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Reducing Offshore Transmission Requirements by Combining Offshore Wind and Wave Farms

Eric D. Stoutenburg, *Member, IEEE*, and Mark Z. Jacobson

***Abstract*—The advantages of combining offshore wind and wave energy into a single farm include reduced hours of zero power output and reduced interhour variability. Both advantages facilitate grid integration of variable renewables. The power output profile of a combined farm with wind and wave is substantially different from a 100% offshore wind energy farm or a 100% wave energy farm. The different power output profile of combined farms with a higher frequency of hourly power output near the annual capacity factor potentially allows for a reduction in the required capacity of the offshore transmission system. The transmission capacity reduction is balanced by the curtailment of energy during the few hours a year that a combined farm generates at full power. An optimization of the transmission capacity for various generation mixes of wind and wave was investigated, and results show that the optimal transmission capacity for a 1000-MW combined farm is approximately 80 MW, or 8%, less than either a 100% wind or 100% wave energy farm.**

***Index Terms*—High-voltage direct-current (HVDC) transmission systems, offshore transmission systems, offshore wind energy farms, wave energy farms.**

I. Introduction

THERE are several quantified and potential advantages to combining offshore wind turbines and wave energy converters into a single offshore marine renewable energy farm [1], [2]. Two quantified advantages that facilitate the grid integration of renewable energy are the reduction in the hours of zero power output and the reduction in variability. Both reduce the requirement for thermal generation capacity and operating reserves. California offshore wind farms could generate zero power for over 1000 h per year and wave farms for over 200 h; farms with colocated wind and wave power could generate zero power for less than 100 h per year [1]. Similarly, combined farms have lower interhour variability quantified by the reduction in three standard deviations of the change in power output between consecutive hours as shown in Fig. 1. When combined with system load interhour variability, this metric estimates load-following reserve requirements [3].

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The authors are with the Civil & Environmental Engineering Department, Stanford University, Stanford, CA 94305 USA (e-mail: estout@stanford.edu; jacobson@stanford.edu).

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One potential advantage investigated in this paper is sharing the electrical infrastructure between wind and wave first explored in [4], a conference paper at the 2010 MTS/IEEE OCEANS, Seattle, WA. This advantage has been similarly demonstrated by interconnecting geographically dispersed wind farms to reduce transmission requirements [5]. The generation profile of a combined farm is different from that of either an offshore wind or wave farm. This suggests that an optimal configuration and rating of the transmission link are dependent on the generation mix of wind and wave in the combined farm. Using the voltage source converter high-voltage direct-current (VSC-HVDC) configuration for transmission from the offshore farm to the onshore substation, an optimization methodology determines the capacity of the transmission line for a given mix of wind and wave for various distances offshore. The optimization identifies the least cost VSC-HVDC transmission line rating and quantifies another potential advantage of building combined offshore marine renewable energy farms that facilitate higher penetrations of renewable energy in support of energy, climate, and environmental policy goals.

II. Power Output Profiles From Offshore Wind and Wave Energy in California

Measured hourly wind speed and wave parameters from 12 buoys off the California coast operated by the U.S. National Oceanic and Atmospheric Administration's (NOAA's) National Data Buoy Center (NDBC) were collected from 1980 to 2008. The wind speed was scaled from the measured 5-m height to the hub height of the V90 3.0-MW Vestas wind turbine using the measured power law wind profile exponent in [6], and the power output was calculated with an interpolated power curve of the V90 turbine. The power output of an individual turbine was scaled using the methodology of [7] and [8] to the aggregate power output of a wind farm accounting for spatial wind speed diversity and rotor wake losses. The significant wave height and dominant (peak) wave period were used to calculate the power output of a 750-kW Pelamis wave energy converter using the methodology in [9]. The power outputs of the wind turbines and wave energy converters were used to generate a time series of the hourly power output of a model 1000-MW farm at each buoy. Other data and methodology details are in [1]. The three buoys (46030 Blunts Reef, 46013 Bodega Bay, 46028 Cape San Martin) with the best wind and wave resources identified in [1] were used as a case study of the optimal transmission capacity. Each of the three buoys selected had between four and eight

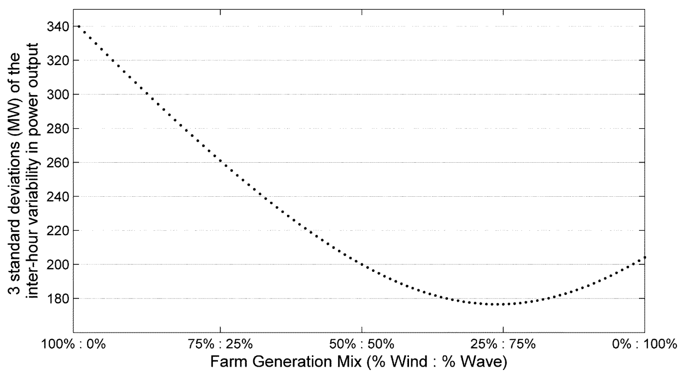

Fig. 1. Three σ of the interhour variability of a 1000-MW offshore wind and/or wave farm at buoy 46030 near Cape Mendocino, CA.

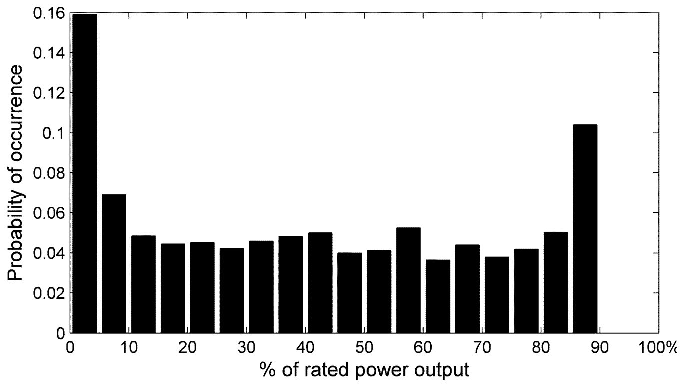

Fig. 2. Annual histogram of rated power output states of a 1000-MW offshore wind farm at buoy 46030.

years in their record of hourly wind and wave measurements that met the data quality standard used in [1].

The entire hourly power output of the modeled wind and wave farms for each buoy was binned by percentage of rated power to create an average annual histogram. These annual histograms, one for each buoy, approach the long term climatic average of the expected frequency of a rated power output state. Fig. 2 shows the annual histogram of a 100% wind farm operating at buoy 46030 off Cape Mendocino with a capacity factor of 41%. Offshore wind farms generate at zero power and near full power after rotor wake losses more than at any other power output state. Although wind speeds generally fit a Weibull distribution, the effect of the cut-in, rated, and cut-out wind speeds of a wind turbine power curve creates the histogram in Fig. 2. With rotor wake losses modeled and observed at 10% or greater [8], their effect reduces the potential full power output, compared with power-curve data, to 90%.

Fig. 3 shows the histogram of a 100% wave farm operating at buoy 46030 with a capacity factor of 28%. The frequency distribution of power output states of a wave energy converter is more similar to the Weibull distribution of the underlying wave energy resource. Wave energy converters, unable to pitch or brake like wind turbines, generate power over a wider band of sea states determined by wave height and period by tuning either the wave energy extraction device or the power takeoff system, or both, to optimize energy capture. Wave energy converters may also experience array losses similar to wind farm rotor wake

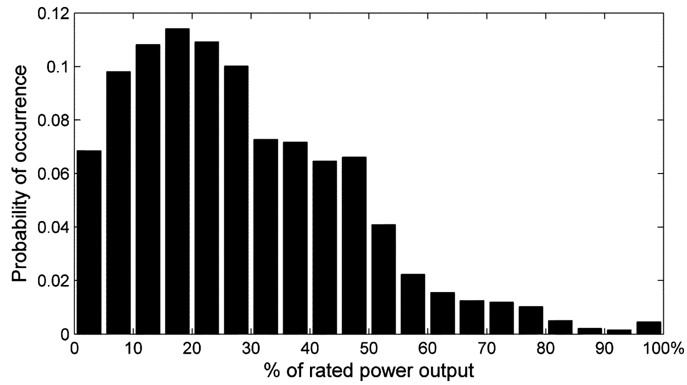

Fig. 3. Annual histogram of rated power output states of a 1000-MW wave farm at buoy 46030.

losses that will reduce the higher power output states. However, there are no large wave energy arrays deployed to provide measured array loss data. Wave tank tests have demonstrated both increased and decreased efficiencies of individual wave energy converters in the presence of other converters depending on device spacing and wave conditions [10], while some numerical studies of arrays assume sufficient distance between devices that no device–device interaction is observed [11]. This study therefore includes no array losses for the wave farm. The difference between the 100% wind farm and the 100% wave farm histograms suggests that a larger transmission capacity is required for offshore wind farms than for wave farms.

Fig. 4 shows the histogram of a combined offshore farm of wind and wave energy with 75% wind : 25% wave, 50% wind : 50% wave, and 25% wind : 75% wave, or equivalently, 750 MW of wind : 250 MW of wave, etc. With 25% wave power, the hours of zero and full power are significantly reduced over the 100% wind farm. The 50% wind : 50% wave and 25% wind : 75% wave farms show an increased frequency of power states near the average capacity factor of the entire farm and further reductions in zero and full power output states. The reduction in zero power output improves grid integration, and the reduction in full power output states implies potential savings by reducing the transmission capacity with only a marginal loss (curtailment) of energy.

Although winds generate the waves in the spectrum for wave energy extraction, waves develop to the height and period sufficient for wave energy converters over a long time and fetch. Therefore, the winds present at a given location are not necessarily coincident with the wave conditions at the same location. Waves generally form from winds in pressure systems far off the coast, such as the Aleutian low in the North Pacific or the Icelandic Low in the North Atlantic, whereas the high winds along the California coast are often generated by the semipermanent Pacific high or a storm front. Similarly, strong winds along the European west coast are often generated by the Bermuda high. This separation between wind conditions and sea states in large ocean basins explains the low frequency of simultaneous zero or full power output for wind and wave power. It is also apparent in the correlation (Pearson's product-moment correlation coefficient r) between the hourly wind and wave power time series. The correlation between wind and wave power at each buoy is

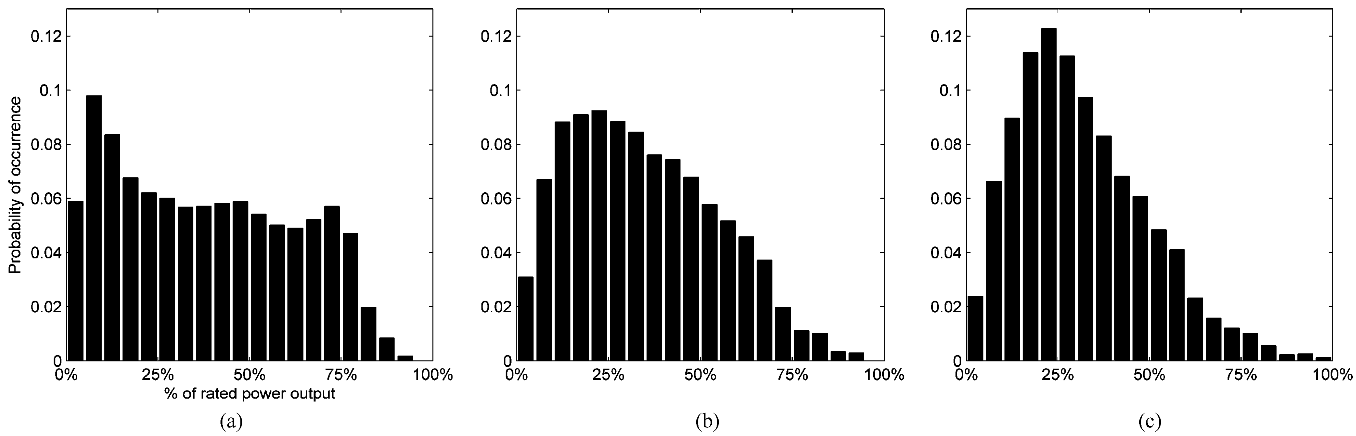

Fig. 4. Annual histogram of rated power output states for a 1000-MW offshore wind and wave farm with various generation mixes at buoy 46030: (a) 75% wind : 25% wave; (b) 50% wind : 50% wave; (c) 25% wind : 75% wave.

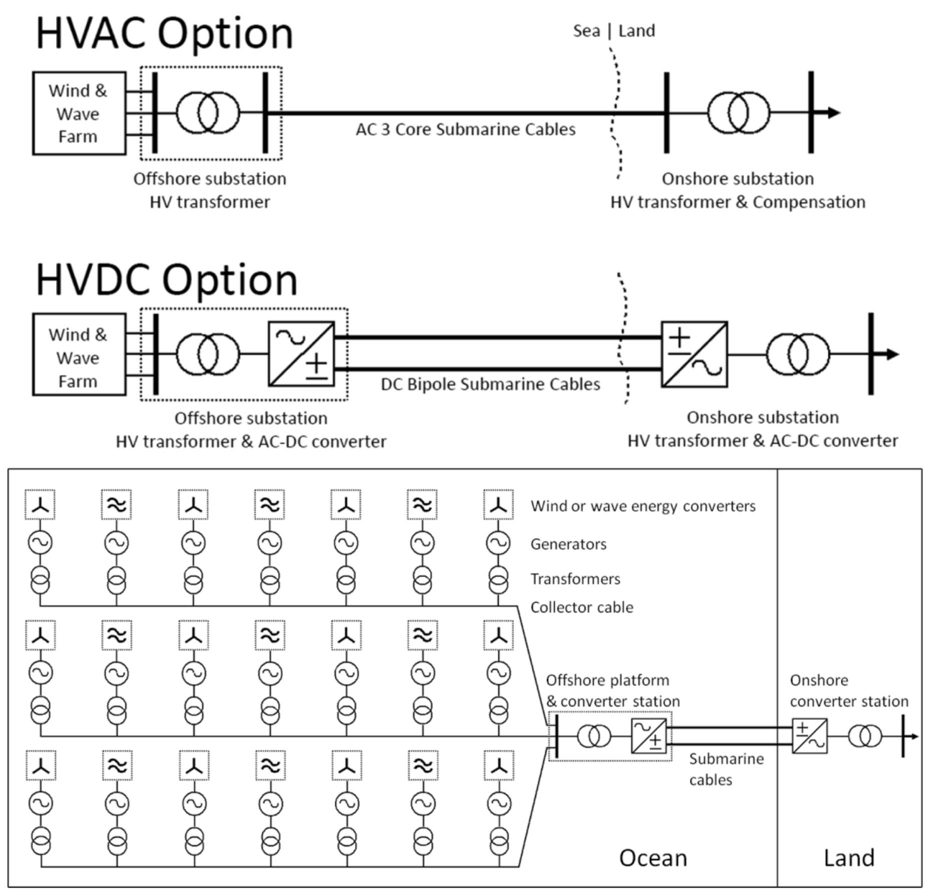

Fig. 5. Offshore transmission options for marine renewables: HVAC or HVDC with example HVDC layout.

low, between 0.28 and 0.46 [1]. This is often lower than the correlation between distant (∼500 km) offshore wind farms or between distant (∼800 km) offshore wave farms in California.

III. Transmission Alternatives for Offshore Renewable Energy Farms

A significant design and cost consideration of offshore renewable energy farms is the subsea transmission link from the farm to the onshore substation. The design selection of the electrical transmission system affects the initial capital cost, the operation and maintenance costs, and the electrical losses over the life of the project. Unlike for onshore wind farms, the electrical transmission system investment for offshore wind farms represents approximately 16% of the total project capital costs [12]. For large offshore wind farms, two transmission options are available—high-voltage alternating current (HVAC) and high-voltage direct current (HVDC)—as shown in Fig. 5. A number of studies have compared these options for offshore wind farms [13]–[29], wave farms [30], and combined wind–wave farms [31]. HVAC is usually more economical up to a distance of 30–60 km and HVDC at greater distances or if certain electrical operating characteristics, such as behavior during a fault, favor HVDC.

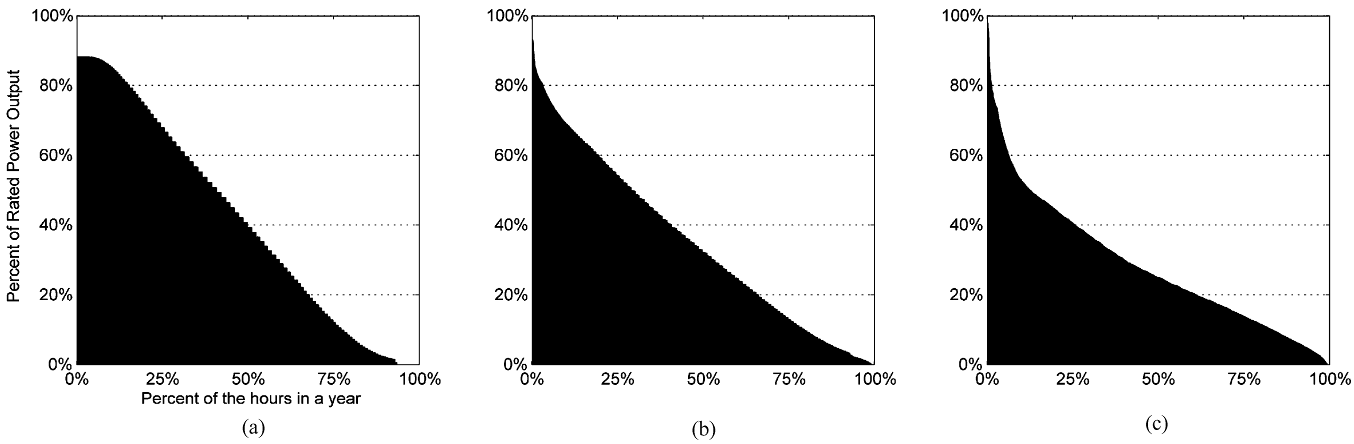

Fig. 6. Generation duration curves showing the cumulative percentage of time a farm operates at a given rated power level in a year: (a) 100% wind farm; (b) 50% wind : 50% wave farm; (c) 100% wave farm.

The topology for HVAC [13]–[17], [24]–[29] is an offshore substation, subsea transmission cables, an onshore substation, reactive compensation, filters, and switchgear. The offshore substation steps the approximately 33-kV collector line voltage up to approximately 132 or 220 kV for transmission to the onshore substation with single or three-core undersea cables. XLPE cables are common, and one 220-kV three-core cable transmits around 285 MW [32]. The environmental effects of electromagnetic fields and the cost of cable laying generally favor three-core cables. The primary disadvantage of the HVAC is the decreasing capacity to transmit active power at long distances because of the cable's capacitance. This requires reactive compensation from a static volt ampere reactive compensator or static synchronous compensator.

The topology for HVDC varies [18], [20], [24], [26], [29], [34], but voltage source converter HVDC (VSC-HVDC) topology has several advantages over line commutated current source converter (LCC/CSC) HVDC. VSC-HVDC has a smaller converter station important for offshore applications, no requirement for an AC reference voltage for commutation, and can transmit power to weak networks. VSC-HVDC consists of an offshore converter station, subsea DC cables, and an onshore converter station [34]. The converter stations include transformers, the AC-to-DC or DC-to-AC converters, switchgear, and filters. The primary advantage of VSC-HVDC over HVAC is the lower cable losses for long distances, improved fault response, and control over active and reactive power. The main disadvantage is the approximately 2% loss in each converter station [15]–[17], [20]. This study optimizes the transmission rating in megawatts of a VSC-HVDC system on the assumption that future larger farms at greater distances offshore and with more requirements for grid integration may likely choose VSC-HVDC over HVAC.

IV. Offshore Transmission Capacity Optimization

A. Optimization Methodology

The optimization of the transmission capacity in megawatts was considered from the perspective of the developer, who having already selected the generation mix of wind and wave

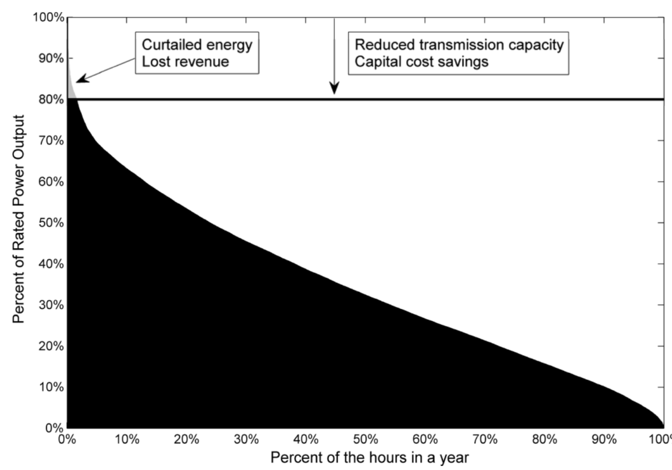

Fig. 7. Graphical example of the transmission capacity optimization problem for a 50% wind : 50% wave farm.

energy in the offshore farm, now seeks to build the optimal transmission system for the farm. The optimal capacity is determined by balancing the reduced transmission capacity capital cost savings with the lost revenues from curtailing energy. Curtailing energy would likely be accomplished with the wind turbines in the offshore farm through pitch control of the blades or selected shutdown of some turbines as is currently done for onshore wind farms to control ramp rates and as required by the grid operator. The histograms of power output can be shown cumulatively with a switch in the axes as generation duration curves in Fig. 6. For all subsequent plots only the 100% wind, 50% wind : 50% wave, and 100% wave cases are shown for clarity. The 50% wind : 50% wave case is representative of the 75% : 25% and 25% : 75% cases for plotting purposes. The optimization problem is shown by example in Fig. 7 with the generation duration curve of a 50% wind and 50% wave energy farm.

The optimal transmission capacity is the capacity at which the marginal revenue from energy sales is equal to the marginal cost of the transmission capacity. The marginal revenue is the increase in the annual energy sales from an incremental increase in the transmission capacity. It is a function of the resource mix

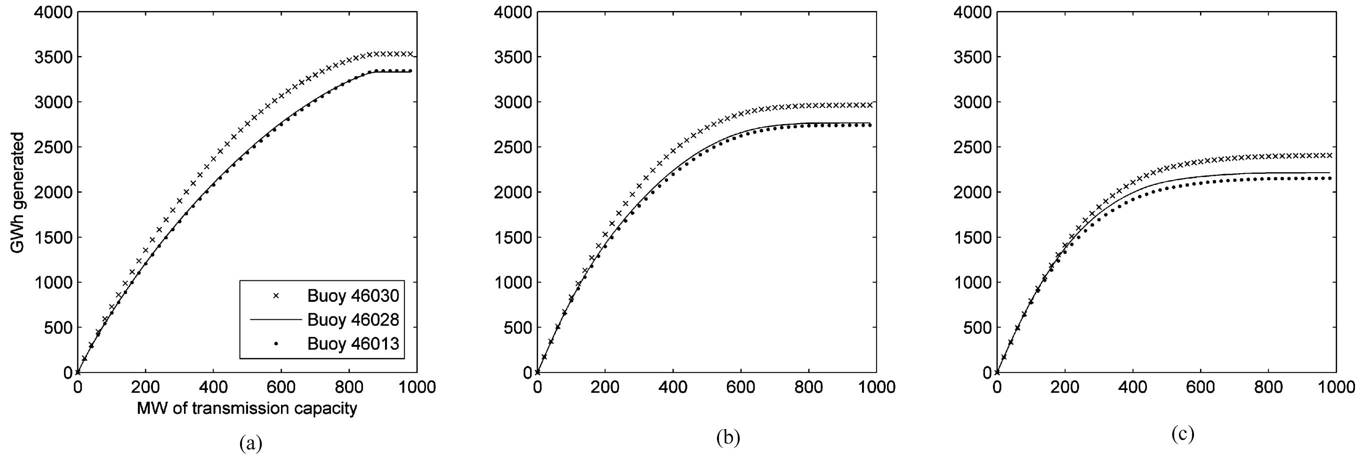

Fig. 8. GWh generated as a function of transmission link capacity for three generation mixes of farms at three buoys: (a) 100% wind; (b) 50% wind : 50% wave; (c) 100% wave.

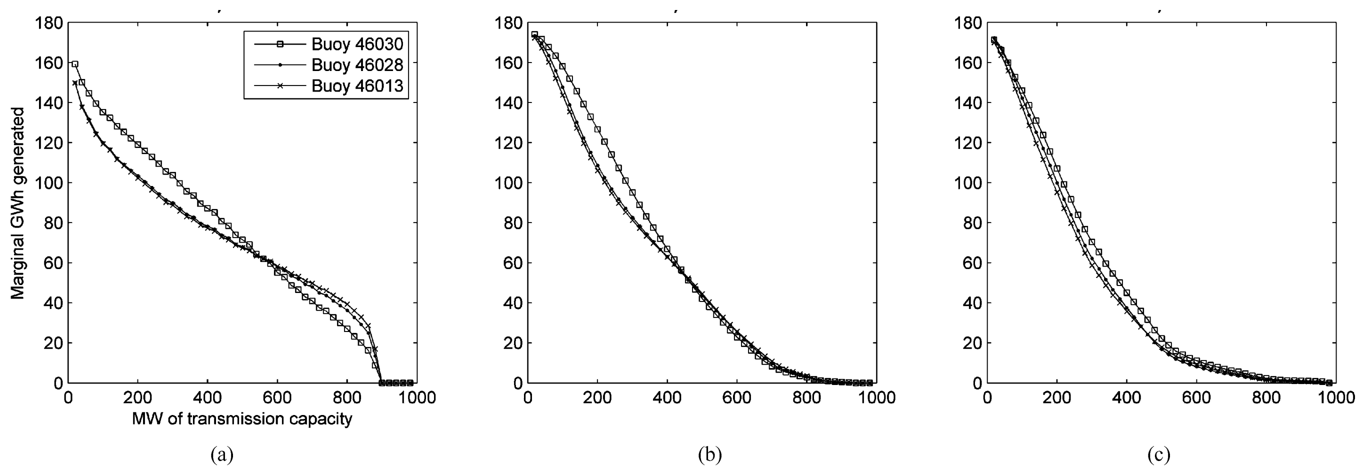

Fig. 9. Marginal increase in GWh generated for an incremental megawatt increase in transmission capacity for three generation mixes of farms at three buoys: (a) 100% wind; (b) 50% wind : 50% wave; (c) 100% wave.

between wind and wave, and the energy price. The marginal cost is the additional levelized cost to build the next increment of transmission capacity. It is a function of the distance offshore, capital cost, and financing terms. VSC-HVDC transmission systems come in discrete units of capacity. Therefore, the optimal transmission capacity is the unit of capacity before the additional marginal cost of a higher unit of capacity is greater than the additional marginal revenue.

B. Effect of Reduced Transmission Capacity on the Amount of Energy Generated

Fig. 8 shows the gigawatt hours (GWh) generated by a 1000-MW farm with a given transmission capacity in megawatts. It shows the effect of reduced transmission capacity on the amount of energy generated. The flattening of the GWh generated curve at high transmission capacities for the 50% wind : 50% wave and 100% wave farms shows the decreasing value of transmission capacity near the full rated power of the farms because the farms operate so few hours at full power. The three buoys situated along 580 km (360 mi) of the California coast have similar profiles. The differences reflect the different capacity factors, especially at buoy 46030 with both a higher wind and wave capacity factor than the other two buoys. The slope of the GWh generated curves in Fig. 8 is the marginal increase in GWh generated for an incremental increase in transmission capacity, as shown in Fig. 9. In a fixed energy price scenario, such as a fixed power purchase agreement price or feed-in tariff, the marginal increase in GWh generated curves in Fig. 9 can be multiplied by the energy price to produce the marginal revenue from an incremental increase in the transmission capacity.

C. VSC-HVDC Transmission Costs

Cost estimates of a VSC-HVDC system were collected from a survey of the literature [13], [15], [17], [20], [25], [28] and presented in Table I. Only the $\pm$150-kV option was considered. These estimates have a wide range of uncertainty because of the ongoing commercialization of the technology, the uniqueness of the costs for specific projects, and the limited number of HVDC component manufacturers. The discrete component sizes indicate a variety of possible combinations.

Optimal HVDC configurations were beyond the scope of this study, but two assumptions were used to generate possible configurations for the 1000-MW farms modeled at the three buoys.

TABLE I
VSC-HVDC SYSTEM COMPONENT PROPERTIES AND COST ESTIMATES

150 kV bipole cables							Converter Station					Platform
Power MW	Area mm 2	Ampacity A	Resistance Ω/km	Cost $K/km	Weight kg/m	Installation $K/km	Type	Power MW	Current A	Converter Loss %	Cost $M	Cost $M
307	630	1023	0.0327	510	21	250	M5	376	1233	1.80%	55	16
353	800	1175	0.0258	590	24	257	M5	376	1233	1.80%	55	16
401	1000	1335	0.0206	650	26	261	M6	573.9	1881	1.80%	84	18
437	1200	1458	0.0172	700	29	268	M6	573.9	1881	1.80%	84	18
478	1400	1594	0.0147	750	32	275	M6	573.9	1881	1.80%	84	18

Notes
1. Power and ampacity rating based on close spacing cable lay
2. Cable cost is per pair of DC bipole cables
3. Cable laying cost is assumed to moderately increase with cable weight and bending radius with $25K/km difference between 630mm2 and 1400mm2
4. Cable losses: copper DC ohmic losses at 70 deg C

Data Sources
Cable & converter data: [32]
Converter losses: conduction & switching [19]
Cable costs & cable laying costs: [12]-[14], [16], [19], [24]
Resistance: [35]
Platform costs: [13], [24]
Converter costs: [14], [16], [19], [24]

TABLE II
POSSIBLE TRANSMISSION SYSTEM CONFIGURATIONS AND COSTS FOR A 1000-MW OFFSHORE FARM

Option	Rating (MW)	+/-150kV Cable (mm^2)	Cable Pairs	Converter Type	Converter Pairs	Total Cost ($M) for given distance (km) 30km	40km	50km	60km
1	614	630	2	M5	2	298	313	328	343
2	706	800	2	M5	2	303	320	337	354
3	802	1000	2	M6	2	427	445	463	481
4	874	1200	2	M6	2	430	449	469	488
5	921	630	3	M5	3	447	469	492	515
6	956	1400	2	M6	2	434	454	475	495

First, a minimum of two complete circuits (cable pair and converter station pair) are required for reliability reasons. This ensures that failure of any one component, converter or cable pair, permits the export of at least half the initial transmission capacity, e.g., failure of one circuit rated at 500 MW allows the 1000-MW farm to export 500 MW on the second circuit. This is a simplification of several studies on component reliability for offshore transmission systems [17], [20], [25]. Second, the circuits must be identical, e.g., two identical 478-MW capacity circuits for 956 MW.

The transmission configurations for a 1000-MW farm using the ±150-kV cable options are shown in Table II. The options represent all possible combinations of double and triple circuit VSC-HVDC configurations (two or three cable pairs and their converter station pairs) based on the available cable sizes and converter ratings to transmit power between 600 and 1000 MW given the discrete rated sizes of available components. Although option 5 with three component sets offers higher reliability than the other options, option 6 offers higher capacity for lower cost. Since reliability was not explicitly quantified in this study, option 5 was not considered further in the analysis. Only the 874- and 956-MW transmission options are possible optimal transmission systems for the 1000-MW farms that were considered.

V. CASE STUDY

The optimal transmission configuration was identified for each of the three buoy locations for five generation mix cases at four distances offshore. The transmission configurations were either the 874-MW option or the 956-MW option. The three buoys were 46030 at Cape Mendocino, 46028 at Cape Martin, and 46013 near Bodega Bay, all off the California coast. The five generation mixes were 100% wind, 75% wind : 25% wave, 50% wind : 50% wave, 25% wind : 75% wave, and 100% wave. The distances were 30, 40, 50, and 60 km offshore. The total capital costs of the transmission configurations were levelized with 8% interest rate over 15 years. The energy price was assumed at $100/MWh (megawatt hour).

The optimization methodology is shown graphically for buoy 46030 for three generation mixes in Figs. 10 and 11. In Fig. 10, the marginal revenue per megawatt for each generation mix is plotted along with the levelized marginal cost for a transmission capacity of 874 and 956 MW. The marginal revenue per megawatt curve has the same shape as the marginal GWh curves plotted in Fig. 9 because the curve is only scaled by the energy price indicating that the generation mix sets the curve's shape entirely. The marginal cost for transmission capacity are the very thin boxes, almost imperceptible, laying on the x-axis.

Fig. 11 is an inset of Fig. 10 showing where the marginal revenue and marginal cost lines intersect and the optimal transmission option can be selected. In Fig. 11(a), the 100% wind farm marginal revenue line intersects the marginal cost line (box) of the 956-MW option near 900 MW. Selecting between the 874- and 956-MW option is done by comparing the area of additional revenue versus the area of additional capital cost if the 956-MW option is selected. The additional revenue is the area marked "R" between the marginal revenue line, a vertical line up from 874 MW, and the line (box) of the 956-MW option. The additional cost is the area marked "C" from the intersection of the 100% wind marginal revenue line and the end of the marginal cost box at 956 MW. The additional cost, area "C," is

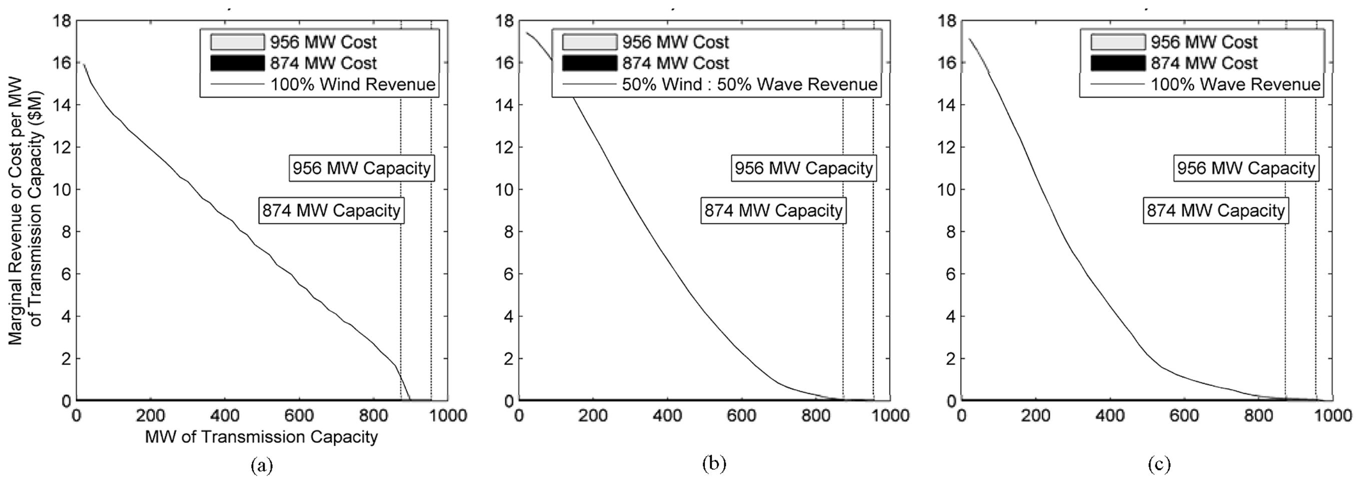

Fig. 10. The marginal revenue from generation and the marginal cost of the transmission system for a 1000-MW farm 30 km offshore at buoy 46030: (a) 100% wind farm; (b) 50% wind : 50% wave farm; (c) 100% wave farm.

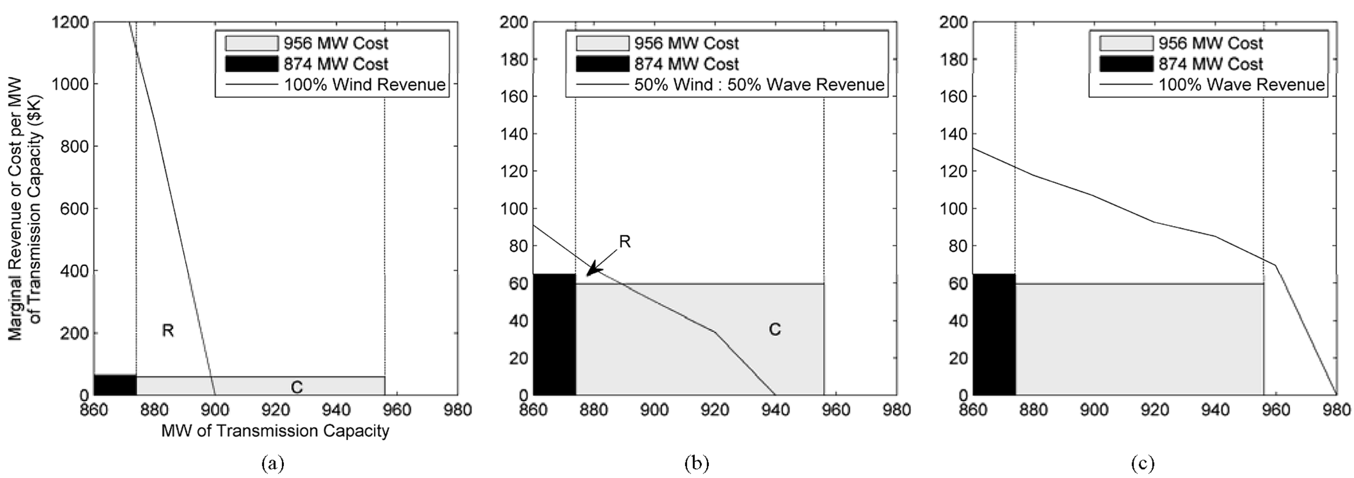

Fig. 11. Inset from lower right of Fig. 10. The marginal costs of the transmission options are shown as boxes. The optimal transmission capacity for the 100% wind and 100% wave farm is the 956-MW option. The 874-MW option is optimal for the 50% wind and 50% wave farm: (a) 100% wind farm; (b) 50% wind : 50% wave farm; (c) 100% wave farm.

smaller than the additional revenue, area "R," gained by transmitting the additional 26 MW (900-MW max wind—874 MW) that the 956-MW option provides to a 100% wind farm. This is the effect of a large number of hours that a wind farm operates at full power. In Fig. 11(b), the same methodology applied to the 50% wind : 50% wave farm results in the smaller 874-MW option because the additional revenue area "R" is less than the additional cost area "C." In Fig. 11(c), the 100% wave farm marginal revenue line is always greater than the marginal cost of the 956-MW line, so 956-MW line is optimal.

Fig. 12, similar to Fig. 11, shows the marginal revenues for all three generation mixes and marginal costs of a transmission system for a farm 60 km offshore near buoy 46030. At 60 km, the 874-MW option is an even stronger case for the 50% wind and 50% wave farm, while the 100% wind and 100% wave farm continue to select the 956-MW option. The effect of distance on the optimization is simply to raise the levelized marginal cost boxes vertically because distance increases the cable supply and installation costs. Changing the HVDC transmission cost estimates or financing terms would have a similar effect.

Table III shows the optimal transmission capacity option for the three buoys with five generation mixes and four distances offshore. Farms with both wind and wave operate so few hours at full power (and zero power) that a lower transmission capacity is optimal over the 30-km distance range and for the three different farm locations (buoys). When 60 km offshore, a 100% wave farm near buoy 46013 results in the lower transmission capacity. A 100% wave farm at any distance near buoy 46028 also results in the lower transmission capacity. It has the lowest wave resource of the three buoys. Any 100% wind farm selects the 956-MW transmission capacity option because of the high number of hours at full power.

Increasing the energy price above the assumed $100/MWh would increase the number of cases where the 956-MW option is selected since every megawatt hour transmitted would be more valuable. However, not until the energy price was over approximately $350/MWh would every farm at every distance and generation mix select the greater 956-MW option. Decreasing the energy price to approximately $60/MWh means every wave farm at all distances and buoy locations would select the lower

TABLE III
OPTIMAL TRANSMISSION CAPACITY IN MEGAWATTS FOR THREE 1000-MW OFFSHORE FARMS AT FOUR DISTANCES OFFSHORE WITH FIVE GENERATION MIXES

Transmission Capacity in MW	Buoy 46030				Buoy 46028				Buoy 46013			
	30 km	40 km	50 km	60 km	30 km	40 km	50 km	60 km	30 km	40 km	50 km	60 km
100% Wind	956	956	956	956	956	956	956	956	956	956	956	956
75% Wind : 25% Wave	874	874	874	874	874	874	874	874	874	874	874	874
50% Wind : 50% Wave	874	874	874	874	874	874	874	874	874	874	874	874
25% Wind : 75% Wave	874	874	874	874	874	874	874	874	874	874	874	874
100% Wave	956	956	956	956	874	874	874	874	956	956	956	874

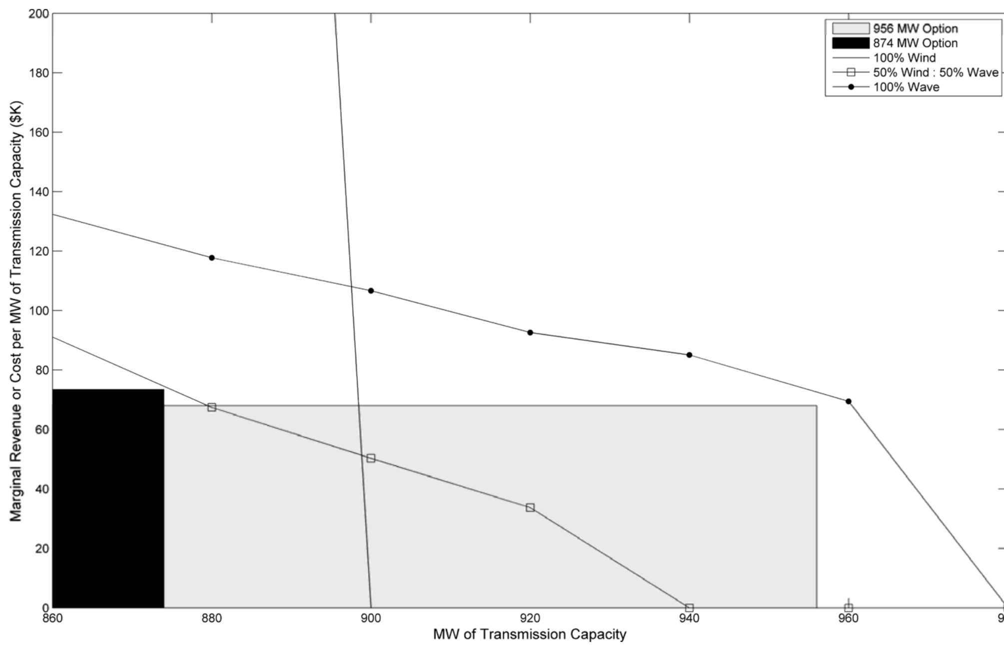

Fig. 12. Marginal revenue and cost for a 1000-MW farm 60 km offshore near buoy 46030.

874-MW option, while all the 100% wind farms would retain the 956-MW option.

VI. Discussion

There are several benefits of a renewable energy farm with combined resources, such as a combined wind and wave farm, operating with less variability over a smaller range near its capacity factor and constrained by a limited transmission capacity. First, it reduces the absolute maximum contingency event if the entire transmission link experiences a fault. This could reduce the required contingency reserves carried by the independent system operator (ISO), particularly if the large offshore farm approaches the capacity of the largest thermal or hydropower unit in the system. Second, by constraining the operating range of the farm through reduced transmission capacity, it further reduces the maximum interhour ramps up or down. This could reduce the required operating reserves held online by the ISO to manage these events. Reducing these operating reserves, often spinning reserves, decreases operating costs and emissions, which reduces the overall system integration costs of renewables.

The three buoys used to site possible wind and wave farms for this analysis were selected based on the high-quality renewable energy resources and were not screened for other important site feasibility criteria for offshore wind and wave farms. The criteria would, for example, include consideration of competing marine spatial uses, depth, environmental impacts, and suitable electrical grid interconnection points. Offshore wind and hydrokinetic projects would go through review and permitting processes at the federal, state, and local levels to address these issues as outlined in [36]. The primary competing marine spatial uses are marine protected areas, shipping lanes, naval exercise areas, and fishing. The three buoys selected do not sit directly in shipping lanes to major ports, naval exercise areas, or marine protected areas [37], [38], although an offshore power plant near buoy 46030 may need to be reconciled with shipping lanes into the Port of Eureka. Buoys 46030 and 46013 lie within NOAA identified "potential future footprint" areas for offshore alternative energy [38]. All offshore power projects are likely to face challenges from fishing interests and environmental concerns that would be handled on a case-by-case basis.

Currently, bottom mounted offshore wind turbines are restricted to maximum depths of approximately 50 m like at Beatrice, Scotland. Wave energy devices, such as the Pelamis, are intended for installation at depth greater than 50 m. Combined farms may be built with consideration of bathymetric lines with wind occupying shallow regions (<50 m) of the farm's footprint and wave the deeper regions (>50 m). Commercial realization of floating offshore wind turbines such as the SWAY® turbine and of wave energy devices such as the Pelamis may be on similar timelines and allow full development of wind and wave farms in deeper water with some possible cost reductions in shared anchor points for mooring lines. Buoy 46030 lies in 82-m depth, and buoy 46013 lies in 116-m depth. Buoy 46028 lies far offshore and at a significant depth of 1158 m that would likely exclude development at the exact location of the buoy. Buoys 46030 and 46013 would be more likely developments based on depth and distance from shore. All three buoys are located offshore California at rural locations without significant onshore electrical transmission lines. This would require overcoming permitting and investment challenges for reinforced or new onshore transmission lines to transfer the power to the major coastal load centers of the San Francisco Bay and Los Angeles Basin, a challenge also faced by onshore wind and solar farms. Buoy 46030 is likely the easiest onshore connection point with a natural gas plant located in Humboldt Bay and three transmission lines running inland [39].

VII. Conclusion

Maintaining resource diversity, such as by combining offshore wind and wave energy, can reduce the impact of variability on the electric power system and facilitate higher penetrations of renewables in support of energy, climate, and environmental policy goals. The benefit of reduced transmission capacity was examined in this study by optimizing the transmission capacity for 1000-MW farms at three locations off the California coast at distances from 30 to 60 km. The power output profiles of a 100% wind farm, a 100% wave farm, and combined farms with wind and wave were shown to be significantly different from each other. The difference in power output profiles resulted in the selection of a lower transmission capacity for the combined farms. The methodology considered the optimal selection from the perspective of the developer. When the utility is responsible for the development of the offshore transmission system, the benefit of combined farms is likely to be even greater as they both generate less variable power and reduce transmission investment costs.

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Eric D. Stoutenburg (M'10) received the B.S. degree in mechanical engineering from the United States Military Academy, West Point, NY, in 2001 and the M.S. degree in civil and environmental engineering from Stanford University, Stanford, CA, in 2008, where he is currently working towards the Ph.D. degree at the Department of Civil and Environmental Engineering.

Mark Z. Jacobson received the B.S. degree in civil engineering, the A.B. degree in economics, and the M.S. degree in environmental engineering from Stanford University, Stanford, CA, in 1988 and the M.S. and Ph.D. degrees in atmospheric sciences from the University of California Los Angeles (UCLA), Los Angeles, in 1991 and 1994, respectively.

He is the Director of the Atmosphere/Energy Program and Professor of Civil and Environmental Engineering at Stanford University. He has been on the faculty at Stanford since 1994.