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A Comparative Analysis and Optimization of Renewable Energy Sources

Abstract

This paper proposes a methodology to optimize the reliability, resilience, and invulnerability of power grids based on a model proposed in a paper by K Ramirez-Meyers et al (2021). It assigns numerical values and coefficients to different power plant attributes and uses a weighted sum approach to calculate an objective function. The optimization equation considers only renewable energy sources and eliminates irrelevant attributes of the model. The methodology employs multivariable optimization to find the best allocation of resources for each power plant. Minimum requirements based on the Californian power grid are defined to ensure superior performance. The results show that a combination of solar and hydroelectric is the best-optimized grid while nuclear is always allocated the least resource through all the optimizations.

Introduction

With the urgent need to address the devastating impacts of climate change, it is crucial to critically examine various aspects of our lives that we have long taken for granted. One of the key areas under intense scrutiny is the energy sector, which has historically relied heavily on the burning of coal and fossil fuels, leading to the dire climate crisis we currently face. The combustion of these carbon-intensive energy sources has unequivocally contributed to the exacerbation of climate change by releasing vast amounts of greenhouse gases into the atmosphere, notably carbon dioxide (CO_2). This excessive emission of CO_2, a major driver of global warming, has disrupted the delicate balance of our planet's climate system, resulting in rising temperatures, extreme weather events, and environmental degradation at an alarming pace. In the last century, new technologies created better ways to generate energy while having less impact on the environment. Solar panels are quite versatile as they can be installed on the roofs of buildings. However, many solar panels are residential since they do not require constant attention, but have a high initial cost and only work in areas that get sunlight (Ryberg, 2018). Wind power is a good alternative in rural areas, but is limited by their geographical location and land area (Ryberg, 2018). For both wind and solar energy, batteries are required in case of times when the fuel for these generators is not present, which would lead to fluctuations in the power grid. Lithium-ion batteries have a wide range of potential uses, and they are best suited to reduce Renewable Energy Source (RES) fluctuation in the utility grid integration sector (Behabtu et al., 2020). Another controversial source is nuclear energy. With disasters such as Fukushima and Chernobyl, it is understandably not people's first choice, but it is a good alternative if power plants are still in fashion. Additionally, nuclear energy facilities actually have different methods to manage and dispose of nuclear waste (Sfen, 2019). Nuclear power plants are silent and produce little to no greenhouse gasses. This means that they could replace all the coal power plants. As for geothermal plants, while geothermal energy is relatively clean, the drilling and extraction methods can harm the environment and upset ecosystems. Lastly, hydroelectric dams could harm the livelihood of those downstream by disrupting the river flow, especially those in developing countries (Human Rights Watch, 2021*)*. However, dams can help with flood prevention, navigation, aquaculture, tourism, ecological preservation, environmental sanitization, development-oriented resettlement, water supply, and irrigation.

Others have done studies trying to compare the different types of energy sources. An article in the *Institute of Physics Publishing* by Ramirez-Meyers and his colleagues titled "How different power plant types contribute to electric grid reliability, resilience, and vulnerability: A comparative analytical framework" studied the differences in energy sources by comparing them in terms of reliability, resilience, and invulnerability. They define reliability as how few disruptions the grid experiences whereas resilience is defined as how fast they recover from disruptions and invulnerability is defined as the minimization of severe disruptions. They use natural gas generators as a benchmark for these factors and found that hydroelectric energy is the most resilient and responsive. There are subcategories within these metrics, which include the generator's ability to reduce power rating, outage frequency, fuel, and grid responsiveness. In these subcategories, the energy source can have one of five rankings; they are either (1)much worse than NGCC (Natural Gas Combined-Cycle), (2)worse than it, (3)similar, (4)better, or (5)much better than it. Some of the subcategories they use only apply to traditional power plants though. An example of this is the "On-site fuel storage" subcategory. They say that, due to the impossibility of storing wind and solar radiation, wind and solar PV are significantly worse than NGCC. While they are technically correct, the product created by wind and solar radiation can be stored in batteries. Even though this means that the energy reserve might be lower than traditional power plants, it is not zero, which is the definition they gave for "much worse than NGCC" in the context of "On-site fuel storage".

This paper will optimize the reliability, resilience, and invulnerability of the Californian power grid. Different power plant parameters are given numerical values and coefficients, and an objective function is calculated using a weighted sum method and multiplication. The optimization equation excludes irrelevant attributes, such as those with discrete values and those that only apply to traditional power plants such as coal. To determine the most effective resource allocation for each power plant, the methodology uses multivariable optimization. To achieve excellent performance, minimum standards based on the current California electricity grid are established.

By determining the best combination of renewable energy sources, we can more effectively allocate our resources by deciding on the optimum renewable energy mix. For instance, solar electricity might be more appropriate than wind power in an area with abundant sunlight and low wind speed. But, wind and hydropower may be more advantageous in an area with strong winds and abundant water resources.

Renewable Energy Sources

1) Nuclear Energy

1.1) How It Works

According to the United States Department of Energy, pressurized water reactors, also known as PWRs, make up more than 65% of the commercial reactors in the US. These reactors push the water into the reactor core at high pressure. Nuclear fission then heats the water in the core, which is subsequently fed into tubes inside a heat exchanger. To produce steam, those tubes warm an additional water source. The electricity is then generated by the steam turning an electric generator. The procedure is then repeated with the core water cycling back to the reactor for reheating.

Nuclear reactors can run constantly due to nuclear fission chain reactions. Nuclear fission creates heat by splitting atoms, specifically an isotope of uranium that has an odd number of neutrons. This isotope of uranium is chosen because it can sustain a nuclear chain reaction. When a neutron is captured, as in the case of Uranium-235 in a thermal reactor, the whole energy is divided among the 236 protons and neutrons that are now present in the compound nucleus. Because of the instability, the nucleus often split into two pieces that each contain around half of its original mass. The emission of several neutrons allows the chain reaction to continue. The total energy released during the fission reaction varies depending on the exact breakdown but outputs 3.2×10^{-11} joules on average in the case of Uranium-235, which is around 82 Terra-Joules of energy per kilogram(World Nuclear Association, *Physics of Uranium and Nuclear Energy*).

1.2) Flaws

The most prevalent kind of nuclear waste is low- and intermediate-level waste. According to the International Atomic Energy Agency (IAEA), almost 95% of the radioactive waste has extremely low or low radioactivity, whereas only 4% is classified as intermediate-level waste. Because of its low radioactivity, intermediate-level waste and low radioactivity are easier to dispose of. Items used in the nuclear power plant such as uniforms, gloves, pieces of equipment, and protective shoe covers fall into this classification. These items can be disposed of in surface-level disposal sites. High-level waste, on the other hand, is what most people associate with when the term nuclear waste is mentioned. According to the IAEA, the total amount of high-level waste is around 1% of the total waste generated by nuclear power plants. Our current method of disposing of such wastes is to keep them in deep geological formations, away from living beings. The waste is then kept for tens of thousands of years, away from living beings. According to Sfren, the French nuclear agency, the potential radiotoxicity of high-level nuclear waste becomes lower than that of natural uranium after approximately 10,000 years (IAEA).

What most people associate nuclear power plant danger with is when the power plant fails. Dramatization of the Fukushima and Chernobyl nuclear power plants is among the most famous. These incidents rendered a massive area around the plant unlivable by any human, even plants and animals are negatively affected. But, according to Our World in Data, nuclear plants are one of the safest forms of energy generation when considering its energy generation and the total number of deaths (Our World in Data).

1.3) Benefits

Nuclear fuel is the most energy-dense source of energy. According to the World Nuclear Association, one kilogram of uranium is around twenty thousand times more energy-dense than coal, generates no net carbon dioxide emissions during energy production, and is easily and cheaply transported. This means nuclear power plants can be set up almost anywhere rather than depending on a specific geographical location such as sunny, windy, or close to a river.

2) Solar Energy (Photovoltaic)

2.1) How It Works

The Photovoltaic cells absorb the incoming photons, excite the electrons within the cells, and send them in motion. In each solar cell, silicons are covered with conductive layers. Because four bonds connect silicon atoms, the electrons cannot move between them. When the cell is hit by photons, an electron is hit and drifts away. But, because the p/n (positive/negative) junction, which is a border between two types of semiconductor materials, is positively charged on one side and negatively charged on the other the electron can only flow in a certain direction.

2.2) Flaws

The initial cost of solar panels is very expensive. According to Forbes, it will take up to 5 to 11 years to break even on the initial cost of the installation, depending on the state you are in. This aligns with another article, which states that, for residential solar, it typically takes 7-10 years to break even on the initial cost. The initial cost is one of the largest barriers to adopting solar panels and solar energy requires batteries that need to be maintained (Forbes 2023).

The raw materials used to create the panels are also sourced from countries that are not in good relations with the United States, which could lead to unwanted side effects. According to the US Department of Energy (DOE), around 12% of the total amount of silicon metal (also known as "metallurgical-grade silicon" or MGS) is turned into polysilicon solar panel manufacturing. China produces around 77% of the world's polysilicon and 70% of the MGS. High temperatures are necessary to transform silicon into polysilicon, and in China, coal is mostly used to power these plants. Additionally, China could use silicon metal as leverage in a trade dispute.

2.3) Benefits

The solar panel can be mounted in small amounts on the roofs of homes, conserving space. Further development can be done to improve the efficiency of photovoltaic panels so that they can absorb more of the sun’s energy. According to the United States Department of Energy, around

173,000 terawatts of solar energy are released onto the Earth continuously, which is more than 10,000 times the world's total energy use (USDE).

3) Wind Turbines

3.1) How it Works

The turbine converts the kinetic energy of the wind into electrical energy by spinning the turbine. The air pressure on one side of the blade falls as the wind passes across it. Both lift and drag are produced by the different air pressures on the blade's two sides. The rotor spins because the force of the lift is greater than the force of the drag. Electricity is produced as a result of the conversion of kinetic energy into rotational energy.

3.2) Flaws

Like solar panels, wind turbines are limited by their geological location. These locations are often in remote areas, which poses another challenge in transporting that energy. Unlike solar panels, most people do not want a massive wind turbine in their backyard since large turbines can be loud and ruin the scenery. Wind turbines also take up a lot of space since they need to be spaced out to improve the efficiency of individual turbines.

3.3) Benefits

Wind turbines can operate without constant human operation, just the occasional maintenance work. According to the United States Department of Energy, utility-scale, land-based wind turbines are one of the most affordable energy sources. Also, as wind energy research and technology evolve, its cost-competitiveness continues to rise.

4) Hydroelectric Dams

4.1) How It Works

Water flows through a pipe—also known as a penstock—and then spins the blades in a turbine, which converts the potential energy of the water into electrical energy by spinning the turbine. Because of this, hydroelectric dams are in locations with a body of flowing water.

4.2) Flaws

The dam has negative effects on the ecology, local culture, and aesthetic aspects, as well as sedimentation. Dams affect the countries downstream that also use the river. The China-backed Lower Sesan 2 dam built in Cambodia is an example of this. In an article by Human Rights Watch, John Sifton, Asia advocacy director, said “The Lower Sesan 2 dam washed away the livelihoods of Indigenous and ethnic minority communities who previously lived communally and mostly self-sufficiently from fishing, forest-gathering, and agriculture,” and that “Cambodian authorities need to urgently revisit this project’s compensation, resettlement, and livelihood-restoration methods, and ensure that future projects don’t feature similar abuses.” China has been building many dams that would negatively affect the livelihood of many people in Southeast Asia. This means that bigger countries can take advantage of smaller ones when building a hydroelectric dam.

In California, the spillways of the Oroville Dam suffered severe damage from storms in early February 2017, making it difficult for floodwater to be released safely. More than 180,000 residents who lived downstream along the Feather River were compelled to evacuate because of the potential for an uncontrolled flow of water from the lake (ESA).

4.3) Benefit

Hydroelectric dams can help with flood prevention, navigation, aquaculture, tourism, ecological preservation, environmental sanitization, development-oriented resettlement, water supply, and irrigation.

5) Geothermal

5.1) How it Works

In general, geothermal power plants draw fluids from underground reservoirs to the surface to produce steam. This steam then drives turbines that generate electricity. There are three main types of geothermal power plant technologies: dry steam, flash steam, and binary cycle. Dry steam plants, the oldest type of geothermal power plants, use hydrothermal fluids that are already mostly steam, which is a relatively rare natural occurrence. The steam is drawn directly to a turbine, which drives a generator that produces electricity. After the steam condenses, it is frequently reinjected into the reservoir. Flash steam plants are the most common type of geothermal power plants in operation today. Fluids at temperatures greater than 182°C/360°F, pumped from deep underground, travel under high pressures to a low-pressure tank at the earth's surface. This generates steam. Binary-cycle geothermal power plants transfer heat from geothermal hot water to another liquid. The heat converts the second liquid to steam, which drives a generator turbine. These types of generators can use lower-temperature geothermal resources, making them an important technology for deploying geothermal electricity production in more locations. Binary-cycle geothermal power plants differ from dry steam and flash steam systems in that the geothermal reservoir fluids never come into contact with the power plant's turbine units.

5.2) Flaws

Geothermal is very limiting in the location the facilities can be built in. This is because locations for large geothermal reservoirs are scarce. Only a few locations have access to geothermal energy, where hot magma rises to the surface and heats the ground to nearly boiling temperatures. Even though geothermal energy generation produces less CO_2 compared to fossil fuels, carbon dioxide is still produced during operations.

5.3) Benefits

The noise levels produced by geothermal power facilities are low and undetectable, at least while they are operating at full capacity. The construction phase of the plants, including excavations, creates a certain degree of noise, but once construction is complete, everything is silent. This means that many geothermal reservoirs don't have to be ruled out for their proximity to humans. According to the Department of Energy's Office of Energy Efficiency & Renewable Energy, Geothermal power plants are also compact. They use less land per gigawatt-hour (404 m^2) than coal plants (3,642 m^2), wind turbines (1,335 m^2), and solar photovoltaic (PV) power stations (3,237 m^2) (Energy.gov).

Methodology

This paper will be analyzing the research paper published in the *Institute of Physics Publishing* by Ramirez-Meyers and his colleagues. With the paper establishing rankings for many attributes of power plants, numerical values will be assigned to have coefficients to optimize. This paper specifically tries to optimize the three metrics proposed: reliability, resilience, and invulnerability, with the percentage of resources allocated to each power plant being the independent variable. Therefore, the formula being used is

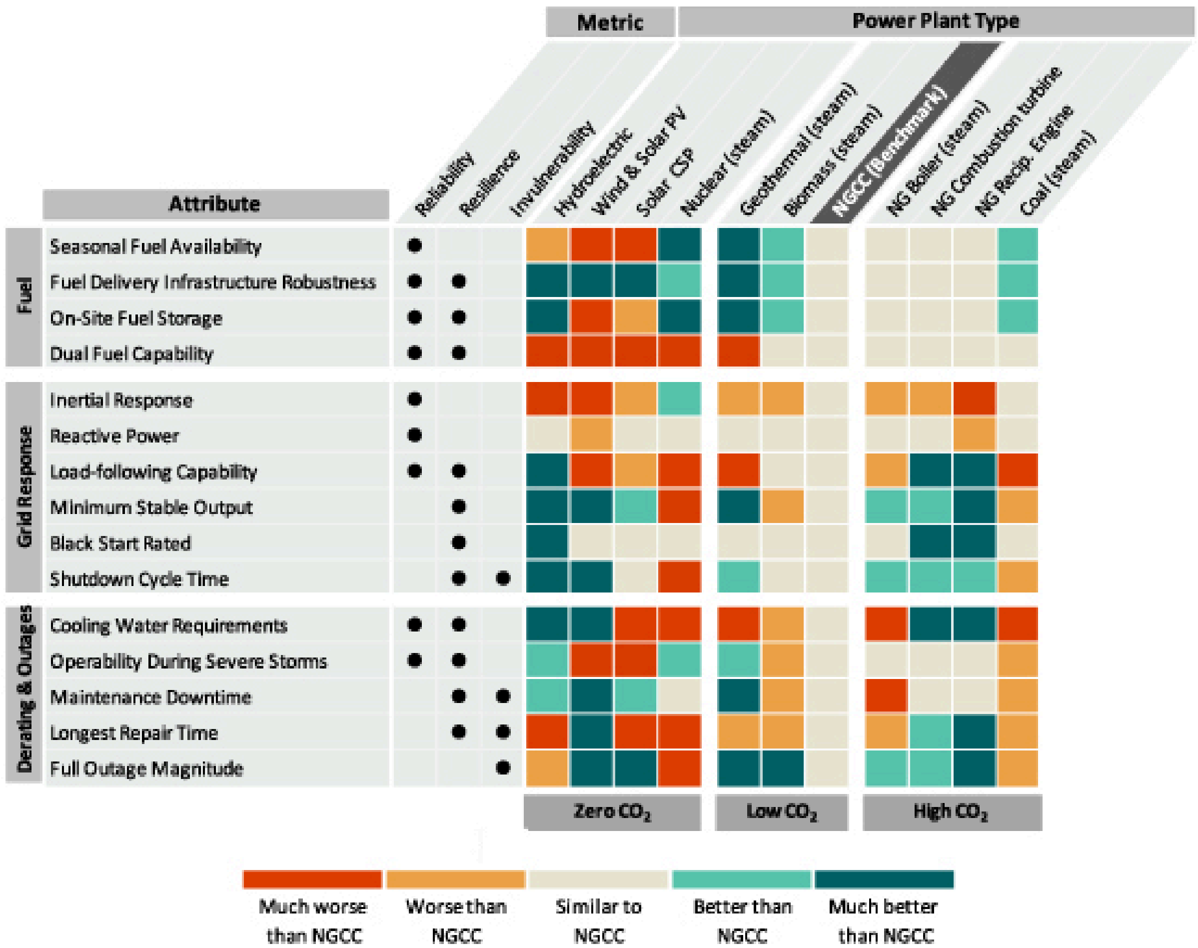
$$F(n_i) = r_1 n_1 + r_2 n_2 + r_3 n_3 + r_4 n_4 + r_5 n_5$$

Where: F is the relative value of the metric being optimized

r_i is the numerical value (coefficient) assigned to the ranking received

x_i is the percentage of resources allocated

Next is to establish the variables of the optimization equation. The paper outlined fifteen possible variables, or attributes, that lead to the reliability, resilience, or invulnerability of a specific power grid set-up as shown below. These attributes are accompanied by five different rankings.



Ramirez-Meyers, K., Neal Mann, W., Deetjen, T. A., Johnson, S. C., Rhodes, J. D., & Webber, M. E. (2021).

To enhance the alignment with the new optimization parameters, irrelevant attributes have been eliminated from this paper, focusing solely on the analysis of zero-emission energy sources.

Irrelevant Attributes

To simplify the optimization problem, Fuel Delivery Infrastructure Robustness is removed from the optimization parameters. Adding it will only slightly affect the results still most of the energy sources have the same rating, except for one that is one rank below it.

The paper defines *On-Site Fuel Storage* as the "ability to store fuel on-site and the average amount stored (in terms of energy required per day of normal operation)". But, since sunlight and wind cannot be stored, they gave them the lowest ranking. Even though this is true, they didn't highlight that the energy can be stored in batteries as a workaround. This unfairly hinders solar and wind energy's ranking and is why it is removed from the optimization parameters.

Dual Fuel Capability is defined as the "ability to switch between liquid and gaseous fuels (dual-fuel) or burn both simultaneously (bi-fuel)". This is not applicable to the four power sources being optimized. This is because renewable energy sources typically have one type of fuel. The definition also says that the different fuels must be liquid and gaseous. Nuclear power plants are capable of using different fuel sources, but they are still solids. This results in all five energy sources being "much worse than NGCC". This means that adding *Dual Fuel Capability* will not make a difference in the optimization of the power grid.

The paper says that *inertial response* is "[the] average amount of kinetic energy that a power plant contributes that helps the grid resist frequency drops, equal to inertia constant (s) × average capacity." This can only be applicable to energy sources that contain large synchronous rotating masses, and which acts to overcome any immediate imbalance between power supply and demand for electric power systems. For this reason, it is removed from the objective function.

Reactive power and *Black Start Rating* are discrete values according to the paper. This means that it cannot be optimized like the other variable. To simplify the optimization process, this variable is not considered in the final optimization.

Cooling Water Requirements don't apply to all but one of the renewable energy sources, nuclear energy as all the other energy sources don't require water as a cooling agent.

Longest Repair Time is also omitted because the definitions provided are too vague to numerically evaluate. They state that the best performance is that the equipment is off-the-shelf while the worst is if the equipment is custom.

Optimization

The type of optimization used is multivariable optimization. Multivariable optimization is a mathematical concept that deals with finding the best solution for a problem involving multiple variables, typically within a specific set of constraints.

The main goal of multivariable optimization is to find the values of the variables that either maximize or minimize a specific objective function. This objective function represents the quantity that needs to be optimized. In this case, the objective function represents the resource allocation to each of the five energy sources. The variables involved in the problem are subject to certain constraints, which can be physical limitations.

In computing the optimization, the computer needs to initialize the optimization process by providing an initial set of values for the variables involved in the problem. This initial guess can be random or based on prior knowledge or estimates. The computer iteratively evaluates the objective and constraint functions, updating the variable values based on optimization-specific measures like gradients or other optimization-specific measures. It checks for maximum by comparing changes in the objective function or variable values against predefined criteria. If the maximum is not reached, the process repeats.

The attributes being used are

Attribute	**Definition**
Seasonal fuel availability	On-demand availability of the upstream fuel source
Load-following capability	Speed at which a generator can start up or change supply without disconnecting from the grid
Minimum stable output	A power plant's minimum output under normal operating conditions, also known as turndown ratio

Shutdown Cycle Time	Number of hours it takes a generator to come back online after it has shut down
Operability during severe storms	Ability to stay on during 'storms and severe weather such as hurricanes
Maintenance downtime	Percent of each year that a power plant is typically shut down for maintenance
Full outage magnitude	Average plant size in MW capacity

Ramirez-Meyers, K., Neal Mann, W., Deetjen, T. A., Johnson, S. C., Rhodes, J. D., & Webber, M. E. (2021).

All the optimizing factors are listed below:

H_x is the coefficient for hydroelectric power for any specific attribute

W_x is the coefficient for wind power for any specific attribute

S_x is the coefficient for solar power for any specific attribute

N_x is the coefficient for nuclear power for any specific attribute

G_x is the coefficient for geothermal power for any specific attribute

n_x is the theoretical percentage of the grid a specific energy source should occupy

$$SFA = H_0 n_H + W_0 n_W + S_0 n_S + N_0 n_N + G_0 n_G$$

$$LFC = H_1 n_H + W_1 n_W + S_1 n_S + N_1 n_N + G_1 n_G$$

$$ODSS = H_2 n_H + W_2 n_W + S_2 n_S + N_2 n_N + G_2 n_G$$

$$MSO = H_3 n_H + W_3 n_W + S_3 n_S + N_3 n_N + G_3 n_G$$

$$MD = H_4 n_H + W_4 n_W + S_4 n_S + N_4 n_N + G_4 n_G$$

$$FOM = H_5 n_H + W_5 n_W + S_5 n_S + N_5 n_N + G_5 n_G$$

$$SCT = H_6 n_H + W_6 n_W + S_6 n_S + N_6 n_N + G_6 n_G$$

SFA: Seasonal fuel Availability

ODSS: Operability During Severe Storms

MD: Maintenance Downtime

SCT: Shutdown Cycle Time

LFC: Load-Following Capability

MSO: Minimum Stable Output

FOM: Full Outage Magnitude

To simplify the optimization problem, it is assumed that the attributes are linear.

The factors leading to Resilience are SFA, LFC, and ODSS

The factors leading to Reliability are LFC, ODSS, MSO, SCT, and MD

The factors leading to Invulnerability are SCT, MD, and FOM

$$Reliability = SFA + LFC + ODSS$$

$$Resilience = SFA + ODSS + MSO + MD + SCT$$

$$Invulnerability = SCT + MD + FOM$$

The weighting of parameters

The definition of the rankings in *Seasonal Fuel Availability* given has no numerical value. Therefore, different values are obtained to make the optimization possible, which are obtained through different means. For example, according to the United States Energy Information Administration, droughts caused electricity generation from California hydropower plants in 2021 to be down 48% from the 10-year average (U.S Energy Information Administration, 2021). Because of this, we could assume the efficiency of current hydropower due to seasons is 52% and assign the parameter with a coefficient of 0.52 (1 - 0.48). For solar energy, we consider the total hours of sunlight in California and the total amount of hours in a year. According to *Weather and Climate,* San Francisco receives 3072 hours of sunlight per year while Los Angeles receives 3259 hours, the average of which is 3165.5 hours. Dividing this by the total amount of hours in a year will give the value of 0.35 when rounding to the second decimal point. According to the United States Geological Survey, the wind energy capacity factor of the United States is 42%. This means that the actual energy produced in a given period is 42% of the hypothetical maximum possible. On the other hand, California's wind energy capacity factor is at 26% (U.S. Geological Survey). Using the United States' average wind energy capacity factor as the benchmark, California's wind energy capacity factor is 62% of the country's average. Therefore, the coefficient of 0.62 is assigned to the seasonal fuel availability of wind. Since nuclear and geothermal scored the highest, the value of 1 will be assigned as its coefficient. For the rest of the coefficients of each attribute, a linear scaling from 0.1 to 1 is used as a numerical definition is given.

The provided information outlines the ranking criteria and numerical values for evaluating various capabilities of a power system.

1) **Load-following Capability:** The performance is ranked based on a numerical value. The best performance is defined as 20% of capacity per minute, while the worst is 2% of capacity per minute. The baseline performance is set at 5% of capacity per minute.
2) **Operability During Severe Storms:** The worst performance is when the power source shuts down during most events, with a ranking of 0.1. The best performance is ranked as 1, indicating uninterrupted operation during severe storms.
3) **Minimum Stable Output:** The ranking for this criterion is expressed as a numerical value. The benchmark performance is set at 20% of capacity, while the poorest performance is at 50% of capacity. The greatest performance is defined as 5% of capacity.
4) **Full Outage Magnitude:** This capability is also ranked using numerical values. The benchmark performance is 520 megawatts, while the worst performance is 1700 megawatts. The best performance is around 47 megawatts. Any ranking between the worst and best is considered to perform halfway between the baseline and the extreme values.

5) **Shutdown Cycle Time:** The benchmark for this capability is 2 hours. The worst performance is 24 hours, indicating a lengthy shutdown period. The best performance is around 0.5 hours, signifying a quick shutdown time.

6) **Maintenance Downtime:** The benchmark for this is 6% of the year. The worst performance is 25% of the year, indicating a lengthy maintenance period. The best performance is around 0.6% of the year, signifying a quick maintenance time.

A different method could be proposed to obtain a more accurate coefficient, but it is beyond the scope of this paper. A linear scale is currently the best method with the resources at hand.

The coefficient of each variable is

$H_0 = 0.52$	$W_0 = 0.62$	$S_0 = 0.35$	$N_0 = 1$	$G_0 = 1$
$H_1 = 1$	$W_1 = 0.1$	$S_1 = 0.25$	$N_1 = 0.1$	$G_1 = 0.1$
$H_2 = 0.75$	$W_2 = 0.1$	$S_2 = 0.1$	$N_2 = 0.75$	$G_2 = 0.75$
$H_3 = 0.9$	$W_3 = 0.9$	$S_3 = 0.8$	$N_3 = 0.1$	$G_3 = 0.9$
$H_4 = 0.75$	$W_4 = 1$	$S_4 = 0.75$	$N_4 = 0.5$	$G_4 = 1$
$H_5 = 0.27$	$W_5 = 0.99$	$S_5 = 0.99$	$N_5 = 0.1$	$G_5 = 0.99$
$H_6 = 1$	$W_6 = 1$	$S_6 = 0.5$	$N_6 = 0.25$	$G_6 = 0.75$

Minimum Requirements of Metrics

The three metrics will have a constraint to that of the Californian power grid. In other words, the theoretical power grid that this paper concludes must not be less reliable, resilient, or invulnerable than the Californian power grid. We can create a model that mirrors the Californian power grid, find the metrics, and use the output of our constraints.

According to the data provided by the California Energy Commission, the breakdown of these sources is as follows: natural gas constitutes approximately 37.9% of the power grid, nuclear energy contributes around 9.3%, hydroelectric power accounts for approximately 10.2%, biomass adds up to approximately 2.3%, geothermal energy makes up around 4.8%, solar energy contributes roughly 14.2%, and wind energy constitutes approximately 11.4% of the grid. It is important to note that these percentages do not sum up to 100% due to the omission of coal and other unspecified energy sources from the equation.

By applying the linear formula to the current composition of the Californian power grid, Inputting these values into the variables (n_x), the minimum values for the metrics of the theoretical power grid is:

$$SFA = H_0 n_H + W_0 n_W + S_0 n_S + N_0 n_N + G_0 n_G > 0.67684$$

$$LFC = H_1 n_H + W_1 n_W + S_1 n_S + N_1 n_N + G_1 n_G > 0.394$$

$$ODSS = H_2 n_H + W_2 n_W + S_2 n_S + N_2 n_N + G_2 n_G > 0.4431$$

$$MSO = H_3 n_H + W_3 n_W + S_3 n_S + N_3 n_N + G_3 n_G > 0.6162$$

$$MD = H_4 n_H + W_4 n_W + S_4 n_S + N_4 n_N + G_4 n_G > 0.64767$$

$$FOM = H_5 n_H + W_5 n_W + S_5 n_S + N_5 n_N + G_5 n_G > 0.64767$$

$$SCT = H_6 n_H + W_6 n_W + S_6 n_S + N_6 n_N + G_6 n_G > 0.59725$$

These constraints are to achieve a better theoretical grid in all the attributes shown. Additionally, all five of the variables must add up to one since the variables represent the percentage of the power grid ($n_H + n_W + n_S + n_N + n_G = 1$).

Computation of The Optimization

Matlab, a mathematical computing environment and programming language created by MathWorks, is used to compute this optimization problem. The code is as follows:

```
% Defining the objective function
objFunc = @(x) -(2.27*x(1) + 0.82*x(2) + 0.7*x(3) + 1.85*x(4) + 1.85*x(5)) * ...
        (4.4*x(1) + 3.1*x(2) + 2.4*x(3) + 1.7*x(4) + 3.5*x(5)) * ...
        (2.02*x(1) + 2.99*x(2) + 2.24*x(3) + 0.85*x(4) + 2.74*x(5));
% Defining the inequality constraints
A = [0.52, 0.62, 0.35, 1, 1;
   -1, -0.1, -0.25, -0.1, -0.1;
   -0.75, -0.1, -0.1, -0.75, -0.75;
   -0.9, -0.9, -0.8, -0.1, -0.9;
   -0.75, -1, -0.75, -0.5, -1;
   -0.27, -0.9, -0.9, -0.1, -0.9;
   -1, -1, -0.5, -0.25, -0.75];
b = [0.61684; -0.364; -0.4031; -0.5662; -0.58675; -0.58767; -0.54725];
% Defining the equality constraint
Aeq = [1, 1, 1, 1, 1];
beq = 1;
lb = [0; 0; 0; 0; 0]; % Lowerbounds
ub = [Inf; Inf; Inf; Inf; Inf]; % Upperbounds
x0 = [0; 0; 0; 0; 0];  % Initial guesses
options = optimoptions('fmincon', 'Display', 'iter');  % Optional: display the iterative progress
[xOpt, fVal] = fmincon(objFunc, x0, A, b, Aeq, beq, lb, ub, [], options);
% Display the optimal solution and objective function value
disp("Optimal solution:");
disp(xOpt);
disp("Objective function value:");
disp(-fVal);
```

***The optimization code has the initial guess of 0 and is unbounded for all the variables**

The code starts with an initial guess we inputted, as indicated in line 16 (Initial guesses). The initial guess can start from zero or the current makeup of California's renewable grid. We could also restrict hydroelectric dams to 15% of the grid, which estimates how many new hydroelectric dams could be built based on the current rate and cost (Person, Escriva-Bou, Mount, & Jezdimirovic).

Results

For the optimization, the objective function will be

$$OPG = (SFA + LFC + ODSS) \cdot (SFA + ODSS + MSO + MD + SCT) \cdot (SCT + MD + FOM)$$

OPG: Optimized Power Grid

The assumption of linearity in each of the three segments is considered as a fundamental assumption. However, by employing a cubic function, the objective function can achieve optimal results for the power grid. This is due to the mathematical property that inputs that are in close proximity on the number line, while subject to a constrained sum, yield a larger value when multiplied, allowing a more favorable overall power grid configuration.

Zero as Initial Guess		**California Power Grid as Initial Guess**	
No upper bounds	*Hydro ≤ 15%*	*No upper bounds*	*Hydro ≤ 15%*
n_H = 0.4005	n_H = 0.15	n_H = 0.2824	n_H = 0.15
n_W = 0.3445	n_W = 0	n_W = 0.114	n_W = 0.114
n_S = 0	n_S = 0.8222	n_S = 0.2654	n_S = 0.7722
n_N = 0	n_N = 0.0001	n_N = 0.093	n_N = 0.951
n_G = 0.255	n_G = 0.3139	n_G = 0.2451	n_G = 0.2040
Output = 15.7144	*Output = 16.786*	*Output = 11.3356*	*Output = 17.2276*

Conclusion

Comparing the results shows that a decrease in solar electricity can be compensated by an increase in hydroelectric dams in addition to wind turbines and vice versa. This means that solar electricity and hydroelectric dams have a lot of overlap when considering the parameters proposed. But, solar most likely has attributes that hydroelectric dams do not, which then can be compensated by an increase in wind turbines. Overall, they show that maximizing solar and hydroelectric dams is the best option. Both results show that nuclear energy is less beneficial than the others because optimization gives either a very low or zero percentage for nuclear energy. The results also show that geothermal energy can fill the gaps in reliability, resilience, or invulnerability. But seeing that it is not the highest shows that it is not the best in any one attribute. This means that it is likely geothermal energy has a decent score in most of the attributes but not the best.

Overall, the optimization results shed light on the trade-offs and synergies between different energy sources. The findings suggest that a combination of solar electricity, hydroelectric dams, and geothermal energy can lead to an optimized energy system, maximizing the defined metrics while considering constraints and preferences. These insights can inform decision-making processes regarding the development and allocation of energy resources sustainably and efficiently.

The results between the constrained and unbounded hydroelectric are unusual mathematically speaking. When a constraint is put on the percentage of hydroelectric power that can be built, the output of the objective function is higher than if the constraint is removed. This is possible due to the behaviors of a gradient when optimizing on a five-dimensional plain.

Interpretation of results

Even though steps have been taken to treat the attributes as real concepts rather than numerical outputs, the paper's results only reflect a theoretical power grid. A major factor often overlooked in theoretical studies is the role of politics. The construction of a power grid requires the involvement of various stakeholders, including government agencies, utility companies, and local communities. Political considerations such as funding availability, regulatory requirements, and public opinion can all play a significant role in determining the feasibility and design of a power grid. Another important consideration is the logistical challenges of building a power grid in a specific location. Depending on the location, there may be physical, environmental, or social factors that need to be considered when designing and building a generator. For example, building a wind turbine in an area with high wind speeds may be an effective way to generate power, but the building process may pose logistical challenges related to transporting equipment and managing environmental impacts. The same goes for hydroelectric dams. As previously mentioned, The Lower Sesan 2 dam is threatening the livelihoods of Indigenous and ethnic minority communities who depend on fishing, forest-gathering, and agriculture.

Possible Errors

Some possible errors in the article are incorrect modeling assumptions and improper selection of optimization parameters. Additionally, we could have redefined “on-site fuel storage” to better fit the optimization problem instead of removing the attribute together, but the limitation of time prevents the option.

For solar power's seasonal fuel availability, this paper assumed that the amount of sunlight California receives is equal to the average between Los Angeles and San Francisco. This estimate is to simplify the paper to achieve a result. A more in-depth analysis can be done to determine the specific amount of energy generation solar and wind energy lost during severe storms. But, that is beyond the scope of this paper.

This paper also assumes that the attributes of each metric have a linear relationship to each other but this might not be the case. The linear relationship is assumed in order to simplify the objective function and most of the constraints. In reality, an increase in one attribute could lead to a non-linear increase or decrease in another. Additionally, no weights are given to each attribute, only the individual energy source's contribution to the attributes. This is due to the limitation in time and the current lack of evidence supporting a definite weight of any attribute even though some attributes are very likely more important than others.

Additionally, due to how the code finds the maximums, the output of the objective function is a local maximum, which may or may not be the absolute maximum. This is because the code starts at the initial guess and tests the values next to it. Whichever value achieves a higher output will be the new starting point. This process iterates until it reaches a point where all the values next to it output a value that is lower than itself. This means that the initial guess of the code will often matter, especially in an objective function with many variables.

Future Study

A point of improvement in this paper is to have a more in-depth analysis of the fluctuations in the electrical output of each energy source throughout the year. We could use a similar model proposed in the paper but the constraints apply to a more specific period in time. For example, the total energy output must not fall below a certain amount on any day throughout the year, and optimization of the grid in a way that is possible or to see if the optimization is even possible.

There are also most likely other factors that contribute to the metrics of an energy source. Finding those factors, on the other hand, is beyond the scope of this paper. But, this could be a potential point of expansion in the field. Having a more in-depth analysis of the relations between the different attributes could also be expanded on.

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