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Wave Energy Integration into Small Islanded Electrical Grids

Task 6

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FINAL TECHNICAL REPORT

Asia Pacific Research Initiative for Sustainable Energy Systems Task

Wave Energy Integration into Small Islanded Electrical Grids

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Executive Summary

The objective of this project was to develop a modeling framework to identify and evaluate techno-economic benefits or issues associated with integrating wave energy along with other variable renewable energy

sources into small, isolated grid systems. This project was subawarded to University of Alaska Fairbanks (UAF) by the University of Hawaii due to the suitability of small, remote Alaskan communities for the research. Yakutat, a small Alaskan community of approximately 600 residents with diesel-based electrical loads of approximately 700 kW, is the focus of the study. The objective was achieved using a mix of tools including the Hybrid Optimization of Multiple Energy Resources (HOMER) model, the UAF-developed Micro Grid Renewable Integration Dispatch and Sizing (MiGRIDS) package, a MathWorks Simulink-based model, collection of high-fidelity wave and solar photovoltaic (PV) resource data, a high fidelity Simulating WAves Nearshore (SWAN) simulation, and satellite-based solar PV estimates. Economic assessments were made using output from MiGRIDS and HOMER. The potential for grid impacts for different mixes of wave and solar PV, a battery energy storage system (BESS), and existing diesel-based electrical generation assets was assessed using a basic Simulink simulation.

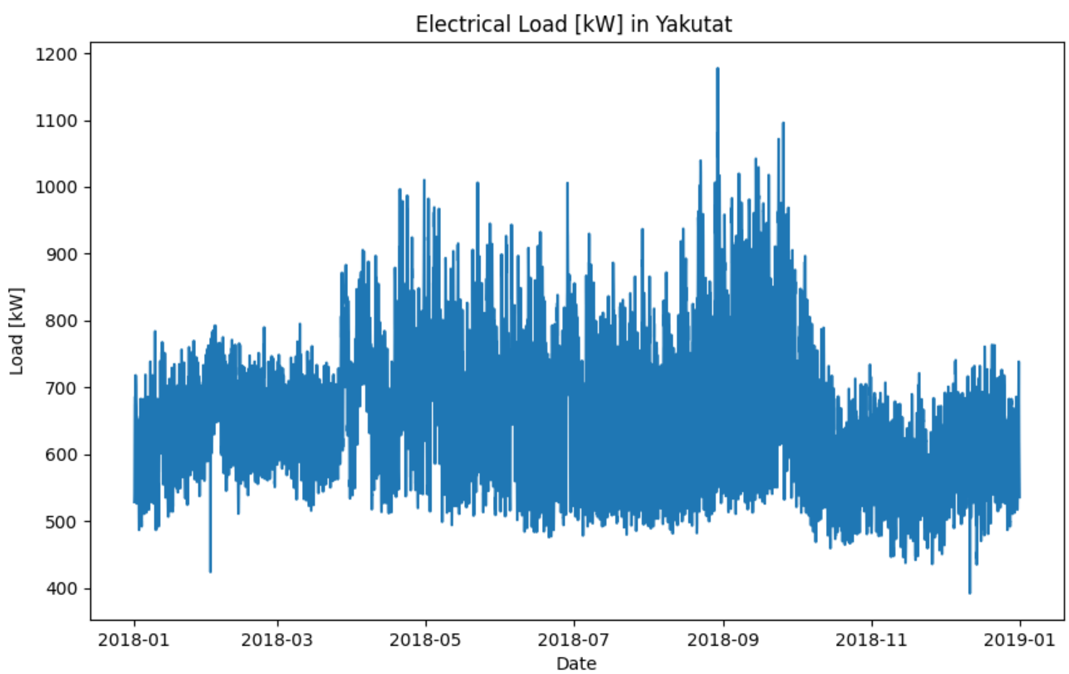

Figure 1. Upsampled timeseries of electrical load for 2018 from Yakutat.

Electrical load data for Yakutat was provided by the Alaska Village Electric Cooperative (AVEC) for the year 2018 in 15 minute resolution. While MiGRIDS (Vandermeer et al. 2018) is intended for working with load data at intervals of several seconds, meaningful estimates of wave power are constrained to longer intervals closer to 5 minutes (Robertson et al., 2021). Thus an interval of 5 minutes was used for all simulations. To obtain 5-minute interval load data, the AVEC-provided data was upsampled using a Langevin algorithm implemented in MiGRIDS (Vandermeer et al., in prep). Upsampled load data is shown in Figure 1. Community electrical demand peaks in summer when the local fish processing plant is operating and varies from a minimum of approximately 500 kW in January to a maximum of over 1000 kW in late summer.

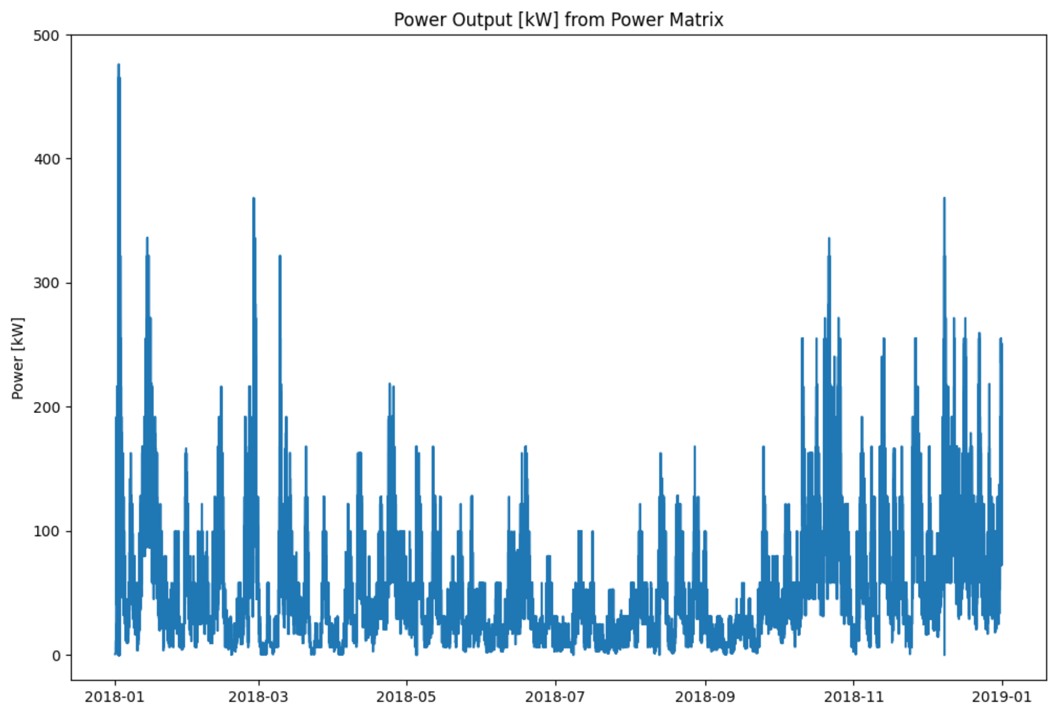

Figure 2. Predicted power output for two 100kW Wave Bob wave energy converters (WECs) for calendar year 2018.

Oceanographic instruments to measure the local wave spectra were deployed beginning in June 2018 and a meteorological station with a Hukseflux SR30 pyranometer to record Global Horizontal Irradiance (GHI) was installed in August 2018. To avoid introducing any unknown biases into the analyses, it was decided that it was important to use wave and solar PV resource estimates from the same time period as the load data. Thus a series of steps were taken in order to synthesize time series of the distributed energy resources that overlapped with the available load data and that were at the same sample interval.

In order to produce synthetic time series of wave power, the regional SWAN model described in Tschetter et al., 2016 was updated to present. While the 2016 SWAN model utilized NOAA's Global Forecast System (GFS) winds for forcing and NOAA WaveWatch III output for boundary conditions, the updated simulation employs winds and wave information from the European Center for Medium range Weather Forecasting's (ECMWF) ERA5 product. The updated SWAN model was used to generate hourly time series of surface wave spectra for the same time period as the load data. SWAN output was validated against two nearby NOAA wave buoys as well as the in situ oceanographic moorings. The hourly SWAN output was then upsampled following Robertson et al. (2021) to match the 5 minute interval of the load data. Predicted electrical outputs were then calculated by applying the 5 minute wave information to the power matrix for a given wave energy converter (WEC). In this manner, a time series of predicted power output for any number or design of WECs can be calculated. An example time series of power output from two 100 kW “Wave Bob” WECs is shown in Figure 2. Finally, custom scripts were written to feed the predicted WEC power output into HOMER and MiGRIDS.

A synthetic time series of GHI was produced using ERA5 data for Yakutat. This data is publicly available from NREL at a 1 hour sample interval. Following Wilber et al. (2018), in situ GHI data measured by the pyranometer on the met station was averaged to hourly. Then each day of satellite data was matched to a “representative day” from the in situ data. Representative days were found by minimizing the mean square error between the two hourly time series day by day. A synthetic time series was then generated by piecing together representative days from the 1 minute data. This time series was then corrected to equal the hourly average values found in the satellite dataset. Finally the time series was averaged to 5 minute intervals. Figure 3 shows the resulting time series with a resolution of 5 minutes that matches the variance of the in situ data and the magnitude of the satellite data.

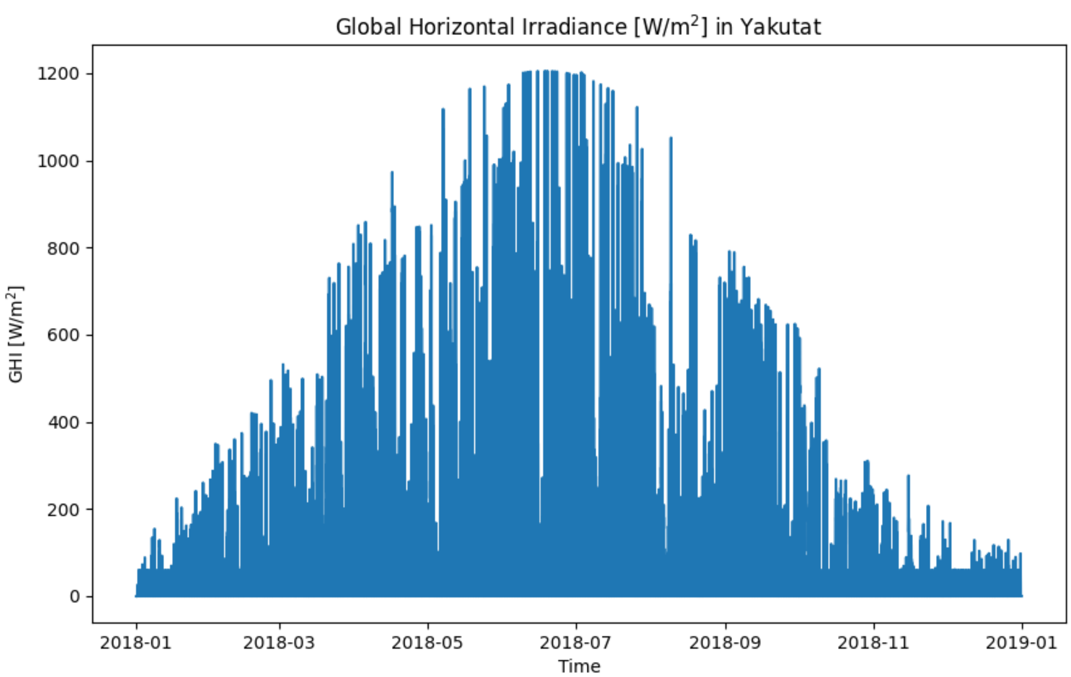

Figure 3. Synthetic timeseries of Global Horizontal Irradiance (GHI) for Yakutat in 2018.

Using these data, a series of HOMER and MiGRIDS simulations were carried out with the goal of quantifying how much, if any, cost savings could be achieved by Yakutat through the introduction of solar PV and wave energy into the community's generation mix.

In order to maximize the potential penetration of the Distributed Energy Resources (DER) into the grid, a BESS was included in most simulations. In addition, the effects of system cost decreases with time were estimated using learning rates estimated from the literature.

Utilizing current conservative cost estimates, diesel generation was found to be the most economic option for the community with DER technologies slightly below cost-parity. However, future projections as early as 2030, with only modest average cost reductions, show the DER technologies could contribute to significant cost savings for Yakutat. It is important to note that since there is such a large amount of uncertainty in the predicted costs for an emerging technology such as WECs, it cannot be emphasized enough that the most important contribution from this work is in the development of the methodologies including the means for including wave energy in simulation tools such as HOMER and MiGRIDS. As costs for WECs become easier to estimate, these tools will provide a powerful means for assessing the potential benefits of integrating this new DER into the generation mix of islanded microgrids.

Whilst preliminary, the Simulink simulations are a first step towards examining the potential for power quality issues when solar PV and wave energy are introduced into islanded microgrids. For example, when the WEC module was included in a basic simulation with two diesel generators matching Yakutat's gensets, the WECs introduced a significant ripple that lead to variations in frequency of O(0.18 Hz). The Simulink simulations in particular require a more in depth parameter space investigation before firm conclusions can be drawn from them. Finally, much of this work is a summary of more detailed information of M. Chamberlain's Master's Thesis "Techno-economic Investigation and Policy Implications of Renewable Energy Integration into an Islanded Diesel-based Microgrid in Rural Alaska" (Chamberlain, 2021).

Electrical Load

Electrical load data for was obtained for the community of Yakutat from the local utility, Alaska Village Electric Cooperative. Many data points were missing from the 15-minute average data that covered calendar year 2018 and 2019. Since the 2018 data contained the fewest gaps (256 hours missing vs. 6768 missing hours for 2019), the choice was made to work with the 2018 data. The average load for 2018 is 665.1 kW with a standard deviation is 111.6 kW. The average load for 2019 is 672.9 kW with standard deviation is 129.2 kW. Community electrical demand peaks in summer when the local fish processing plant is operating and varies from a minimum of approximately 500 kW in January to a maximum of over 1000 kW in late summer.

The 2018 load time series contained no gaps longer than a week. Gaps were filled by replacing the missing values with data from the same day of the week from the previous week (nearest neighbor interpolation). The 15-minute data was then upsampled using a Langevin algorithm implemented in MiGRIDS (Vandermeer et al., in prep). Upsampled load data is shown in Figure 4.

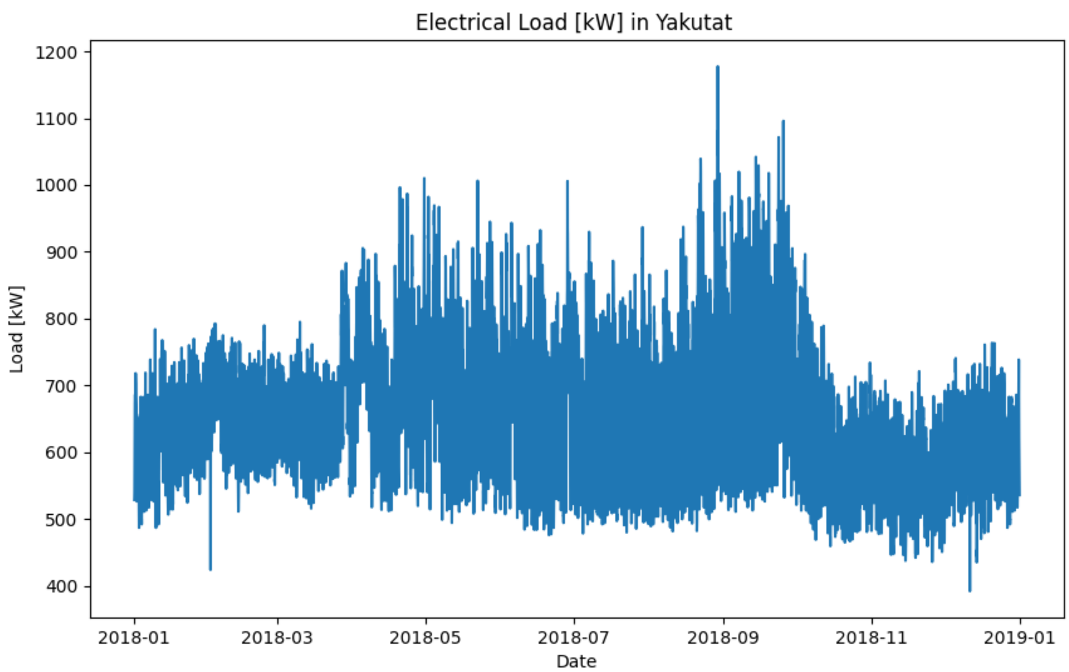

Figure 4. 5-minute time series of electrical load from the community of Yakutat, Alaska.

Solar Photovoltaic Resource Data

In situ solar photovoltaic resource was measured using a meteorological station (met station) purchased and deployed under these funds. Because only 2018 load data was available, a synthetic time series of global horizontal irradiance (GHI) for 2018 was generated from the met station. This process and details of the met station are described below.

To measure the in situ solar photovoltaic resource, a met station was installed in Yakutat in September 2019 at the municipally owned water treatment plant that previously housed the community owned fish processing plant (Figure 5). The fish processing plant was moved to a new location over a decade ago. The approximate location of the met station (59°33.1137'N and 139°44.6653'W) is shown in Figure 6.

Figure 5. The met station along the shore of Monti Bay in Yakutat.

Figure 6. Approximate site of the meteorological station is indicated by the star.

Equipment installed on the met station are shown in Table 1.

Table 1. Equipment installed on the met station.

Item	Description
RM Young 3002 Anemometer	Cup style anemometer measures the wind velocity and direction.
Campbell Scientific CR1000 Data Logger	Research Grade Data Logger
Campbell Scientific CS215 Temperature/ RH probe	Temperature/ Relative Humidity Probe
Campbell Scientific CS100 Barometer	Barometer
CS320 Pyranometer	Digital Thermopile Pyranometer
SR30 Pyranometer	Digital Thermopile Pyranometer

Overlapping solar and electrical information were obtained as follows. ERA5 reanalysis data publicly available from NREL at a 1-hour sample interval was obtained. Following Wilber et al.

(2018), in situ GHI data measured by the met station pyranometer was averaged to hourly. Then each day of satellite data was matched to a "representative day" from the in situ data. Representative days were found by minimizing the mean square error between the two hourly time series day by day. A synthetic time series was then generated by piecing together representative days from the 1-minute data. This time series was then corrected to equal the hourly average values found in the satellite dataset. Finally the time series was averaged to 5 minute intervals. Figure 7 shows the resulting time series with a resolution of 5 minutes that matches the variance of the in situ data and the magnitude of the satellite data.

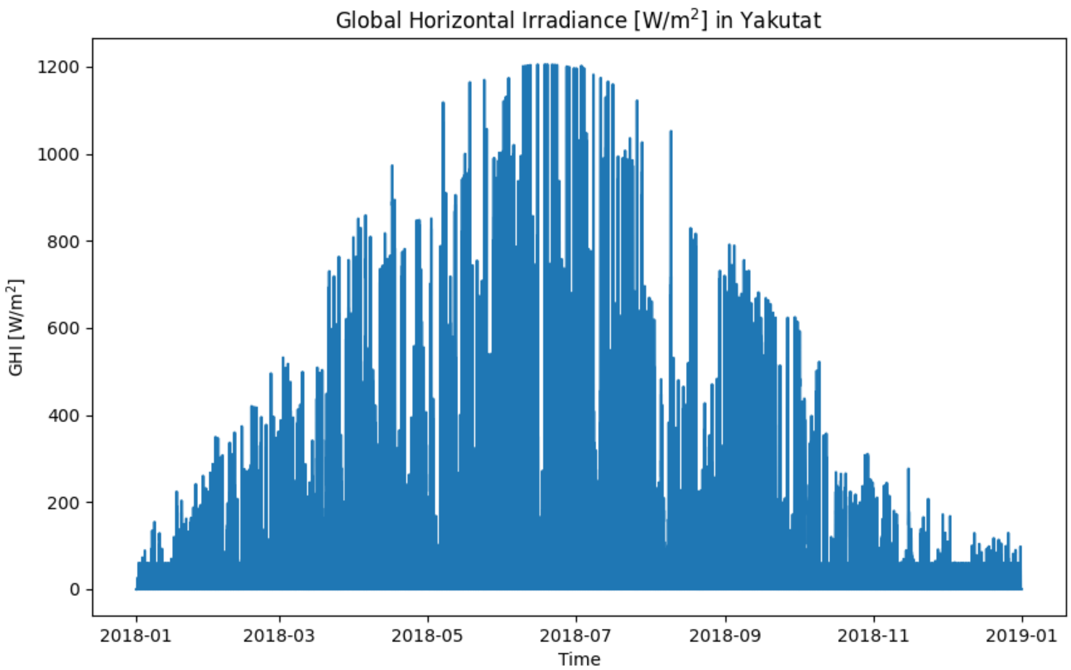

Figure 7. Synthetic timeseries of Global Horizontal Irradiance (GHI) for Yakutat in 2018.

Wave Resource Data

In situ oceanographic moorings purchased with Office of Naval Research under a separate award to UAF were deployed off the coast of Yakutat with funds from the Bureau of Ocean Energy Management (Figure 8 and Figure 9). The initial mooring deployment took place in June 2018. Final recovery occurred in October 2019. The three moorings included two acoustic Doppler current profilers (ADCPs) equipped to measure surface gravity waves, necessary to estimate the available wave resource for the region.

Figure 8. Oceanographic moorings shown just prior to deployment in June 2018.

Figure 9. Location of the oceanographic moorings.

Similar to the solar resource information, because the in situ wave time series do not fully overlap with the 2018 electrical load data, it was necessary to generate a synthetic time series of wave energy for the full calendar year 2018. This was accomplished by updating the regional SWAN model described in Tschetter et al., 2016 to present. The SWAN output is a timeseries of surface wave spectra which are then processed following IEC Technical Specification 62600-101 to produce time series of Hm0 (significant wave height, m), omnidirectional wave power (J, kW/m) and energy period (Te, s). SWAN model domains are shown in Figure 10.

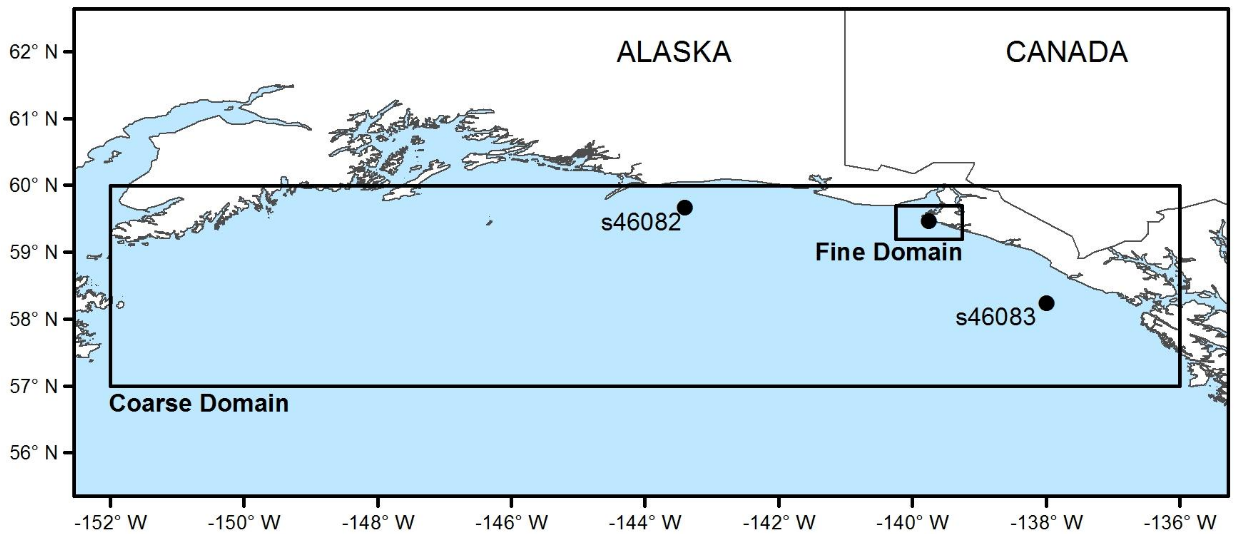

Figure 10. Coarse and fine model domains for the updated SWAN simulations including the location of the two closest NDBC buoys, s46082 and s46083.

While the 2016 SWAN model utilized NOAA's Global Forecast System (GFS) winds for forcing and NOAA WaveWatch III output for boundary conditions, the updated simulation employs winds and wave information from the European Center for Medium range Weather Forecasting's (ECMWF) ERA5 product. The updated SWAN model was used to generate hourly time series of surface wave spectra for the same time period as the load data. SWAN output was validated against two nearby NOAA wave buoys (NDBC buoy 46082 and buoy 46083) as well as the in situ oceanographic moorings.

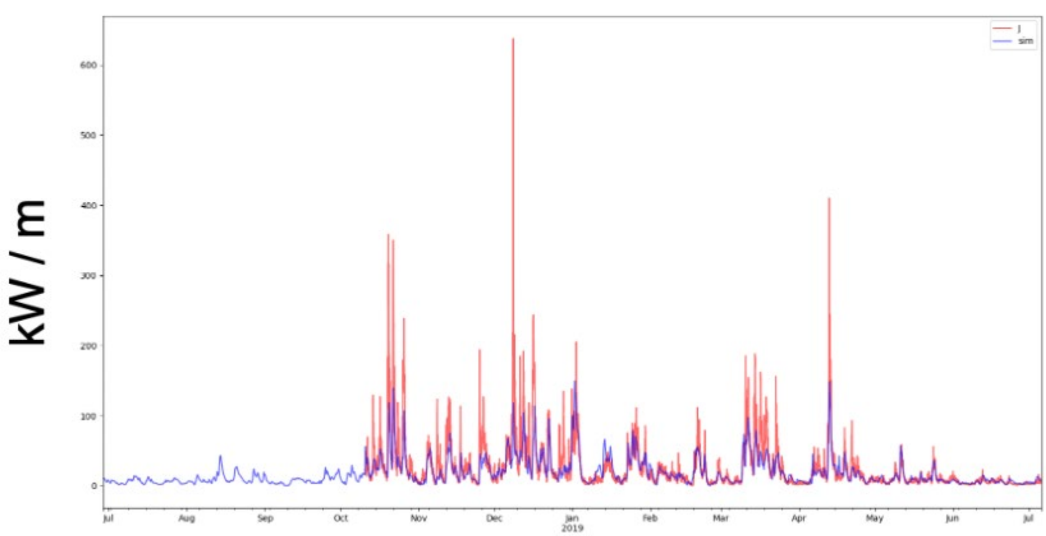

*Figure 11. Comparison between the ADCP (red) and synthetic (blue) time series of omnidirectional wave power, J (*kW/m*) for 2019.*

Table 2. Comparison between SWAN simulations and in situ data. The ADCP comparison is between the nearest SWAN grid point from the fine scale simulation while the NOAA buoys are compared to the newest grid point from the coarse scale simulation.

Station	Metric	N	RMSE	PE	SI	Bias	R
ADCP	J (kW/m)	6423	26	46.6	0.964	-5.49	0.76
	Hm0 (m)	8802	0.564	23.3	0.325	-0.087	0.8422
	Te (sec.)	8802	1.29	10.5	0.139	-0.012	0.668
NDBC 46082	J	16640	29.5	49	1.07	-7.7	0.775
	Hm0	16640	0.834	24.5	0.394	-0.311	0.819
	Te	16640	1.65	15.5	0.193	0.476	0.537
NDBC 46083	J	16592	19.9	49.2	0.737	-20.2	0.852
	Hm0	16592	0.558	22.6	0.267	0.0087	0.883
	Te	16592	1.44	12.41	0.166	-0.24	0.652

Hourly SWAN output was then upsampled following Robertson et al. (2021) to match the 5-minute interval of the load data. Predicted electrical outputs were then calculated by applying the 5-minute wave information to the power matrix for a given wave energy converter (WEC). In this manner, a time series of predicted power output for any number or design of WECs can be calculated. An example time series of power output from two 100 kW "Wave Bob" WECs is shown in Figure 12.

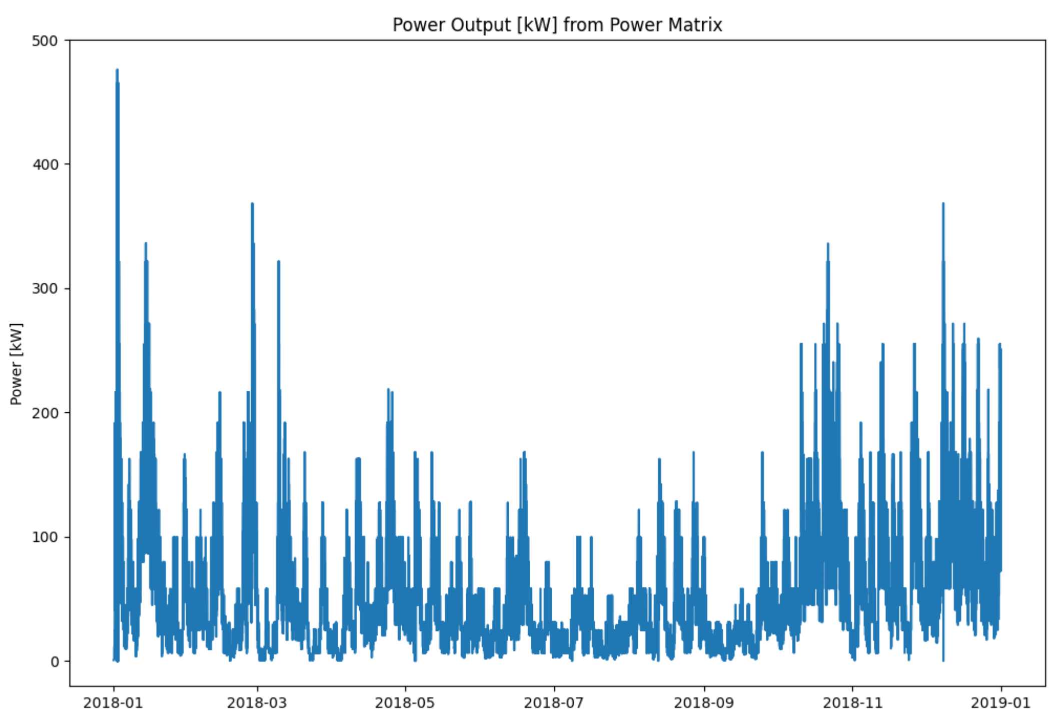

Figure 12. Predicted power output for two 100kW Wave Bob WECs for calendar year 2018.

HOMER, MiGRIDS and Simulink Simulations

The following sections are a summary of M. Chamberlain's Master's Thesis (Chamberlain, 2021).

HOMER Simulations

The results from the HOMER simulations highlight the following aspects for the integration of WECs, PV and a BESS in the grid of Yakutat:

- A BESS is an important component of renewable energy (RE) integration. It allows to increase the economic value of the RE generation components (PV and WEC) by a remarkable amount (up to 17% for the maximum simulated renewable capacity). An adequately sized BESS is also able to reduce the Levelized Cost of Electricity (LCOE), depending highly on the level of RE integration and the associated costs for the BESS installation and operation. However, a BESS alone, in combination with no RE generation devices, is found to have almost no beneficial effect in optimizing the operational loading on the Diesel generators.
- The strong price fluctuations of Diesel fuel over the years have exposed the village of Yakutat and many other remote communities to proportionately strong variations in LCOE. Therefore, the introduction of a future carbon tax would increase the Diesel fuel cost, but that increase would fall into a smaller range than the already existing variability of fuel prices. However, it must also be acknowledged that upon introduction of a future carbon tax, the threshold costs for the RE technology's economic viability would decrease.
- With the projected cost developments of RE and with current Diesel fuel costs, the WEC and PV installations lead to LCOE reductions already in the near-term. In the medium to long-term they can lead to LCOE reductions of 0.05 to 0.10 USD/kWh for moderate scenarios or up to 0.15 USD/kWh in the more optimistic scenarios for RE costs. These results constitute a significant cost reduction (between 10% and 30%), in context of the current electricity rates, which average around 0.54 USD/kWh
- When comparing WEC and PV generation, it became apparent that WEC technology yielded a higher energy output, resulting in a higher technological capacity factor by a factor of three, due to its less intermittent nature. Consequently and importantly, this justifies the installation of WEC units, even if the total costs of WEC per kW capacity are significantly higher than PV.
- The simulations also show how the RE costs become an increasingly small amount of the total net present cost in the hybrid system. This is a notable advantage for the integration of RE into the grid and in a future sizing step, the Diesel generator capacity can be reduced. However, the grid-forming ability, redundancy and reliability that the Diesel generators provide must also be kept in mind.

MiGRIDS Simulations

The results from the MiGRIDS simulations highlight the following aspects for the integration of WECs, PV and a BESS in the grid of Yakutat:

- The combination of RE with Diesel generators forces the Diesel generators to adapt not only to the load but also to the input of the RE sources. The introduction of a BESS can significantly increase the operational loading of the Diesel generator as it allows more flexibility by essentially shifting the load or the excess generation on an hourly or daily basis. Higher operational loading increases the efficiency of the Diesel generators and can increase their lifespan.
- The implemented dispatch logic can have a large influence on the outcome of the simulations, as can be observed by the differences between the HOMER and the MiGRIDS simulation outcomes.
- The BESS discharge power is an important metric when considering the battery's ability to provide SRC. The energy content of the BESS, which can be translated to the discharge duration, has a large influence on the ability of the BESS to beneficially displace fuel usage and increase the penetration of RE into the microgrid.
- The optimal energy content and discharge power of the BESS depend on the level of RE integration and on the application priority the BESS has. BESS with shorter discharge duration have the ability to provide SRC and bridge the system long enough for a Diesel generator to be switched online. BESS with longer discharge durations have the ability to displace more fuel and increase the RE integration.

Simulink Simulations

The Yakutat microgrid was modeled in Simulink to test the response of the system to different combinations of renewable integration. Given the complexity and individuality of a precise microgrid electrical model, the goal of this Simulink model is to anticipate possible grid stability issues that may arise from RE integration and to make basic predictions about how the grid may react to (or absorb) some of this induced instability. The goal behind the Simulink model is not to achieve a precise result, which would require a very large amount of data collection and calibration to determine all the necessary grid and component parameters.

With this goal in mind, the grid model was designed to correspond to existing available grid components and where no information was available, estimates were made in line with modeling suggestions and standard values in MATLAB Simulink.

Base Case

In the Base Case the grid has two Diesel generators with 1285 and 1245 kW respectively and a load of 900 kW is applied. To test the frequency variability, a load of 150 kW is added to the system at simulation second 250.

The grid frequency stabilizes at 60.63 Hz, which represents a deviation from the nominal frequency of 60 Hz. This is due to internal governor settings, where the droop control regulates the synchronous machine mechanical power input. It is assumed that there is a droop offset in the system, which is considered acceptable, as the system is stable and the main interest is the change in frequency as a response to events in the grid. Figure 13 shows the frequency dip at 250 seconds, when the load is applied. The frequency dip is approximately 0.1 Hz and persists for several seconds, which represents a longer reaction time than would realistically be expected. The reaction time is dependent on the Diesel generator inertia. This parameter was set to achieve a steady reaction and to avoid an overcompensation of the governor that would lead to perturbations.

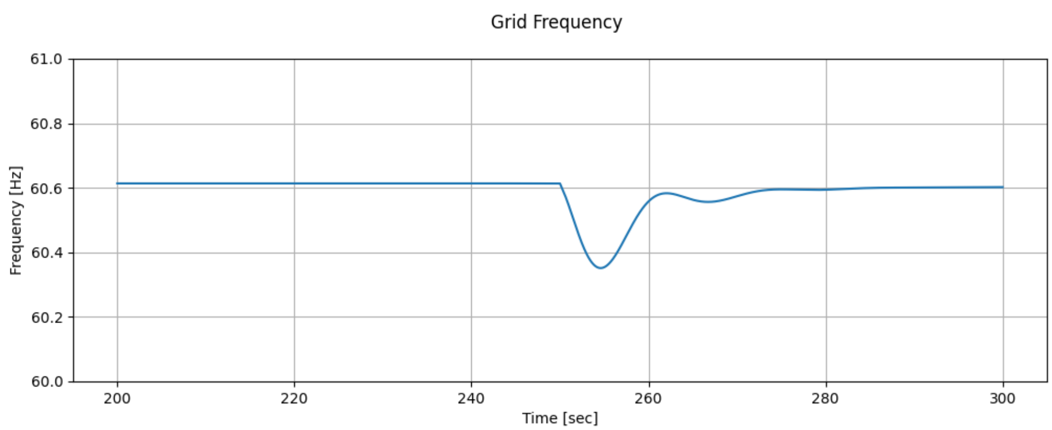

Figure 13. Frequency for grid model with two Diesel generators (1285 and 1245 kW) and a 900 kW load, with a 150 kW load added at 250 s.

Wave Energy Converter

The wave energy converter was designed using a standard synchronous machine in Simulink, as this represents a likely generator setup for the WEC (after the damping system and the hydraulic motor). For the input values, the generator speed is not regulated by the governor, as for the Diesel generators, but is dependent on the incoming wave energy. As the wave energy is smoothed by the WEC hydraulic system, the mechanical input for the synchronous machine is defined as a wave form with a higher period compared to expected values in Yakutat and with an amplitude that seeks to represent averaged (smoothed) values over several wave periods.

Using the approach outlined above, the grid frequency was found to fluctuate periodically with the same wave period as the mechanical power input for the synchronous machine used to simulate the WEC, as previously described. The frequency fluctuation is in the range of ±0.18 Hz, which is quite significant. Microgrids generally have more power quality issues compared to larger interconnected grids, due to their inherently different system inertia, which is less capable of absorbing load or generation fluctuations. As discussed in Chamberlain (2021), there are many grid and component parameters that influence the reaction of the grid and affect the reaction time and speed, thus, determining the stability of the grid. A part of the simulated frequency can be seen in Figure 14, resulting from the same model as the Base Case, but with an added 600 kW WEC, with the same load of 150 kW added at 250 s. To be noticed is the different scale when comparing the Figure 13 and Figure 14. Further details can be found in Chamberlain (2021).

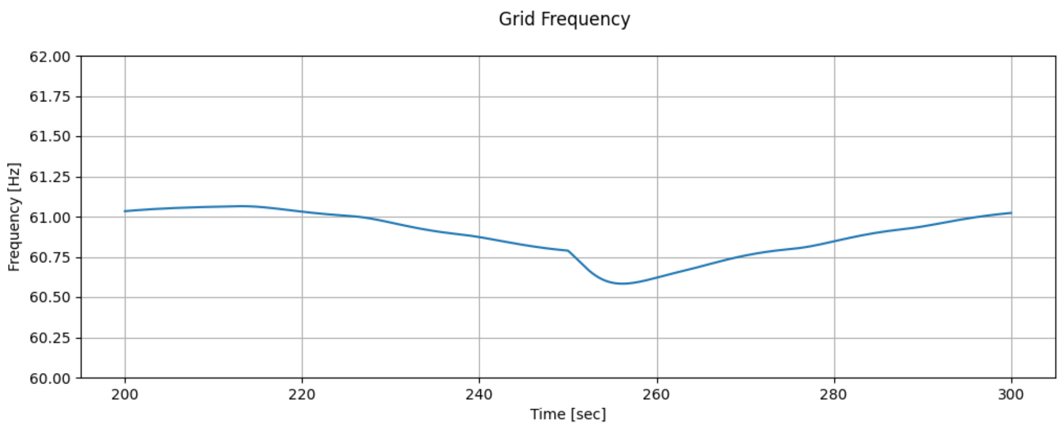

Figure 14. Frequency for grid model with two Diesel generators (1285 and 1245 kW) and a 900 kW load, with a 150 kW load added at 250 s.

Summary and Conclusions

The Yakutat Wave Energy Project has been ongoing since 2012 including significant in situ data collection on the wave (Tschetter et al., 2016) and more recently solar photovoltaic resource (herein). More recently, significant effort has been put into resolving lingering questions pertinent to permitting (Essential Fish Habitat, Marine Mammal Presence, etc.). The most recent environmental and permitting related results are summarized in Kasper et al. (in prep).

The most significant gap in this work at this time is related to knowledge gaps around the performance of wave energy converters at time scales less than 5 minutes which are relevant to power system transients, dispatch and ultimately fuel savings in microgrid systems. This work has made strides in addressing some of these questions including setting up frameworks to more comprehensively address these issues as more information becomes publicly available about short-time scale performance of WECs but much work remains to be done. UAF has recently been awarded follow-on funding from the Department of Energy to address some of these integration issues for both WECs as well as for Current Energy Converters, using modeling tools such as MiGRIDS, HOMER and proprietary tools such as Siemens PSS/E.

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