FESC Phase 2 Technology Commercialization Projects

High Efficiency Black Polymer Solar Cells
(Progress Report)

PI: Dr. Franky So
External Collaborators: John Reynolds, Georgia Tech
Industry Partner: Sestar Technologies, LLC
Students: Cephas Small and Song Chen

Description: The objective of the proposed project is to synthesize broadly absorbing, black colored (PBLACK) polymers with especially high charge mobilities and to fabricate the highest performance polymer solar cells possible. Specifically, we will synthesize polymers with absorption band ranging from 400 nm to beyond 1 µm with carrier mobilities higher than 10^{-4} cm^2/Vs. Polymer-fullerene (both $PC_{60}BM$ and $PC_{70}BM$ along with more recently developed derivatives) blend morphology will be optimized using different solvent/heat treatments as well as additives to the blends. The final device will be enhanced using anode and cathode interlayers to enhance carrier extraction to the electrodes. With the ability to synthesize broadly absorbing polymers, control the donor-acceptor phase morphology and engineer the device structure, it is expected that the power conversion efficiency of polymer solar cells can reach 10% at the end of the two-year program.

Summary of Progress

Polymer bulk heterojunction solar cells based on low bandgap polymer:fullerene blends are promising for next generation low-cost photovoltaics. While these solution-processed solar cells are compatible with large-scale roll-to-roll processing, active layers used for typical laboratory-scale devices are too thin to ensure high manufacturing yields. Furthermore, due to the limited light absorption and optical interference within the thin active layer, the external quantum efficiencies (EQEs) of bulk heterojunction polymer solar cells are severely limited. In order to produce polymer solar cells with high yields, efficient solar cells with a thick active layer must be demonstrated. In this work, the performance of thick-film solar cells employing the low-bandgap polymer poly(dithienogermole-thienopyrrolodione) (PDTG-TPD) was demonstrated. Power conversion efficiencies over 8.0% were obtained for devices with an active layer thickness of 200 nm, illustrating the potential of this polymer for large-scale manufacturing. Although an average EQE > 65% was obtained for devices with active layer thicknesses > 200 nm, the cell performance could not be maintained due to a reduction in fill factor. By comparing our results for PDTG-TPD solar cells with similar P3HT-based devices, we investigated the loss mechanisms associated with the limited device performance observed for thick-film low-bandgap polymer solar cells.

1. Funds leveraged / New Partnerships Created

New collaborations		
Partner name	Title or short description of the collaboration	Funding, if applicable

Proposals						
Title	Agency	Reference Number	PI, Co-investigators and collaborators	Funding requested	Project time frame (1 year, 2 years, etc.)	Date submitted
Dipole Engineering for polymer solar cells	DOE Basic Energy Science		Franky So (UF) John Reynolds (Georgia Tech)	$840,000	3 years	November, 2012

Grants Awarded					
Title	Agency	Reference Number	PI, Co-investigators and collaborators	Period of Performance	Funding awarded

2013 Annual Report

High efficiency polymer solar cells with thick films and prototypical structure for printing

Based on the demonstration of high efficiency polymer solar cells based on a low bandgap donor-acceptor copolymer with alternating dithienogermole-thienopyrrolodione (DTG-TPD) repeat units last year, we further present high efficiency inverted polymer solar cell with thicker active layers that will potentially facilitate the production yield of roll-to-roll printing process. One key factor for improving the large-scale R2R processing compatibility of polymer solar cells is the active layer thickness required to ensure high manufacturing yields in PV modules. Most high efficiency laboratory-scale devices demonstrated have an active layer with a thickness of about 100 nm which is too thin for R2R processing to ensure a pinhole-free film. Obtaining high efficiency devices with active layers thicker than 200 nm is critical for commercialization. To achieve high efficiency with an active layer thickness larger than 200nm, we fabricated the device containing a bottom transparent oxide electrode, a ZnO-PVP composite layer with UV-ozone treatment, a photo-active layer composed of PDTG-TPD and fullerene, a layer of molybdenum oxide and a top electrode—silver. In addition, the efficiency loss mechanism in the thick devices was studied in depth by the measurement of field dependent external quantum efficiency spectra and photoconductivity analysis. The work is done in collaboration with Dr. John Reynolds at Georgia Institute of Technology.

Figure 1 shows the photocurrent density–voltage (*J*−*V*) characteristics and the corresponding external quantum efficiency (EQE) spectra for inverted PDTG-TPD:$PC_{71}BM$ solar cells with 105 nm, 204 nm, and 258 nm-thick active layers. Figure 1 a shows that the short-circuit current density (*J*sc) increases with increasing active layer thickness due to enhanced light absorption, with the highest *J*sc of 16.1 mA cm^{-2} obtained for the device with an active layer thickness of 258 nm. The integrated current density from the EQE spectra, shown in Figure 1 b, is consistent with the measured *J*sc with 5% deviation. The difference in the EQE spectra is due to optical interference effects between the incident light and light reflected from the Ag back electrode. For devices with thickness $L \geq 200$ nm, the interference effects no longer affect the photocurrent density of the device and the active layer absorbs most of the incident light below 700 nm, resulting in EQEs above 70% from 400 nm to 700 nm.

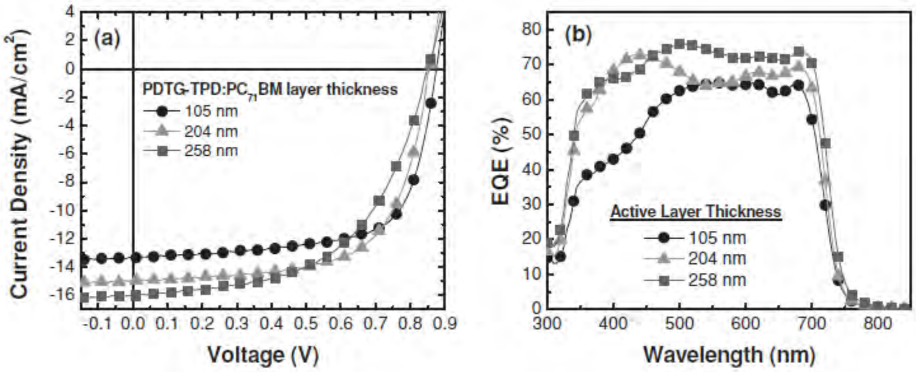

FIGURE 10 (A) CURRENT DENSITY VERSUS VOLTAGE CHARACTERISTICS FOR PDTG-TPD:PC 71 BM SOLAR CELLS WITH 105 NM, 204 NM, AND 258 NM-THICK ACTIVE LAYER. (B) CORRESPONDING EXTERNAL QUANTUM EFFICIENCY (EQE) SPECTRA FOR THE DEVICES.

TABLE 1 AVERAGED SOLAR CELL PERFORMANCE FOR PDTG-TPD:PC 71 BM DEVICES WITH VARIOUS ACTIVE LAYER THICKNESS UNDER

Active Layer Thickness	J_{sc} (mA cm^{-2})	J_{sc} (EQE) (mA cm^{-2})	V_{oc} (V)	FF (%)	PCE (%)
90 nm	12.5 +/−0.1	12.3	0.88	68.5 +/−0.1	7.5 +/−0.1
105 nm	13.3 +/−0.2	13.0	0.87	68.7 +/−0.3	7.9 +/−0.1
153 nm	13.5 +/−0.4	13.5	0.86	68.1 +/− 0.3	8.0 +/−0.2
204 nm	14.9 +/−0.3	14.7	0.86	64.5 +/−0.7	8.2 +/−0.2
258 nm	16.1 +/−0.2	16.0	0.85	54.1 +/−0.9	7.4 +/−0.1
409 nm	15.2 +/−0.1	14.9	0.82	41.6 +/−0.9	5.2 +/−0.1

Table 1 summarizes the average solar cell parameters for the PDTG-TPD:$PC_{71}BM$ devices with an active layer thickness varying from 90 nm to 409 nm. The reduction in FF observed for PDTG-TPD solar cells with increasing active layer thickness is the major factor limiting the device performance. A power conversion efficiency (PCE) of 7.9% is obtained for the device with a 105 nm thick active layer, which is consistent with our previous report. The efficiency remains constant for devices with $L \leq 204$ nm, with an average PCE of 8.2% being obtained for devices with an active layer thickness of 204 nm. Above 200 nm, the FF reduction becomes significant, dropping from 69% in 105 nm film to 42% in 409 nm film.

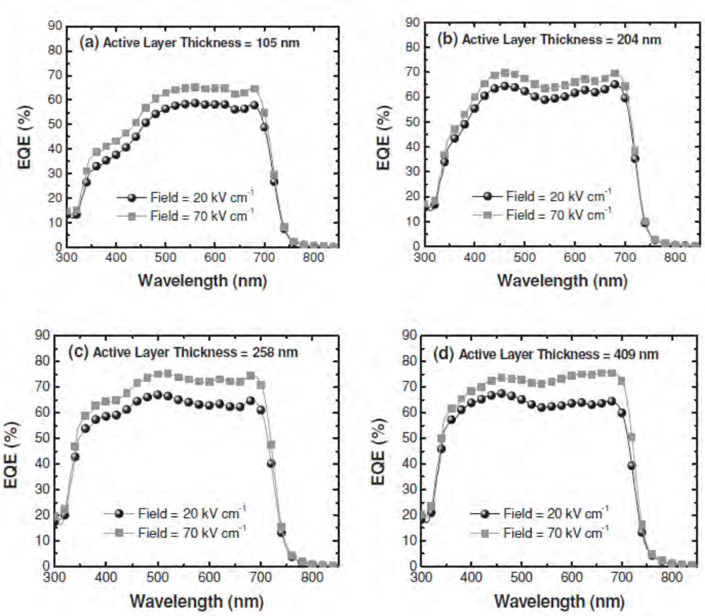

FIGURE 11 FIELD-DEPENDENT EQE SPECTRA FOR PDTG-TPD:PC 71 BM SOLAR CELLS WITH (A) 105 NM, (B) 204 NM, (C) 258 NM AND (D) 409 NM-THICK ACTIVE LAYER. THE EQE SPECTRA WERE MEASURED AT INTERNAL

To determine the root cause for the reduction in FF observed in thick-film PDTG-TPD:$PC_{71}BM$ solar cells, the EQE spectra for the thin-film and thick-film devices were measured under different values of internal electric field. **Figure 2** shows the field-dependent EQE spectra for devices with 105 nm, 204 nm, 258 nm, and 409 nm-thick active layers, respectively. By measuring the EQE as a function of internal electric field (E), approximated as $E = (Voc-V)/L$, the effect of series resistance can be eliminated. For the device with an active layer thickness ≤ 204 nm, increasing the applied field from 20 kV cm^{-1} to 70 kV

cm^{-1} leads to a uniform enhancement in EQE across the entire spectral range. The increased applied field enhances the extraction of photogenerated charges equally across the EQE spectrum. Interestingly, for devices with $L > 204$ nm, a stronger field dependent enhancement in EQE is observed in the spectral range from 500 to 750 nm when the applied field is increased from 20 kV cm^{-1} to 70 kV cm^{-1}. This wavelength range corresponds to the absorption spectrum for a pristine PDTG-TPD film. For devices with a thick active layer, the build-up of charges in PDTG-TPD:PC_{71}BM will hinder charge collection and contribute to the FF reduction in thick solar cells.

To study the role space-charge accumulation plays in PDTGTPD: PC_{71}BM solar cells with a thick active layer, we employed the SCL photocurrent model to confirm that the electrostatic space-charge limit was reached in our thick devices. We compared the results for PDTG-TPD:PC_{71}BM solar cells with similar devices based on P3HT:PC_{61}BM, since P3HT solar cells provide a model system for studying space-charge effects. The effective photocurrent J_{ph}, normalized to the saturation photocurrent $J_{sat} = qG_{\max}L$, was plotted on a double logarithmic scale against the effective voltage across the device, given by $V_{\text{eff}} = V_0 – V$. Here, V_0 is defined as the voltage where $J_{ph} = 0$ and is slightly larger than Voc. This "corrected" photocurrent analysis is a widely used tool for analyzing recombination loss processes in organic solar cells. **Figure 3a** shows the results for the PDTG-TPD:PC_{71}BM solar cells with 105 nm, 258 nm and 409 nm - thick active layer. For the device with a 105 nm thick active layer, two different voltage regimes can be observed. For $V_{\text{eff}} < 0.30$ V, J_{ph} steadily increases with voltage due to the competition between diffusion and drift for photo-generated carrier transport at low field. For $V_{\text{eff}} > 0.30$ V, the photocurrent saturates with increasing voltage. In this saturation regime, the internal field is strong enough to efficiently extract photogenerated carriers and the high field is responsible for the dissociation of *e*-*h* pairs. The voltage corresponding to the short circuit condition falls within the saturation regime, indicating that the high J_{sc} and FF obtained for this device is due to efficient charge collection by the internal electric field. For the device with a 105 nm active layer, space charge effects were not observed based on the data shown in Figure 3a. As the active layer thickness for PDTG-TPD cells increased above 200 nm, a square-root effective voltage dependence on J_{ph} is observed. This $J_{ph} \propto V^{1/2}$ corresponds to the onset of space-charge limited photocurrent in thick PDTG-TPD cells assuming a $J_{ph} \propto G^{3/4}$ dependence is also observed. The solid lines in Figure 3a correspond to $J_{ph} \propto V^{1/2}$. For the 409 nm-thick device, the $J_{ph} \propto V^{1/2}$ regime extends to the short circuit condition, which correlates well with the reduction in Jsc and FF observed in this device. These results are in contrast with those found in **Figure 3b** for P3HT:PC_{61}BM.

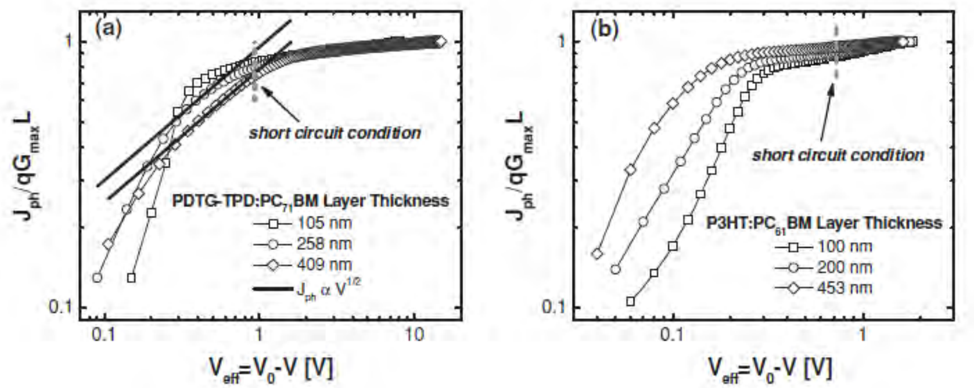

Figure 12 Effective photocurrent density (J ph) normalized by J sat = qG max L as a function of effective voltage (V_{eff}) under 100 mW cm^{-2} illumination for (a) PDTG-TPD:PC$_{71}$BM cells with 105 nm, 258 nm, and 409 nm-thick active layer, and (b) P3HT:PC 61 BM cells with 100 nm, 200 nm, and 453 nm-thick active layer. Dashed lines highlight the value of V_{eff} corresponding the short-circuit condition ($V_{eff} = V_0$). The solid lines correspond to $J_{ph} \propto V^{1/2}$ fits of the photocurrent in the SCL regime for PDTG-TPD solar cells.

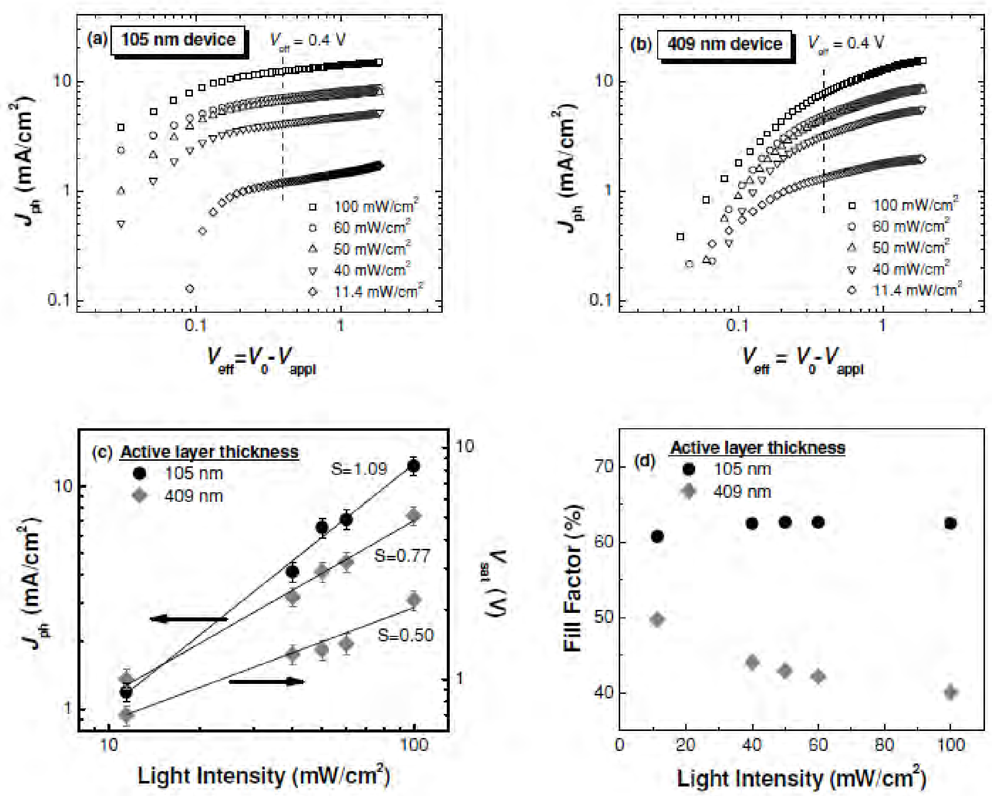

FIGURE 13 LIGHT INTENSITY DEPENDENT STUDY FOR PDTG-TPD:PC$_{71}$BM SOLAR CELLS WITH THIN AND THICK ACTIVE LAYER. $J_{PH} - V_{EFF}$ CURVES FOR THE (A) 105 NM-THICK AND (B) 409 NM-THICK DEVICES UNDER VARIOUS LIGHT INTENSITIES (FROM 11.4 TO 100 MW CM^{-2}). (C) EFFECTIVE PHOTOCURRENT DENSITY (J PH), SATURATION VOLTAGE (VSAT), AND (D) FILL FACTOR AS A FUNCTION OF INCIDENT LIGHT INTENSITY FOR THE SAME DEVICES. THE $J_{PH} - P_0$ CURVES WERE MEASURED AT V_{EFF} = 0.4 V.

The dependence of J_{ph} and FF on incident light intensity (P_0) was plotted for the 105 nm and 409 nm-thick PDTG-TPD:PC$_{71}$BM solar cells (see **Figure 4**). Neutral density filters were used to control the incident light intensity, which was varied from 11.4 to 100 mW cm^{-2}. The $J_{ph} - P_0$ data for the thin and thick PDTG-TPD:PC$_{71}$BM devices, shown in Figure 4c, was extracted from the $J_{ph} - V_{eff}$ curves shown in Figures 4a and b. For the solar cell with a 105 nm-thick active layer, J_{ph} showed a linear dependence on light intensity with the slope of the linear fit tothe data equal to 1.09. In contrast, a slope of 0.77 is observed for the 409 nm-thick PDTG-TPD solar cell. The ∼ 3/4 power dependence of J_{ph} on the incident light intensity confirms the occurrence of SCL photocurrent in PDTG-TPD:$PC_{71}BM$ solar cells at low bias. The dependence of the saturation voltage (V_{sat}) on incident light intensity provides further evidence, in which a slope of 0.50 is extracted from the $V_{sat} - P_0$ data. To form a more clear physical picture, the light-intensity dependence of the FF was also analyzed and plotted in Figure 4d. The FF remained relatively constant with incident light intensity for the 105 nm-thick solar cell, which is expected since the device is not space-charge limited at $P_0 = 100$ mW cm^{-2} and the thickness is sufficiently thin to ensure efficient charge extraction. For the 409 nm-thick PDTG-TPD solar cell, a 24% enhancement in FF was observed as the incident light intensity was decreased from 100 mW cm^{-2} to 11.4 mW cm^{-2}. By lowering P_0 and, consequently, reducing the generation rate of charge carriers in the thick PDTG-TPD:PC 71 BM active layer, space-charge buildup was reduced. As a result, enhanced charge carrier collection and FF was observed in the solar cell. Despite this enhancement, the FF of the 409 nm-thick device at low light intensity does not reach the value obtained in the 105 nm device. This result indicates that the reduced photocurrent observed for thick-film devices could not be completely recovered despite lowering the incident light intensity. There is still some degree of limited charge collection occurring in thick-film PDTG-TPD:$PC_{71}BM$ solar cells.

To conclude, the loss mechanism in thick-film PDTGTPD:$PC_{71}BM$ solar cells have been investigated. For polymer solar cells with an active layer thickness up to 200 nm, efficiencies in excess of 8.0% were obtained for devices under AM 1.5G illumination at 100 mW cm^{-2}. For $L > 200$ nm, the SCL photocurrent regime is reached, leading to limited charge collection efficiency in the devices due to space-charge accumulation. The onset of space-charge accumulation also coincides with reductions in FF and hence power conversion efficiency in thick devices. These results indicate that although high efficiencies can be obtained in solar cells with low-bandgap conjugated donor-acceptor polymers, the high density of photogenerated charge carriers could severely limit the performance of solar cells with a thick active layer.

Florida Advanced Technological Education Center (FLATE)

Education - Technician Based Workforce

(Progress Report)

PI: Marilyn Barger

Description: FLATE (Florida Advanced Technological Education Center) will partner with FESC to develop statewide curriculum frameworks for technical A.S./A.A.S. degree programs supporting existing and new energy business sectors. FLATE will develop and have processed through the FLDOE the industry-validated student competencies of the frameworks. FLATE will also develop new courses required for each new program of study. Additionally FLATE will help state and community colleges implement the new frameworks in their institutions. To support the new curriculum, FLATE will work closely with the FESC Public Outreach and Industry Partnership programs to provide professional development opportunities for teachers and faculty to upgrade and update their knowledge base.

Budget: $300,000.
Universities: FLATE/Hillsborough Community College

FLATE External Collaborators: Brevard Community College; Tallahassee Community College; Daytona State College; Central Florida Community College; Polk State College; Florida State College at Jacksonville; Valencia Community College; Palm Beach State College; School District Hillsborough County; Florida Department of Education – Division of Adult and Career Education; West Side Technical School; USF College of Engineering; Madison Area Technical College ATE project for Alternative Energy certifications; Milwaukee Area Technical College Energy Conservation and Advanced Manufacturing Center (ECAM); Florida Energy Workforce Consortium (FEWC); TECO; Progress Energy; ISTEC (Ibero Science and Technology Education Consortium), Usurbil GLBHI (Spain); TKNIKA - Innovation Institute for Vocational Training (Spain); Center for Energy workforce Consortium (CEWD); UF Industrial Assessment Center; CREATE NSF Center for Alternative Energy; EST2 NSF ATE Grant project; DOE's Office of Energy Efficiency & Renewable Energy; Gulf Coast State College; Palm Beach State College; University of South Florida's College of Engineering; University of Miami; University of Alabama; Rutgers University; Energy Reduction Solution, SMC Corporation of America, Energy Conservation Group; Florida Solar Energy Consortium; Tampa Bay Regional Business Plan Energy Efficiency and Conservation Sub-Committee.

Progress Summary

The development of the process for the Florida State College System to respond to FESC's long term strategy to bring energy related technologies out of the Florida University System is well underway. Activities this year included identifying the current status of credit and non-credit energy related courses within the State College System. In addition, online curriculum related to Alternative Energy Systems has been developed. FLATE has the college contacts and process in place to respond to any FESC and/or regional economic development authority request to provide assistance to a designated State College because of a technician workforce development need as identified or triggered by a new or expanding energy related company's operations in the State.

Since October 1, 2012 FLATE achieved several milestones. Together with the National Science Foundation-funded Energy Systems Technology Technicians (EST^2) project team, FLATE has developed a new Industrial Energy Efficiency specialization for the Engineering Technology (ET) Degree and associated College Credit Certificate.

Engineering Technicians are widespread in a variety of occupational areas, including electronics, applied technologies, manufacturing, and composites fabrication, to name a few. The new Industrial Energy Efficiency specialization track and college credit certificate (CCC) for the AS/AAS degree in Engineering Technology, comes at a time when green job sectors such as energy efficiency, are flourishing. Interest in reducing operating costs through energy efficiency maximization is growing significantly, both in Florida and throughout the nation. Collaboration with industry subject matter experts has allowed us to tailor the energy efficiency specialization curriculum and match training directly to industry needs.

Industry partners have indicated a need for energy efficiency measures to help their bottom line, and as a result the new specialization/CCC is designed to help incumbent technicians in manufacturing or industrial occupations find ways to save money through efficiency in their industrial setting, or prepare students to become energy managers or auditors. Upon completion of the program, students will be armed with the knowledge and skills necessary to implement energy efficiency strategies in industrial processes and systems, and as a result impact the bottom line. It will help the student prepare to become a SEP-Superior Energy Performance Certified Systems Practitioner and a CEM Certified Energy Manager. The program will also help train workers who will assist a company in achieving the ISO 50001 standards related to energy management, as well as ISO 14001:2004 to assure a company's stakeholders that measures are being taken to improve their environmental impact.

The EST^2 team (comprising individuals from Brevard Community College, Florida State College at Jacksonville, Tallahassee Community College and Hillsborough Community College), submitted the framework to the Florida Department of Education at the beginning of 2013 and colleges will be able to implement it in the 2013-2014 academic year.

Program Title: Industrial Energy Efficiency Specialist (CCC)
Career Cluster: Manufacturing

CIP Number	TBD
Program Type	College Credit Certificate (CCC)
Program Length	21 Credit Hours (Primary), 24 Credit Hours (Secondary)

This certificate program is part of the Engineering Technology AS/AAS degree program (1615000001/0615000001).

FLATE and FESC coordinated a second highly successful energy workshop (the last one was held in September 2011 in Gainesville), for high school and college educators, as well as industry partners, hosted by the Florida Solar Energy Center (FSEC) in Cocoa, FL on January 25, 2013. Forty attendees attended a wide variety of presentations, went on a tour of the amazing FSEC facilities and participated in a Professional Development activity focused on solar energy applications. Feedback received was overwhelmingly positive.

FLATE and FESC coordinated an Advisory Working Group Meeting in Orlando, FL on February 28, to develop a curriculum plan for the Industrial Energy Efficiency Technician (IEET) Specialization. Sixteen members from academia and industry worked on the following focus statement for the workshop, "An industrial energy efficiency technician implements energy efficiency strategies in industrial processes and systems in order to improve an organization's bottom line and reduce environmental impacts."

As a result of the meeting, a comprehensive list of IEET Resources was compiled and classes were identified as well as their associated learning outcomes.

Finally, FLATE regularly updates / presents information about energy curriculum and training issues at the statewide Florida Engineering Technology Forum that meets twice per year at various colleges across the state. Many of these schools are looking to add "energy" curriculum and/or programs and are requesting guidance on what industry is asking for across the state and what and how other colleges are implementing credit programs. The goal of these activities is to keep colleges working together and sharing curriculum rather than develop independent programs not properly aligned to statewide frameworks. The ET Forum most recently met April 4 - 5 in Clearwater at St. Petersburg College.

Activities for the 2012-2013 year are listed below.

- Presented at the Florida Association of Science Teachers Conference in October, 2012 with Mark Dick (Tallahassee Community College), "Energy Camps that are Energizing", highlighting the Teacher Energy Workshops and Energy Summer Camps for students offered over the summer by all EST 2 partners.
- Attended the Florida Energy Workforce Consortium Meeting in November 2012 and March 2013.
- Presented "Industrial Energy Efficiency Competencies for Associate Degree Programs", at the Interstate Renewable Energy Council (IREC) Clean Energy Workshop in Albany, NY, November, 2012.
- Attended the Manufacturers Association of Florida Summit in December 2012 and surveyed 40 manufacturers about the need for energy efficiency trained technicians. The overwhelming majority of manufacturing members who completed the survey strongly supported the new IEET CCC since manufacturers need solutions to their high cost associated with energy consumption. A focus group meeting was held in Orlando, in February 2013 with industry, university faculty, tech center faculty and state college personnel/faculty. The focus group meeting was a scaled down, Designing a Curriculum (DACUM) that produced potential courses and course content for the proposed IEET program. The course creation validated the IEET program framework content that went to the FL Department of Education for approval at the beginning of this year, and will be implemented in the 2013-2014 academic year.
- Coordinated a second Community College Energy workshop for 40 attendees at the Florida Solar Energy Center (FSEC) in Cocoa, January 25, 2013.
- Was instrumental in the selection of Hillsborough Community College as a winner of the (Sustainability Education and Economic Development) Green Genome Award which recognizes exemplary community colleges nationwide that have taken a strategic leadership role in sustainability and green economic and workforce development.
- Attended and was part of an Energy Efficiency and Conservation Panel at 2013 Beyond Sustainability 37th Annual Conference at Hillsborough Community College, Plant Ybor City in February.
- Participated in, "An Energy Literate Citizenry from K-to-Gray: A Webcast on the Department of Energy's Energy Literacy Initiative", in March.
- FLATE hosted the Engineering Technology (ET) Forum in St. Petersburg on in April. (Energy Efficiency Specialization was presented).
- Planning is underway to host a third summer energy program for under-represented middle school students, to be held July 8 – 11 at HCC's SouthShore Campus in Ruskin, FL in conjunction with the EST2 grant partners (BCC, TCC and FSCJ).

Funds leveraged/new partnerships created: FLATE has leveraged its NSF and FESC resources to help Brevard Community College to apply for and be awarded a very competitive NSF grant, $ 500,000, implement two energy related specialization within the A.S. Engineering Technology Degree. In addition, FLATE was able to secure a $ 100,000 award from NSF to develop a faculty/student interchange that will allow Florida to benefit from the well advanced energy related technology educations practices at technology colleges in Spain.

FESC
Florida Energy Systems Consortium

FESC OUTREACH PROGRAM

Educational Outreach Programs
(Final Report)

PI: Dr. Pierce Jones, Director, Program for Resource Efficient Communities (PREC)

Outreach Team Members:
- Dr. Kathleen C. Ruppert
- Hal S. Knowles III
- Nicholas Taylor
- Dr. Barbra Larson
- Craig Miller
- Ms. M. Jennison Kipp Searcy

Executive Summary

The goal of the program is to develop educational outreach programs and materials designed to deliver practical, applicable information and knowledge on energy-related topics to the general public as well as targeted to specific audiences such as builders, planners, engineers, architects, small businesses, local governments, and utilities through the Cooperative Extension Service and others. By focusing educational programming on climate and efficient use of energy and water, the program aims to provide the knowledge needed by building and energy professionals, local governments, and the general public, to significantly reduce greenhouse gas emissions in Florida.

Sustainable Floridians[SM] Program

The outreach team developed the Sustainable Floridians[SM] Program during the reporting period. The program details and progress are given below.

Sustainable Floridians[SM] is a statewide educational program that was piloted in 2010 and 2011 to teach Floridians how to improve their economic, environmental and social sustainability and that of the communities in which they reside. The program was developed at the University of Florida's (UF) Department of Family, Youth and Community Sciences in collaboration with the UF/IFAS Program for Resource Efficient Communities, the UF Office of Sustainability and UF/Extension Faculty in seven counties.

The program's curriculum is both educational and action-oriented, and is directed at citizens who enroll in the class through a County Extension Office participating in the program.

<u>*Goals and Objectives:*</u>
The Sustainable Floridians[SM] course encourages individuals and communities to become more resilient at the local community level. Beyond the objective of developing an educated citizenry, the goals include:
- Increasing participants' knowledge about sustainability issues at the global, state and local levels,
- Providing information that identifies Florida-specific actions for conserving energy and water,
- Motivating participants to implement conservation and efficiency actions that save resources and money, and

- Creating opportunities for community level leadership in sustainability education in a variety of settings from offices to community and neighborhood organizations

Participants meet with the program facilitator for six to seven weekly sessions. The classes include topics such as Why Should I Care?; Principles of Sustainability; Energy; Water; Transportation and Land Use; Food Systems; Consumerism; Community Leadership, etc. The course is very participatory and a variety of teaching methodologies are used including weekly handouts, multi-media presentations, supplemental readings and a textbook that allow participants to examine the material individually and then collectively. The course engages participants in group discussion, group and individual reflection, and personal action.

One example of a successful program is Pinellas County. Pinellas County Extension offered the program as part of the pilot initiative and continues to offer it as part of its sustainability curriculum. Pinellas County, one of 35 coastal counties in Florida, borders Tampa Bay and the Gulf of Mexico, has a population of 916,000 residents, and is considered the 6th most densely populated county in the state. Sustainability is a critical issue for a 97% "built-out" county with 25 different local governments. Although a challenge, balancing resource use with human and economic needs is critical to a successful and thriving local economy. Achieving this goal is possible with a motivated, engaged and educated citizenry. Since the start of the program, Pinellas trained 66 participants who have donated over 1,800 volunteer hours, a value of $33,588 (using $18.66 per hour as provided by Extension).

In Leon County, graduates are serving as facilitators for local EcoTeams, which are discussion circles organized within neighborhoods, faith organizations and other groups, under the sponsorship of Sustainable Tallahassee, a partnership umbrella NGO.

In addition, all participants are encouraged to track their monthly energy, water and vehicle miles travelled, and use consumption logs to develop a personal sustainability plan.

The Sustainable Floridians^{SM} program has proven instrumental in filling the need for sustainability education within the community-at-large. The participatory course structure allows trainees to explore a range of educational material that will encourage sustainable practices and improve the economic, environmental and social conditions of their communities.

The County Extension offices are well positioned to provide education at the local level and possess the necessary infrastructure to support sustainability education at the community level.

The Sustainable Floridians^{SM} program is now active in four counties…Leon, Osceola, Pinellas, and Sarasota. Marion County had an active program but the coordinator recently moved to take a position in Mississippi. Several other counties are contemplating beginning the program in the near future. While some counties train the participants to fulfill volunteer roles, other counties see the program as solely an educational program that they believe will have a ripple effect of educating others.

The program, up until recently, had no statewide coordination following completion of the pilot program. Now, with the assistance of UF's Office of Sustainability, UF's Program for Resource Efficient Communities through the Florida Cooperative Extension Service is working with county Extension faculty to develop curriculum review teams, an advisory committee, and all of the actions and activities needed to operate a statewide program. While in the midst of updating existing modules, along with creating new materials and determining efficiencies of scale, the program is continuing to gain statewide interest as indicated by the 16 counties represented at a recent in-service training.

PAPER

A Critique of Alternative Power Generation for Florida by Mechanical and Solar Means

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ABSTRACT

Using observations of surface winds, solar radiation, ocean currents and waves collected by the University of South Florida, Coastal Ocean Monitoring and Prediction System (COMPS), augmented by other data and numerical model simulations, we address the potential for electrical power generation for Florida by harnessing the natural energy sources of wind and solar, along with ocean currents and waves. We begin by identifying what nature offers. For wind and solar, we use specifications from existing, commercially available devices to convert nature's bounty to power-generation estimates. In the absence of mature, commercially available devices for ocean currents and waves, we draw upon physical principles to arrive at power-generation estimates for these potential sources. On the basis of what nature offers and what machinery may be capable of producing, we then make reasonable extrapolations on what these estimations may mean in a practical sense for supplying energy to society. Power generation from these naturally occurring, alternative energy sources, particularly wind and solar, may provide a means for supplementing power generation by conventional fuels but does not provide a replacement for conventional fuels.
Keywords: alternative power generation, ocean observations, windmills, watermills, waves, solar

Introduction

When compared with other locales, the potential for electrical power generation by alternative energy sources may seem to be relatively good for Florida, a subtropical peninsula, which is nearly surrounded by water and bathed in sunlight. Herein, we critically assess this potential using observations of winds, incoming short-wave radiation, ocean currents and waves, supplemented by other data and model simulations. The Ocean Circulation Group at the College of Marine Science, University of South Florida (OCG-CMS-USF), through the CMS Coastal Ocean Monitoring and Prediction System (COMPS), began collecting such serial observations on the West Florida Continental Shelf (WFS) in 1998. We analyze these data to determine the energy fluxes (energy per unit area per unit time) that are available through natural processes, then transform these energy fluxes into practical power-generation time series based on either commercial literature or physically reasonable assumptions, and then compare the results with consumptive metrics. The purpose is to demystify the concept of alternative power generation by mechanical and solar means and to place realistic expectations on what may be achievable for the state of Florida under typical, natural conditions. While our work is specific to Florida (and primarily west central Florida), the findings, with some modifications, are expected to also apply elsewhere.

The article is organized as follows. Each of the subsequent four sections deals with power-generation potential by winds, ocean currents, ocean waves, and incident solar radiation, respectively. For each medium, we use either WFS observations collected by the COMPS program, or model simulations, along with specifications from commercially advertised devices, or reasonable assumptions, for converting the natural energy fluxes to power generation. Given nature's bounty and how much of this may be converted to electrical power, the Discussion section then presents these findings relative to consumptive metrics, such as the requirement for powering a household and the economics of doing this. Not included, however, are any discussions on other complicating matters such as electrical transmission, storage, or daily to seasonal variations in peak or base loads that must be accommodated on a utility scale. Conclusions follow in the last section.

Wind

The Data

An offshore array of WFS COMPS moorings (Figure 1) was initiated in

FIGURE 1

Map of the West Florida Continental Shelf COMPS stations. Observations from mooring C10, located approximately 25 nm offshore from Sarasota, FL, are used herein.

1998. In addition to measurements of velocity, temperature, and salinity over the water column, as many as five surface moorings also collected meteorological data. Water velocities (currents) were measured using RD Instruments (now Teledyne) acoustic Doppler current profilers (ADCP), and meteorological variables were measured using either Coastal Environmental Systems (CES) Weatherpaks or Woods Hole Oceanographic Institution (WHOI)-designed Improved METeorological/Air-Sea Interaction METeorological (IMET/ASIMET) sensor suites. The surface moorings all measured air and sea surface temperatures, relative humidity, barometric pressure, and wind speed and direction. The IMET/ASIMET system and one of the Weatherpaks also measured downward long-wave and short-wave radiation. The IMET/ASIMET sampling consisted of 12; 5-s intervals formed into a 1-min average every 20 min. The Weatherpak data were collected every second for 15 min and averaged to provide 15-min samples. After quality control, these (either 15- or 20-min) samples were then formed into hourly averages for further analysis. A review of these observations is provided by Weisberg et al. (2009).

Wind speed and direction were measured using RM Young 5103 Wind Monitor sensors at either 2.8 or 3.2 m above the sea surface on the IMET/ASIMET or the Weatherpak buoys, respectively. In either configuration, these observations were adjusted to a standard 10 m height above sea level using a log boundary layer scaling under neutral stability (e.g., Large & Pond, 1981). For the purpose of applying such buoy wind observations to large-scale commercial wind turbines, a further adjustment was needed to account for the turbine hubs being located some 80 to 100 m above the sea surface. Using a 100-m hub height, we estimated the wind speed there (U_{100}) from the wind speed at the standard 10-m level (U_{10}) by

$$U_{100} = U_{10} \frac{\log(z/z_0)}{\log(10/z_0)} \tag{1}$$

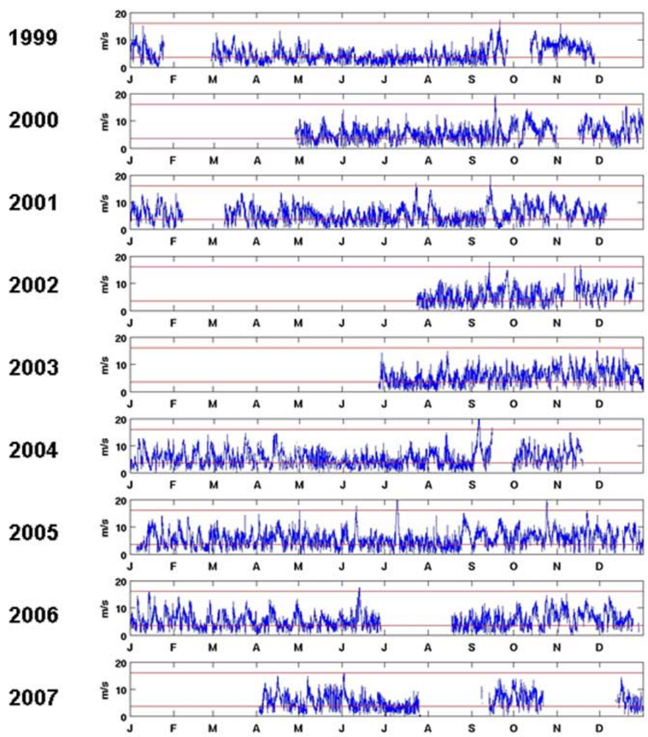
where z_0 is the surface roughness, which, for open water exposure, was taken to be 0.015 m. Recognizing that such log layer scaling (yielding an amplification factor of 1.35) is merely an approximation, we acquired National Centers for Environmental Prediction (NCEP) North American Mesoscale (NAM) modeled wind results as a check. Downloaded from http://nomads.ncdc.noaa.gov/data/namanl/ for six sites along a shore-normal line intersecting Sarasota, FL, for the period 1/1/12 to 4/12/12 (such multiple level results are not available for earlier times), a linear regression between winds modeled at 10 and 80 m heights (the lowest levels available) for the offshore open water exposure sites yielded a coefficient of 1.16, less than the log layer scaling result. Thus, the use of 1.35 as a conversion factor from 10 to 100 m winds is offered as a conservative estimate, overestimating, versus underestimating the winds aloft, on average.

On the basis of these (hourly averaged) wind observations scaled to a hub height of 100 m, and using mooring C10, located about 25 nm offshore from Sarasota, FL, Figure 2 shows what was available for wind power generation at this site over the 8-year interval, from 1999 to 2007. The values range from zero to around 20 m s^{-1}, but with the higher end occurring only on rare occasions during the passage of tropical storms.

Whereas our analysis is limited to a single point off the west central Florida coast, these winds are representative of winds elsewhere in Florida with some caveats. On both long-term and seasonal averages, the winds tend to increase from north to south by virtue of the trade winds' meridional structure and Florida peninsular land effects (e.g., Weisberg et al., 2009; Liu & Weisberg, 2005), which also results

FIGURE 2

Hourly averaged winds scaled to 100-m hub height using C10 observations from 1999 (top) through 2007 (bottom). The lower and upper red lines indicate the turbine cut-in value of 3.5 m s^{-1} and the rated power-generation wind speed of 14 m s^{-1}, respectively.



in the trade winds being a little stronger on the east coast. For synoptic scale weather events, the entire state of Florida is similarly affected. On the diurnal time scale, the east coast sea breeze tends to be more regular than that on the west coast.

Converting Wind Speed to Electrical Power-Generation Potential

Commercially available wind turbines are discussed with respect to their nameplate-rated power-generation capacity. This can be misleading because the actual power output depends on wind speed. As a representative example we consider a General Electric (GE) 3.6 MW Offshore Series Wind Turbine, with specifications that are available in a brochure, which may be downloaded from the manufacturer's Internet site. From the wind load-power curve, we see that the turbine does not begin to produce electrical power until the wind speed exceeds 3.5 m s^{-1} (the cut-in wind speed). Power generation then increases with increasing wind speed, reaching the nameplate-rated capacity (3.6 MW) at a wind speed of 14 m s^{-1} (the rated wind speed), and the device ceases power generation and shuts down when the wind speed exceeds 27 m s^{-1} (the cut-out wind speed). The lower and upper horizontal lines on Figure 2 represent the cut-in and the nameplate-rated capacities for the GE 3.6 MW turbine, respectively. From 8 years of WFS data, we see that the winds at 100-m hub height fail to drive the turbine some 20% of the time and that rarely do the winds reach the nameplate rated capacity.

To determine what the power output may be when the turbine is running, we fitted a polynomial to the power curve provided by the brochure, and we used this to convert wind speed to power output for speeds between the cut-in and rated capacity values. For wind speeds between 14 and 27 m s^{-1}, the output was held constant at 3.6 MW (Figure 3). The results, further averaged to provide daily values, are shown in Figure 4, from which several points are clear. First, the nameplate-rated capacity is rarely achieved. Second there are many days (excluding the larger interval data gaps) when the cut-in speed of 3.5 m s^{-1} is not exceeded, and hence no power is generated. Third, when looking at the climatological monthly mean time series (the lowest panel) obtained by averaging all Januarys, all Februarys, etc., we see that minimum and maximum power generation occurs in summer and fall months, respectively. The monthly mean minimum is about 0.6 MW, the monthly mean maximum is about 1.8 MW, and the grand average across all years and months is about 1 MW. The minimum in summer months is troublesome for Florida because that is when the demand for air conditioning is the largest.

Ocean Currents

The Physics

Unlike windmills, where commercial maturity provides known power-generation potential, watermills driven by ocean currents remain in development. Estimating the potential for power generation by ocean currents requires that we begin from first principles. Available power, P, for potential extraction from ocean currents is the kinetic energy flux, $\frac{1}{2}\rho V^3$, times the area, A, of the device used for extracting

FIGURE 3

A polynomial fit to a power curve provided for a GE 3.6 MW wind turbine (see ge_36_brochure.PDF available at http://www.gepower.com). The power curve gives the machine output in kW as a function of wind speed in m s^{-1}.

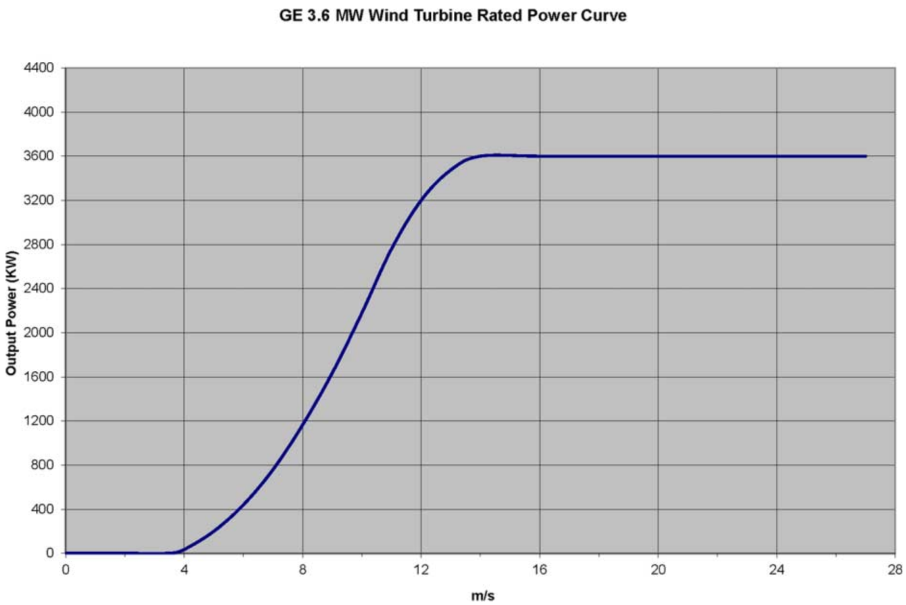
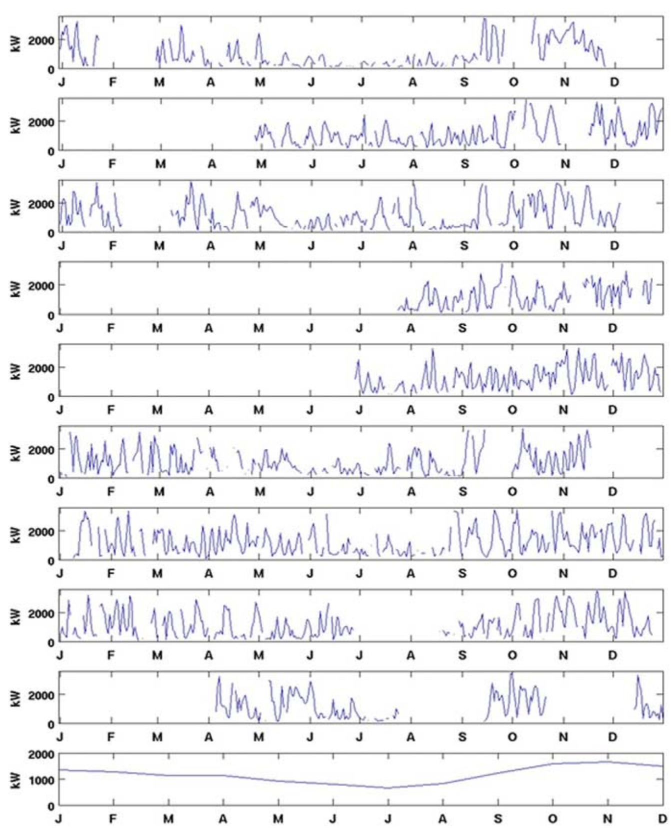


FIGURE 4

Daily-averaged power and climatology of power using C10 wind speed observations scaled to 100 m hub height, from 1999 (top) through 2007 (bottom).



this flux, or $P = \frac{1}{2}\rho V^3 A$, where the units for P are watts (W). Watermills, like windmills, are subject to the same hydrodynamic limitations embodied in Betz's law (Betz, 1920), which states that the maximum power that may be extracted is 59% of the kinetic energy flux offered by nature. Additional loses come from the efficiency of the device itself, such that the expected power-generation potential for either a windmill or a watermill is in the approximate range of 40-50%.

Watermills, like windmills, are also expected to have a cut-in speed threshold below which they will not function. In other words, a baseline torque is necessary to drive an electrical generator. Given that torque equals force times distance, it is proportional to the pressure on a turbine blade times both the area and the length of the blade. A dimensional analysis, making use of Bernoulli's theorem, suggests that the cut-in speed may scale as $S_w = S_a\sqrt{\rho_a/\rho_w}\frac{L_a}{L_w}$, where S denotes the cut-in speed, ρ the density and L the length, and the subscripts a and w denote air and water, respectively. Using the cut-in speed for the GE 3.6 MW turbine and its length scale and assuming that a watermill may have a length scale about an order of magnitude smaller than the windmill, we arrive at a cut-in speed estimate of around 1 m s^{-1} for the watermill. Granted, this is a very crude estimate, but what it does suggest, even if off by a factor of two to four, is that typical coastal ocean current speeds on the continental shelf (away from tidal inlets), which are of order 0.2 to 0.5 m s^{-1} (e.g., Weisberg et al, 2009; Liu & Weisberg, 2005), are too small to drive watermills. Nevertheless, Florida does have a strong western boundary current seaward of its continental shelf, for which we can examine the potential utility of power generation by watermills. For the west coast of Florida this western boundary current is the Gulf of Mexico Loop Current, which feeds into the Gulf Stream on the east coast of Florida. Being that the Gulf Stream is tightly constrained to flow between Florida and the Bahamas, this is the most practical place for considering power generation by watermills.

Application to the Gulf Stream

The Gulf Stream, as it flows through the channel between Florida and the Bahamas, is highly baroclinic, with maximum speeds generally located at the surface toward the western side of the channel (see Figure 5, after Leaman et al., 1987). Speeds near the surface, and approximately within a baroclinic Rossby radius of deformation from the Florida side, are as high as 2 m s^{-1} (4 kts), diminishing rapidly with depth to about 1 m s^{-1} at 300 m depth and then to less than 0.5 m s^{-1} below 500 m depth. The total volume flux through the Florida Straits has long been recognized to be around 30 × 10^6 m^3 s^{-1} (or Sverdrups) (e.g., Stommel, 1965; Niiler & Richardson, 1973; Leaman et al., 1987).

For our purposes, we use velocity time series simulated by a numerical circulation model to estimate the power-generation potential for the Gulf Stream. The model chosen is the global Hybrid Coordinate Ocean Model (HYCOM) run by the U.S. Navy Research Laboratory and the HYCOM consortium (e.g., Chassignet et al., 2007, 2009). Figures 6 and 7 show volume and kinetic energy transports, respectively, for transects at the latitudes of Miami, FL, and Palm Beach, FL. In each of these figures, the transports were calculated over three different depth intervals, 0 to 50 m, 50 to 300 m, and 300 m to the bottom, plus the total transports across the entire cross sections. The first of these figures provides a check on the HYCOM simulation. From it, we see that the total transports properly represent the observations to within reasonable bounds on natural variability and measurement error. This provides justification for using these model simulation results to discuss the kinetic energy flux and how these integrate to provide estimates on power-generation potential.

Two practical considerations come to play. First, with sea state under northerly winds being very large at times across the Florida Straits, it would be difficult, if not impossible,

FIGURE 5

A Gulf Stream cross section for the north component of velocity sampled at 27°N (from Leaman et al., 1987).

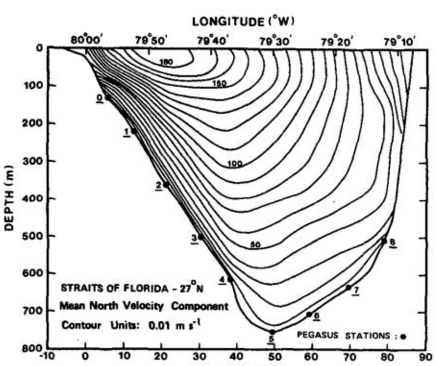


FIGURE 6

Gulf Stream volume transport across two sections between Florida and the Bahamas at the latitudes of Miami, FL, and Palm Beach, FL, calculated for the calendar year 2008 using a Global HYCOM simulation. Transports are shown for three different depth intervals, plus the total transport across the entire cross sections. The dashed lines on the bottom panel provide the year-long averages. (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2012/00000046/00000005.)

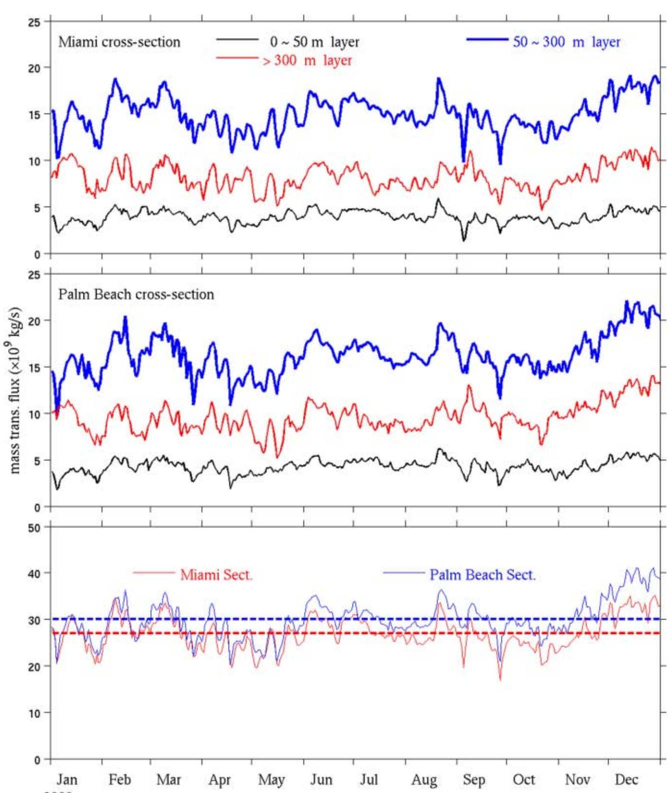
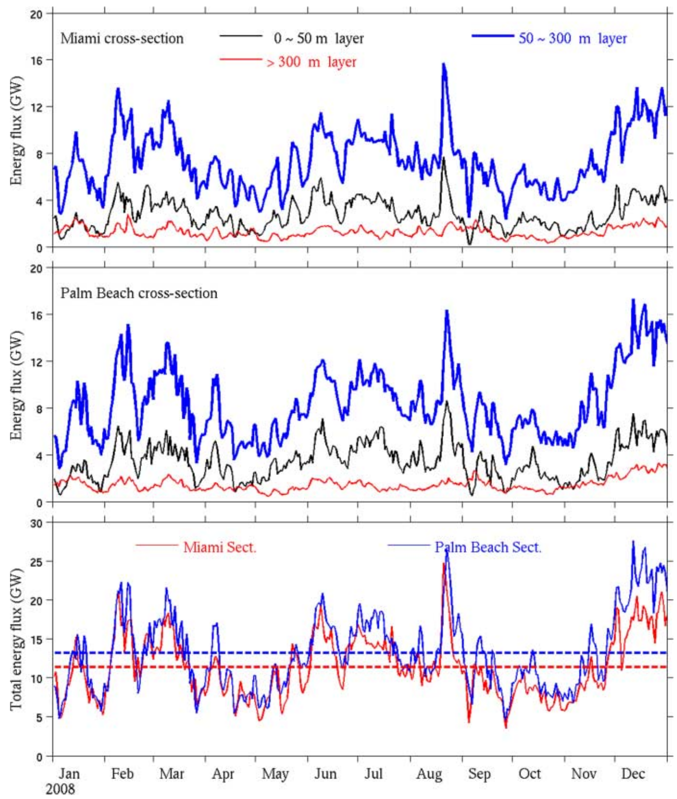


FIGURE 7

Gulf Stream kinetic energy transport across two sections between Florida and the Bahamas at the latitudes of Miami, FL, and Palm Beach, FL, calculated for the calendar year 2008 using a global HYCOM simulation. Transports are shown for three different depth intervals, plus the total transport across the entire cross sections. The dashed lines on the bottom panel provide the year-long averages.



to operate turbines within the upper 50 m of the water column. For instance, the wavelength for a deep-water wave of 8 s period is 101 m; hence, particle speeds for waves of longer period would impact the flow field at 50-m depth. Second, with current speeds generally less than 0.5 m s^{-1} below 300 m there is likely little potential for energy generation by watermills below that depth. Given these practical considerations, it is reasonable to limit our attention to a depth interval of 50-300 m.

For the depth range of 50-300 m, Figure 7 shows that the annual mean power that may potentially be tapped by watermills is about 7.4 and 8.3 GW at the Miami and Palm Beach transects, respectively. These potential values are less than the corresponding total Gulf Stream cross-sectional annual mean power estimates (surface to bottom) of 11.4 and 13.2 GW, respectively. The approximate 2.7 and 4.3 GW of the upper 50 m, respectively, are not available, nor are the approximate 1.3 and 1.4 GW below 300-m depth, respectively, for the practical reasons just provided. Moreover, the application of Betz's law, plus additional mechanical loses reduces the power potential by at least 50% to about 3.7 and 4.1 GW for the Miami and Palm Beach transects, respectively. Further recognizing the impossibility of filling the entire cross section depth range with turbines reduces these numbers by at least another order of magnitude. The end results are the more realistic potentials of 370 and 410 MW for these Miami and Palm Beach sections, respectively. But even these numbers are likely to be overestimates because any watermill will have a water load-power curve just like a windmill (e.g., Figure 3) so its power output will be further reduced from that potentially provided by nature. Given what an actual watermill cut-in speed and water load-power curve may be, it is probably reasonable to reduce the above by a factor of two and settle on about 200 MW as a potential estimate. This would be equivalent to what may be obtained from about 200 (GE 3.6 MW) windmills if operated under West Florida wind conditions (Converting Wind Speed to Electrical Power Generation Potential).

Because windmills installed on either land or offshore and watermills installed within the Gulf Stream (the most powerful of the ocean currents adjacent to the United States) tend to have similar promise for power generation, it is useful to consider two additional factors. The first is a matter of scale. Being that windmills and watermills rely on products of fluid density times fluid velocity cubed times area ($\rho V^3 A$), it is apparent that (with air being approximately a thousand times less dense than water while air velocity is about ten times faster than water) the area necessary to generate comparable amounts of power in air and water are the same. This begs the question: if the size of the machinery must be the same in air and water, why would we choose to work in a fluid medium (water) that is technologically so much more challenging than air? The second consideration is even more daunting. Windmills deployed in air operate within the lower

100 m of the atmosphere or in the lower part of the frictional boundary layer, which is driven by and continually replenished by the geostrophic interior that extends to the tropopause, some 10 km aloft. Watermills, in contrast, operating across a major portion of the water column, are in the geostrophic interior itself and hence, unlike windmills, have no natural means for replenishing the energy that they may extract. It is for this reason that windmill farms may have closely spaced units with additional windmills even distributed downwind from one another. Watermills, in contrast, cannot share this deployment strategy. Once power is removed from a cross section, it cannot be readily replenished. For these two reasons, even in the swiftest of currents, like the Gulf Stream, the notion of power generation by watermills tapping the kinetic energy flux seems very limited when compared with what may be achieved by windmills.

Ocean Waves

The Physics

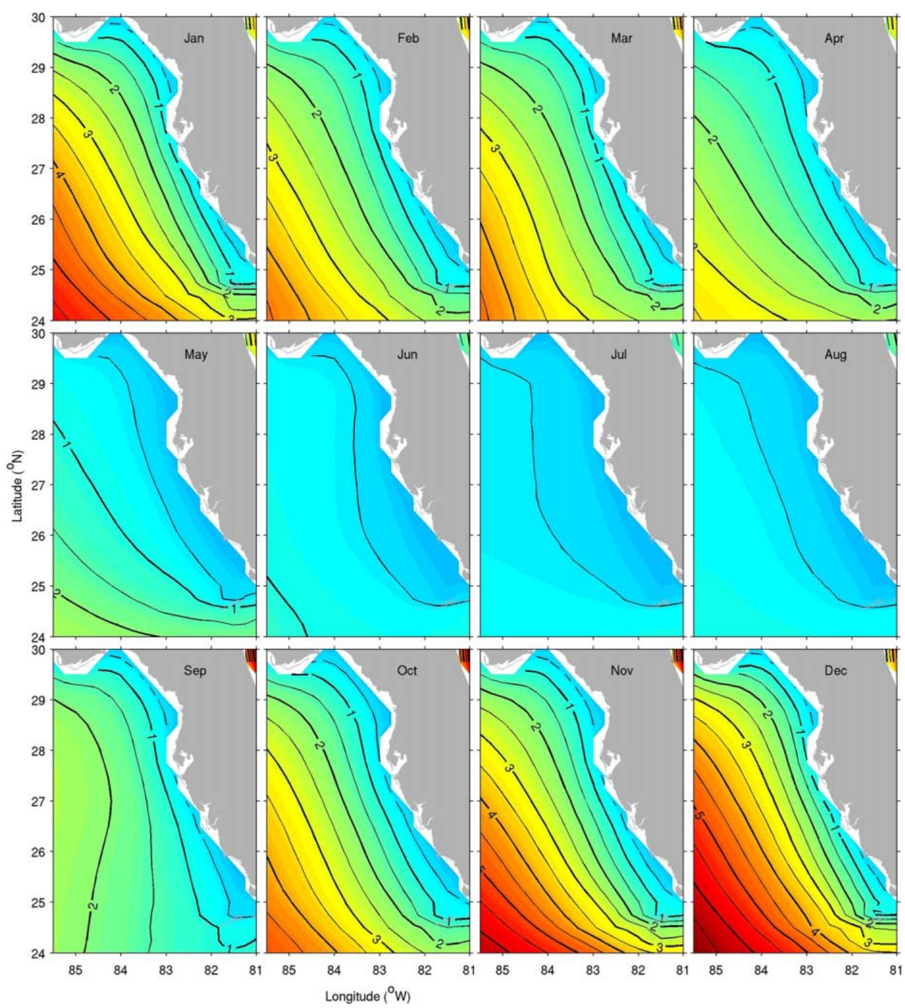
Waves, like currents, also possess an energy flux that may be tapped by mechanical devices. The available power, P_W, for potential extraction from ocean gravity waves is the total mechanical energy flux per unit wave crest width, $\frac{1}{2}\rho g a^2 C_G$, times the crest width length, L, of the device used for extracting this flux, or $P_W = \frac{1}{2}\rho g a^2 C_G L$, where g is the acceleration of gravity, a is the wave amplitude, C_G is the group velocity, and the units for P_W are watts. An alternative expression for P_W, based on significant wave height and application of the deep water dispersion relation, is $P_W = \frac{1}{2} H_s^2 TL$, where T is the wave period and significant wave height H_s is defined as the average of the highest third of the waves.

Application to the WFS

Several point measurements of surface gravity waves are available for the WFS, either from COMPS observations or a NOAA NWS weather buoy. As it is more instructive to look at the entire field of waves and how this varies throughout the year, we opted to base our estimates on numerical model simulations, of which there are several. The longest of these is from the NOAA application of the WaveWatch III model, e.g., Tolman (1991, 1999, 2010). Figure 8 shows a monthly mean wave energy flux per unit crest width climatology for the WFS with contour units of kW m^{-1} calculated from an 8-year analysis of WaveWatch III model results inclusive of 1999 to 2007. A robust annual cycle is seen with minimum wave energy in summer and maximum wave energy in winter, similar to that of the significant wave height measured at NDBC Buoy 42036 (Liu et al., 2010). This finding

FIGURE 8

Monthly mean surface gravity wave energy flux per unit crest width calculated for the WFS using the WaveWatch III reanalysis from 1999 to 2007. The contour units are kW m^{-1}, and each of the monthly climatologies is calculated by averaging all similar months, i.e., all Januarys, all Februarys, etc.



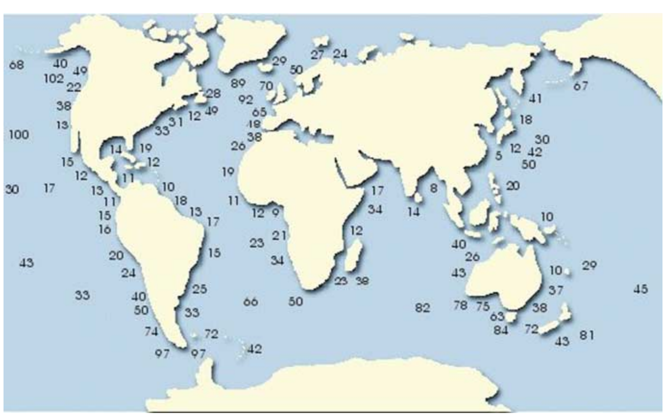
is consistent with the prevailing wind directions for the WFS varying from southeasterly in summer to northeasterly in winter (e.g., Liu & Weisberg, 2005). With low wave energy, the WFS is not very promising for alternative power generation by tapping the energy flux of surface gravity waves, except perhaps for running low power instruments *in situ*.

The east coast of Florida does have a larger wave climate, especially north of the Bahamas where the entire fetch of the north Atlantic comes to play. But even there the energy flux per unit crest width remains small compared with other higher energy coastlines worldwide (Figure 9), where tens to even a hundred kW m^{-1} are potentially available. As with electrical generation potential using ocean currents, the question becomes one of feasibility. Is there enough energy potentially available to justify the costs for extraction and can the technical challenges be met?

The commercial literature and commercial advocate group studies (e.g., McGowen et al., 2005) suggest that wave energy extraction is economically feasible for regions with energy flux per unit crest width greater than 15 kW m^{-1}. Two examples of devices under development are (1) a large snake-like set of linked cylinders that extract wave energy via undulations across a large linked cylinder length (e.g., 180 m for the 4-m diameter Pelamis WavePower device; http://www.pelamiswave.com) and (2) a 4-m diameter buoy that tracks the vertical motion associated with wave propagation past a fixed point (e.g., Ocean Power Technologies, Inc., http://www.oceanpowertechnologies.com). The first of these uses the length of the device to extract a major portion of the wave energy flux past the 4-m diameter cross section; the second of these is more limited in the percentage of the flux that can be extracted. Without questioning any of the details (see the industry brochures), it is clear that for either of these devices the total flux that may potentially be tapped is whatever passes the 4-m device width. So in either case, the question becomes: can some fraction of 15 kW m^{-1} times 4 m provide an economically feasible source of power (assuming that 15 kW m^{-1}, as promoted, is a viable level)? At best, assuming complete extraction with no loses (itself impossible), devices such as these can garner at most 60 kW.

FIGURE 9

Global wave energy flux per unit crest width (after McGowen et al., 2005).



Solar

The Observations

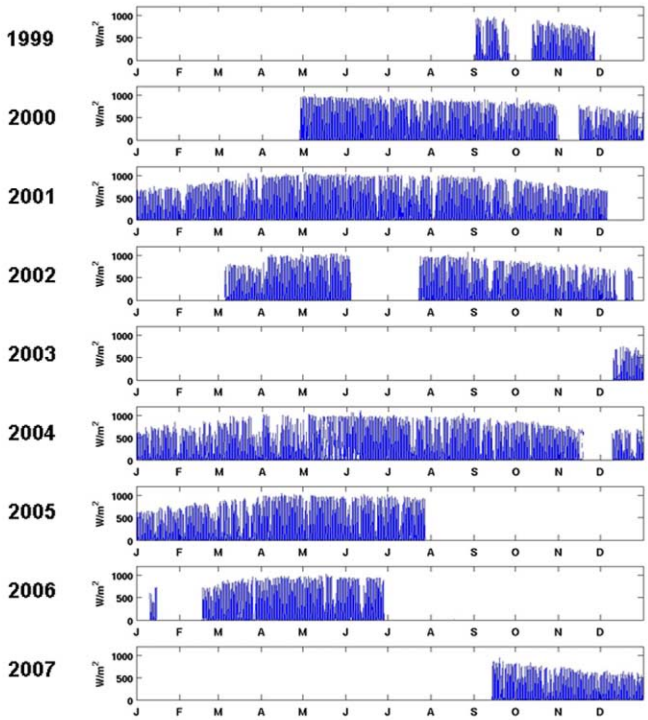
Two of the COMPS buoys carried downward short-wave radiation sensors. Here we will use the most complete of these from mooring C10, located approximately 25 nm offshore from Sarasota, FL, where an Eppley PSP sensor was mounted as part of the IMET/ASIMET suite of air-sea interaction sensors. The veracity of these measurements for our purposes here follows from previous studies that utilized these data to diagnose the net surface heat flux and the associated variations on water column temperature (e.g., Virmani & Weisberg, 2003, 2005). Figure 10 provides these hourly sampled, solar insolation data that were collected approximately 2.5 m above the sea surface for the 8-year interval, from 1999 to 2007. On an hourly basis, we see that the daily maximum insolation varies from as high as 1,000 W m^{-2} in spring and summer to as low as 500 W m^{-2} in fall and winter. Averaging diurnally to account for the fact that there is no incoming short-wave radiation at night, we find highest daily mean values ranging from about 300 W m^{-2} in summer to 150 W m^{-2} in winter.

Equivalent Energy Generation Potential Using Solar Panels

As with our analysis of wind energy generation, which recognized the maturity of the industry and hence allowed for us to choose a vendor with established product specifications, we do the same here for solar power. The example used is a Siemens SP75 solar panel. The method employed to determine the output of such a solar

FIGURE 10

Hourly sampled time series of incoming short-wave radiation measured 2.5 m above mean sea level at mooring C10 located approximately 25 nm offshore from Sarasota, FL. Shown are 8 years of observations spanning 1999 (top) through 2007 (bottom).



panel is to calculate the equivalent number of hours for which such panel would capture insolation at a 1,000 W m^{-2} level. Thus, we computed an annual mean, hourly insolation curve for 2001 (the year for which our data are most complete) and integrated the area under that curve to arrive at an equivalent area (insolation × time) at an insolation level of 1,000 W m^{-2} (Figure 11). Given that the Siemens SP75 solar panel is rated to output 75 W at an insolation of 1,000 W m^{-2}, we then determined the daily mean output for the device to be 404 W h (based on the equivalent solar production day of 5.39 h). Dividing by 24 h gives 16.8 W as the average output for this annually averaged day, and dividing by the area of the solar panel (0.63 m^2) gives 26.7 W m^{-2} as the daily averaged power output per unit area under WFS daily averaged insolation for this particular solar panel.

This technique (just demonstrated for an annually averaged diurnal cycle) was applied on a daily basis to convert observed incoming short-wave radiation to solar panel output normalized to a square meter. The results were then averaged diurnally to provide daily averaged power generation time series for the entire 8 years of record. Figure 12 shows the daily results, along with a climatological monthly mean time series (the bottom panel) obtained by averaging all of the Januarys, all of the Februarys, etc.

The daily averages range from essentially zero on strongly overcast days to 40 W m^{-2} on clear summer days. When averaged over the month we see a minimum in winter of about 20 W m^{-2} and a maximum in spring of about 38 W m^{-2}. The

FIGURE 11

The 2001 annually averaged daily insolation curve observed at C10 (blue) with equivalent number of hours at 1,000 W m^{-2} (black), where the areas under either of these distributions (blue or black) are the same.

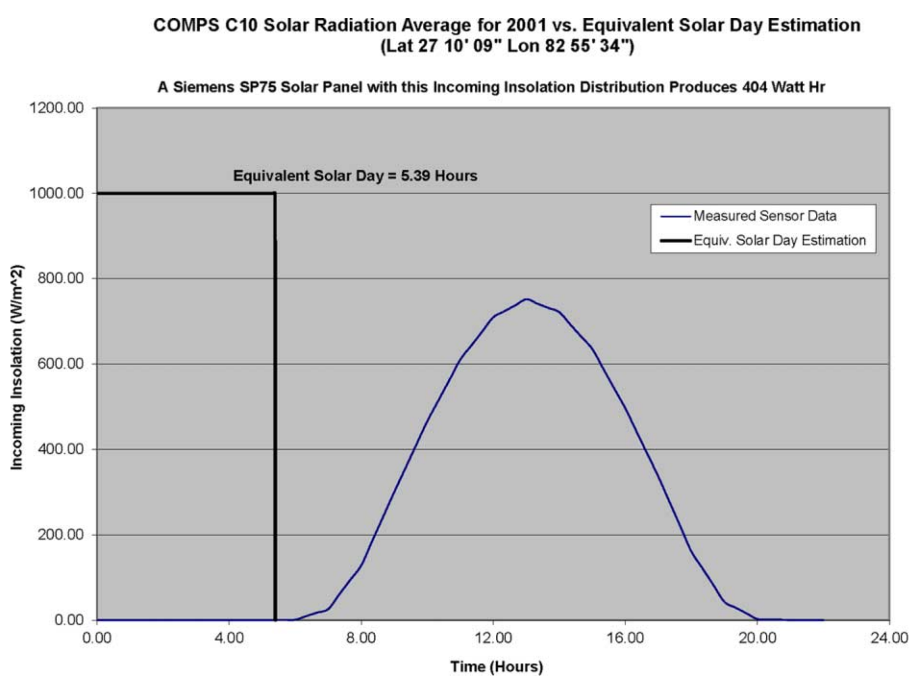
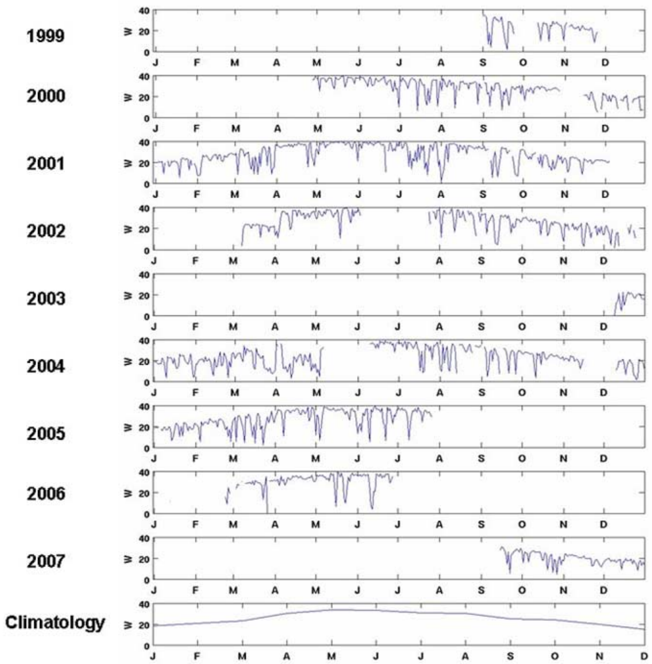


FIGURE 12

1999 through 2007 time series of daily average solar panel output based on observed insolation from C10 and climatology.



average across the entire year is about 25 W m^{-2}.

Discussion

Electrical power generation by windmills, solar panels, watermills (ocean current turbines), and wave devices have been topics of discussion for several decades. Wind and solar applications are mature, and commercial devices may be purchased and operated. Currents and waves applications have not reached a similar level of maturity. Devices exist and some have undergone field tests, but none are commercially viable yet. That in itself speaks to the relative utility of these concepts. The application of over a decade of coastal ocean observations from the WFS (augmented by model simulations) supports this viewpoint that alternative power generation from wind and solar sources appears to be more promising than that from ocean currents and waves.

Further appreciation of this finding follows from a few simple economics considerations. We begin with the known cost for powering a modest home. As an example, consider a 2,000 $feet^2$ Florida apartment that consumes about 1.7 kW of electrical power on annual average at a cost of about $140 per month or $1,680 per year. If we were to transition from conventional fuels to wind power by deploying a machine equivalent to a GE 3.6 MW turbine, we would average 1 MW of production, sufficient (on annual average) to power 588 such homes. The present cost for powering these homes based on conventional fuels and rounded is $1,000,000. A cost effectiveness transition to wind power would therefore require that the combined amortization, maintenance, energy storage, transmission and distribution, salaries, general and administrative costs, plus shareholder profits be about $1,000,000 per year for such a windmill. Whereas the specific costs for turbine purchase and installation are not readily available, anecdotal, nonrefereed literature suggests that these range between $1.2 and $2.6 million per MW of nameplate capacity. Thus, depending on the amortization of these capital costs, wind power may be approaching cost effectiveness. Support for this comes from an Associated Press article suggesting that the electrical delivery cost for a wind farm proposed offshore of Cape Cod, MA, will be roughly twice that by conventional fuels. So while the costs for electrical power generation by wind is higher than by conventional fuels, wind power generation may be economically feasible in the future, consistent with the fact that the wind power industry is indeed a mature one.

As with wind, it is difficult to find straightforward information on solar panel costs. Systems installation costs are estimated at about $1,000 m^{-2}, and with an annually averaged solar panel power production of 26.7 W m^{-2} by observed Florida insolation, the cost per watt would be about $38. Thus, the solar panel cost for a modest 1.7 kW house would be about $64,000, some 38 times the present annual cost of electricity by conventional fuels. This of course does not include any considerations of metering or storage strategies or properly sizing a system to actually meet user needs. While the above estimate may not be out of the realm of what may be reasonable based on amortization costs, any individual home owner would be hard pressed to justify such investment without a major subsidy.

The economics take a rapid turn for the worse when considering either ocean currents or waves. Ocean currents, as discussed in Ocean Currents, require similar sized machines (watermills) as for wind, and the energy extraction potential is much more limited than for wind, even when considering a massive current like the Gulf Stream. Moreover, it would be impractical to deploy watermills of the same size as windmills; hence many more, much smaller watermills would be necessary than for windmills, greatly compounding the costs for an equivalent amount of energy. This is even before any consideration is given to the technical challenges of deploying and maintaining a large number of mechanical devices in a swift ocean current. From these arguments, we must conclude that alternative electrical power generation by ocean currents for any regional utility application would be both prohibitively costly and impractical. It is therefore not surprising that this industry remains in a developmental versus a mature stage.

Waves, in our opinion, are even more impractical than currents for utility scale power generation. Consider, for instance, either the approximate 4-m buoy or 180-m-long cylinder discussed in Ocean Waves. Even for seas with energy flux per unit crest width of 15 kW m^{-1}, these machines would have the potential to generate no more than 60 kW per machine, much less when necessary loses are considered. Using present electric costs as documented for a 1.7 kW house, 60 kW is worth about $59,000 per year. Considering the need to swap out machines for servicing perhaps twice yearly, if not more frequently, it might cost more just for the ship time necessary to deploy and recover these machines than the value of the electricity that they could potentially generate and that does not include any of the costs for purchasing the machines and establishing the infrastructure for their use.

In summary, the economics for alternative power generation by wind and solar means may result in cost-effective strategies in the future, whereas those for ocean currents and offshore waves will not, at least for projects in which large quantities of power are required, such as powering a major urban area. Other inhibiting considerations also come into play. Although our cost estimates are based on annually averaged quantities, it must be recognized that it is not uncommon for winds to be low enough to fail completely as an energy source (about 20% of the time on the WFS) and similar can be said of solar insolation. Thus, neither of these two potential alternative power-generation sources can fully replace power generation by conventional fuels; they can only supplement the use of conventional fuels.

Windmills of the type required to supplement large power needs are also massive in size. To provide a sense of spatial scale, a professional football stadium stood up on end provides an analogy to the equivalent cross sectional area that would be occupied by a large windmill. Accommodating such structures along highly populated coastlines would be difficult. Florida, with its highly developed, tourist-oriented, coastline would likely not be amenable to situating offshore utility-scale wind farms in sight of land. The use of solar panels in an array large enough to supplant a conventional facility also suffers from such matters of spatial scale. For instance, based on Florida insolation, replacing a 1.8-GW power plant, such as the Tampa Electric Company Big Bend facility (located on the east shore of Tampa Bay) would require 90 km^2 of solar panels, plus other storage devices required to accommodate evening hour or extended days of low insolation. Lacking installations of such massive scale, it remains unknown whether or not their maintenance would even be feasible.

Conclusions

Based on analyses using coastal ocean observing system data for winds, incoming short-wave radiation and ocean currents, supplemented, as needed, by numerical model simulations, the following conclusions may be drawn. First, there are good reasons why industries pertaining to electrical power generation by the alternative means of wind and solar are much more mature than those pertaining to ocean currents and waves. Wind and solar sources of energy do provide promise for alternative power generation on a utility scale, whereas for many physical and practical reasons, ocean currents and waves do not. Second, even if wind and solar power in Florida are eventually produced in an economically competitive way (which requires a much more detailed economics analysis), these power sources may only be able to supplement power generation by conventional fuels or other means. They cannot replace presently required base load power-generation capacity.

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References

Betz, A. 1920. Das Maximum der theoretisch möglichen Ausnutzung des Windes durch Windmotoren, Zeitschrift für das gesamte Turbinenwesen. 20. September 1920.

Chassignet, E.P., Hurlburt, H.E., Smedstad, O.M., Halliwell, G.R., Hogan, P.J., Wallcraft, A.J., … Bleck, R. 2007. The HYCOM (HYbrid Coordinate Ocean Model) data assimilative system. J Marine Syst. 65:60-83. http://dx.doi.org/10.1016/j.jmarsys.2005.09.016.

Chassignet, E.P., Hurlburt, H.E., Metzger, E.J., Smedstad, O.M., Cummings, J., Halliwell, G.R., … Wilkin, J. 2009. U.S. GODAE: Global ocean prediction with the HYbrid Coordinate Ocean Model (HYCOM). Oceanography. 22:48-59. http://dx.doi.org/10.5670/oceanog.2009.39.

Large, W.G., & Pond, S. 1981. Open ocean momentum flux measurements in moderate to strong winds. J Phys Oceanogr. 11:324-36. http://dx.doi.org/10.1175/1520-0485(1981)011<0324:OOMFMI>2.0.CO;2.

Leaman, K.D., Molinari, R., & Vertes, P. 1987. Structure and variability of the Florida vurrent at 27N: April 1982–July 1984. J Phys Oceanogr. 17:565-83. http://dx.doi.org/10.1175/1520-0485(1987)017<0565:SAVOTF>2.0.CO;2.

Liu, Y., & Weisberg, R.H. 2005. Patterns of ocean current variability on the West Florida Shelf using the self-organizing map. J Geophys Res. 110:C06003. http://dx.doi.org/10.1029/2004JC002786.

Liu, Y., Weisberg, R.H., Merz, C.R., Lichtenwalner, S., & Kirkpatrick, G.J. 2010. HF radar performance in a low energy environment: CODAR SeaSonde experience on the West Florida Shelf. J Atmos Oceanic Technol. 27(10):1689-710. http://dx.doi.org/10.1175/2010JTECHO720.1.

McGowen, C., Bedard, R., & Lenssen, N. 2005. Ocean tidal and wave energy, renewable energy technical; assessment guide-TAG-RE, EPRI, Palo Alto, CA, 2005, 1010489.

Niiler, P.P., & Richardson, W.S. 1973. Seasonal variability of the Florida current. J Mar Res. 31:144-67.

Stommel, H.M. 1965. The Gulf Stream: a physical and dynamical description. Berkeley, CA: University of California Press. 248 pp.

Tolman, H.L. 1991. A third-generation model for wind waves on slowly varying, unsteady and inhomogeneous depths and currents. J Phys Oceanogr. 21:782-97.

Tolman, H.L. 1999. User manual and system documentation of WAVEWATCH-III version 1.18. NOAA / NWS / NCEP / OMB Technical Note 166. 110 pp. http://dx.doi.org/10.1175/1520-0485(1991)021<0782:ATGMFW>2.0.CO;2.

Tolman, H.L. 2010. WAVEWATCH III (R) development best practices Ver. 0.1. NOAA / NWS / NCEP / MMAB Technical Note 286, 19 pp.

Virmani, J.I., & Weisberg, R.H. 2003. Features of the observed annual ocean-atmosphere flux variability on the West Florida Shelf. J Climate. 16:734-45. http://dx.doi.org/10.1175/1520-0442(2003)016<0734:FOTOAO>2.0.CO;2.

Virmani, J.I., & Weisberg, R.H. 2005. Relative humidity over the West Florida Continental Shelf. Mon Weather Rev. 133:1671-86. http://dx.doi.org/10.1175/MWR2944.1.

Weisberg, R.H., He, R., Liu, Y., & Virmani, J.I. 2005. West Florida shelf circulation on synoptic, seasonal, and inter-annual time scales. In Circulation in the Gulf of Mexico, W. Sturges and A. Lugo-Fernandez, eds., AGU monograph series. Geophysical Monograph. 161:325-47.

Weisberg, R.H., Barth, A., Alvera-Azcárate, A., & Zheng, L. 2009. A coordinated coastal ocean observing and modeling system for the West Florida Shelf. Harmful Algae. 8:585-98. http://dx.doi.org/10.1016/j.hal.2008.11.003.