Offshore Wind and Tidal Energy Integration into Power System Linear Programming Capacity Model

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Research Project

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Abstract

This report examines the feasibility and economic implications of integrating offshore wind and tidal energy into the United States energy grid, with a focus on California. Offshore wind and tidal energy are increasingly recognized as viable alternatives to fossil fuels, however, their integration into existing energy systems requires careful planning and analysis for significant investments. This report uses Switch, a power system capacity expansion model that uses linear programming to minimize the cost of the system while meeting renewable energy standards. Offshore wind and tidal modules are implemented and the procedure is detailed in this report. The findings indicate the potential of offshore wind in the long term, while tidal power has a large price barrier that limits its potential. The report concludes by analyzing how different methods of building offshore turbines may have an impact on their potential and recommends using them as distributed energy resources to supply electricity to underserved regions.

Contents

1 Introduction

The global energy landscape is undergoing a significant transformation as nations strive to reduce greenhouse gas emissions and transition towards sustainable energy sources. Among these sources, offshore wind and tidal energy hold immense potential, offering clean and reliable alternatives to traditional fossil fuels. Almost 40% of the United States population lives in coastal communities that have immediate access to the ocean for energy needs [1]. Thus, offshore wind and tidal energy integration would have an immediate impact on surrounding energy loads. As a result, the United States has slowly begun following the trend of offshore wind from other countries such as China [2]. Due to not having an existing infrastructure to embed these renewable technologies, each technology's inherent intermittency, and geographical constraints, there must be extensive planning for building out energy sources, transmission networks, and grid options.

To do this, modeling of energy capacity is essential to ensure investments into energy infrastructure are not only fulfilling energy demands but are cost-effective. This paper investigates and uses the Switch model, which is a modeling platform used to examine least-cost energy systems given extensive parameters and environmental quality standards [3]. It builds out energy generation technologies up to 2050 to determine the long-term effects of building technologies currently, due to the long lifespans of electric grids. Within it, modules for offshore wind and tidal energy are added, which adds their generation megawatt (MW) outputs and associated costs, and the cost-effectiveness of each is determined.

2 Background on Energy Methods

Offshore wind and tidal energy were chosen for this investigation due to their lack of presence in the United States. Solar and wind energy have been heavily studied and modeled, which has led to both public and private investments in infrastructure to support grid integration. As such, offshore wind and tidal energy are described and inspected to determine if the theoretical benefits can outweigh any drawbacks.

2.1 Offshore Wind Energy

In the United States, wind power has the largest share of renewable energy with about 43% of renewable energy and 8.4% of the country's electricity overall [4]. This is primarily onshore wind, which is the more developed technology that uses wind turbines located on land. Due to cost efficiency with minimal infrastructure needed to construct it, it became highly prevalent throughout the United States. Its technology matured rapidly from its vitality to achieving commitments from the Kyoto Protocol, which led to an efficient alternative to long-distance transmission to land-constrained regions with reduced environmental impact on the land around it [5]. However, wind speeds on land are inconsistent and often change directions, which limits electricity generation. Since onshore wind is intermittent at best, it proves difficult for load planning, as it can bolster an existing electric grid and only serve as a load adjuster or smoother during high peak hours [6].

Offshore wind generation utilizes turbines, similar to onshore wind turbines. Figure 1 shows a diagram of a typical wind turbine used within an offshore turbine. The rotor is directly connected to a low-speed shaft, which rotates at about 30-60 revolutions per minute (RPM), which corresponds to the amount of times the blade rotates. The gearbox connected to the rotor increases the rotational speed to 1000-1800 RPM, which is sufficient speed to move a generator to produce electricity [8]. The generator then produces 60-cycle alternating current (AC) electricity, typically through magnetic induction. Multiple turbines collectively contribute to a wind farm, typically containing tens to hundreds of turbines.

On average, offshore wind turbines have a larger rotor diameter and are taller than onshore wind turbines, which allows them to capture more energy through wind shear and increased wind speed from less obstructing objects [9]. Another crucial factor for offshore wind turbines apart from the wind speed is the depth and distance from the shore. Being closer than 30 meters to the shore allows turbines to be mounted to steel tubes driven into the seabed or gravity-based designs called monopiles. In transitional waters, or 30-60 meters deep, lattice structures are used to harness the tower to the seabed. Finally, deeper waters warrant floating substructures held down by anchors [10]. These three designs allow the turbine to reach high enough to capture winds away from the shore. However, distances away from the shore pose unique challenges to transporting the power from the generator to the

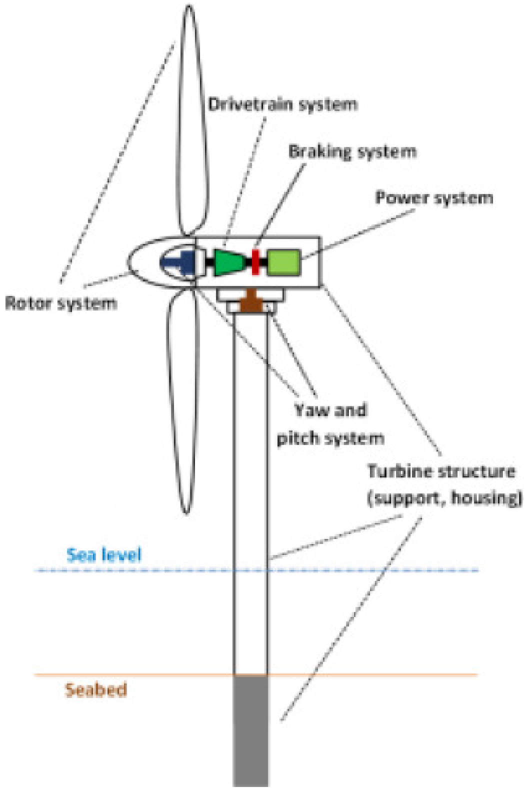

Figure 1: Diagram of offshore turbine structure [7]

shore. In smaller turbine arrays, the voltage is sufficient to allow undersea AC cables to connect turbines to a substation on the shore, but larger farms are routed to offshore transformers that raise the voltage to transport efficiently before transmission to shore.

Recently, the United States has encouraged growth in offshore wind investment. Auctions are used to sell offshore wind licensing areas in the ocean, and there is a declining trend in auction prices partially due to cost reductions due to other countries advancing their wind technology [11]. The United States can stay competitive in a global market in offshore wind, with limiting factors such as a domestic supply chain becoming less of a concern. Furthermore, the engineering process, capital cost reductions, and development of floating substructures have allowed for an easier and more economical installation of turbines [11]. An increased water depth of projects opens the door for more turbine installation sites, particularly for the western coast of the United States due to its narrow continental shelf and declining slope. Turbine capacity is also increasing steadily, which demonstrates more MW can be generated for fewer resources. This growth in rated power has contributed to lower offshore wind costs. Finally, the levelized cost of offshore wind has been reduced through the factors mentioned above, which contributes to a more economically efficient use of offshore wind to be deployed.

2.2 Tidal Energy

The United States has engaged in hydropower facilities, but primarily through hydroelectric dams. However, tidal energy plants work similarly, though instead of using the aggregate flow of water as dams do, the movement of water through the tides propels turbines to move. Figure 2 demonstrates a simple tidal turbine, which shows how the tidal current going in one direction pushes the turbine. Because water is significantly denser than air and could have foreign objects in it, turbines must be sturdier and heavier than wind turbines, which causes them to be more expensive but capture more energy with the same size blades [12]. Tidal power is also significantly less intermittent and predictable than both onshore wind and solar energy, which allows more consistent energy generation.

The main limitations of tidal energy have been cost and location. The tidal energy industry is largely emerging now, with barriers to overcome in terms of supply chain development. However, the United States already has three projects in development for tidal power plants, with two in Maine and one pilot project in the East River of New York [12]. The other limitation is the locations in which tidal plants can be constructed. There needs to be a minimum of 10 feet of tidal range for economic electricity output, which limits the locations of development due to the variable seabed. There are still places with immense tidal potential, the largest being the Cook Inlet in Alaska with almost 18 GW of tidal energy potential, which could power Alaska's road-connected communities twenty times over [13]. However, the Department of Energy has begun investing in tidal and river current energy systems because of its unique way of providing clean power to rural and remote island communities near tidal energy zones [14]. As such, tidal energy systems are in a unique position to determine the economic viability of building out sites, which is why capacity modeling is necessary.

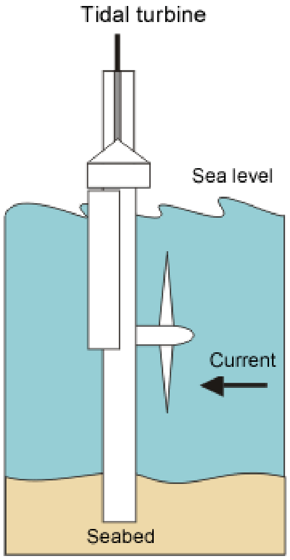

Figure 2: Diagram of tidal turbine structure [7]

3 Switch Linear Programming Capacity Model

Switch is a power system planning model that uniquely analyzes the design and investment plans for future power systems with large shares of renewable energy, storage, and demand response. It is a capacity expansion model that invests in different generation and transmission sources to examine least-cost energy systems designed to meet reliability, performance, and environmental quality standards. This report will utilize Switch primarily for California, though it has been expanded to explore energy options in the Western Electricity Coordinating Council (WECC), China, Chile, and Nicaragua with future plans in Africa and India.

Switch operates at different levels of temporal, spatial, and operational resolutions to allow in-depth analysis for grids that will last until at least 2060. Since electric grid components have lifetimes of decades, multi-stage investments are modeled through flexible temporal data structures capable of a multitude of sampled or defined time series. Operational timescales will reflect annual, seasonal, weekly, diurnal, and hourly variability of load including wind, solar, and hydro generation profiles [15]. Historical models use hierarchical time structures or probability distributions, but this disregards chronological sequences of system conditions because hourly balancing requirements are easier to address outside of planning investments. However, adding intermittent renewable sources makes hourly time slices important to planning capacities, especially with battery storage and load-shaving considerations.

Since Switch models power systems over large geographical scales, it hosts a modular architecture that allows the use of transport network models [15]. The spatial resolution is either copperplate or transport model. Copperplate uses a single-zone formulation for smaller networks that shows power transport within smaller grids. Those are interconnected through a transport model to represent inter-regional power transfers in many zones. Transport models allow balancing between granularity and tractability in expansion models by using linear terms to represent the cost and capability of the network.

Switch takes a unique approach to operational resolution that allows consideration of operating reserve and unit commitment (UC) decisions. Traditional capacity models assume loads can be met at any time point by any generator, which ignores UC. However, considering these and reserve requirements provides a better assessment of which technologies should be built in systems of highly renewable sources [15]. Switch utilizes linearized UC and solves mixed integer linear programming (MILP) with binary variables to represent power decisions with constraints in startup costs. This allows modularity for dispatch and investment rule customization which is especially useful for storage and generators [15].

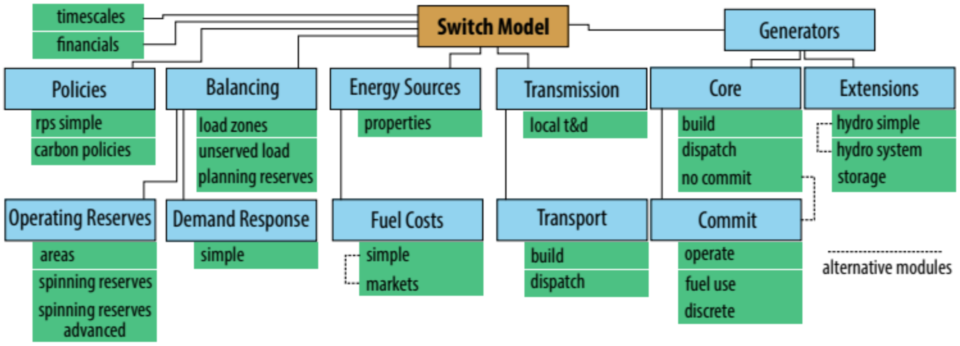

Figure 3: Package structure of Switch [15]

The Switch model is primarily written in Python and uses a hierarchy of modules to structure optimization problems. A diagram of the package structure is shown in Figure 3. Each module package, in green, serves a specific function in terms of adding information to the objective function and is defined as the blue name by the energy market function it serves. Each package tree adds constraints and variables to the model. The two essential modules to set up the framework of the model are timescales and financials.

The timescales package allows different temporal dimensions to be defined to produce different scales if the model is configured for higher granularity. Periods are multi-year timescales that describe when investment decisions are taken, which incorporate annualized costs. Timeseries sets allow for defining consecutive time points within a period, which could range from a day to a year. This allows specific load supply and generation options to ensure intermittent generation accurately meets loads at each defined granularity. Within a time series, timepoints are used to index variables such as demand and generation profiles, which is about an hour or more. This allows costs to be associated with hourly units. Timepoints are weighed within each period and treated as recurring segments, so these weighted times are used to calculate values on a per-year basis instead of per-period, which is beneficial for developing short-term investment decisions.

The financials package defines the financial parameters and the overall cost minimization objective function. The objective function is as follows:

$$min \sum_{p \in P} d_p \left\{ \sum_{c^f \in C^{fixed}} c_p^f + \sum_{t \in T_p} w_t^{year} \sum_{c^v \in C^{var}} c_p^v \right\}$$

with

$$d_p = \frac{1-(1+r)^{-y_p}}{r} * (1+r)^{-st_p - baseyear}$$

At its base, the objective function minimizes the net present value of all investment and operation/maintenance costs. Table 1 includes definitions of each variable. It calculates the discount factor at each particular year to convert annual payments during a period to a lump sum and changes each

Variable	Definition
P	Investment periods
d_p	Discount factor
C^{fixed}	Fixed cost components
w^{year}	Weight of timepoint in year
T_p	Timepoints in period p
C^{var}	Variable cost components
r	Discount rate
y_p	Length of period p (years)
st_p	Year period p begins

Table 1: Optimization function Variables with their definitions.

lump sum to a net present value. The rest of the minimization function is summing the fixed costs with the variable costs weighed by each weighing factor with the associated timepoint per year and variable cost. Since modules add various costs to the equation, both fixed or variable, the C^{var} and C^{fixed} are dynamic lists that are compiled at runtime to include all parameters, decision variables, and expressions to account for any constraints defined. Since this list is defined at runtime, it allows manipulation of which modules contribute to the function, which allows only relevant modules to be easily selected to isolate decisions, such as removing operational costs of transmission lines, leading to faster execution or greater spatial/time resolution.

Each package provides additional constraints to the optimization function that are solved against. The following are significant constraints that often have a high impact on the solution. The balancing module defines the power balance equation, which ensures the injected power to the system is the same as the power withdrawn. The Generators module ensures cumulative installed capacity is defined by the previous and current-period installed capacity, enforces nonnegativity of builds, and fixes legacy or maximum capacity for resource-limited generation projects. The policies module is optional but defines constraints relating to any governmental policy that the buildout would have to obey, such as numerically constraining buildouts to fit the Renewable Portfolio Standard policy scheme. This allows only building out models that fit the United State's mission to reduce greenhouse gases by a certain quantity, and customizing this module can propose new policies to enforce.

Relevant customizable package trees to this report are the Generators, Policies, Energy Sources, Fuel Costs, and Transport packages. The Fuel Costs and Transport are taken at their default packages from the assumption that existing infrastructure to deliver electricity to coastal loads already exists in coastal communities, and the primary cost will be the introduction of the generators themselves. Thus, fuel costs are already negligible due to these being renewable sources, and the transport costs are negligible as well. The properties package in Energy Sources will have the metadata on offshore and tidal energy to reflect any nuances of generation for the model. The offshore and tidal generation projects will be added to the inputs and then parsed through the Generators package, which determines which projects to build out and how many projects to dispatch in any given time series. This will work in conjunction with the Policies package, which is edited to reflect benefits to industry partners to construct offshore wind plants, such as tax credits.

Once the modules are filled out and the objective and constraint are defined, an abstract model is instantiated by reading in various input files to populate the dynamic lists. Afterwards, a linear programming solver is used to find the optimal and dual solution. Pyomo is used for the construction of the optimization modeling problem itself, which is an open-source optimization modeling language in Python. This paper uses the Gurobi solver, which takes in the model as a matrix, solves for the decision variables in MILP using the simplex method and mixed integer programming, and the results are parsed back into CSV files and visual representations. Since the objective function is linear concerning costs, LP solvers such as Gurobi are guaranteed to return an optimal solution that finds the minimal values of each cost while meeting all load and sustainability requirements.

4 Investigation and Implementation

This report investigates the development of offshore wind and tidal energy plants in three major locations in or near California: Morro Bay near San Luis Obispo, Humboldt Bay in the north Bay Area, and the Gulf of California off of Baja California.

4.1 Blue Economy ArcGIS and Location Selection

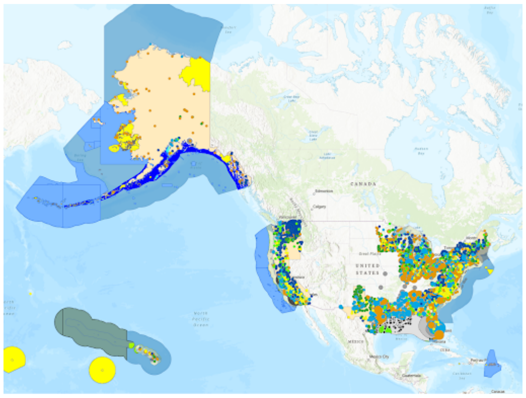

Figure 4: Composite blue economy ArcGIS map

To implement offshore and tidal energy modules into Switch, a comprehensive understanding of the blue economy was required. The blue economy is the summation of sustainable uses of ocean resources for economic growth, which includes renewable marine energy, fisheries, waste management, and maritime transport [16]. Research has expanded into this field for promising explorations into the blue economy while aiming to protect marine ecological environments since its sales, $610 billion in 2020, were greater than both agriculture and utilities in the United States [17]. To gain a comprehensive understanding of the blue economy and energy sources to supply it, a report was developed through the Renewable and Appropriate Energy Laboratory (RAEL) in collaboration with UC Berkeley and Tufts University students [18]. This report compiled an inventory of industries existing and planned in the United States utilizing ArcGIS modeling software. Its overlaid map layers create a composite map that shows individual sites, energy potential, or relevant power information to blue economy supply and demand. This is shown in Figure 4, which is the total overlaid map. By cross-referencing blue economy demand to its supply based on the map, locations for renewable generation can be optimized for transmission cost, generation potential, and need for energy. Using ArcGIS Pro, the feature to calculate the minimum distance from any point on the map was used to determine optimal locations for offshore wind development. Furthermore, wind speed was maximized using this map and overlaid with major energy use centers to optimize transmission costs.

Using the map, offshore wind locations were selected with viable infrastructure relating to the marine industry, and verified using external sources. The blue economy demand and supply were concentrated in two areas along California, and this lined up with the Biden Administration's instructions for offshore wind through the Department of Interior Bureau of Ocean Energy Management (BOEM) [b]. The first of these is Humboldt Bay, which is located about 200 miles north of San Francisco, California. It has the highest annual average wind speeds in the region, which provides the greatest potential for energy generation. The BOEM estimates about 1.5 gigawatts (GW) of electricity capacity at this location [19]. Furthermore, Humboldt County has the largest Native American population in California, and supporting an offshore infrastructure would provide energy support to an underserved population. Companies have already begun bidding and winning leases to start offshore wind projects in this area, and these projects are accounted for in the model. The second location is Morro Bay off the coast of San Luis Obispo, California. This is a large bay that is capable of generating 3 GW of electricity, and San Luis Obispo County uses about 1.7 GW of electricity [19]. The county also pays more for electricity compared to the state average, while consuming more than a third less electricity than the national average [19]. Therefore, this site was selected as it provides immediate potential for impact to fully service a location with higher electricity costs.

Due to the United States's low usage of tidal power thus far, an independent site was chosen for tidal energy considerations. The Gulf of California was chosen for consideration for this report. It has the largest tidal range in the vicinity of California and Mexico, which provides more potential for power generation [20]. Furthermore, the return period of storms is lower than in other regions, which reduces the risk of damage to equipment [20]. Theoretical annual energy yield in the northern region of the gulf was up to 50 kWh/m^2 and can service surrounding coastal areas [21]. The output of this project is estimated to this value for the Switch model, and this is assumed to have transmission to California due to its vicinity.

4.2 Switch Development

The development of the modules essentially adds further constraints to the objective function that defines how offshore and tidal energy should be handled. In each, Expressions and Variables are defined to add to Constraints for the linear programming model. In particular, these constraints have to follow LP and simplex method LP rules to ensure convex constraints. From the definition of LP, this guarantees a unique solution.

Inputs to the model without modifying the module structure provide the basis for calculating all costs and energy outputs. Variables take this information within the modules to form each relevant data frame. The model reads these inputs through CSV files. The following files were edited to incorporate offshore and tidal energy information, with specifics available in the Appendix. The graph_tech_types.csv file contains each type of generation technology and defines the energy source when tracking solutions to graph outputs. Offshore wind and tidal energy were added here to include their values in graphs if built out and is shown in section 10.1. After this is defined, the generation_projects_info.csv is populated with any potential projects. It contains multiple fields, including generation source and technology, load zone, variability of generation, cost per MW, operating costs, capacity limits, build capacity, efficiencies, and more. Offshore and tidal projects in development are collected and listed in this file to add to the model. These projects were chosen due to proximity to the locations selected for California, and an example is available in Appendix section 10.2.

The main purpose of adding modules to the existing Switch infrastructure is to add constraints to the optimization problem and limit the set of generation and load options within the optimization function itself. Modularizing into separate files allows for seamless integration into the existing Switch framework, especially when adding generation sources that were not present before. One use case of the modules is to incorporate cost benefits that are not easily added to input files, such as tax credits. Tax credits are especially significant for emerging renewable technologies, as there exist policies to help with the large capital cost of building each generator. Concerning offshore wind and tidal energy, there are tax credits that affect both kWh produced and capital investments into renewables. The Inflation Reduction Act (IRA) increased tax credits for wind energy projects that begin construction before 2025 [22]. From this, there are two major tax credits. The Renewable Electricity Production Tax Credit (PTC) is a federal income tax credit on every kWh of electricity supplied to the power grid. The basis used for this report is the extension of the IRA into 2024, which is $0.026 per kWh. Another significant factor is the Business Energy Investment Tax

Credit (ITC), which is a tax credit for capital investments in renewable energy projects. For offshore wind projects, this represents a credit of 6 to 30% of expenditures, which is significant for these capital-intensive technologies. These tax credits are implemented in the Switch model by defining Expressions and Variables in a Pyomo abstract model. The annualized tax credits are essentially prorating the annual variable and capital costs, and the following is the model for the PTC, where G is the set of generators, PTC is the tax credit per kWh, DG_i is the dispatched kWh for generator i, and VC_i is the variable cost at generator i:

$$\sum_{i \in G} PTC * DG_i + VC_i$$

An implementation of the Python code of a module is available in the Appendix in section 10.3. When such modules are added to the Switch model runner, it provides the extra constraints to minimize. The model was 352,823 rows by 419,707 columns in terms of equations generated from the inputs.

5 Results and Analysis

5.1 Model Outputs

The model uses baseline inputs from the Renewable Energy and Appropriate Laboratory's repository, which contains data for the Western Electricity Coordinating Council (WECC). However, for the use of this report, any generation and loads are limited to California to isolate localities where offshore wind and tidal energy would directly impact. Solving this problem on this existing and projected renewable model took 23.04 minutes to run, which included constructing the model, solving based on the constraints, and generating output plots and spreadsheets as outputs. The model was constructed successfully and due to it following dynamic convex programming rules, the objective was minimized successfully. The optimal objective was $2.037 * 10^8$, which represents the total cost of the system.

There are many spreadsheets and graphs generated from the model which give a holistic view of the power system modeled by Switch. These include composite maps of transmission lines built out, battery or fuel storage duration, energy balances, curtailment periods, capacity values by period, build-out and fuel use rate, and load balancing. The following are relevant outputs from the model that impact financial decisions for offshore wind and tidal energy.

One metric for the success of this model is the level of emissions outputted by each technology. It is considered successful if the emission level is reduced by a significant amount while meeting all required load levels for any energy sink. The model builds a constraint that all loads must be met to an adequate level, therefore only the total emissions from the model can be considered. The model aims to minimize emissions with an additional constraint to being emission-free by 2050. This was achieved in the optimal solution, with the following figure showing total emissions per period of 10 years:

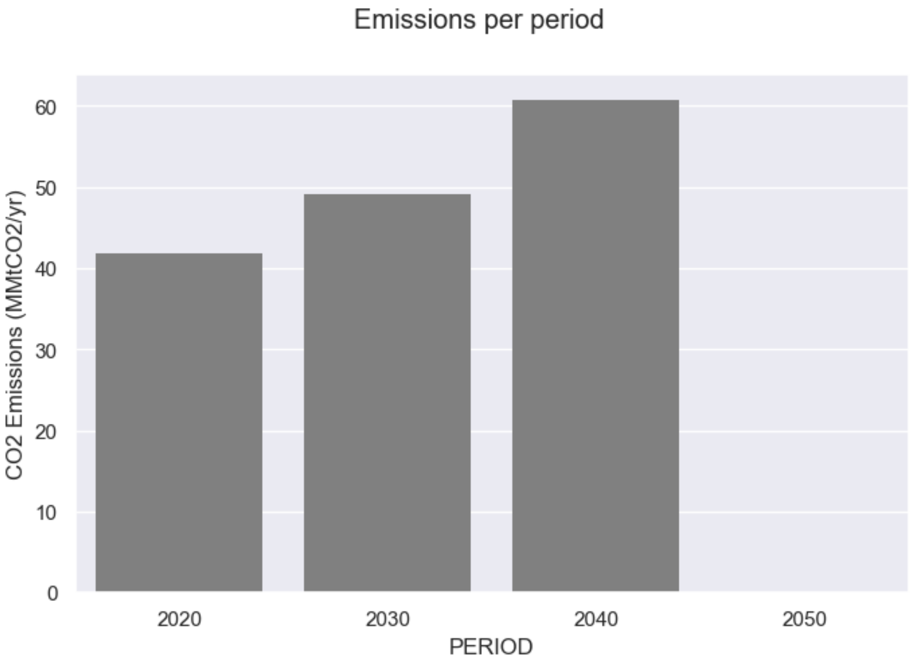

Figure 5: Emissions with 2050 having zero emissions as a constraint

The maximum yearly annual emissions are 60,815,000 metric tons of CO_2, which was during the 2040 period. While the goal to reduce emissions to zero is extremely ambitious, the highest emitting year during this model is still significantly lower than current emitting levels, with California emitting

Period	Offshore Wind MW	Tidal Energy MW
2020	0	0
2030	0	0
2040	250	0
2050	2100	0

Table 2: Built out MW per technology

Period	Offshore Wind GWh	Tidal Energy GWh
2020	0	0
2030	0	0
2040	563.4	0
2050	4732.9	0

Table 3: Power dispatch per technology

about 324,000,000 metric tons of CO_2 in 2021 [23]. This is a reduction of 82% of existing carbon emissions, which is significant enough to consider the emissions a valid success factor.

The next observations to make are if any additional capacity of offshore wind or tidal energy sources was used from the model. Table 2 has the outputs that detail how many MW were built out for each period for specific technologies. This does not include existing facilities that already exist.

The MW built out corresponds directly to dispatched power per technology. A post-solve method in Switch calculates the gigawatt hours (GWh) in a typical year for each technology in the model. Table 3 presents these values.

As shown, offshore wind is built out in future years, which takes into account the decreasing costs of offshore wind. This does not include government policies that may support this, as the ITC and PTC currently do but expire in 2025. Based on this information, offshore technology is trending in the correct direction and with additional investment to decrease costs further, demonstrates its long-term potential for serving loads. While its output is significantly lower than other well-established technologies such as solar or wind, the fact that it was built out in the later periods of the model demonstrates its usability. On the other hand, tidal energy was not built out. This can be attributed to its immensely high capital costs that serve as a high barrier to any investment. Despite limited tax credit incentives, the cost of tidal energy prevents investment into the industry and thus remains untested, as estimates say tidal energy costs \$130 to \$280 per MWh, while onshore wind energy is significantly lower, with a lower bound of \$20 per MWh [24].

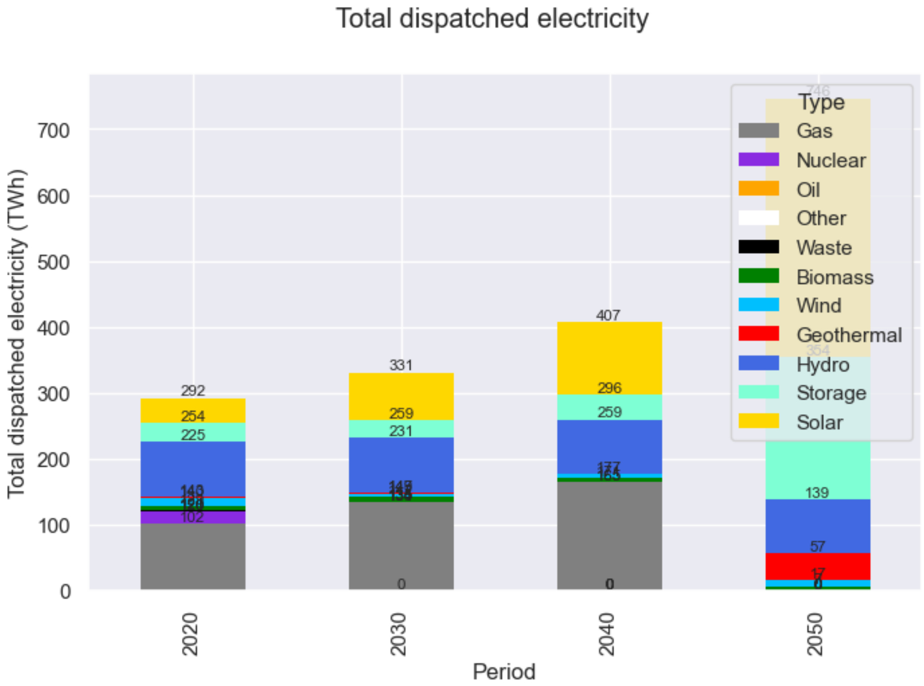

Figure 6: Total dispatch by generation type

Figure 6 shows the total dispatched electricity per type of generation technology. The first three periods have gas-powered generators as the predominant sources, with solar and hydropower as the next largest. Offshore is lumped together with onshore in this graph. Though the legend covers it, solar will become the dominant source along with storage in 2050, which removes the need for a gas-powered generation. However, there is wind present in the long term. Even with the relatively increased costs, the presence of wind in conjunction with solar shows its potential. Tidal power is not present as it was not dispatched, which further demonstrates its infeasibility unless costs decrease. As this analysis was considered with transmission across California as a whole, another point of consideration is how these turbines should be constructed together. The following section shows two options that increase the value of offshore wind in particular.

5.2 Distributed Energy Resources

Distributed Energy Resources (DERs) are modular generation and storage technologies that either provide energy or capacity. Usually smaller in size, they allow localized energy needs to be met, such as an increased battery capacity near a factory. DERs can utilize many types of technologies that allow modularization into smaller generation projects, such as photovoltaics, turbines, and more [25]. A grouping of DERs makes up a distributed generation system, which enables and controls power flow amongst various intakes and outputs depending on immediate, local demand. The alternative to this solution is a centralized approach, which is a classical approach that concentrates energy production in a small area and uses a large distribution network to deliver power along sites using substations.

Offshore or tidal turbines can be configured into DERs, which would allow locations to service larger coastal blue economy areas such as fisheries or ports. Each smaller set of turbines would allow peak load shaving during significant hours of operation. This is particularly impactful as offshore wind speeds peak at similar load leaks, which reduces the need for peak power procurement and deferred asset upgrades. This enables direct consumption of energy with limited transmission and allows cheaper, cleaner energy for locations with high energy demand. Since DERs do not depend on a larger grid to operate, they are less susceptible to blackouts and are reliable during outages, which is especially important in coastal areas where tsunamis, hurricanes, or other hazardous events increase as sea levels rise. One argument against offshore turbines is the aesthetic concerns, as locals may not enjoy turbines extremely close to shores. However, if used as DERs amongst high industry areas that use power, such as loud fisheries, consumers are less likely to consider the aesthetics of the area. While the centralized method's primary benefit is the ease of use through an existing infrastructure of the old electric grid, the long-term benefits of treating turbines as DERs outweigh the benefits in the short term. The use of smaller wind turbines being built out through Switch demonstrates its potential for cost reduction and can support a burgeoning blue economy with more demand increasing at the coast. As the cost of turbines trends down through increased investment, existing blue economy facilities can benefit from lower demand charges as more serviceable areas appear.

6 Conclusion

This report investigated offshore wind and tidal energy plants and showed their respective feasibility using the Switch linear programming capacity model. After utilizing the interactive ArcGIS map, locations for the offshore wind turbines and marine energy were chosen proximate to California based on blue economy demand, supply, and potential for energy generation. After implementing various modules, the optimization cost minimizer function was edited and a unique solution was obtained and analyzed. The capacity model solution allowed a comprehensive showing of the economic viability of building out offshore and tidal turbines along the coast of California. Offshore wind shows considerable potential due to policy support from the United States in the form of tax benefits. While tidal energy was considerably less favorable, the limiting factor was the cost of building the turbines, which has demonstrated limited investment interest and therefore may produce far long-term solutions. The economic value of these technologies was viewed and their implementation methods were analyzed, in particular distributed or centralized systems. From the different benefits and concerns, using turbines as DERs demonstrated long term long-term value for infrastructure investment and overall demand satisfaction.

7 Future Work

This report covers the discussion of offshore wind and tidal energy, and the highly modular structure of Switch enables any number of renewables to be integrated into the model. As such, future work can include more types of renewable energy that may not be extensively covered in the model thus far, such as hydrogen-splitting power plants. Switch has been used to cover different geographical regions, including China and parts of Africa in addition to the United States, so a larger model can be encompassed to foster relations between intergovernmental energy departments to improve transmission, such as between the United States and Canada or Mexico. Finally, since there are always irregularities in energy grids, future work can incorporate non-linearities into the model and possibly develop a nonlinear capacity model that ventures further into AC network models, which require more data due to requiring iterative solutions. Optimizing the speed of this capacity model can further allow larger models to be developed.

8 Acknowledgements

I would like to thank Professor Robert Pilawa-Podurski and Professor Daniel Kammen, my advisors. I would also like to thank RAEL and everyone involved in the laboratory for all their support.

9 References

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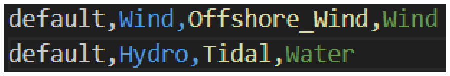
10 Appendix

10.1 graph_tech_types.csv

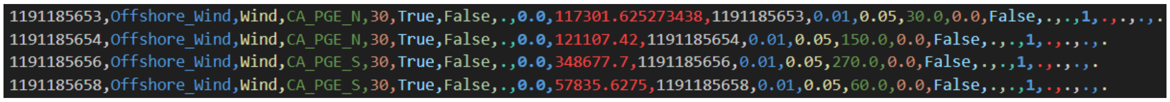


```
default,Wind,Offshore_Wind,Wind
default,Hydro,Tidal,Water
```

Screenshot of entry in graph_tech_types.csv

In order of the columns, the values are the map type, generation type, generation technology, and energy source.

10.2 generation_projects_info.csv

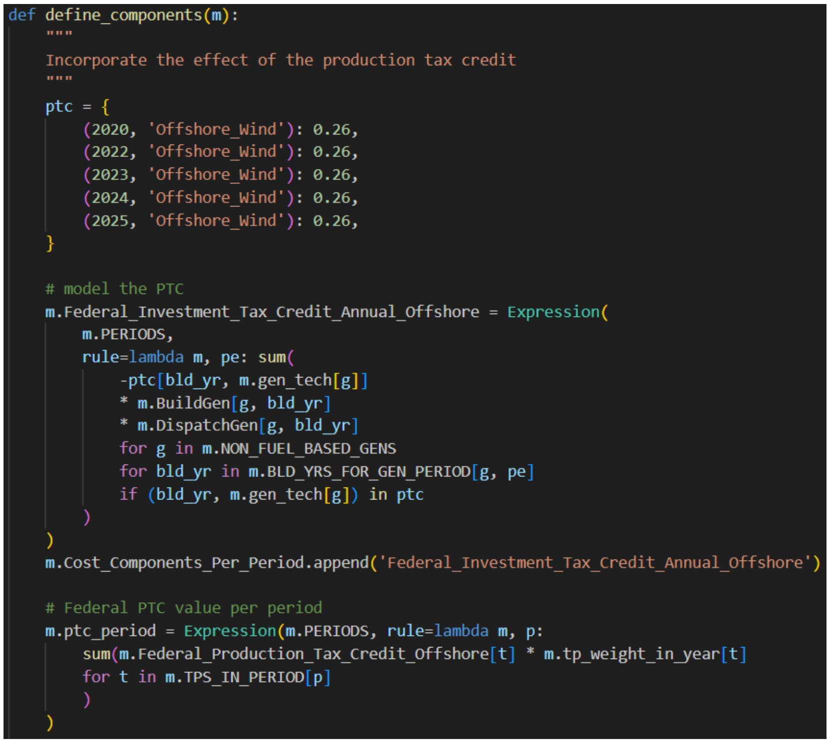


```
1191185653,Offshore_Wind,Wind,CA_PGE_N,30,True,False,.,0.0,117301.625273438,1191185653,0.01,0.05,30.0,0.0,False,.,.,1,.,.,.,.,.
1191185654,Offshore_Wind,Wind,CA_PGE_N,30,True,False,.,0.0,121107.42,1191185654,0.01,0.05,150.0,0.0,False,.,.,1,.,.,.,.
1191185656,Offshore_Wind,Wind,CA_PGE_S,30,True,False,.,0.0,348677.7,1191185656,0.01,0.05,270.0,0.0,False,.,.,1,.,.,.,.
1191185658,Offshore_Wind,Wind,CA_PGE_S,30,True,False,.,0.0,57835.6275,1191185658,0.01,0.05,60.0,0.0,False,.,.,1,.,.,.,.
```

Screenshot of entry in generation_projects_info.csv

In order of the columns, the values are generation project ID, technology used, energy source, generator load zone, generator maximum age, variability of generation, baseload, full load heat rate, variable operating maintenance costs, connection cost per MW, generation ID from database, scheduled outage rate, forced outage rate, capacity limit in MW, minimum build capacity, cogeneration technology, storage efficiency, storage to release ratio, cap reserves, self-discharge rate, generator land use rate, and storage energy to power ratio.

10.3 Module Code Snippets



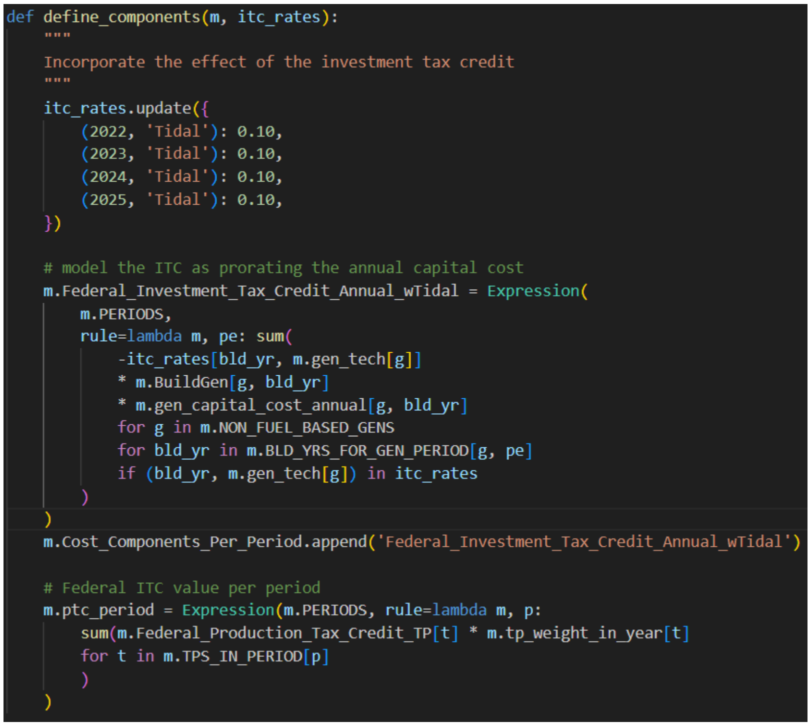
```
def define_components(m):
    """
    Incorporate the effect of the production tax credit
    """
    ptc = {
        (2020, 'Offshore_Wind'): 0.26,
        (2022, 'Offshore_Wind'): 0.26,
        (2023, 'Offshore_Wind'): 0.26,
        (2024, 'Offshore_Wind'): 0.26,
        (2025, 'Offshore_Wind'): 0.26,
    }

    # model the PTC
    m.Federal_Investment_Tax_Credit_Annual_Offshore = Expression(
        m.PERIODS,
        rule=lambda m, pe: sum(
            -ptc[bld_yr, m.gen_tech[g]]
            * m.BuildGen[g, bld_yr]
            * m.DispatchGen[g, bld_yr]
            for g in m.NON_FUEL_BASED_GENS
            for bld_yr in m.BLD_YRS_FOR_GEN_PERIOD[g, pe]
            if (bld_yr, m.gen_tech[g]) in ptc
        )
    )
    m.Cost_Components_Per_Period.append('Federal_Investment_Tax_Credit_Annual_Offshore')

    # Federal PTC value per period
    m.ptc_period = Expression(m.PERIODS, rule=lambda m, p:
        sum(m.Federal_Production_Tax_Credit_Offshore[t] * m.tp_weight_in_year[t]
        for t in m.TPS_IN_PERIOD[p]
        )
    )
```

Screenshot of PTC implementation

The above is the implementation of the offshore PTC, which removes costs from the objective function in non-fuel-based generation and modifies the constraints after the fact. It uses periodic timescales as this is the finest level the tax incentives can operate on. The operating values, such as spinning reserve requirements, are approximated similarly to onshore wind. This is a reasonable assumption to make because the regulations for turbines are similar, so the relative data should be similar as well.



```
def define_components(m, itc_rates):
    """
    Incorporate the effect of the investment tax credit
    """
    itc_rates.update({
        (2022, 'Tidal'): 0.10,
        (2023, 'Tidal'): 0.10,
        (2024, 'Tidal'): 0.10,
        (2025, 'Tidal'): 0.10,
    })

    # model the ITC as prorating the annual capital cost
    m.Federal_Investment_Tax_Credit_Annual_wTidal = Expression(
        m.PERIODS,
        rule=lambda m, pe: sum(
            -itc_rates[bld_yr, m.gen_tech[g]]
            * m.BuildGen[g, bld_yr]
            * m.gen_capital_cost_annual[g, bld_yr]
            for g in m.NON_FUEL_BASED_GENS
            for bld_yr in m.BLD_YRS_FOR_GEN_PERIOD[g, pe]
            if (bld_yr, m.gen_tech[g]) in itc_rates
        )
    )
    m.Cost_Components_Per_Period.append('Federal_Investment_Tax_Credit_Annual_wTidal')

    # Federal ITC value per period
    m.ptc_period = Expression(m.PERIODS, rule=lambda m, p:
        sum(m.Federal_Production_Tax_Credit_TP[t] * m.tp_weight_in_year[t]
        for t in m.TPS_IN_PERIOD[p]
        )
    )
```

Screenshot of ITC implementation

The above is the implementation of the tidal energy ITC. It represents a similar methodology to PTC, as the model backend uses the cost of building the system in conjunction with the electricity produced, which is what the PTC uses to calculate costs.