[[1]](#footnote-1)

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***Abstract*—Energy system planning and modeling is a critical step in designing power systems that operate safely and reliably for electricity consumers. The need for developing accurate plans is even more important when considering that many federal, state, and local governments have set aggressive goals for transitioning to high-penetration renewable energy systems over the next 30 years. Thus, there exists the need to create high fidelity models for power system transitions that take into account resource availability, grid stability, and system cost, amongst other factors. There are several challenges that must be addressed when considering what a 100% renewable energy system will look like. These include the intermittent nature of wind and solar power, operator regulations that require certain levels of load carrying capability, daily and seasonal changes in load, and predicted changes to the load itself over time. The following report presents a plan for a 100% renewable energy system for the City of San Diego that aims to estimate what generator capacities will be required to meet demand and what costs will be associated with such a system. It also addresses ancillary services and utility rate structures.**

***Index Terms*—Battery Storage, Capacity Expansion Modeling, Demand Response, Effective Load Carrying Capability, Electric Vehicles, Energy Modeling, Geothermal Energy, Renewable Energy, Reserve Margins, Residential Solar, Resource Adequacy, Solar Energy, Time-of-Use Utility Rates, Wind Energy.**

# I. INTRODUCTION

E

nergy systems are expensive, high impact assets that are relevant to nearly every aspect of day-to-day life. As the world continues to rely more on renewable energy resources, there will follow a growing need to build accurate system models that ensure capital investments are worthwhile and provide long-term stability and reliability to power grids. Energy systems are also multifaceted and can take many forms depending on the objective and of the system and the load they serve.

The goals of this project were to create an energy plan for a 100% renewable energy system that is able to serve a provided load at the lowest cost while maintaining grid reliability. The load provided was time-synchronous, so a secondary objective was to build a time-synchronous model that addressed these goals at each timestep for which there was load data. A scaled down load profile of San Diego Gas and Electric (SDG&E) at 5-minute intervals was the primary model input. The load profile was from 2012 so weather data from the same year was used to model weather-dependent generators like wind power and solar photovoltaics (PV). The geographic area in question was constrained to the municipal borders of the City of San Diego and land within 50 miles of those borders in any direction. Only renewable energy generation technologies were considered. A “renewable” energy source was defined as a resource that occurs naturally or would naturally replenish itself with time. This included: wind energy, solar energy, hydroelectric energy and geothermal energy. Storage technologies such as lithium ion batteries and pumped-hydro storage were also considered renewable if they were charged using a renewable technology. It was also assumed that the power system would utilize existing transmission lines with the only cost incurred being spur costs. The theoretical completion year for the energy system was 2025. It was assumed that there would be no lead times on construction and capital costs of generators would reflect projected prices for 2025. It was also assumed that if any existing generating plants were to be utilized, they would be built brand-new and therefore be subject to full capital cost. ICTs were applied to solar, wind, and geothermal generator costs based on actual federal credit rates in 2022.

To build an accurate model, data on existing conditions was gathered to determine what capacity of renewable energy was already available. Plants in operation, plants under construction, and plants in the planning phase were all considered. Solar and wind resource availability data was gathered based on the locations of existing generator plants. Models of each generator type were created to generate output profiles based on 2012 resource data. Requirements for system generators beyond serving the provided load were also considered. These included projecting changes to load based on EV and residential solar adoption, resource adequacy requirements, n-1 contingency, and reserve margins. Cost data associated with each generator and storage technology was gathered and included capital, fixed O&M, and variable O&M costs. All of the data collected was configured as inputs to a capacity expansion model. The model was run and used to determine the most cost effective total capacity mix, generation mix at each timestep, and total project costs. Finally, a utility rate structure was constructed.

# II. Existing Conditions

To begin with existing conditions, data gathering the information for current generators within a fifty mile radius of San Diego County was found using the EIA (Energy Information Administration) interactive map [1](Citation). This interactive tool has information for all types of generators within a user defined area. Using the filter tool to display only renewable energy and transmission lines within the limits initially given by project requirements yielded the following map:

Map

Description automatically generated

*Fig XX: EIA map with filters for renewable energy generators and transmission lines*

During our research we found details such as generating capacity and we broke down this capacity by generator type to derive total generating capacity of assets in the area. Using reasonable assumptions for omitting pilot projects the following table shows each total generating capacity per technology.

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Table XX: Breakdown of generating assets by resource type

The EIA database also contains information for each generating station monthly production data. Finding existing monthly data from each facility would be a valuable resource to have to be able to compare with GenX model to be able to determine accuracy of model predictions compared to existing generation data for each technology. The generating year selected was 2012 as it was the same year that weather data for GenX model would be used. The problem with this was many generators in the area were not operational in 2012 as they were built after this year. This presented a challenge but luckily some facilities did have information dating back to that year. The information that was available was for Kumeyaay Wind and for ISH Solar and Univ. of California San Diego, the monthly production graphs for wind and solar facilities are shown in the tables below.

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FIG XX: Wind and solar monthly generation reported data for 2012

This monthly generating data was compared with GenX models with similar characteristics to determine a confidence level that the model was accurate and could be a reliable model going forward.

Another existing condition which evaluation was required was the load profile for the area for which this project consisted of. This was provided in 5 minute data intervals and further dissection was needed to correctly place in load bins to determine time periods where load requirements were very close throughout the year. This was used by GenX model to effectively calculate what generation available depending on the time of the year would be necessary to meet that particular time period’s load. The dissected model for the load can be seen in the following graph:

Chart, bar chart

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FIG XX: 2012 yearly load profile broken in to load groups

Combining these two pieces of information proved useful to properly determine the needs and current system capabilities to meet this demand.

# III. Generation Requirements

Use either the Microsoft Equation Editor or the MathType plugin, which can be obtained from

To evaluate the potential of each renewable resource, models for each generator type were created. These included a model for utility-scale solar, residential solar, utility-scale wind, utility-scale geothermal, and utility-scale hydropower. The utility-scale solar and wind models were created using PySAM and used existing plant locations and total capacities as iterative inputs, with each plant modeled individually at 30-minute time steps. The power output profiles for each generation type were then aggregated into two time series files, one for wind and one for solar. The solar model was created using a generic PV Watts Power Purchase Agreement SAM model with single-axis tracking, bifacial modules. A 1.3 DC/AC ratio was used with a 96% inverter efficiency. Initial values for soiling and shading losses were 3% and 2% respectively. An azimuth angle of 180° (due south) was used for all models. A utility-solar control model was also generated to validate the assumptions made. This was done by modeling the 2012 outputs for the ISH Solar and Univ. of California San Diego plants and comparing them to their actual output data. This analysis found that total annual modeled energy generation exceeded actual generation by roughly 20%. The shading and soiling losses of the generic model were adjusted to 8% and 5.5% respectively. This brought the modeled output to within a 10% of actual output, an acceptable margin of error. Figure X below shows the results of this control analysis. It should be noted that the (2) plants in question were brought online in 2011 and were not operating at full capacity for the first (3) months of 2012. Data from these months were therefore treated as outliers and excluded. The wind model was created using a generic Windpower Power Purchase Agreement SAM model using spec data from a Vestas V150 4.2 MW turbine. This design had a 150m rotor diameter and hub height of 105m. A shear coefficient of 0.2 as assumed [2] (Turbine Specs).

Chart, line chart

Description automatically generatedFigure X. PV Model Control Analysis

The residential solar model was created using a Detailed PV Power Purchase Agreement SAM model. A single location in the center of San Diego was selected for resource data. The module selected was LG Electronics Inc. LG400Q1C-A6 and the inverter selected was SolarEdge Technologies Ltd: SE11400H-US [208V]. Systems were assumed to have a fixed axis, as is typical for residential solar. (3) residential solar models were generated with azimuth angles of 90°, 180°, and 270°. The total capacity assigned to each model followed the breakdown of actual azimuth angle data from California Distributed Generation Statistics for residential solar panels. The details of this breakdown can be found in section X. A total capacity of 40 MW of residential solar was modeled.

The hydroelectric generator model was created using actual output and capacity factor data from EIA for the (2) plants considered within the area in question: Bear Valley (1.4MW) and Rancho Penasquitos (4.6MW).

The geothermal model was created using a Geothermal PPA SAM model. The geothermal resource was evaluated based on NREL’s U.S. geothermal resource maps [3] [Geothermal Resource]. Due to the lack of hydrothermal resources within 50 miles of San Diego, enhanced geothermal plants were selected as the plant design. An area near San Diego with relatively high favorability for enhanced geothermal resources was then identified. Due to lack of data on actual resource temperatures, conservative estimates were made when modeling these generators. Resource temperatures of 190°C at a depth of 3km were chosen based on typical, low-end operating conditions of these plants [4] [ENHACNED GEOTHERMAL]. A binary-cycle was selected as the heat-converter for these plants due to its favorability for low temperature resources [5] [BINARY-CYCLE]. Reserve capacities implemented to meet necessities of a large incursion of VREs (Variable Renewable Energy) is very hard to estimate as there is debate on the correct amount for a 100% renewable energy macro grid. For this project it was decided to use two different reserve strategies [6] (Book Citation). The first is a load following reserve, these are very fast acting resources that fill in the gap during normal operations should weather resources drop such as a large cloud passing a major part of solar generation or wind taking a dip in wind speed. This phenomena will cause fluctuations in frequency which can compromise grid stability negatively. To prevent this the use of Battery Storage as load following reserves will provide needed stability to a 100% renewable energy grid. Load following resources will act as shock absorbers to these momentary conditions of major difference between generation and demand. Examples of these markets are Frequency regulation and Fast Frequency response which will be used in our proposed strategy to keep a reliable and stable grid with large penetration of VREs.

Secondary reserves will also be required to be able to be dispatched for longer term durations to combat power imbalance or generator failures. These contingency reserves will account for 15% load at any given time and should be dispatched between 2 to 15 mins after an event deems it necessary. These reserves are made to last a longer time than load following reserves and give the system longer term stability. In this project’s model a contingency reserve of 15% was selected based on existing grid system operators as well as generator plant sizes in this system [6] (Book CItation).

To better project how the use of energy would change by the year 2025, a baseline understanding of the current customer base was needed. We approximated our rate base as a fixed percentage of the current SDGE rate base, calculated as the fraction of the total annual energy consumption in the provided load profile divided by the SDGE’s projected “managed consumption” in 2022 [7] (ref). The managed consumption figure includes BTM generation offsetting load. Using this methodology, we estimated our rate base as 1.92% of SDGE’s. To determine the projected amount of distributed solar generation for 2025, some scaling and linear regression techniques were deployed. First, data was collected from the California Distributed Generation Statistics database [8] (CDGS). This dataset includes information on all interconnected solar projects in the state, including data on SDG&E territory. The SDG&E territory data was filtered to include only projects approved after 2012 (the year that the provided load data correlates to). After this year, a total of 1,674 MW of distributed solar power was installed in the SDG&E territory. Scaling this down with the aforementioned 1.92% scaling factor produces an estimated 32MW of distributed generation by 2022. A linear regression was then applied to this data to approximate the amount of solar generation by 2025. The data was also divided into three respective cardinal directions to better estimate energy production in the later stages of modeling. A graph depicting this analysis can be seen in Figure T1 below. By 2025, the total distributed solar generation will be 40MW. To model this in GenX, 32MW was treated as existing capacity at zero cost that cannot be curtailed. The additional 8MW by 2025 was modeled as capacity that will be built for zero cost and will be able to be curtailed. To be clear, this is a policy choice on our behalf; we plan to respect the NEM contract of existing customers without the threat of curtailment, but reserve the right to curtail generation from any new generation installed starting in 2023.

Chart, line chart

Description automatically generatedFigure T1: Distributed solar generation in San Diego scaled down. 32MW in 2022, 40MW predicted in 2025. Broken between East facing, South facing, and West facing panels.

A similar approach was employed for estimating the expected electric vehicle load on the system. Due to the availability of data, we used EVs in San Diego county as a proxy for EVs in SDGE territory (which is essentially just San Diego county with a sliver of orange county as well). EV adoption trends were gathered from the California Energy Commision (ref), and we employed logistic regression to estimate that there will be about 285,000 EVs SDG&E territory in 2025. To create a load profile that accurately portrays this charging load, a software tool called EVI-Pro by NREL was used [9] (reference). The load profile was generated with a 5 minute interval over the course of the day and scaled down using the scaling factor of 1.92% from before. This was then added to each day of the original provided load, increasing it by about 4MW on average. By including this additional load, our model will be able to account for the increasing number of electric vehicles on the road by 2025.

# IV. System Modeling

In order to find the optimal generation mix and investment decisions required to satisfy load, the data collected during the generation requirements phase of the project was run through GenX, a capacity expansion modeling software. The objective function of the optimization was cost, with constraints coming from various inputs such as total available generator capacity and ramp rates. Another important input to the model was ELCC factor, discussed in the generator assumptions section below. Financial inputs for annual capital cost ($ / MW), annual fixed O&M cost ($ / MW), and variable O&M cost ($ / MWh) for each generator were also required. Municipal bond rates and ITCs for renewable technologies were also given as inputs. The main financial inputs to the GenX model can be found in Table X below. A municipal bond rate of 3% was used in the model to calculate interest rates associated with investments BOND RATES. A demand response program was also factored into GenX. This included an 8% participation rate at $20-savings / kWh and a 1% participation rate $5-savings / kWh.

Shape

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*Table XX: Caption blah blah*

For the generator types selected, several assumptions needed to be made that are required by GenX. Ramps rates are an important consideration for the model to dispatch power appropriately. The maximum ramp rates of wind, solar, and battery storage was assumed to be 100% per minute. A 15% per min ramp rate was chosen for hydro [10] (reference) and geothermal power [11] (reference). All generator types have a minimum power output of 0% except for geothermal at 10% (when committed). To ensure our portfolio met Caliifornia’s resource adequacy standards, we added an RA constraint to our GenX model, which requires a planning reserve margin to be maintained at all periods in the simulation. To model unavailability due to unforced outages or resource unavailability, we used the effective load carrying capability (ELCC) for each resource in our model, as estimated by the CPUC for 2035 in their 30MMT greenhouse gas scenario (ref). While not perfect, the portfolio of the 30MMT scenario should most closely match our portfolio, and therefore the ELCC’s should be similar. With more years worth of load data we would be able to run an ELCC calculation ourselves to improve the accuracy of our model. We note here that this RA requirement drove the bulk of the investment in our portfolio, with shadow prices reaching nearly $36,000/MWh for a few hours in July.

After running the GenX model, a portfolio describing the required generating capacity mix was produced. This mix represents the amount of installed generator capacity that is needed to meet our load while also adhering to our various constraints. Figure T2 below shows the complete breakdown of the generation mix.

Chart, bar chart

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Figure T2: Proposed Installed Capacity Mix. Note that distributed generation is broken into existing and new installations.

There are several items of note with this breakdown. Rather than having any pumped hydro storage, the model deemed that it was more optimal to meet all storage requirements using 35.23MW of 8-hour Li-Ion Batteries. This is only 10% of the current battery power capacity in San Diego. At this power level, 280MWh of batteries are needed. Additionally, the model also calls for nearly three times as much capacity for utility-scale solar compared to what is currently installed in the area surrounding San Diego. But with more than 5kWh/m2/day of global horizontal solar irradiance in the San Diego area, this should not be an issue [12] (reference). The wind capacity that is needed is lower than the current capacity at only 50MW. A small amount of hydropower needs to be used at 6MW alongside 85MW of enhanced geothermal power.

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Figure X. Dispatch Stack for Week in July When Grid is Most Stressed

A dispatch stack for a week in July is shown above in Figure X. The time of most stress on the grid occurs when load is high but the solar resource is relatively low. It should be noted that during this time period, the system relies heavily on geothermal energy which causes daily spikes in LMP due its relatively high variable cost. This demonstrates the value in investment for geothermal energy as a dispatchable generator with high ELCC.

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Caption

A dispatch stack for a week in November is shown above in Figure X. During the week of lowest solar resource, the grid is shown to be relying heavily on wind power but also geothermal energy. LMP is also seen to spike when geothermal energy is used or when batteries that were charged using geothermal energy are being discharged.

Achieving a 100% renewable energy grid for San Diego may be achievable but will it meet the current market prices to make it a financially sound investment. Using the cost assumptions mentioned in previous section to determine the financial metrics obtained from this project the table below summarizes

Table

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Table XX: Financial costs compared to current costs of energy (Citation)

Table above shows the annual costs broken down by services and adjustments. Levelized cost of energy refers to raw price for generating 1 kWh considering all associated costs to produce. This is then broken down to a yearly rate for which each year of the lifetime of the project one unit of energy will cost. Annual Capital Costs are the capital expenses required to purchase and build new generators to meet this model parameters over the lifetime of each generation facility (Geothermal: 30 years , Solar: 25 years, Wind: 20 years, Battery Storage: 10 years) Annual variable costs are costs which are dependent on current market prices, tax credits, O&M costs; demand response payments are payments expected for incentive programs for ratepayers who choose to participate in these programs estimations are based off of 1.92% of current SDG&E population. Annual Energy billing payments are estimated payments for the net energy generated in any given year to the generators. This yielded total annual costs of 186 Million dollars yearly cost or Levelized Cost of Energy (LCOE) 0.424/kWh this value is almost triple the current SDG&E LCOE of 0.149$/kWh.

Utility Rate Structure

We are calling for a rate structure that is reflective of how costs are incurred. With a generation mix that has near-zero marginal costs much of the time, but is capacity constrained in a small concentration of hours, incentivizing customers to consume electricity when it is plentiful and conserve when it is scarce will be much more important with our generation mix. We propose passing through the average LMP for each hour of the day, meaning that energy will be virtually free during times with good solar production, and pricing rising towards the marginal cost of geothermal ($46/MWh) during the evening hours in late summer. We also plan to pass through RA shadow prices (expected to peak at $34,800/MWh), but spread these costs out over the entire year for each customer so that bills are not an order of magnitude higher in August than in all other months. We plan to inform customers via text when RA periods are expected in order to facilitate conservation. For T&D costs, we propose keeping rates the same as they are now, but are open to the idea of restructuring those rates with coincident peak pricing as well in order to further incentivize conservation when it is needed most.

# V. Conclusion

## The goal of this project was to develop a 100% renewable energy plan for the City of San Diego given a load profile and geographic constraints. This was done by evaluating the existing conditions of San Diego’s grid, building models for renewable energy generators, and evaluating generator requirements beyond serving the load. The outcomes of this research and analysis were used in a capacity expansion model to determine generator capacity and investment requirements.

## We are confident that our proposed generation portfolio represents the most cost effective portfolio that meets the requirements of 100% renewable energy while maintaining reliability. Costs are significantly higher than current SDGE supply costs, but this is the price of sprinting so quickly to a full 100% renewable mandate. We note that relaxing the constraint to even just 95% renewable would likely lead to a significant reduction in costs given that natural gas plants have significantly lower capital costs than geothermal while providing similar levels of resource adequacy (the constraint driving the bulk of our expenses). Taking a more holistic view, the added costs in electricity due to the 100% renewable requirement is small in comparison to the benefits of leading the nation towards a renewable energy future.

Appendix

Appendixes, if needed, appear before the acknowledgment.

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Issuing Organization. (year, month day). *Title*. [Type of medium]. Available: site/path/file

*Example:*

1. U.S. House. 102nd Congress, 1st Session. (1991, Jan. 11). *H. Con. Res. 1, Sense of the Congress on Approval of Military Action*. [Online]. Available: LEXIS Library: GENFED File: BILLS

*Basic format for patents:*

J. K. Author, “Title of patent,” U.S. Patent *x xxx xxx*, Abbrev. Month, day, year.

*Example:*

1. G. Brandli and M. Dick, “Alternating current fed power supply,” U.S. Patent 4 084 217, Nov. 4, 1978.

*Basic format**for theses (M.S.) and dissertations (Ph.D.):*

J. K. Author, “Title of thesis,” M.S. thesis, Abbrev. Dept., Abbrev. Univ., City of Univ., Abbrev. State, year.

J. K. Author, “Title of dissertation,” Ph.D. dissertation, Abbrev. Dept., Abbrev. Univ., City of Univ., Abbrev. State, year.

*Examples:*

1. J. O. Williams, “Narrow-band analyzer,” Ph.D. dissertation, Dept. Elect. Eng., Harvard Univ., Cambridge, MA, USA, 1993.
2. N. Kawasaki, “Parametric study of thermal and chemical nonequilibrium nozzle flow,” M.S. thesis, Dept. Electron. Eng., Osaka Univ., Osaka, Japan, 1993.

*Basic format for the most common types of unpublished references:*

J. K. Author, private communication, Abbrev. Month, year.

J. K. Author, “Title of paper,” unpublished.

J. K. Author, “Title of paper,” to be published.

*Examples:*

1. A. Harrison, private communication, May 1995.
2. B. Smith, “An approach to graphs of linear forms,” 2014, *arXiv:2105.02824*.
3. A. Brahms, “Representation error for real numbers in binary computer arithmetic,” IEEE Computer Group Repository, Paper R-67-85.

*Basic formats for standards:*

a) *Title of Standard*, Standard number, date.

b) *Title of Standard*, Standard number, Corporate author, location, date.

*Examples:*

1. IEEE Criteria for Class IE Electric Systems, IEEE Standard 308, 1969.
2. Letter Symbols for Quantities, ANSI Standard Y10.5-1968.

**First A. Author** (Fellow, IEEE) and all authors may include biographies if the publication allows. Biographies are often not included in conference-related papers. Please check the Information for Authors to confirm. Author photos should be current, professional images of the head and shoulders. The first paragraph may contain a place and/or date of birth (list place, then date). Next, the author’s educational background is listed. The degrees should be listed with the type of degree in what field, which institution, city, state, and country, and year the degree was earned. The author’s major field of study should be lowercase. 

The second paragraph uses the preferred third person pronoun (he, she, they, etc.) and not the author’s last name. It lists military and work experience, including summer and fellowship jobs. Job titles are capitalized. The current job must have a location; previous positions may be listed without one. Information concerning previous publications may be included. The format for listing publishers of a book within the biography is: *Title of Book* (publisher name, year) similar to a reference. Current and previous research interests end the paragraph.

The third paragraph begins with the author’s preferred title and last name (e.g., Dr. Smith, Prof. Jones, Mr. Kajor, Ms. Hunter, Mx. Riley). List any memberships in professional societies other than the IEEE. Finally, list any awards and work for IEEE committees and publications.

**Second B. Author**, photograph and biography not available at the time of publication.

**Third C. Author, Jr.** (Member, IEEE), photograph and biography not available at the time of publication.

1. [↑](#footnote-ref-1)
2. It is recommended that footnotes be avoided (except for the unnumbered footnote with the receipt date on the first page). Instead, try to integrate the footnote information into the text. [↑](#footnote-ref-2)