

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

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January 22, 2024

# NREL's Research and Innovation



## Renewable Power

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Solar  
Wind  
Water  
Geothermal



## Sustainable Transportation

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Bioenergy  
Vehicle Technologies  
Hydrogen



## Energy Efficiency

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Buildings  
Advanced Manufacturing  
Government Energy Management



## Energy Systems Integration

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High-Performance computing  
Data Visualizations

# NREL Marine Energy R&D: Techno-economics

Techno-economic analysis evaluates the economic and technical performance through:

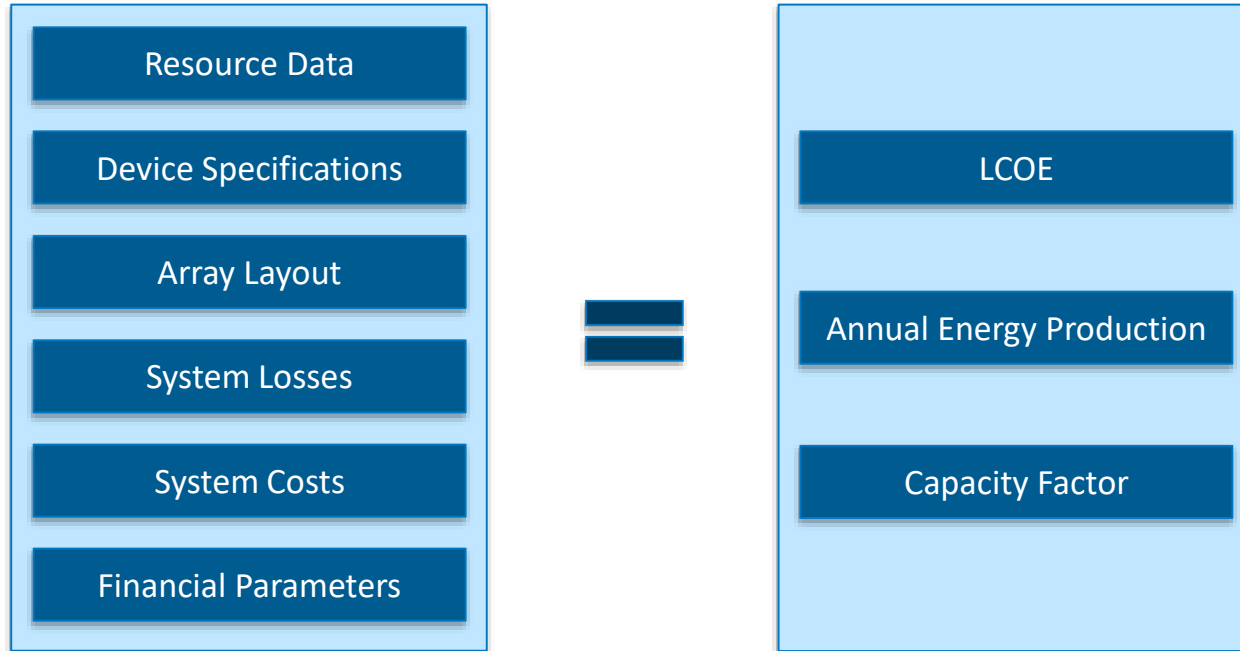
- Benchmarking/baselining
- Comparative studies of emerging technology to some existing commercial or reference benchmark
- Power performance modeling
- System cost-estimating
- Levelized cost of energy analysis
- Tool Creation
- Customized analysis for end users

<https://www.nrel.gov/water/economic-analysis.html>

# System Advisor Model (SAM)

- The System Advisor Model (SAM) is a free, publicly available modeling software designed to evaluate system design, performance, and project economics for a suite of renewable energy technologies.
- SAM's marine energy module offers multiple simulation options for wave and tidal energy systems:
  - Power performance modeling to estimate AEP
  - Levelized cost of energy calculator
  - Financial cash flow model

# Modeling Marine Energy Systems



# Levelized Cost of Energy (LCOE)

$$LCOE = \frac{CAPEX * FCR + OPEX}{AEP}$$

- CAPEX: Capital expenditures
- FCR: Fixed-charge rate
- OPEX: Operational expenditures
- AEP: Annual energy production

# Fixed-Charge Rate

FCR as baked in assumptions!

$$D = \tau \times \sum_{t=1}^{t=6} \frac{MACRS_t}{(1+r)^{t*}(1+i)^t}$$

$$FCR = \frac{r}{1 - \frac{1}{(1+r)^N}} \times \frac{1-D}{1-\tau}$$

Symbol	Variable	Standard Value
$r$	Real discount rate (i.e. real WACC)	.07
$i$	Inflation rate	.025
$\tau$	Composite federal-state tax rate	.396
$MACRS_t$	Depreciation schedule	MACRS 5-Year Property
$D$	Present value of depreciation tax shield	.309
$N$	Project economic life	20 Years
$FCR$	Fixed charge rate	.108

# Cost Breakdown Structure

CapEx			
CBS #	Level	Category	Description
1	1	Capital Expenditures (CapEx)	All installed costs incurred prior to commercial operations date (COD). CAPEX components include marine energy converter, balance of system, and financing.
1.1	2	Marine Energy Converter (MEC)	Converts kinetic energy from water into three phase alternating current (AC) electrical energy.
1.1.1	3	Structural Assembly	Primary energy capture (e.g. float paddle, turbine, flap, etc.) and supporting structural components.
1.1.2	3	Power Take-Off System (PTO)	Power Take-Off System is comprised of a drivetrain (converts the energy captured by the device into mechanical power), a generator (converts mechanical power into electrical power), short term storage, and power electronics.
1.1.3	3	Mooring, Foundation, and Sub-Structure	All elements of the marine energy converter mooring system and/or foundation
1.2	2	Balance of System (BOS)	
1.2.1	3	Development	All activities from project inception to financial close, where financial close is the date when project and financing agreements have been signed and all the required conditions have been met.
1.2.2	3	Engineering and Management	Engineering and management activities from financial close through commercial operation date (COD).
1.2.3	3	Electrical Infrastructure	All electrical infrastructure to collect power from generators and deliver to the grid.
1.2.4	3	Plant Commissioning	Cost incurred by owner or prime contractor to test and commission the integrated power plant.
1.2.5	3	Site Access, Port & Staging	Activities and physical aspects of a staging port. Elements needed to support the delivery, storage, handling, and deployment of marine energy converter (MEC) components.
1.2.6	3	Assembly & Installation	Assembly and installation activities conducted at the staging port and at the project site. Assume financial costs related to warranties, contractor insurance, Selling, General & Administrative (SG&A), profit margin, etc., are loaded in day rates for vessels, labor, and equipment.
1.2.7	3	Other Infrastructure	Other capital investments made by the project company prior to commercial operation date (COD).
1.3	2	Financial Costs	
1.3.1	3	Project Contingency Budget	Liquid financial instrument set up to respond to "known unknown" costs that arise during construction, does not include contingences set by manufactures and contractors as part of supply contract pricing.
1.3.2	3	Insurance During Construction	Insurance policies held by owner during construction period, can include construction all risk, marine cargo, commercial general liability, workers compensation, environmental site liability, pollution liability, etc. Does not include insurance held by contractors.
1.3.3	3	Carrying Costs During Construction (Construction Financing Costs)	Carrying charges of expenditures on equipment and services incurred before commercial operation date (COD).
1.3.4	3	Reserve Accounts	Payments (before commissioning) into reserve accounts. Generally required by either financiers or regulators.

- Uniform format to categorize cost for Marine Energy devices
- Organized by category with levels from 1-6
- Higher level numbers have higher level of detail
- Aids in uniform comparative analysis and can be used to collect consistent data



# ME SAM: Wave Resource

- Resource: Humboldt Bay in Eureka, California
- SAM has multiple site locations in the library
- User may upload resource joint probability distribution
- User can search and download wave resource data

The screenshot displays the 'Wave Energy Resource Library' interface. At the top, there is a search bar and a 'Refresh Library' button. Below this is a table listing various wave resource sites. The 'Humboldt Bay - DOE Reference' site is highlighted in purple. Below the table, there is a section for 'Annual Frequency of Occurrence of Sea States from Library' which includes a grid of joint probability distribution data for different wave heights and periods.

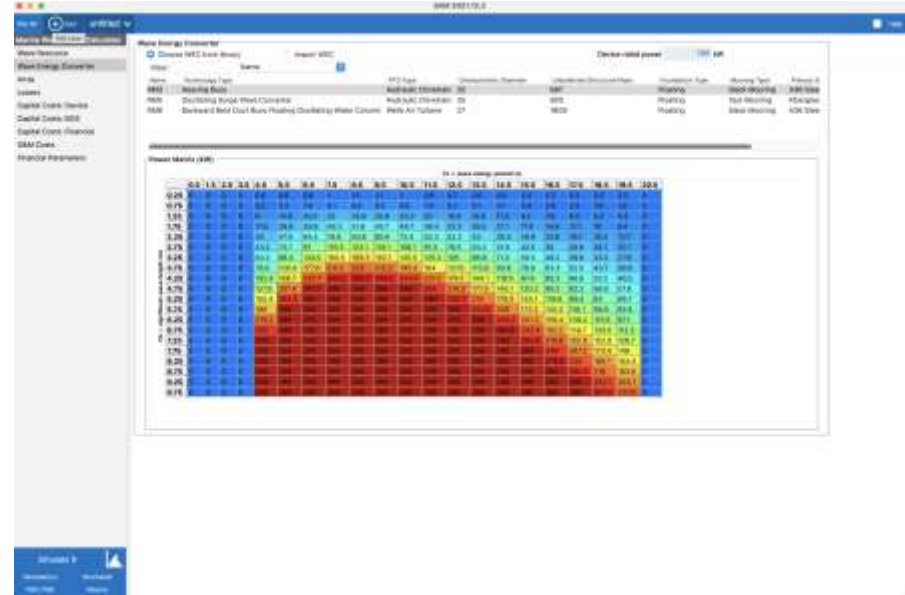
Site	Dir	Wave	Country	Latitude	Longitude	Nearest Buoy Number	Access Power-Flex	Seabottom	Sea Ric
USA/E FIP	Dirch	North Carolina	United States	36.1658	-75.3400	44305	3.29	Gently Sloping	Sandy
U.S Navy Wave Energy Test Site (AWETS)	Kauaioka (Island of Oahu)	Hawaii	United States	21.47	-157.79	11301	14.3	Highly Sloping	Sandy
Northshore North	Neaport	Oregon	United States	46.6888	-124.181	46094	17	Gently Sloping	Soft S
Jarvisville's Pier	Neaport	North Carolina	United States	35.8123	-75.5643	44305	6.28	Gently Sloping	Sandy
Northshore South	Neaport	Oregon	United States	42.187	-122.219	42094	43.7	Gently Sloping	Sandy
California Central Coast South	Lompoc	California	United States	34.521	-120.609	46219	39.8	Gently Sloping	Sandy
Humboldt Bay - DOE Reference	Eureka	California	United States	40.8416	-124.046	46212	32.3	Gently Sloping	Sand S

Below the table, there is a section for 'Annual Frequency of Occurrence of Sea States from Library'. This section includes a grid of joint probability distribution data for different wave heights and periods. The grid shows the probability of dominant waves for various combinations of wave heights (0.0 to 6.75 m) and periods (0.0 to 26.5 s). The data is presented in a color-coded format, with blue cells indicating higher probabilities.

At the bottom of the interface, there are several summary statistics: Probability of dominant wave: 0.66, Dominant wave height: 7.75 m, Dominant wave period: 7.6 s, Frequency sum: 99.88 %.

# ME SAM: Wave Energy Converter

- Device: US Department of Energy's Reference Model 3 (RM3)
- SAM has Reference Model power matrices that a user may select
- User can upload their own power matrix



# ME SAM: Array Layout

- 100-unit array (10 x 10)
- 600 meter spacing
- Distance to shore: 5000 meters
- Water depth: 50 meters
- Floating foundation

The screenshot displays the ME SAM software interface for configuring an array layout. The main window is titled "untitled" and shows the "Array Layout" configuration screen. The interface is divided into several sections:

- System Status:** Includes options for "Use a single device" and "Specify array rated capacity". The "Number of devices in array" is set to 100, and the "Rated array capacity" is 238777 kW.
- Array Layout:** Contains input fields for:
  - Number of rows: 10
  - Devices per row: 10
  - Spacing between devices in a row: 600 m
  - Row spacing: 600 m
  - Distance to shore: 5000 m
  - Water depth: 50 m
  - Cable system overhead: 10 %
  - Floating array:
  - Build export cable redundancy:
- Calculated Cable Lengths:** Displays the results of the calculations:
  - Inter-array cable length: 195345.000 m
  - Export cable length: 1055.000 m
  - Water cable length: 8200.000 m
- Array Layout Diagram:** A 10x10 grid of blue dots representing the array layout. The x-axis is labeled "meters" and ranges from 0 to 9500. The y-axis is labeled "meters" and ranges from 0 to 5000. An arrow indicates the "Wave direction" pointing upwards.

Below the diagram, a note states: "Row spacing affects calculated cable lengths but not array energy production."

# ME SAM: WEC Plant Losses

- 95% availability
- 2% transmission losses
- Note: SAM does not estimate wake losses and should be accounted for here

The screenshot shows the SAM 2021.12.2 software interface for WEC Plant Losses. The sidebar menu includes: Wave Resource, Wave Energy Converter, Array, Losses, Capital Costs: Device, Capital Costs: BOG, Capital Costs: Financial, O&M Costs, and Financial Parameters. The main window displays the following loss categories and percentages:

Loss Category	Percentage
Array Spacing Losses	0%
Resource Overprediction Losses	0%
Transmission Losses	2%
Array/Device Downtime Losses	5%
Additional Losses	0%
<b>Total Losses</b>	<b>7%</b>

# ME SAM: System Costs

Device Costs (Capital)

The capital cost on the Financial Parameters page is the sum of the total cost on the Device, BOS, and Financial Capital Costs pages. On this page, enter itemized capital costs for the device in \$ or \$/KW, check **Override Cost Structure** to enter the total device capital cost as a single value, or choose **Use Modeled Value** to have SAM automatically calculate the device cost. See Help for details.

Device costs = Structural assembly costs + Power take-off system costs + Mooring, foundation, and substructure costs

	Input option	Modeled value	User input	Category cost
<b>Structural assembly</b>	Use Modeled Value (\$) <input checked="" type="radio"/>	\$198,679,674	0	\$198,679,674
<b>Power take-off system</b>	Use Modeled Value (\$) <input checked="" type="radio"/>	\$44,014,126	0	\$44,014,127
<b>Mooring, Foundation, and Substructure</b>	Use Modeled Value (\$) <input checked="" type="radio"/>	\$52,549,711	0	\$52,549,711
<b>Total device costs</b>				\$295,243,512

Override cost structure

- + Structural Assembly Cost Breakdown
- + Power Take-off System Cost Breakdown
- + Mooring, Foundation, and Substructure Cost Breakdown

- Selected SAM's modeled value for all costs
- All costs may be customized by the user

# ME SAM: Financial Parameters

- Used the default fixed-charge rate of 10.8%
- Financial parameters may be customized by the user

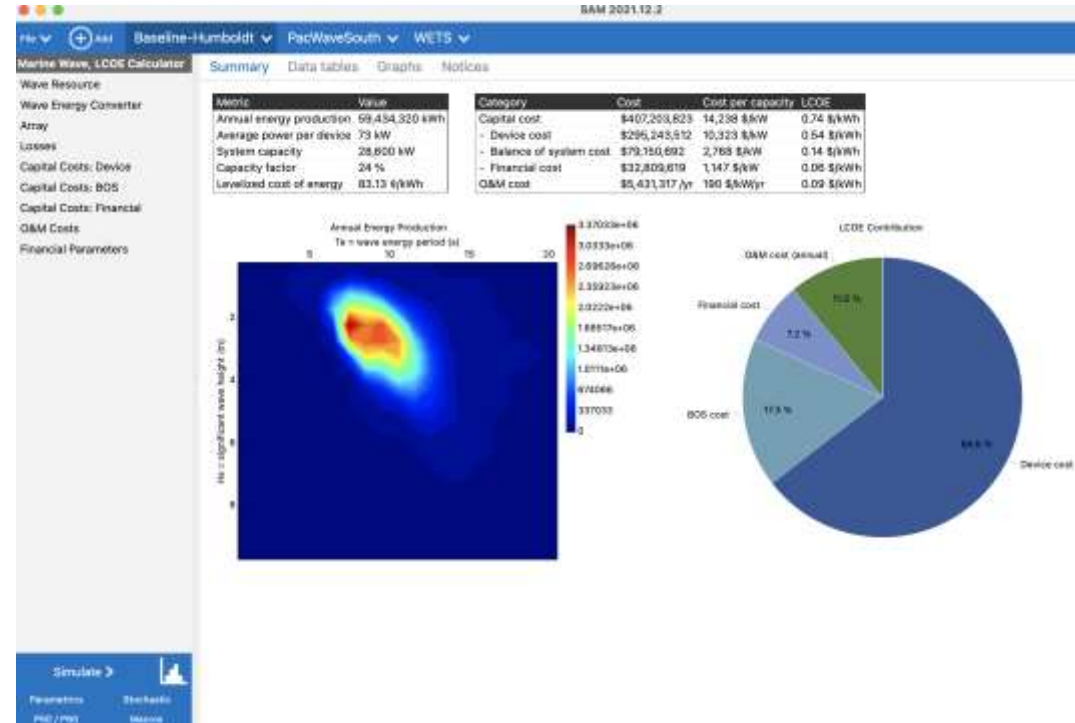
The screenshot displays the SAM 2021.12.2 LCOE Calculator interface. The left sidebar shows a navigation menu with 'Financial Parameters' selected. The main window is titled 'LCOE Calculator' and contains the following sections:

- Capital and Operating Costs:**
  - System capacity: 28,800.00 kW
  - Capital cost: 407,203,822.5 \$
  - Fixed operating cost (annual): 5,431,316.00 \$
  - Variable operating cost: 0 \$/kWh
- Financial Assumptions:**
  - Enter fixed charge rate (selected) / Calculate fixed charge rate
  - Fixed charge rate (real): 0.108
  - Analysis period: 20 years
  - Inflation rate: 2.5 %/year
  - Internal rate of return (nominal): 13 %/year
  - Project term debt: 00 % of capital cost
  - Nominal debt interest rate: 4 %/year
  - Effective tax rate: 28 %/year
  - Depreciation schedule: Edit... % of capital cost
  - Annual cost during construction: Edit... % of capital cost
  - Nominal construction interest rate: 3.5 %/year
- Reference Values:**
  - Capital recovery factor (CRF): 0.000
  - Project financing factor (PFF): 0.000
  - Construction financing factor (CFF): 0.000
  - Capital cost (CC): 407,203,822.5 \$
  - Fixed operating cost (FOC): 5,431,316.00 \$
  - Variable operating cost (VOC): 0.00 \$/kWh
  - WACC (for reference only): 0.000

The formula for LCOE is shown at the bottom:  $LCOE = (FCR \cdot CC + FOC) / \text{Annual Energy} + VOC$ .

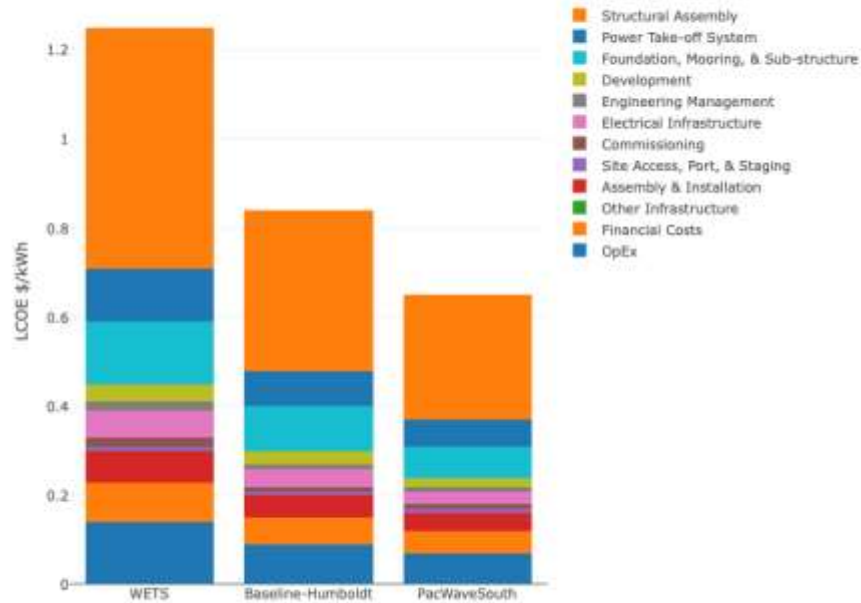
# ME SAM: Baseline Results

- AEP: 59,434 MWh
- Capacity Factor: 24%
- Avg power per device: 73 kW
- System Capacity: 28.6 MW
- LCOE: \$0.83/kWh
- Note: LCOE is higher than the original reference model report



# ME SAM: Site Location Case Comparison

LCOE Contribution

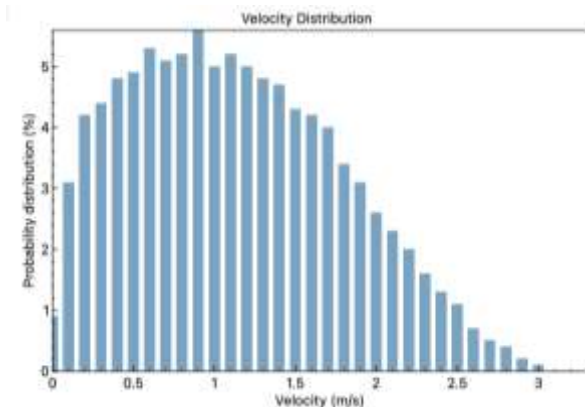
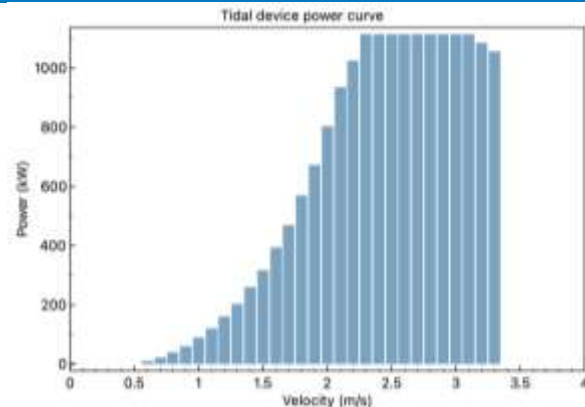


	WETS (Kaneohe, Oahu, HI)	Humboldt Bay (Eureka, CA)	PacWave South (Newport, OR)
Levelized Cost of Energy	\$1.24 /kWh	\$0.83 /kWh	\$0.65 /kWh
Annual Energy Production	39,844,224 kWh	59,434,320 kWh	75,937,816 kWh
Capacity Factor	15.9%	23.7%	30.3%
Capital Expenditures	\$14,238 /kW	\$14,238 /kW	\$14,238 /kW
Operational Expenditures	\$190 /kW/yr	\$190 /kW/yr	\$190 /kW/yr
Fixed Charge Rate	10.8%	10.8%	10.8%



# ME SAM: Tidal Energy Modeling

- SAM's tidal module has similar methodology and workflow to the wave energy module
- Requires a power curve for the tidal device
- Requires tidal resource histogram for the site location
- Tidal resource data library



# SAM Summary

- Use SAM for a fast and standardized techno-economic assessments
- Standardized reporting
- Custom macros
- Hybrid system modeling
- Regular updates typically in November each year

Download SAM here:

<https://sam.nrel.gov/download.html>

# Q&A

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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the US Department of Energy Water Power Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

