Techno-economic Modeling of Marine Energy Systems with the System Advisor Model

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I. Introduction

The system Advisor Model (SAM) developed by the National Renewable Energy Laboratory with funds by the United States (US) Department of Energy (DOE) is a free, publicly available modeling software designed to evaluate renewable energy system design, performance, and project economics. Since the software's launch in 2007, new versions have been released annually, adding to the collection of technologies and financing options it can accommodate. The marine energy module, which includes wave and tidal energy technologies, were added to SAM in 2019. SAM's marine energy module is a standardized, user-friendly modeling platform that estimates annual energy production (AEP), capital expenditures (CapEx), operational expenditures (OpEx), the levelized cost of energy (LCOE), and other metrics for marine energy systems [1].

The SAM wave energy module has new resource modeling capabilities by leveraging data from the Wave Hindcast Dataset enabling users to download wave resource data using latitude and longitude coordinates. The Wave Hindcast Dataset, funded by the DOE, is the highest-resolution time-series wave resource data available for US waters spanning the years 1979-2020 with a 3-hour timestep. The Wave Hindcast spatial dataset has an unstructured grid of data containing 15 million grid points with spatial resolution as fine as 100 to 200 meters in shallow water. SAM downloads dataset variables (significant wave height, energy period, omnidirectional wave power, water depth) as time-series data, which can be formatted into an annual joint probability distribution, as shown in Fig. 1, depending on analysis preferences.

Te = wave energy period (s)

Hs = significant wave height (m)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5
0.25	0	0	0	0	0	0	0	0.02	0.03	0	0	0	0	0	0	0	0	0	0	0	0
0.75	0	0	0	0	0.02	0.46	1.49	2.68	1.91	1.1	0.53	0.17	0.02	0	0	0	0	0	0	0	0
1.25	0	0	0	0	0.01	0.59	4.11	5.56	4.48	2.74	1.28	0.67	0.33	0.07	0.02	0.02	0	0	0	0	0
1.75	0	0	0	0	0	0.12	3.27	5.14	4.62	3.93	2.11	1.24	0.76	0.31	0.1	0.03	0	0	0	0	0
2.25	0	0	0	0	0	0	0.92	5.25	3.68	4.14	2.87	1.31	0.84	0.42	0.2	0.08	0.02	0	0	0	0
2.75	0	0	0	0	0	0	0.14	2.43	2.6	2.82	2.85	1.57	0.8	0.32	0.14	0.06	0.02	0	0	0	0
3.25	0	0	0	0	0	0	0	0.45	1.54	1.47	1.96	1.42	0.79	0.32	0.11	0.04	0.02	0.01	0.01	0	0
3.75	0	0	0	0	0	0	0	0.05	0.49	0.63	1.08	1.01	0.63	0.29	0.1	0.05	0.02	0	0	0	0
4.25	0	0	0	0	0	0	0	0	0.09	0.21	0.45	0.56	0.42	0.21	0.07	0.02	0.02	0	0	0	0
4.75	0	0	0	0	0	0	0	0	0.02	0.08	0.12	0.26	0.27	0.19	0.07	0.02	0.01	0	0	0	0
5.25	0	0	0	0	0	0	0	0	0	0.03	0.03	0.11	0.15	0.13	0.07	0.02	0	0	0	0	0
5.75	0	0	0	0	0	0	0	0	0	0	0	0.02	0.07	0.05	0.05	0.02	0	0	0	0	0
6.25	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.04	0.02	0.01	0	0	0	0	0
6.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0.02	0	0	0	0	0	0
7.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 1. Annual Joint Probability Distribution for Humboldt Bay, CA, USA.

The SAM tidal energy module resource modeling capabilities are more limited in comparison to the wave energy module as tidal resource datasets in the US are more limited. However, tidal time-series datasets for select locations in the US exclusive economic zone (EEZ) have been added to SAM within the tidal resource library, which is included in the newest SAM version. The tidal energy datasets available in the SAM library are from the National Oceanic and Atmospheric Administration's Current Measurement Interface for the Study of Tides (C-MIST) tool. The tidal resource data is available to use for time-series calculations or can be converted to an annual probability distribution.

The resource data can then be used to estimate annual energy production once the marine energy technology is defined by the user. The SAM wave energy module has multiple wave energy converter (WEC) power matrices available in the SAM's WEC library or a user can upload a custom power matrix. The SAM tidal module has multiple tidal energy converter (TEC) power curves available in the SAM's TEC library or a user can upload a custom power curve for a TEC device. The device power performance characteristics are combined with the resource data assumptions about the array layout and device losses for power performance modeling.

For both the tidal and wave modules, users must provide basic information about the array such as number of devices, device spacing, water depth, and distance to shore. If the user does not have detailed array layout information, SAM provides default values for spacing, water depth, and distance to shore. Using this information, the model will estimate electrical cable lengths required for a square array. Additionally, the user may define array losses related to array spacing, resource overprediction, electrical transmission, downtime, or any other miscellaneous losses. Alternatively, the user may choose to use the SAM default values for array losses, which assumes 5% downtime losses and 2% transmission losses. Once the array layout and losses are defined, the model is able to estimate annual energy performance (AEP) for the array.

SAM offers two financial modeling options for both wave and tidal: the fixed-charge-rate LCOE model or the power purchase agreement cash flow model. Both models require the user to enter cost inputs for the system or to use SAM's modeled cost values. The LCOE model can be used with time-series resource and power performance data or probabilistic data (like joint probability distributions), whereas the cash flow model requires the use of time-series data. Once a simulation is complete, SAM offers built-in analysis tools, data visualization, standardized reporting, and the ability to create customized macros for specific analysis objectives.

II. METHODS

In this work, SAM is used to conduct case studies for both wave and tidal energy systems. Each case study provides an overview of performance and cost modeling using SAM, while also highlighting the tool's built-in analysis and reporting capabilities.

A. *Wave energy case methods*

The first case study uses SAM's wave energy module to model DOE's Reference Model 3 (RM3), a wave energy point absorber, as a 100-device array. RM3 device specifications are shown in Table I [2]. SAM's default values are assumed for both the array layout and array losses as shown in Table II.

Table I. RM3 device specifications.

Description	Specification
Device architype	Two-body floating point absorber
Float diameter	20 m
Unballasted structural weight	687 Mg
Foundation type	3-point slack mooring
Operational depth	Free surface
Rated power	286 kW

Table II. RM3 array modeling assumptions.

Description	Specification
Location	Humboldt Bay, Eureka, CA, US
Number of devices	100
Number of devices per row	10
Number of rows	10
Spacing between devices in rows	600 m
Row spacing	600 m
Water depth	50 m
Distance to shore	5000 m
Total losses	7%

B. *Tidal energy case methods*

The second case study uses SAM's tidal energy module to model DOE's Reference Model 1 (RM1), a horizontal axis tidal turbine, as a 100-device array located in Puget Sound, Washington. RM1 device design specifications are shown in Table III [2].

Table III. RM1 device specifications.

Description	Specification
Device architype	Tidal axial-flow turbine
Number of rotors per device	2
Rotor diameter	20 m
Tower height	45 m
Foundation type	Monopile
Embedment depth	15 m
Operational depth (hub centerline)	20 m
Power per rotor	0.5 MW
Rated power per device	1 MW
Rated current speed	2.0 m/s
Operational current speed	0.5 – 3.0 m/s

The analysis uses tidal resource velocity distribution data and the RM1 power curve data that are available in the SAM tool. The tidal array modeling specifications used in this analysis, shown in Table IV, are identical to the array layout used for RM1 in the Reference Model project [2].

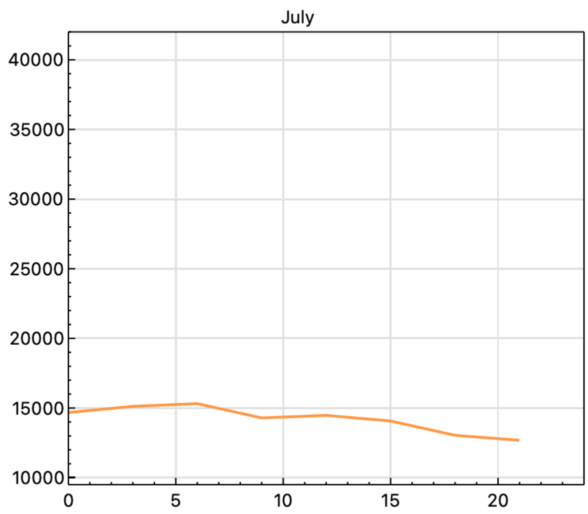
Table IV. RM1 array modeling assumptions.

Description	Specification
Device Type	RM1
Location	Tacoma Narrow, Puget Sound, Washington, US
Number of devices	100
Number of devices per row	5
Number of rows	20
Spacing between devices in a row	115 m
Row spacing	400 m
Water depth	50 m
Distance to shore	150 m
Total losses	7%

III. RESULTS

C. *Wave energy case results*

Using Wave Hindcast resource time-series data accessed from SAM, combined with SAM's default values for array design parameters and losses, AEP is estimated to be 59,434 MWh per year for the wave energy case. In addition to AEP, SAM produces monthly energy generation profiles for RM3, as shown in Fig. 2.



For the wave energy case, SAM estimates an LCOE of $0.83/kWh with a CapEx of $14,238/kW and an OpEx of $190/kW per year. The LCOE percent contribution for each cost category is shown in Fig. 3.

Fig. 2. Daily energy production (kWh) for 100-device RM3 array in the month of July.

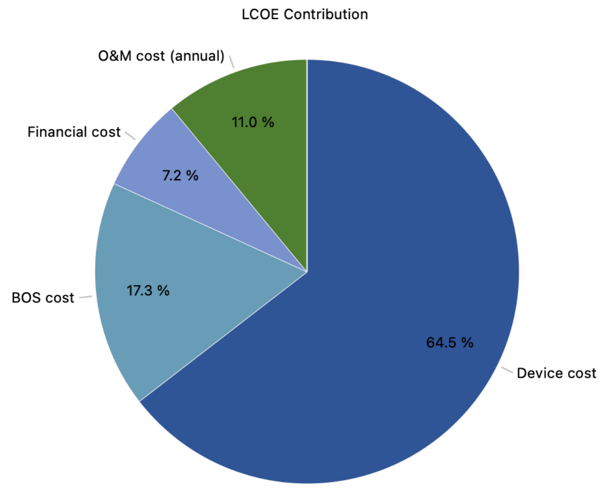


Fig. 3. RM3 LCOE percent contribution by cost category.

D. *Tidal energy case results*

The AEP estimate produced by SAM for the RM1 array is 216,152 MWh per year. The annual energy produced at each velocity bin is shown in Fig. 4.

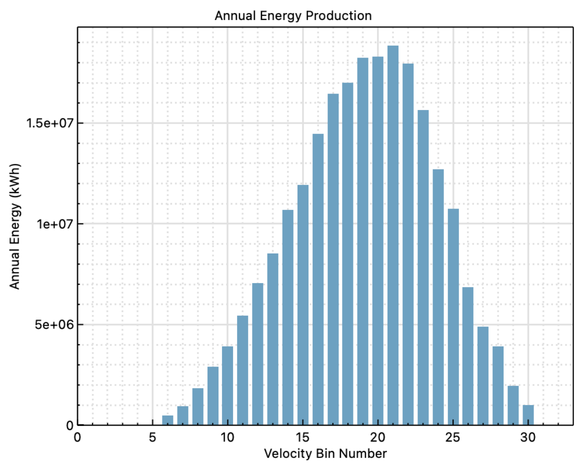


Fig. 4. Estimated AEP for each velocity bin in the 100-device RM1 array.

SAM's cost modeling capability is used to estimate the tidal energy project CapEx of $3,896/kW, OpEx of $159/kW per year, and a LCOE of $0.30/kWh. Figure 5 shows the LCOE percent contribution of each cost category for the RM1 100-unit array.

IV. DISCUSSION & CONCLUSION

These case studies highlight the analysis capabilities of SAM and demonstrate how users can assess the techno-economic performance of marine energy systems for a range of purposes including quick initial screenings to more detailed feasibility studies. In addition to the visualizations shown, SAM has standardized reporting features which may be beneficial for communicating about marine energy projects to investors or other stakeholders. These case studies are used to illustrate SAM modeling basics, to inspire discussion and to solicit feedback to shape future SAM tool development, as a majority of new SAM development features are inspired by user feedback.

REFERENCES

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