit values analyzed in our paper remain constant through the proposed time frame and are not subject to seasonal variance.
2. Our model assumes that Solar Energy with Storage will achieve a similar unit energy value as Large Hydro Energy since storage will help mitigate the impact of solar energy fluctuation in daytime/nighttime and weather conditions, achieving a similarly stable energy value as large hydro.
3. Based on the Palo Alto Electric Load Projections through 2045, the projected annual energy needed for Palo Alto is estimated to be between 1100 and 1300 GWh in mid to high scenarios (City of Palo Alto, 2024, p. 59). For our model purpose, we will use the upper bound, 1300 GWh, as the required annual energy load for Palo Alto.
4. For large hydro-energy generation, our model assumes each large hydro facility produces the same unit energy value per GWH. This assumption is made due to the missing entry of the large hydro project “Western Base Resource” in the “Valuation of Current Electric Supply Portfolio” table (City of Palo Alto, 2024, p. 69). At the same time, it is being considered in the levelized cost for large hydro in the “Current Electric Supply Portfolio” Table (City of Palo Alto, 2024, p. 61).

## System Design Proposal

Our proposal aims to provide a safe, reliable, environmentally sustainable, and cost-effective plan for the city of Palo Alto to transition to 100% renewable energy. To meet our goals, we looked into the cost and benefit of both economic and environmental impact from 5+1 different renewable energy sources: the existing five sources in geothermal, landfill gas, large hydropower, solar power without storage, and wind, plus the additional source of solar power with storage.

We've devised a mathematical model that will optimize the output distribution of these renewable energy sources by minimizing the total cost and maximizing the benefit while meeting the minimum energy output threshold of 1300 GWh as described in the Global Assumptions. Our model considers both the economic and environmental costs and benefits of these renewable energy sources. Based on the output from our model, we create the energy distribution pie chart in Figure 3. The percentage of each renewable energy source is shown in Table 7.

## Existing Renewable Energy Cost-Benefit Analysis

To better estimate the total cost and benefit, we must look into these energy sources' economic and environmental impacts. We started by analyzing the distribution of renewable energy output and economic cost/benefit in Palo Alto. Five renewable energy sources currently contribute to the city's energy pool: Geothermal, Landfill Gas, Large Hydropower, Solar Power without storage, and Wind. The economic cost metrics were analyzed using levelized cost and contracted cost shown in the "Current Electric Supply Portfolio" table (City of Palo Alto [CoPA], 2024, p. 61) and the "Current Electric Supply Portfolio" table (CoPA, 2024, p. 69).

### Weighted Levelized Cost Analysis

Based on the current electric supply portfolio in Palo Alto (CoPA, 2024, p. 61), we analyzed the weighted levelized cost ($L_s$) in thousands of dollars per Gigawatt hour ($1000/GWh) generated energy for each energy source $s \in \{$ Geothermal, Landfill Gas, Large Hydroelectric, Solar without Storage, Wind$\}$ using the Weighted Levelized Cost($l_i$) and Annual Energy($e_i$) for each contracted renewable energy project.

The definition and calculation of these metrics are listed in Table 6 in the Mathematical Models section. Using the calculation formula in Table 6, we get the weighted levelized cost for each energy source. The weighted cost analysis gives us Table 1 with weighted levelized cost.

| Renewable Energy Type | Annual Energy Output (GWh) | Weighted Levelized Cost ($L_s$)($1000/GWh) |
|---|---|---|
| Geothermal | 88 | 79 |
| Landfill Gas | 104 | 83.576923 |
| Large Hydro | 390 | 81 |
| Solar without Storage | 396 | 63.441919 |
| Wind | 43 | 58 |

Table 1. Weighted Levelized Cost for Renewable Energy Sources

From Table 1 and Figure 1, landfill Gas has the highest weighted levelized cost (over $83/MWh), followed by large hydropower and Geothermal. Wind has the lowest levelized cost and may be a good candidate for expanding its energy output.

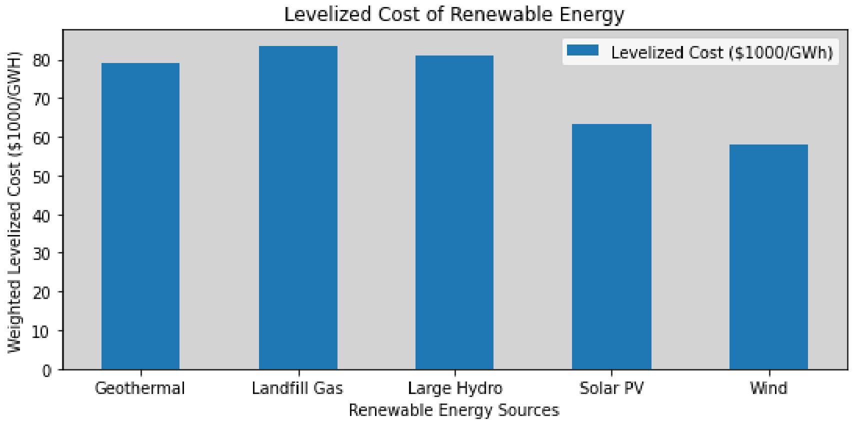

Figure 1. Weighted Levelized Cost for Renewable Energy Sources

Energy Value Benefit Analysis

Based on the valuation of the Current Electric Supply Portfolio (CoPA, 2024, p. 69), we analyzed the economic benefit of existing renewable energy sources using the Energy Value Rate ($R_S$) and Unit Energy Value ($U_S$) (see definitions in Table 6). We use the Energy Value Rate ($R_S$) to measure the actual energy value (benefit) of each dollar spent on the corresponding renewable energy and use Unit Energy Value ($U_S$) to measure the actual energy value (benefit) of each energy unit ($/MWh or $1000/GWh) generated.

Table 2 and Figure 2 show the energy value rate of existing renewable energy sources.

| **Energy Type** | **Contracted Cost ($M)** | **Energy Value ($M)** | **Energy Value Rate ($R_S$)** |
|---|---|---|---|
| Geothermal | 6.9 | 5.5 | 0.7971 |
| Landfill Gas | 10.5 | 7.1 | 0.6762 |
| Large Hydro | 8.1 | 8.0 | 0.9877 |
| Solar without Storage | 25.1 | 14.3 | 0.5697 |
| Wind | 2.5 | 2.4 | 0.9600 |

Table 2. Energy Value Rate for Renewable Energy Sources

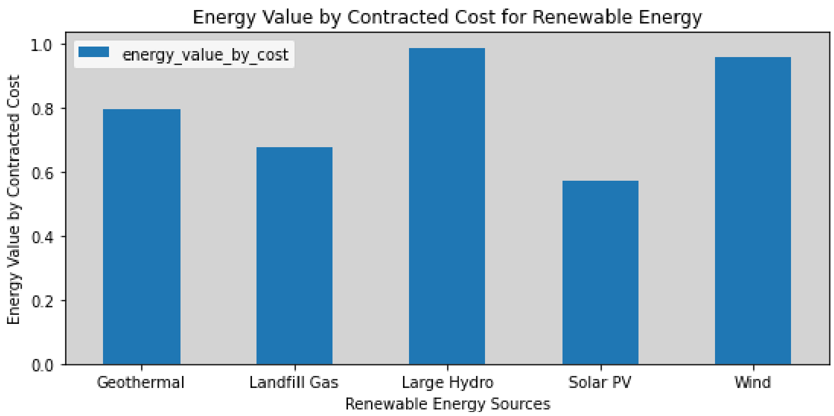

Figure 2. Energy Value Rate for Renewable Energy Sources

## Cost-Benefit of Existing Renewable Energy

Based on the above analysis of Palo Alto's existing renewable energy distribution, we calculate the cumulative benefit-cost ratio of the existing renewable energy output in Table 3.

| **Renewable Energy Sources** | **Existing Energy Output (GWh)** | **Existing Investment Cost ($1000)** | **Existing Benefit Energy Value ($1000)** | **Existing Cumulative Benefit-Cost Ratio** |
|---|---|---|---|---|
| Geothermal | 88 | 6,952 | 5,500 | 0.80827<br>$(=\frac{60500}{74851})$ |
| Landfill Gas | 104 | 8,692 | 7,100 | |
| Large Hydro | 390 | 31,590 | 31,200 | |
| Solar without Storage | 396 | 25,123 | 14,300 | |
| Wind | 43 | 2,494 | 2,400 | |
| **Total** | **1021** | **74,851** | **60,500** | |

Table 3. Cost-Benefit Table of Existing Renewable Energy

## Environmental Cost-Benefit Analysis

Each renewable energy source has its environmental impact, which is challenging to quantify with a monetary valuation. However, these renewable energy sources have in common that they all incur the environmental costs of carbon emission during their manufacturing and installation stage and near-zero emission during operation once established, gaining environmental benefit in the operation phase.

In this paper, we try to analyze and estimate each renewable energy type's environmental cost and benefit value based on its total lifetime carbon footprint. To find the environmental cost of each energy source, we must first find the amount of carbon each source produces during its lifetime, expressed in pounds per kilowatt-hour(lbs/kWh). The social cost of 1 ton of carbon, i.e., the economic damages resulting from emitting one additional ton of carbon dioxide, is estimated to be $50 (Cato, 2024). Using this, we can find the environmental cost of carbon for each source using the formula:

$$EC_s = G_s * \frac{1\ ton}{2000\ b} * \frac{\$50}{1\ ton} * \frac{1000\ kWh}{1\ MWh} = 25 * G_s$$

To find the environmental benefit of each energy source, we look at the average amount of carbon that energy sources in the US generate per kilowatt-hour because that tells us how much carbon was saved by choosing a carbon-neutral energy source. The average lbs of carbon produced per kilowatt-hour in the US is 0.86 lbs/kWh, which amounts to $21.5/MWh.

Table 5 shows the carbon emission, environmental cost/benefit, and the net environmental benefit for each renewable energy source.

| Renewable Energy Type | Carbon Emission ($G_s$) (lbs/kWh) | Environmental Cost ($EC_s$) ($/MWh) during manufacturing/ installation | Environment Benefit ($EB_s$)($/MWh) during operation | Net Environmental Benefit ($N_s$) |
|---|---|---|---|---|
| Geothermal | 0.16 | 4.04 | 21.5 | 17.46 |
| Landfill Gas | 0 | 0 | 21.5 | 21.5 |
| Large Hydro | 0.053 | 1.32 | 21.5 | 20.18 |
| Solar without Storage | 0.125 | 3.13 | 21.5 | 18.37 |
| Solar with Storage | 0.125 | 3.13 | 21.5 | 18.37 |
| Wind | 0.030 | 0.75 | 21.5 | 20.75 |

Table 5. Environmental Cost-Benefit Table for Renewable Energy Sources

## Solar With Storage Cost-Benefit Analysis

Beyond the existing renewable energy types in Palo Alto, we also analyzed the cost-benefit of an enhanced solar solution: Solar with Storage. Currently, solar energy generation in Palo Alto is not equipped with storage and is highly susceptible to weather conditions and energy output fluctuation during the day and night. Energy storage will mitigate these risks and provide a more stable and reliable energy supply as a +1 renewable energy source.

We identified the Weighted Levelized Cost ($L_s$) and Unit Energy Value ($U_s$) for solar with storage based on the information that solar with storage's cost "values are $23.00 per megawatt-hour to $39.00 per megawatt-hour higher than the standalone PV LCOE [Solar Levelized Cost of Energy]" (*Levelized Cost of Solar plus Storage*, n.d.). We will use the ($23, $39) interval's midpoint, $31/MWh, as the extra cost of solar with storage. Therefore, we have 63.442+31=94.442 as the weighted levelized cost for solar with storage. For Unit Energy Value, since we don't have the existing Energy Value data for solar with storage, we derived the value based on the global assumption #2 that solar with storage will provide similar or equivalent unit energy value as large hydropower in this case, its $U_s$ value at \$80/MWh, same as that of the hydropower.

Table 4 shows the consolidated Weighted Levelized Cost and Unit Energy Value analysis for the 5+1 renewable energy sources.

| **Renewable Energy Source** | **Weighted Levelized Cost ($L_s$)(\$1000/GWh)** | **Unit Energy Value ($U_s$) (\$1000/GWh)** |
|---|---|---|
| Geothermal | 79 | 62.5 |
| Landfill Gas | 83.5769 | 68.269 |
| Large Hydro | 81 | 80 |
| Solar without Storage | 63.442 | 36.111 |
| **Solar with Storage** | **94.442** | **80** |
| Wind | 58 | 55.814 |

Table 4. Consolidated Table of $L_s$ and $U_s$ for 5+1 Renewable Energy Sources

## Mathematical Models

With the above cost-benefit analysis on both the economic and environmental impact of 5+1 renewable energy sources, we devised our model for the optimized distribution of energy output to achieve the goals of transitioning to 100% renewable energy with minimal total cost and maximal benefit.

### Variables Definition

To explain our model clearly, we first define all the variables and their calculations in Table 6.

| **Variables** | **Definition** | **Calculation/Relationship** |
|---|---|---|
| $\boldsymbol{E_s}$ | Total Annual Energy Output (GWh) for renewable energy source *s* | $E_s = \sum_{i=1}^{k} e_i$ (k: number of contracts for *s*) |
| $e_i$ | Annual Energy Output (GWh) for individual contract *i* for renewable energy source *s* | |
| $\boldsymbol{L_s}$ | Weighted Levelized Cost (\$/MWh) for renewable energy source *s* | $L_s = \frac{\sum_{i=1}^{k} l_i * e_i}{\sum_{i=1}^{k} e_i}$ (k: number of contracts for *s*) |
| $l_i$ | Levelized Cost(\$/MWh) of contract *i* for renewable energy source *s* | |

| Variables | Definition | Calculation/Relationship |
|---|---|---|
| **$C_s$** | Total Contracted Cost in millions of dollars ($M) for renewable energy source *s* | $C_s = \sum_{i=1}^{k} c_i$ (k: number of contracts for $s$) |
| $c_i$ | Contracted Cost in millions of dollars ($M) of contract *i* for renewable energy source *s* | |
| **$V_s$** | Total Energy Value ($M) for renewable energy source *s* | $V_s = \sum_{i=1}^{k} v_i$ (k: number of contracts for $s$) |
| $v_i$ | Energy Value ($M) of contract *i* for renewable energy source *s* | |
| **$R_s$** | Energy Value Rate for renewable energy source s | $R_s = \frac{V_s}{C_s}$ |
| **$U_s$** | Unit Energy Value ($/MWh) for renewable energy source s | $U_s = \frac{V_s}{E_s}$ |
| **$G_s$** | Carbon Emission (lbs/kWh) for renewable energy source s | $EC_s = 25 * G_s$<br>$N_s = EB_s - EC_s$ |
| **$EC_s$** | Environmental Cost ($/MWh) for renewable energy source s | |
| **$EB_s$** | Environmental Benefit ($/MWh) for renewable energy source s | |
| **$N_s$** | Net Environmental Benefit ($/MWh) for renewable energy source s | |
| **$x_s$** | Optimized Output (GWh) renewable energy source s | |

Table 6: Model Variables Definition and Relationship

## Model Design

To design the most effective model using Python, we identify the goals of our proposal to transition to 100% renewable energy in Palo Alto

- Minimize investment cost for renewable energy generation
- Maximize the benefit (total energy value) from the invested renewable energy contracts
- Meet the minimum energy output threshold (constraint) of 1300 GWh/year

Based on these goals, we designed a linear optimization/programming model with a target function and constraint function which aims to minimize the total investment cost while maximizing the total energy value with consideration of environmental impact and energy output constraints.

We define our target function to be minimized by our model as follows

$$\boldsymbol{T = \sum_{s=1}^{k} w_s x_s}$$

where the target function $T$ has a coefficient vector W which is a cost vector with the weighted cost $w_s$ for each renewable energy source $s$. We define the weighted cost for each renewable energy source as follows to meet our goal of minimizing total investment cost and maximizing the total energy value.

$w_s = \frac{L_s}{R_s} - N_s$ where $s \in$ {renewable energy sources, such as Geothermal and landfill Gas}

We also define the following inequality constraint to ensure our total proposed annual energy output meets the minimum 1300 GWh/year requirement.

$\sum_{s=1}^{k} A_s * x_s \geq 1300$ ($A_s$: coefficient of inequality constraints for energy source $s$)

Our model also considers the environmental impact and the contract availability of each renewable energy source, reflected in the boundary variable $D_s$ allocated to each energy type. $D_s$ defines the [lower_bound, upper_bound] of energy output $x_s$ for the energy source $s$. For landfill gas, no contract provider is available after the current contracts expire in 2034. Therefore, we assign [0, 0] as its bound. For large hydro, it takes a long time for a new plant to become operational with high economic impact during the construction phase; the most realistic plan is to renew the current contract and cap the current output; hence, we assign its bound to [0, 390]. There is no limit for both solar types as [0, None]. Due to its reliability and consistency under different times and weather conditions, the city is looking to expand its capacity for geothermal energy. Hence, we set its bound to [88, None] to at least meet the current output. For wind energy, it is less stable and highly weather-dependent. Therefore, we limit its upper bound to 100 GWh (about 2x of existing output).

Model Result

The model is implemented using the Python library linprog and it generates the energy output result in Table 7 and the distribution percentage in Figure 3 for each renewable energy output.

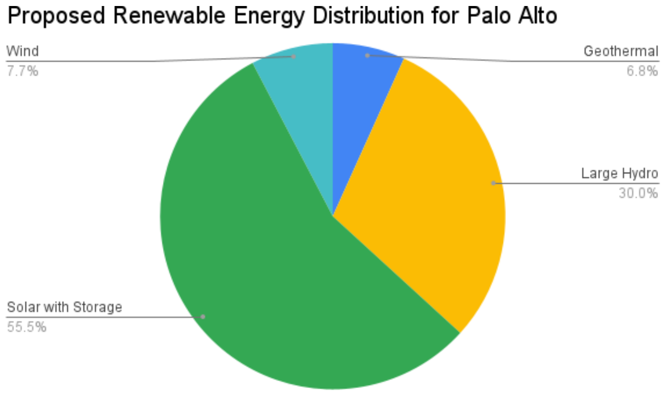

Figure 3. Proposed Renewable Energy Distribution

| Renewable Energy Type | Weight Cost ($w_s$) ($1000/GWh) | Bounds ($D_s$) | Optimized Output ($x_s$) (GWh) | Proposed Energy Distribution Percentage |
|---|---|---|---|---|
| Geothermal | 81.649 | [88, None] | 88 | **6.8%** |

| Renewable Energy Type | Weight Cost ($w_s$) ($1000/GWh) | Bounds ($D_s$) | Optimized Output ($x_s$) (GWh) | Proposed Energy Distribution Percentage |
|---|---|---|---|---|
| Landfill Gas | 102.0997 | [0, 0] | 0 | **0%** |
| Large Hydro | 61.8325 | [0, 390] | 390 | **30%** |
| Solar with Storage | 77.2524 | [0, None] | 722 | **55.5%** |
| Solar without Storage | 92.9861 | [0, None] | 0 | **0%** |
| Wind | 39.6667 | [0, 100] | 100 | **7.7%** |

Table 7. Proposed energy output/distribution for each renewable energy source

## Cost-Benefit Analysis of Proposal

Using the model we created for renewable energy investment with our target to minimize the total cost and maximize the total energy value with at least 1300 GWh annual energy output, we can analyze the benefit-cost ratio (BCR) based on our model's investment distribution of renewable energy sources.

$$\text{BCR} = \frac{\sum_{s=1}^{5} B_s * O_s}{\sum_{s=1}^{5} L_s * O_s}$$

| Renewable Energy Sources | Proposed Energy Output ($O_s$) (GWh) | Proposed Investment Cost ($L_s * O_s$)⬚($1000) | Proposed Benefit ($U_s * O_s$)($1000) | Proposed Cumulative Benefit-Cost Ratio | Existing Cumulative Benefit-Cost Ratio |
|---|---|---|---|---|---|
| Geothermal | **88** | 6,952 | 5,500 | **0.88903**<br>($= \frac{100041}{\mathbf{112529}}$) | 0.80827<br>(see Table 3) |
| Large Hydro | **390** | 31,590 | 31,200 | | |
| Solar with Storage | **722** | 68,187 | 57,760 | | |
| Wind | **100** | 5,800 | 5,581 | | |
| Solar without Storage | 0 | N/A | N/A | | |
| Landfill Gas | 0 | N/A | N/A | | |
| **Total** | **1,300** | **112,529** | **100,041** | | |

Table 8. Cumulative Benefit-cost Ratio

The proposed distribution's benefit-cost ratio is much higher than the current ratio (0.8866>0.8083), which means that the energy is much more efficient and flexible, increasing the value of the energy produced. The main reason for this difference in the benefit-cost ratio is the addition of solar energy with storage because solar energy produced in the morning and afternoon can be used at night when demand is much higher.

When looking at individual energy sources in Figure 1 and Figure 2, Landfill gas has the highest levelized cost and the lowest energy value rate, so we removed it from our proposed energy distribution. When looking at hydroelectricity, you can see that it has both high levelized cost and high energy value rate because it is versatile, and output can be increased during peak hours to keep up with the energy load. Similarly, Geothermal energy has a relatively high levelized cost and decent energy value rate. An advantage of geothermal energy not covered by our models is that it is not affected by the different seasons, i.e., it produces the same amount of energy during the winter and summer. Wind energy has a low levelized cost and a high energy value rate, making it a precious energy source. On the other hand, solar energy has a low levelized cost and a low energy value rate. This may seem puzzling, but it is due to most of the solar energy being produced during midday while the peak energy use hours are during the night, which means that the value of solar energy drops significantly, as illustrated by the Duck Curve (EIA, n.d.). A solution to this is a solar energy storage system that will allow the solar energy produced during the day to be used at night. The effect is shown in the higher benefit-cost ratio for the proposed distribution, which includes solar energy storage.

## Implementation Strategy

### Palo Alto City Council Proposal

Dear Council Member,

We are writing to propose a solution to one of Palo Alto’s most pressing concerns: procuring cost-effective renewable energy. Recent data has shown that Palo Alto will not be able to meet future energy needs due to expiring contracts and an increase in energy load every year, leading to a predicted deficit of around 300 GWh in 2045. As such, here is our proposal to secure more renewable energy for Palo Alto:

- Renew or sign a contract with the Geothermal project for around 88 GWh, as the current one expires.
- Continue the contracts with the Large Hydroelectric Plants to continue generating 390 GWh.
- Sign/Continue contracts with Solar projects for a total of 650 GWh.
- Increase the current contract or sign additional contracts with offshore wind energy projects to generate a total of 100 GWh of wind energy annually.
- End contracts with Landfill Gas projects after expiration due to their high weighted cost of $102 /MWh, lower energy value of $68 /MWh, and lack of contract providers.
- Install Compressed Air Energy Storage for solar generation facilities to alleviate grid stress and provide saved energy during peak hours. This will increase solar energy's value and reliability, making it a better alternative to the current solar system without storage.

To implement this proposal, Palo Alto must first find and sign new contracts with some projects. Since it takes half a year to a year to negotiate and sign a contract and 6-8 years to get the contract completed and able to start generating electricity, it is essential to negotiate and sign these new contracts 7-9 years earlier than when you want the energy to be produced.

In addition to managing the new contracts, implementing a storage system for solar energy is necessary. Compressed Air Energy Storage (CAES, n.d.) is the most cost-effective storage option, as it compresses air underground to store energy. It typically takes 1.5-2 years to set up and has a levelized cost of about $31/MWh or $31,000/GWh.

We believe these modifications to Palo Alto's energy system are the most feasible and cost-effective ways to convert to nearly 100% carbon-free energy while supplying enough annual energy output to operate the city.

Sincerely,
*** and ***

## Job/Career Research

### Jim Stack, Ph.D.

Dr. Stack is a senior resource manager at City of Palo Alto Utilities who received his bachelor's degree in mechanical engineering from Bucknell University and his Ph.D. in Mechanical Engineering from the University of California, Berkeley. Initially, he wanted to design and improve engines and wind turbines, but he quickly realized he was not suited for life in a research lab. Therefore, while pursuing his Ph.D., he also took classes in energy and public policy, which greatly piqued his interest; he credits these classes with significantly enhancing his practical understanding of the technical challenges society faces, laying a solid foundation for his career. Nevertheless, he still believes that a background in engineering gave him the analytical skills necessary to methodically solve complex problems.

While in graduate school, Dr. Stack completed two energy-related internships, one at the U.S. Government Accountability Office and the other at the California Public Utilities Commission. These experiences ultimately enabled him to secure a job as an energy analyst specializing in electric utility work at a consulting firm, The FSC Group. After a year of starting this role, he realized he did not like the consulting aspect of the field, so he left and got a job working at the City of Palo Alto Utilities.

As a senior resource manager for the City of Palo Alto Utilities, he frequently reviews proposals from renewable energy developers regarding new power sources for the city. His role requires him to analyze these proposals' long-term financial implications and benefits to determine their viability for the city. This analysis involves utilizing financial formulas, such as calculating the net present value of future costs and revenues. Additionally, he employs stochastic modeling and statistical analysis to project future uncertainties. His role entails strategic planning and analysis, project management, financial analysis, risk management, and working with stakeholders.

A typical day for Dr. Stack involves phone calls with energy suppliers and lawyers, crafting Excel models, composing reports, and preparing presentations for utility management. He notes that the most significant challenge in his role is making robust long-term choices amidst considerable uncertainty. To address this, his approach involves conducting extensive research to fully understand the uncertainties at play, followed by applying mathematical models to best predict future scenarios.

According to Glassdoor (2024), the average salary of a senior resource manager in the U.S. is $100,613. This job closely resembles that of a utility manager, which is expected to grow 28% from 2018-2028 (Zippia, n.d.). Additionally, there are various similar jobs, including energy analyst, renewable energy consultant, environmental engineer, urban planner, and utility manager.

### Mária Telkes, Ph.D.

Mária Telkes was a physical chemist and biophysicist credited for inventing the first solar-powered heating system. She majored in mathematics and completed her B.A. and Ph.D. in physical chemistry from the University of Budapest. During her illustrious career, Mária Telkes worked in diverse environments. She was a biophysicist at the Cleveland Clinic Foundation and worked as a research engineer at Westinghouse Electric to devise mechanisms for converting thermal energy into electrical power. She also significantly contributed to the Solar Energy Conversion Project at the Massachusetts Institute of Technology (MIT) to develop thermoelectric devices that utilized sunlight. Additionally, at the U.S. Office of Scientific Research and Development, she invented a solar distiller designed to desalinate seawater and convert it into drinking water, which saved the lives of many US military personnel during World War II.

Furthermore, Mária Telkes made significant advancements in solar energy, utilizing mathematical models to predict and optimize performance, earning multiple patents and creating several inventions. Most notably, she created the first modern solar-heated home in 1948, which utilized the principles of thermal energy conversion and implemented an inventive application of solar power. She also "assisted the U.S. Department of Energy in developing the world's first solar-electric residence." Her contributions extended to improving heat-exchanger technology, devising solar stoves and heaters, and even developing a universal solar oven that could be used in various geographical locations and climates. (Rafferty, n.d.).

According to the U.S. Bureau of Labor Statistics (2023), the median annual salary for a biophysicist is $103,810, and the job is expected to grow 7% from 2022 to 2032. Biophysicists usually conduct their experiments and analyze findings in laboratories. Some similar jobs include biomedical engineer, chemical engineer, mechanical engineer, and material scientist.

## Thesis Defense

The global sustainability shift underscores the need for local actions, particularly in energy transition strategies. Our proposal delineates a strategic plan for Palo Alto to transition to 100% renewable energy. By assessing the economic and environmental implications of current and potential renewable energy sources, we aim to offer a viable model for the city's energy future.

## Model Strengths

1. Our proposal is very feasible because it keeps many parts of the Palo Alto energy system the same while changing some energy sources and installing storage. As long as the city council approves, this can be done relatively easily.
2. Our model considers many aspects of each renewable energy source, including the levelized cost, energy value at the LMP (Localized Marginal Pricing) Node, and environmental costs/benefits.
3. The incorporation of solar energy with storage solutions addresses the intermittency issues associated with renewable energy sources, particularly solar power; it ensures a consistent and reliable energy supply, enhancing the resilience of Palo Alto's energy system against fluctuations in energy production and demand and significantly contributes to the stability of the local grid.
4. Our proposal aims to cut carbon emissions and pollution, minimizing environmental impacts and maximizing social benefits. By meticulously analyzing the lifecycle carbon footprint of each energy source and optimizing the energy mix, we aim to significantly reduce greenhouse gas emissions and local pollution. Hence, this will foster local job creation in the renewable energy sector for the community. Our approach positions Palo Alto as a leader in environmental innovation.
5. Our analysis demonstrates the long-term cost-effectiveness of transitioning to renewable energy by intentionally selecting energy sources and incorporating energy storage solutions; this maximizes the return on investment for the city, promising to stabilize and potentially lower energy costs.

## Model Limitations

1. Throughout the paper, we have focused on the annual energy output and annual energy needed to power the city. However, the energy load and output from the contracted projects differ depending on the time of the year. For example, solar energy produces around 50% less energy in the winter than in the summer (CoPA, 2024, p. 73). This causes a deficit of energy during the winter as solar, hydro, and wind energies produce less energy then and a surplus of energy during the summer. As such, Palo Alto needs to buy energy from other sources not necessarily renewable during the winter to fill in the needed energy. Storages also would not help because storages can only hold energy for a few days and cannot store energy for the winter months.
2. Palo Alto currently uses Large Hydroelectricity as a main source of electricity and does not plan to stop using it because of its versatility, but it causes environmental damage, as mentioned in the environmental impact section below. This causes it not to be considered renewable by the state of California, though the US government considers it renewable.
3. We used data from existing contracts with Palo Alto, which does not account for the possible technological advances in renewable energy industries. Currently, the levelized cost for solar energy is much lower than the levelized cost presented in the Palo Alto data due to this technological gap, as the contracts were made years ago.

## More About Environmental Impact

Despite its efficiency and energy throughput, hydropower has a fairly big ecological impact on the ecosystem compared to other renewable energy sources. The main problems caused by hydro dams include flood land use, wildlife impacts, and greenhouse gas emissions (Union of Concerned Scientists, 2013). On the other hand, hydropower facilities have beneficial environmental impacts, such as providing a source of irrigation, controlling water flow to prevent flooding, and recreational advantages (Gracon LLC, 2021). In terms of impact timeframe, hydropower's adverse impact on carbon emission mainly occurs during the construction of dams, ranging from 2-4 years (*How Long Will a Hydro Project Take*, n.d.). However, the impacts of land use and wildlife are generally long-lasting.

Solar energy also has a non-negligible environmental impact on land use in operation and water use during manufacturing, with hazardous materials in the thin-film PV cells (Union of Concerned Scientists, 2013). Other impacts include loss of habitat of wildlife and native vegetation. However, despite these impacts, solar energy has a net positive environmental effect: in addition to lowering greenhouse gas emissions, it helps promote respiratory health by reducing nitrous oxides, sulfur dioxide, and particulate matter emissions (Aggarwal & Fields, 2019).

Geothermal energy can cause a few negative impacts on the environment. It can cause air and water pollution and uses much water to cool its system when the water could be used for something better. Geothermal plants can leak sulfur, chlorides, silica compounds, vanadium, arsenic, mercury, nickel, and other toxic heavy metals, which, if concentrated, could impact wildlife. The timeframe for these environmental impacts may span the operational lifetime of geothermal plants–up to 80-100 years (Enel Green Power, 2022). However, reducing these adverse effects to an acceptable level is also possible.

Wind energy is one of the few energy sources that does not pollute the air or water. The only downside to wind energy is its impact on wildlife and its noise, which can be disturbing. However, offshore wind farms, which Palo Alto is currently looking into, are located in the sea, making their impact on wildlife negligible. There are also concerns about birds dying from wind turbines, but less than 1 in 4000 bird deaths can be attributed to wind turbines, making it negligible (Orsted, n.d.).

## Conclusion

This study presents a comprehensive proposal for the city of Palo Alto to transition to 100% renewable energy, leveraging its existing commitment to sustainability and carbon neutrality. Our analysis encompasses a local assessment of current and future energy needs, a detailed system design proposal integrating diverse renewable sources, and a rigorous cost-benefit analysis to ensure economic viability and environmental benefits. By adopting mathematical modeling techniques, we have optimized the energy mix to prioritize solar with storage while also maintaining significant contributions from large hydro and wind energy, thus addressing both reliability and cost-effectiveness. With the implementation of our proposal, Palo Alto can continue to lead by example in the transition toward a more sustainable world.

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## Appendix

### Code Implementation

The main Python code implemented the model that generated the optimized energy source distribution.

```
from scipy.optimize import linprog
'''
Renewable Energy Type: Geothermal, Landfill Gas, Large Hydro, Solar with Storage, Solar without
Storage, Wind
Setting weighted cost and bounds for each renewable energy type
'''
# input weighted list
WC = {'Geothermal': 81.649, 'Landfill_Gas': 102.0997, 'Large_Hydro': 61.8325,
'Solar_w_Storage':77.2524, 'Solar_no_Storage':92.9861, 'Wind':39.6667}

weighted_cost = list(WC.values())
energy_types = list(WC.keys())

# Bounds for each energy source output (each variable should be non-negative)
bounds = [(88, None), (0, 0), (0, 390), (0, None), (0, None), (0, 100)]

# since linprog has no lower bound parameters, use the negative of energy output
# as the upper bound to generate the same lower bound constraint
energy_demand = 1300
A_ub_ce = -1/energy_demand
b_ub = [-1]
A_ub = [[A_ub_ce, A_ub_ce, A_ub_ce, A_ub_ce, A_ub_ce, A_ub_ce]]

energy_output_result = linprog(weighted_cost, A_ub=A_ub, b_ub=b_ub, bounds=bounds,
method='highs')
print("Status:", energy_output_result.message)
print("Optimal allocation:")
for i, var in enumerate(energy_types):
    print(f"{var} =", round(energy_output_result.x[i], 2))
```

Output of the Python Code:

```
Status: Optimization terminated successfully. (HiGHS Status 7: Optimal)
Optimal allocation:
Geothermal = 88.0
Landfill_Gas = 0.0
```

```
Large_Hydro = 390.0
Solar_w_Storage = 722.0
Solar_no_Storage = 0.0
Wind = 100.0
```