Imperial College London

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MSc in Environmental Data Science and Machine Learning

Independent Research Project
Final Report

An Investigation into Tidal Range Energy Integration in the UK's Renewable Energy Mix

by

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September 2023

Abstract

In the face of escalating environmental challenges and growing demands for sustainable energy, this study delves into the integration of tidal range energy within the UK's renewable energy mix. Utilizing the Python for Power System Analysis (PyPSA) model and other pertinent tools, we investigated the potential of tidal energy in the UK and assessed its role in meeting the nation's energy demands. Results indicate that tidal energy, as a predictable and reliable form of energy, holds significant promise within the UK's renewable energy portfolio. Additionally, the study underscores the importance of optimizing tidal energy systems and the potential of multi-sector coupling, offering valuable insights for future energy system planning. In conclusion, tidal energy emerges as a pivotal renewable energy source, crucial for the UK's aspirations towards a low-carbon and sustainable energy future.

1 Introduction

1.1 Power System and Renewable Energy

Power systems play a crucial role in providing electricity to meet the growing energy demands of modern societies. A power system, also known as an electrical grid, encompasses the generation, transmission, and distribution of electricity to end consumers. [1]

The primary goal of a power system is to ensure the reliable and efficient supply of electricity. It involves the integration of various components, including power plants, transmission lines, substations, transformers, and distribution networks. These components work together to deliver electricity from the generation sources to homes, businesses, and industries. [2]

Power systems face several challenges and considerations. One of the key challenges is the integration of renewable energy sources into the power grid. With the increasing focus on sustainability and reducing greenhouse gas emissions, renewable energy generation from sources like solar, wind, and hydro has witnessed significant growth. However, the intermittent nature of these sources introduces complexities in maintaining grid stability and managing fluctuations in supply. [3, 4, 5, 6]

1.2 Tidal range energy

Tidal range energy is a highly predictable form of renewable energy that leverages the differential in water levels, or the tidal range, caused by the gravitational pull of the moon and the sun. It offers a reliable and sustainable solution for electricity generation. Unlike wind and solar energy, tidal range energy can be accurately forecasted years in advance due to the predictability of the astronomical tides. The principal mechanisms to harness tidal range energy are through tidal barrages, tidal lagoons, and dynamic tidal power (DTP) systems. [7]

The potential of tidal range energy is dependent on the geographical location. Ideal locations have large tidal ranges and suitable topography for infrastructure development. The Bay of Fundy in Canada and the Severn Estuary in the UK are prime examples of sites with high tidal range energy potential. [8, 9, 10, 11, 12] The environmental impact of tidal range energy, while generally less harmful than fossil fuel-based energy sources, should still be carefully assessed. Building structures like tidal barrages can impact marine and bird life, alter sediment dynamics, and affect navigation and recreational activities. Hence, thorough environmental impact assessments are crucial before the development of tidal range energy projects. [13, 14, 15]

Optimization of tidal range energy systems involves various factors, including the design of turbines, the arrangement of infrastructure, and the operational strategy. This includes deciding the best time to generate power, given the tides and energy demand patterns, and the optimal size and layout of the infrastructure to maximize energy generation and minimize environmental impact. [16, 17, 18, 19, 20, **?**, 21]

The integration of tidal range energy with other energy sources is an important aspect of renewable energy system design. The predictability of tidal range energy can provide a balance to intermittent renewable sources like wind and solar power, contributing to a more resilient and reliable energy grid. Its integration could also involve energy storage systems to manage the supply-demand balance and ensure a consistent power supply during periods of low tide. [22, 23]

In conclusion, tidal range energy, while not yet widely utilized, offers significant potential as a predictable and reliable source of renewable energy. The assessment of resources and impacts, optimization strategies, and integration efforts are critical aspects to consider in harnessing tidal range energy effectively and sustainably.

1.3 PyPSA model

The Python for Power System Analysis (PyPSA) model is a cutting-edge tool that is incredibly useful for integrating renewable energy sources into a power system. [24, 25]

PyPSA is a free software toolbox for simulating and optimizing modern power systems. [26] This includes systems with high penetrations of renewable energy sources, such as wind and solar power. The model is designed to provide a high degree of flexibility and scalability, allowing users to study small microgrids or large-scale systems that span continents.

In conclusion, PyPSA is a powerful tool for modeling and optimizing power systems with a high share of renewable energy. Its ability to handle the complexity and variability of renewable resources makes it a valuable resource for power system planners and operators. However, the inclusion of tidal energy in PyPSA would further enhance its capabilities, providing a more comprehensive view of the opportunities and challenges associated with integrating renewable energy into the power system.

2 Methods

2.1 uptide

Tidal height data were obtained using the FES2014 tidal dataset, which provides amplitudes and phases of a wide range of tidal constituents at a spatial resolution of 1/16°$\times$1/16°. The tidal height time series is constructed from eight tidal components: Q1, O1, P1, K1, N2, M2, S2, K2. Utilising the interpolation function in the uptide package obtains a time series of tidal heights at the corresponding coordinates of the input cutout grid, with a temporal and spatial resolution consistent with that of the cutout grid in atlite.

2.2 Tidal range model

The Tidal power plant operation model primarily simulates the evolution of water levels between the internal water body (η_i) and the open ocean (η_o) and computes the associated tidal power plant performance information.

The 0-D model does not account for the impact of adding impoundments or the functioning of related hydraulic features on the fluctuation of water levels in the surrounding water system.

$\eta_o(t)$ is obtained as a function by interpolating a time series of grid tidal heights. Elevation of open water body and the operational control variables as well as the lagoon specifications together determine the change in flow (Q), and therefore, the next timestep internal water body height. This process is based on the following equation:

$$\frac{d\eta_i}{dt} = \frac{Q_s(m, H, t) + Q_t(m, H, t)}{A_s(\eta_i)} \tag{1}$$

Here $A_s(\eta_i)$ is the wetted area (m^2) of the tidal differential structure, which is set here as a constant that does not vary with depth, and is estimated from the maximum usable area of the mesh calculated by land use availability. Qs and Qt are the flow rates (m^3/s) through the sluice and turbine, and here it is assumed that the height of the internal water body in the reservoir is kept constant. The head difference $H = \eta_o - \eta_i$ can be used to calculate Qs (based on orifice equation) and the hill chart parameters of the turbine, including Qt and Pt. The specific operation model of the tidal differential power plant is described in detail in Angeloudis et al.. [17]

2.3 Atlite

In the atlite, a module for obtaining tidal height data was implemented as well as functions for obtaining relative tidal energy information, which include theoretical tidal range energy resource (kWh/m^2), installable tidal power plant capacity density (MW/m^2), and capital cost (€$/kW$) and specific generation time series (MWh/MWp).

The theoretical resource density of tidal range energy is calculated by the following equation:

$$PE = \sum_{i=1}^{n} \frac{1}{2} \rho g H_i^2 \tag{2}$$

For each grid cell, the tidal range (H) time series is calculated, i is the number of consecutive falling and rising. rho is the density of seawater, and g is the acceleration due to gravity. The resulting contour map of the UK potential tidal range energy density (in kWh/m^2) is shown in Fig. 1.

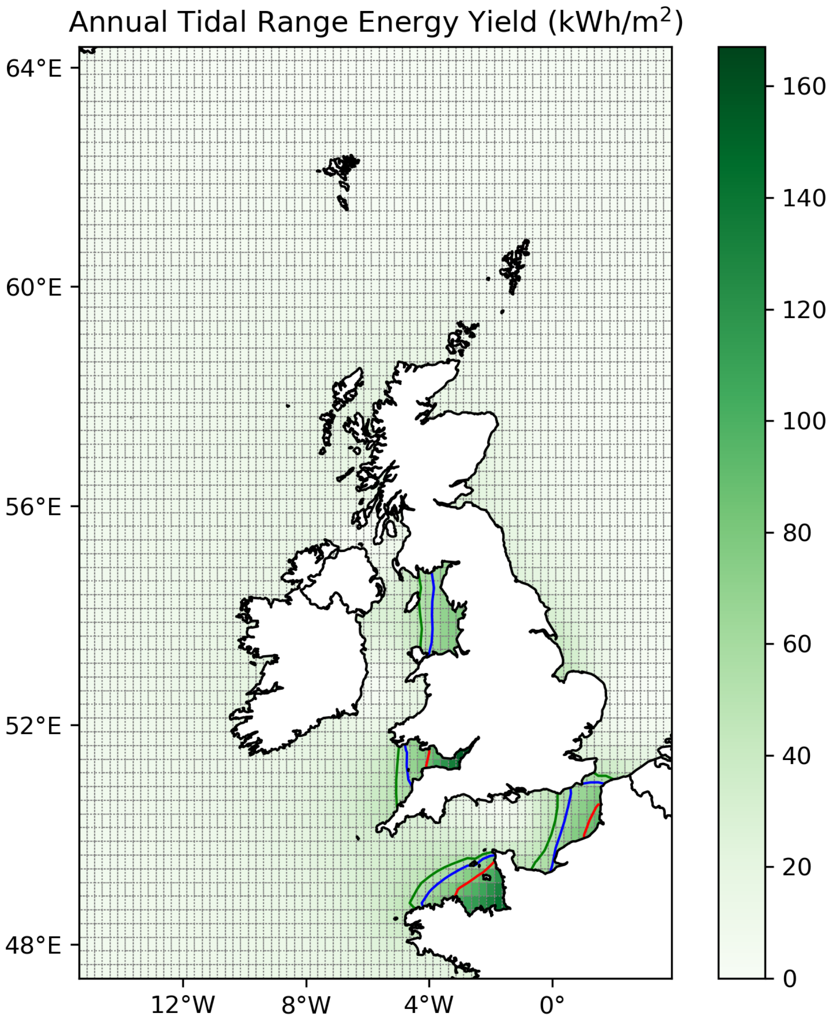

Figure 1: Annual Tidal Energy Yield (KWh/m^2) of the UK.

Tidal power plant installable capacity density is calculated as follow:

$$CD = 2 \times efficieny \times \frac{\rho g DH^2}{2 \times 12.42 \times 3600 \times cf} \tag{3}$$

DH is the mean tidal height of time series, efficiency is the empirical resource conversion efficiency, cf is the estimated value of the capacity factor of the tidal differential power plant, and 12.42 refers to hours in a M2 tidal cycle, and there are two tidal ranges generated in a cycle, thus multiplying by 2 before the whole equation.

The capital cost consists of three main components: the turbine cost, the caisson cost and the impoundment cost. It is for a lagoon/barrage whose required area and capacity are known. As an input of PyPSA-Eur technology cost, tidal power plant cost is gained from an average cost of all simulated grid.

Specific power generation time series of the tidal range power plant is calculated from the tidal power plant operation 0-D operation model, which is implemented as described above. Specific power generation is the amount of energy generated per unit of installed capacity. This metric indicates the efficiency of the power generation system in converting installed capacity into actual power generation. It can be converted to static capacity factor by averaging the specific generation over the simulation time length.

Python code for calculating generation time series is shown in the following code listing.

```
# sum of generation
generation = cutout.tidalplant(lagoon='20MW', operation='two-way', area=
    available_area)
# static capacity factor
cf = cutout.tidalplant(lagoon='20MW', operation='two-way', area= available_area,
     capacity_factor=True)
# generation time series
profiles, capacities = cutout.tidalplant(lagoon='20MW', operation='two-way',
    area= available_area, layout=layout, matrix=availability, return_capacity=
    True)
# https://github.com/ese-msc-2022/irp-zz5322/blob/main/atlite/atlite/convert.py

```

There are three configuration of 'lagoon' which represents the capacity of individual turbine: '20MW', '30MW', '40MW'. Three way of 'operation' which represents the operation mode of turbine: 'ebb-only', 'two-way', and 'two-way-pump'. 'area' is the required area of impoundment.

Layout is used to assign the capacity to be built in each of the grid cells. To compute the layout of plant, the installable potential in each grid cell is multiplied with the capacity factor at each grid cell, because it is supposed that more generators are installed at cells with a higher capacity factor. Matrix is the availability that a technology can be installed at each grid cell and each node and it is used to aggregate the grid cells to buses. Availability is deciced by the CORINE land use data, Natura2000 nature reserves and GEBCO bathymetry data as well as global shipping traffic density from the World Bank Data Catalogue.

2.4 PyPSA-eur

The study focuses on the United Kingdom as the research subject, utilizing weather data and historical electricity generation and demand data from the year 2019, as well as technology cost data projected for the year 2035. The analysis adopts an "electricity-only" scenario, simulating the power system and its optimization under the assumption of a carbon dioxide emission constraint of 100 million metric tons. This approach offers insights into the dynamics of the UK's power sector, considering the interactions between renewable energy sources, electricity generation, and demand within the specified emission constraint framework.

3 Result

3.1 Atlite

For the resolution of grid cells, tidal range model is defined as an object and simulation of operation is run in each grid where availability is not zero. The result of the simulation is the generation time series of each grid cell. The generation time series is then aggregated to buses, which is the smallest unit of the PyPSA-Eur model. One of the result of the simulation is shown in Fig. 2. The location this grid is marked with red line in Fig. 3.

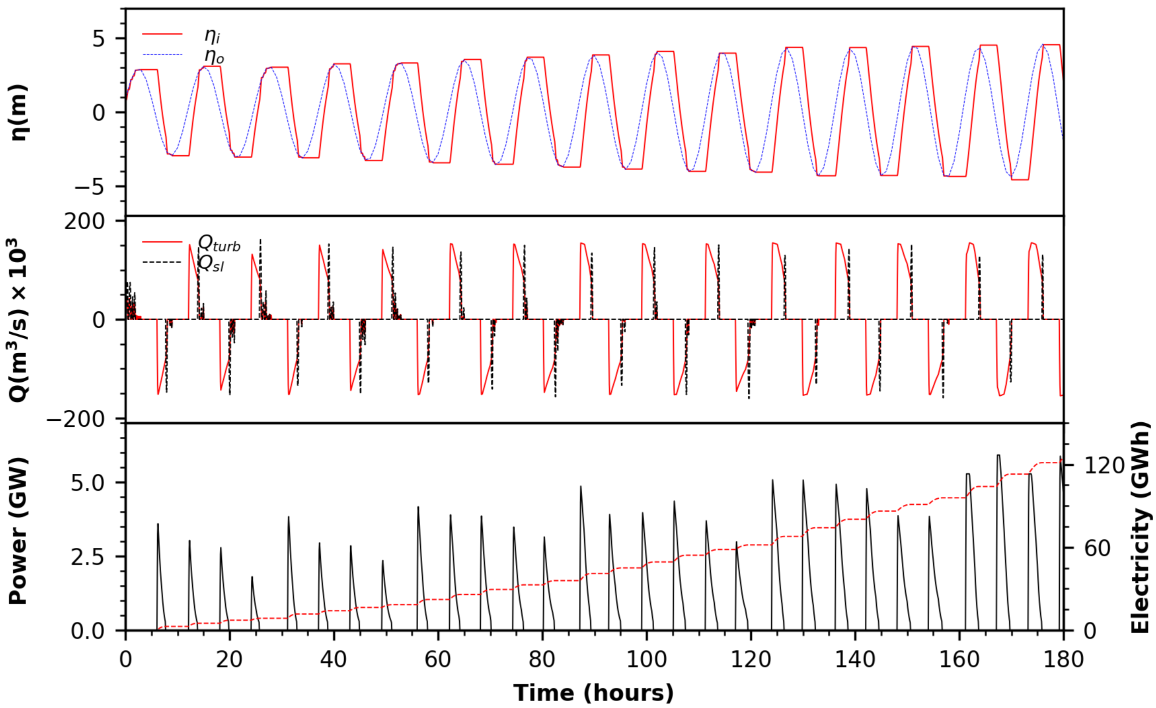

Figure 2: 0-D tidal range model

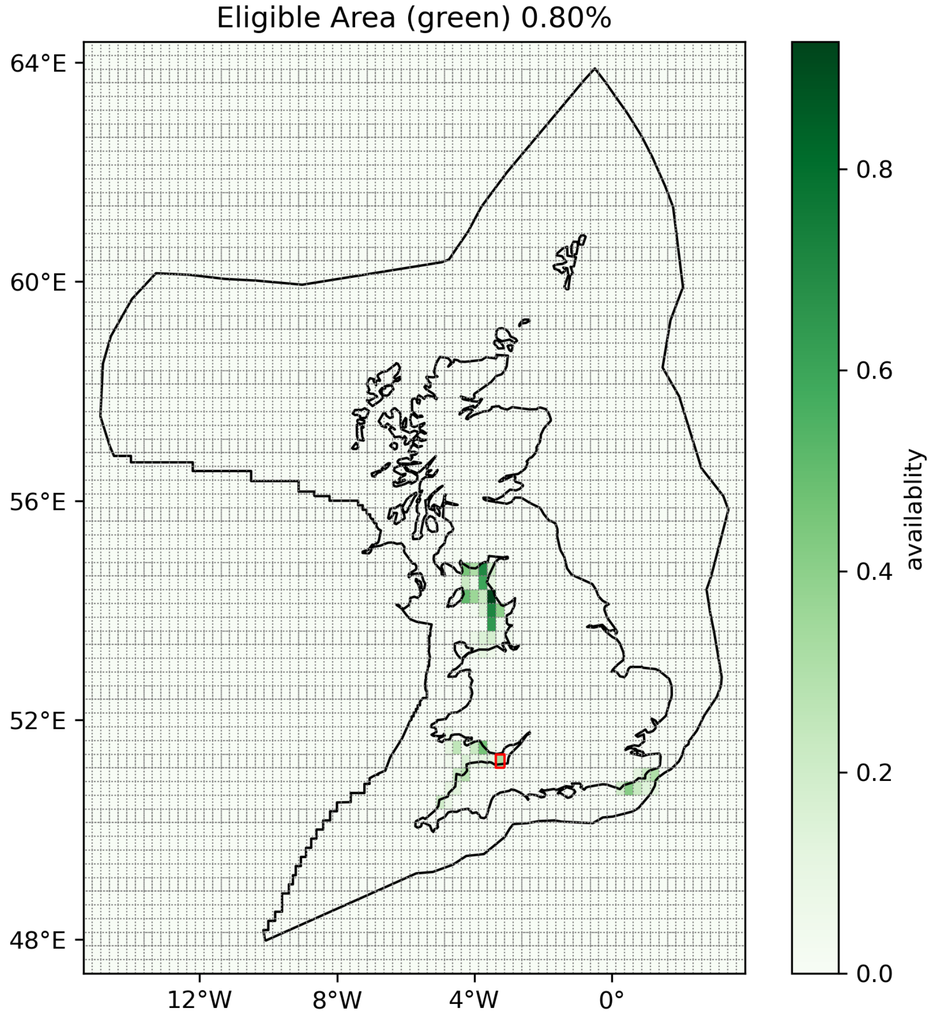

Figure 3: Eligible area

For the resoultion of buses, the result of atlite conversion will be aggregated to offshore regions of the UK which are resulted from the simplification and clustering of network in PyPSA-Eur. In Fig. 4, there are 82 regions and only 28 regions that have values.

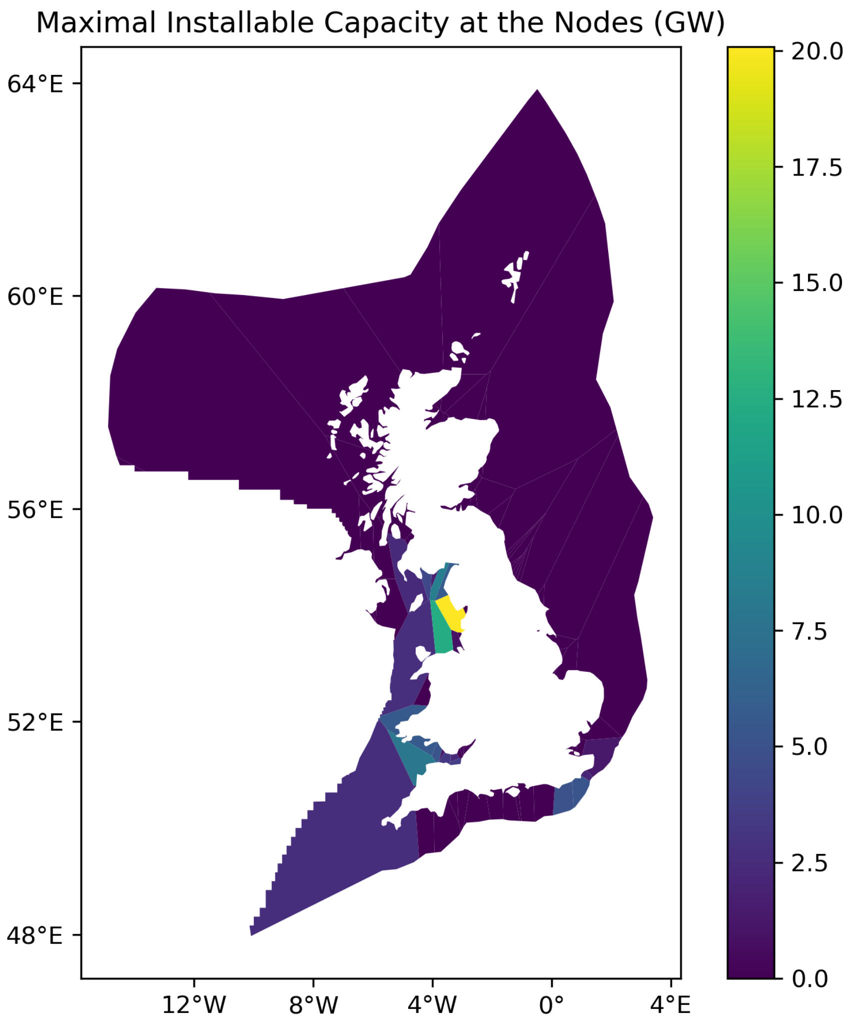

Figure 4: Installable capacity

Overall, it is assumed that exploitable areas are those with water depths $<$ 30 m, an annual yield above 50 kWh/m^2. Moreover, ship density threshold is set to 400, only CORINE category 44 (ocean) and 255 (unknown) are included, and natural protected area is excluded. Then approximately 5792 km^2 of sea is exploitable in the UK (Fig. 3), which contributes to a total potential energy of 393 TWh per annum. It is observed that the theoretical resource is mainly located in along the UK coasts of Liverpool Bay, the Severn Estuary and Bristol Channel, the Wash, and southeast England. [20]

Comparing to the result of earlier research which estimates the total potential energy of the UK to be 683 TWh per annum [20], the result of this research is lower out of more constraints, especially when considering ship threshold.

Table 1
Theoretical resource

	Eligible Area (km^2)	Installable Capacity (GW)	Annual Energy Yield (TWh)
all constraints	5792	105	393
no ship threshold	9229	174	657

3.2 PyPSA-Eur

The optimization of the power system using PyPSA has led to an efficient allocation of installed capacities across various energy carriers, aligning with the overarching goal of minimizing costs while adhering to a carbon dioxide emission constraint of 100 million metric tons. The optimized installation capacities for different energy carriers reflect the tailored response of the system to achieve cost-effectiveness while mitigating emissions.

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Among the energy carriers, tidal energy emerges as a focal point of the study. With an optimized installed capacity of 44.95 GW (Fig. 5), tidal energy underscores its significance as a key contributor to achieving emission reduction targets while ensuring a reliable and sustainable energy supply. This substantial allocation to tidal energy highlights its potential to harness the predictable and abundant energy from tidal movements, positioning it as a pivotal component in the UK's transition towards a cleaner energy mix.

```
carrier
CCGT           34.797920
biomass         6.725600
coal            3.816819
nuclear         8.779000
offwind-ac      5.435190
offwind-dc      4.947242
oil             0.100000
onwind         14.100999
solar          13.462451
tide           44.948224
Name: p_nom_opt, dtype: float64
```

Figure 5: PyPSA-Eur optimized installed capacities

Furthermore, the optimization results showcase the dynamic interplay between various energy sources. Offshore wind, both AC and DC, emerge as valuable contributors, indicating their role in capitalizing on the UK's vast offshore wind potential. Solar and onshore wind also play significant roles, contributing a combined installed capacity of approximately 27.56 GW. The optimization process has effectively balanced the energy portfolio, leveraging each energy carrier's strengths to collectively meet the electricity demand while adhering to stringent emission constraints.

In conclusion, the optimized installation capacities obtained through the PyPSA optimization reflect a strategic allocation of resources to meet energy demand, minimize costs, and achieve emission reduction goals. The substantial emphasis on tidal energy underscores its potential as a crucial element of the UK's sustainable energy future, marking a key milestone in the country's transition towards a low-carbon and resilient power system.

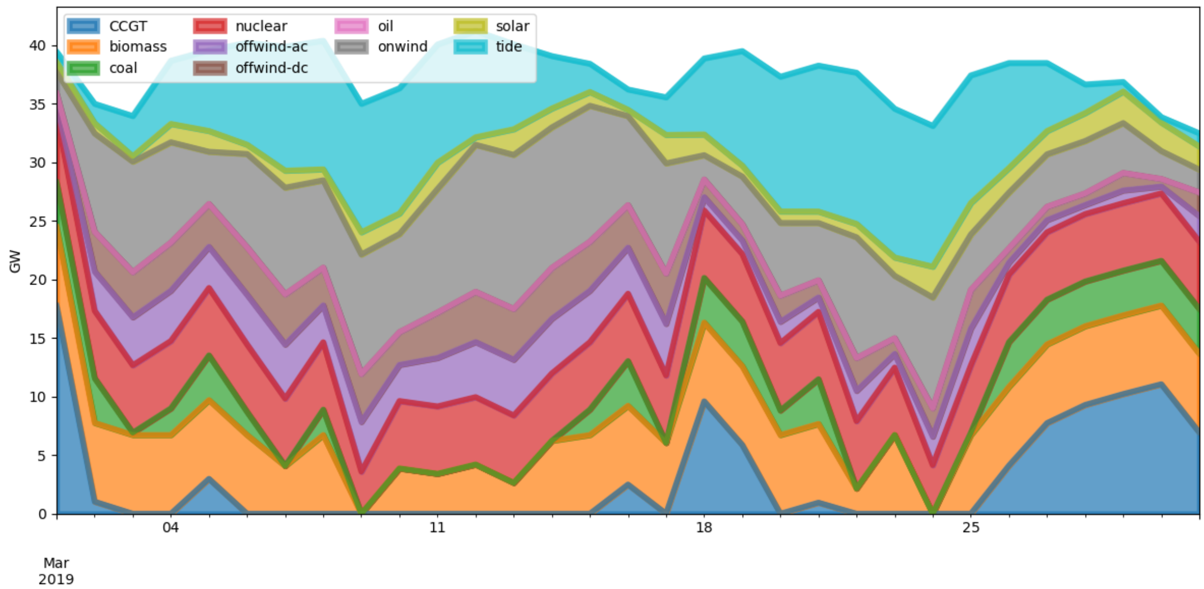

Figure 6: PyPSA-Eur optimized generation in Mar. 2019

4 Disscussion and conclusion

Model Validation and Limitations: This study acknowledges the absence of rigorous model validation. The methods employed for estimating turbine and sluice quantities using capacity density and required area are approximate. A lack of appropriate validation and comparison diminishes the confidence in these estimations. Furthermore, the calculation of capital cost per kilowatt exhibits significant deviations. The reliance on a single cost value for plants of varying scales introduces bias. A more robust approach is necessary to account for the cost variations inherent to different plant sizes. Costs play a pivotal role in influencing network optimization results, warranting meticulous calculations instead of simple mathematical averages.

Optimization of Tidal Range Power Plants: Optimization strategies hold the potential to significantly enhance the generation efficiency of tidal range power plants. However, due to computational resource limitations, the implementation of adaptive optimization based on grid resolution remains unexplored. Nonetheless, by applying grid masks, the number of grids requiring computation can be substantially reduced. This approach effectively minimizes computational workload, offering an avenue for optimizing calculations. Leveraging the spatial constraints inherent to the layout of tidal range energy installations could yield optimized outcomes while mitigating resource constraints. Future investigations should focus on refining optimization techniques to harness the full potential of tidal range power plants, while considering computational efficiency and system constraints.

Inclusion of Tidal Stream Energy: The comprehensive integration of various forms of marine renewable energy, including offshore wind, wave energy, and tidal range energy, has been addressed. However, the integration of tidal stream energy, which holds substantial potential, remains relatively unexplored. Notably, the United Kingdom has allocated 40 MW of contracts for difference to tidal stream energy in 2022. [27] To enhance decision-making accuracy within existing technological paradigms, the incorporation of tidal stream energy into both the Atlite model and the PyPSA framework is essential.

Multi-Sector Coupling: While PyPSA-Eur lends itself to the integration of multiple sectors, such as industry, transportation, and agriculture, this study solely focused on the electricity sector. The untapped potential of multi-sector coupling is an area deserving further exploration. Coupling electricity with other sectors can result in synergistic benefits that can lead to more efficient energy utilization and contribute to the overall sustainability of the energy transition.

Foresight Scenarios and Planning: Multi-sector coupling scenarios offer invaluable insights into the energy landscape's short- and long-term planning. Two primary foresight scenarios, namely ”myopic” and ”overnight,” stand out. The ”overnight” approach facilitates the redesign of the energy system to meet demand, offering a macro-level perspective. On the other hand, the ”myopic” approach [24] delves into progressive network changes, elucidating transition paths over time. These scenarios collectively hold the potential to guide energy system development through holistic and dynamic planning strategies.

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