# Achievable Renewable Energy Targets

## For Puerto Rico's Renewable Energy Portfolio Standard

## Final Report

Agustín A. Irizarry-Rivera, Ph.D., P.E.
Department of Electrical and Computer Engineering
agustin@ece.uprm.edu

José A. Colucci-Ríos, Ph.D., P.E.
Department of Chemical Engineering
biodieselpr1@aol.com

Efraín O'Neill-Carrillo, Ph.D., P.E.
Department of Electrical and Computer Engineering
oneill@ece.uprm.edu

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# 1 Achievable Renewable Energy Targets

## 1.1 Introduction

We have performed a preliminary but realistic estimate of each renewable energy resource, and related technologies, available in Puerto Rico for electricity production. These are; biomass - including waste-to-energy, micro hydro, ocean – in the form of waves, tides, currents and ocean thermal, solar radiation (to be used thru photovoltaic technology) and solar thermal, wind – to be exploited at the utility level (wind parks) as well as small wind. The estimate also includes a preliminary assessment on the use of fuel cell technology.

This estimate has been restricted using realistic constraints such as: estimated availability of the resource under consideration, estimated required surface area or "foot print", seasonal cycles, state of available technology (commercial and prototype) and estimated capital costs.

This estimate provides the quantitative means to compare among renewable electricity production alternatives based on the amount of electricity that each resource may provide.

Also, a more realistic estimate for ocean, solar (photovoltaic) and wind resources has been done as requested by the Puerto Rico Energy Affairs Administration (PREAA). This estimate is based on the aforementioned criteria plus: weather effects, day/night cycles, state of available technology (commercial, prototype or laboratory available), costs such as capital investment (including retrofitting of existing facilities) and maintenance and operation, electric grid interconnection issues, and others as needed to realistically constrain the resource under investigation.

This estimate of renewable energy available in Puerto Rico for electricity production has been performed to provide guidance to those responsible of establishing an energy policy that ensures that a minimum amount of renewable energy is included in the portfolio of electricity resources serving Puerto Rico. Adequate targets, as a function of time, may be developed for example using a Renewable Energy Portfolio Standard (RPS). A RPS is designed to increase the use of renewable energy for electricity production by requiring that a specified percentage of the electricity for the state be generated from renewable sources. Such requirements exist in various countries and states of the United States and a first step in establishing a RPS is the study described in this report.

### 1.2 Report content

This chapter, Chapter 1, aims to summarize the main findings of our work. Each following chapter covers in detail a specific renewable resource and its related technologies.

Chapter 2 covers wind energy. We offer a description of wind turbine components, manufacturers for both small and large turbines, wind measurements fundamentals, and publicly available wind data for Puerto Rico. Using this data we show a seasonal, as well as a diurnal/nocturnal variation analysis. A conservative estimate of land use, potential number of turbines to be installed and estimated energy production for both large and small wind turbines is presented.

Chapter 3 covers ocean energy from tides, submarine currents, waves and thermal gradients. From ocean data for Puerto Rico, and the current state of available technology, we conclude that the energy content of both tides and submarine currents is insufficient to economically produce electricity and thus merit no further analysis at this point in time. As more data becomes available for submarine currents, and technology advances, it may be beneficial to revisit these two sources of energy.

The rest of Chapter 3 is dedicated to the analysis of Ocean Thermal Energy Conversion (OTEC) and ocean waves with the latter being of more immediate application since nearly commercial off-shore devices and experimental shore devices are being deployed around the World.

Chapter 4 covers Puerto Rico´s solar resource and briefly presents solar thermal technologies capable of using this resource. We define the geometrical relation between the sun and available solar resource at a given site and discuss how direct and diffuse radiation can be obtained from global measured solar radiation. We also discuss de variability and uncertainty of solar radiation data. We then present solar data for Puerto Rico and present an estimate of solar isolation, in the form of a map, for Puerto Rico. Finally a review of the main solar thermal technologies, for electricity production, is presented.

Chapter 5 covers photovoltaic technology for electricity production. We provide a description of major photovoltaic system components; solar panels, inverters, batteries and charge controllers, as well as their costs. An estimate of photovoltaic energy generation is presented.

Chapter 6 covers biomass and its potential use for electricity production. We discuss the availability and variability of both agricultural and solid waste biomass as well as the available commercial and prototype conversion technologies to produce electricity using these resources. Finally an estimate of capital cost and of potential electric energy contribution is presented.

In Chapter 7 we cover fuel cells as a technology with potential to be combined with others in this study to produce renewable electricity. We explain the technology, commercially available and prototypes, and provide information on its markets. Footprint, an estimate on capital costs and an estimate of potential electric energy contribution is also presented.

Finally, Chapter 8 studies the possibility of using micro hydroelectric technology for electricity production. A comprehensive discussion on micro hydroelectric technology is presented, including cost and the micro hydroelectric potential in Puerto Rico.

## 1.3 Summary of results

The renewable energy resources we have studied have significant physical differences among themselves. For example biomass is measured in tons, with a great variety of heat content, while solar radiation is measured in Watts per square meter per year ($W/m^2$ per year). The variability, the change in availability with time, of these resources is also measured differently. Crops have different cycles (annual, semi-annual and such), the most obvious solar cycle is day to night while the wind changes randomly.

Due to the different nature of the resources the available technology for electricity production from them varies as well, including the fact that some of it is commercially available while other is at the prototype or laboratory level.

Thus these renewable energy resources and related technologies are intrinsically difficult to compare. In an attempt to compare them in this summary we have selected three parameters, namely; required surface area, or "footprint", capital costs and potential electric energy contribution from each resource. The remaining parameters studied in this work, the estimated availability and variability of each resource and the state of the technologies used to harvest their energy, are more justly discussed in the following chapters of the report. Table 1-1 shows a summary of the results.

Table 1-1 Summary of required surface area, capital costs and potential electric energy contribution from each resource/technology.

| Renewable resource/technology | Footprint estimate<br><br>Installed capacity per unit area<br><br>[MW/km$^2$] | Capital costs estimate<br><br>Millions of US dollars per MW electric<br><br>[M$/MW] | Electric energy production estimate<br><br>MWh per year if 10% of the resource is used to produce electricity<br><br>[MWh/year@10%] | Comments |
|---|---|---|---|---|
| Wind (total) | - | - | 2,977,052 | 14.4% of the 2006 electric energy demand [a] |
| • small | 0.3 [b] | 2.01 | 35,842 [c] | |
| • large inland | 5 [d] | 1.20 | 323,760 [e] | |
| • large offshore | 5 [d] | 2.00 | 2,617,450 [f] | |
| | | | | |
| Ocean (total) | | | 16,935,360 | 82.2% of the 2006 electric energy demand [a] |
| • OTEC | A 5 MW prototype, platform occupies 3660 m$^2$. See [t] | Unknown [g] | Unknown | |
| • waves/offshore attenuator (Pelamis) | 37.5 [h] | 8.3 | 16,394,560 [i] | |
| • waves/shore Oscillating Water Column (LIMPET) | 25 MW/km [j] | 3.5 | 540,800 [k] | LIMPET´s facilities are about 7.5 m wide. |
| | | | | |
| Solar (total) | | | 3,900,000 | |
| • photovoltaic | 130 | 7.5 to 9.1 [l] | 3,900,000 | 18.9% of the 2006 electric energy demand [a] |
| Biomass | | | | |
| • agricultural | 0.15 – 3.0 [m] | 0.5 – 3.5 [n] | 1,200,000 (traditional) – 24,000,000 (microalgae) [o] | 5.8 to 116.5% of the 2006 electric energy demand [a] |
| • waste | 1,000 – 1,500 [p] | 1.0 – 5.0 [q] | ~90,000 [r] | 0.4% of the 2006 electric energy demand [a] |

Table 1-1 Summary of required surface area, capital costs and potential electric energy contribution from each resource/technology (cont.)

| | | | | |
|---|---|---|---|---|
| Fuel cells | 3,000 [s] | 5.0 – 7.0 | Unknown | Highly dependent on availability of Liquefied Natural Gas (LNG) |
| | | | | |
| Micro hydro | 240 | 4.0 | 2,628 | 0.01% of the 2006 electric energy demand [a] |
| | | | | |
| Annual cumulative energy production, if 10% of wind, ocean waves and solar photovoltaic is used to produce electricity. | --- | --- | 23,812,412 | 115.5% of the 2006 electric energy demand [a] |
| Annual energy production, if 10% of agricultural biomass, from microalgae, is used to produce electricity. | --- | --- | 24,000,000 | 116.5% of the 2006 electric energy demand [a] |
| Annual energy production, if 10% of wind, ocean waves, solar photovoltaic and agricultural biomass, from microalgae, is used to produce electricity. | --- | --- | 47,812,412 | 232% of the 2006 electric energy demand [a] |

a. According to the "Banco de Desarrollo Económico de Puerto Rico" in 2006 Puerto Rico demanded 20,600,000 MWh of electricity.

b. For small wind turbines we use a very conservative estimate that each wind turbine will occupy approximately 20,000 m² (5 cuerdas/turbine) or 0.02 $km^2$ per turbine. Bornay Inclin 6000 turbines are chosen for the estimate.

c. Energy production assumes Bornay Inclin 6000 wind turbines, or similar, at 25 m height and wind regime as measured in the southeast coast of Puerto Rico.

d. Corresponds to a conservative separation of 10 rotor diameters in the direction of prevailing wind for large turbines. It is most important to note that at least 90 to 95% of the land use in a wind farm is available for agriculture or other uses.

e. Energy production assumes Gamesa G58 wind turbines, or similar, at 50 m height and wind regime as measured in the southeast coast of Puerto Rico.

f. Energy production assumes Fuhrlander FL2500 wind turbines, or similar, at 100 m height and wind regime as measured in the east coast of Puerto Rico.

g. No reliable cost data is available to judge the economic feasibility of OTEC technology. Although the concept is well understood and the resource is available in Puerto Rico no one in the World has built a commercial OTEC plant.

h. A 37.5 MW Pelamis array contains 50 devices in two kilometers long and half kilometer wide arrangement.

i. Total north-west sea area is approximately 862 $mi^2$ (2241 $km^2$), thus 10% is about 224 $km^2$. A single Pelamis device is estimated to produce about 1,463.8 MWh per year in the north-west sea of Puerto Rico.

j. LIMPET facilities are about 7.5 m wide, thus we specify their footprint using MW per kilometer of length.

k. Puerto Rico´s north shore length is estimated at a length of 160 km, thus 10% is about 16 km. A 1 MW OWC plant is estimated to produce about 1,352 MWh per year assuming a 15% attenuation in wave power as it arrives to the shore.

l. Assuming grid-connected, net metering systems without batteries. The lower estimate corresponds to systems where the owner is knowledgeable of electric systems and can do some of the design, purchase, installation and maintenance by him/herself. The economic analysis in Chapter 5 is done using the more conservative cost figure of 9.1 $/W.

m. Estimated for agricultural productivity of biofuels from ground soil crops (1,000 gallons/yr-ha) to microalgae (20,000 gallons/yr-ha). 12 kW/gal/hr was assumed for electricity generation.

n. Only includes the agricultural and biofuel production investment. Power generation investment not included. Based on lignocellulose and microalgae biofuel production preliminary estimates at large capacity (> 10MGPY).

o. 100,000 hectares (10% of PR) was used for the estimate.

p. Based on Thermal Waste to Energy facilities footprint.

q. The variability is based on the level of regulations that is required and the nature of the technology (from Incineration, Plasma to Gasification). More information is required.

r. Only vegetation and organics were considered (3,731 tons/day) @ 10% of the resource.

s. Based on Fuel Cell Energy DFC1500MA™ unit. Does not include Fuel Storage footprint if required (not piped in).

t. The maximum number of adjacent OTEC platforms, thus their MW/$km^2$, will be restricted by the capacity of the sun to heat the discharged cold water and keep the required temperature gradient. The environmental effects of the discharge must be studied and could restrict the maximum number of adjacent OTEC platforms even further.

### 1.3.1 A comment on energy conservation and efficiency

This study did not cover the potential benefits of energy conservation and energy efficiency, particularly the use of residential solar thermal water heaters as immediate and economic alternatives to displace electric generation. These merit further study.

### 1.3.2 Comments on ocean energy technologies

Ocean waves have extraordinary potential. With close to 17,000,000 MWh of potential annual production (if we only use 10% of the available ocean space in the North West coast) this resource represents the largest, naturally produced, untapped energy resource for Puerto Rico.

Given the current development of these technologies ***we recommend to perform pilot plant studies in Puerto Rico that includes actual ocean wave measurements and technology validation***.

Environmental, social and community concerns must be addressed in parallel with engineering developments for the sustainable use of ocean waves to produce electricity. Public policy, for licensing ocean space to harness its energy, must be developed.

Another important finding is that potential electric generation from ocean currents and tides, using currently available technology, is too small in comparison to wave energy and thus economically unfeasible.

Although Puerto Rico is considered by many to possess excellent potential for OTEC, many unknowns regarding the technical, ecological, economical and social viability of this technology are still to be addressed.

Groups currently proposing OTEC for Puerto Rico do not disclose their economic and financial estimates to maintain a commercial advantage over other proponents. It is not possible to make a reliable economic comparison with other technologies under this lack of available data.

OTEC is a potentially disrupting technology to the environment given the massive flows of sea water necessary to achieve megawatt levels of power generation. This includes piping (20–40 ft diameter), pumps, etc. Maintenance costs considering corrosion and bio-fouling must be estimated carefully and conservatively.

The social and community site specific impacts such as fishing, ocean recreational sports, and coastal tourism developments must also be discussed in detail.

Given these uncertainties and advanced level of development of other technologies, OTEC falls under a second tier type category. Note, however, that OTEC is considered a "baseload" alternative versus other renewable resources that are more variable in nature.

### 1.3.3 Comments on biomass

Another alternative resource that was only assessed in the preliminary study is biomass which included both agricultural based and solid waste. The preliminary analysis show that agricultural biomass from microalgae has an impressive potential. **Annual electric energy production, using only 10% of the potential harvest of microalgae, is estimated at 24,000,000 MWh, a**

**figure that exceeds the 2006 electric energy demand of 20,600,000 MWh.**

This finding becomes even more important if we consider that biofuels are a source of **power <u>and</u> energy** not just energy. Wind, ocean waves and solar photovoltaic are subject to fluctuations in the source of energy making them energy producers that require either energy storage, not necessarily in the form of electricity, or careful and precise grid management to allow for continuous supply of electric power.

This extraordinary potential can not be tapped easily. Many hurdles lie in the path of using 10% of the potential harvest of microalgae in Puerto Rico. Among these are:

1. The "fuel vs. food" debate has not occurred in a sustainable, i.e. inclusive and participative, manner in Puerto Rico. The benefits of using agricultural land to harvest microalgae must be carefully weighted against its harms. The current philosophy, as stated in Puerto Rico´s Constitution, is that food comes first.

2. Puerto Rico´s Constitution explicitly forbids the use of government owned agricultural land to grow non-food crops. If the "fuel vs. food" debate is settled in a manner, or even a limited manner, that permits the use of agricultural land to produce "fuel crops" a Constitutional change is still needed to take advantage of the many acres of fallow government owned agricultural land. The political process to produce such change has in itself many hurdles.

3. Even if the "fuel vs. food" debate is settled permitting the use of agricultural land to produce "fuel crops", and the Constitution is

changed to make it legal, the agricultural sector still needs major restructuring.

Puerto Rico´s agricultural sector has been declining for decades. The use of outdated technology, lack of interest and support from the Puerto Rico government to this sector, non-consensus among farmers on the right strategies to improve, lower profit margins versus high tech higher paying jobs and foreign competition are just a few of the reasons for the decline. In addition, many farmers can not resist the high, immediate, financial gains of converting farm land into real state developments. The lack of a well articulated, well implemented, modern plan for the use of land exacerbates this situation.

In summary, an inclusive debate on the "fuel vs. food", changes to the Puerto Rico´s Constitution and a major overhaul to the agricultural sector are needed in order to tap the potential benefits of using microalgae to produce not just biofuels, thus electricity, but other Fs (Feed, Feedstock, Fibre and Fertilizer).

### 1.3.4 Comments on photovoltaic electric generation

The least intrusive renewable energy resource technology considered in our study is solar photovoltaic. Contrary to other countries were photovoltaic farms are considered, in Puerto Rico photovoltaic roofs were the main focus of the study. We have selected this approach based on Puerto Rico's high population density and historic single family housing trends.

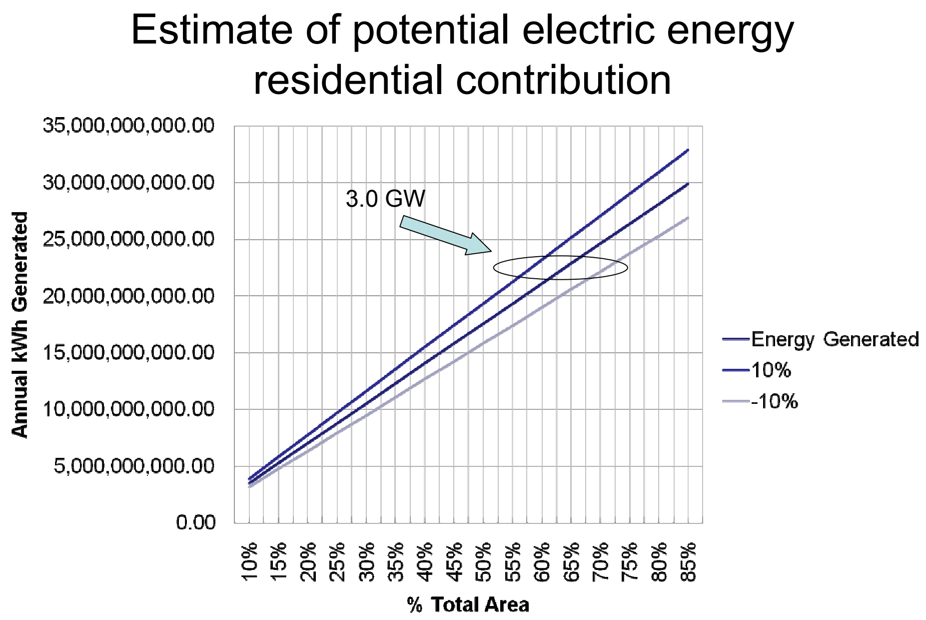


Figure 1.1 Estimate of solar photovoltaic electric energy contribution form residential applications.

Approximately 65% of residential roofs can provide the total electrical energy, not power, that is generated in Puerto Rico, as shown in Figure 1.1.

The highly distributed nature of this alternative, with hundreds of thousands of potential energy generators, also possesses interesting challenges regarding the integration and interconnection of these systems. Nonetheless, the energy generation potential is so significant that even 10% of the households can provide close to 20% of the overall energy demand. Developments in energy storage technologies should provide an opportunity for even greater penetration of photovoltaics.

We believe photovoltaic generation to be the least environmentally intrusive, and the one with minimum possibility of social and community conflicts during deployment, among the renewable energy resources and technologies considered in this study. Photovoltaic panels installed in roofs are virtually non-visible and the noise level of auxiliary equipment, such as the fan from DC/AC converter, is negligible. An important issue to consider is the "right to the sun", an issue that will emerge as more PV systems are installed in rooftops.

Again, perhaps the most important challenge, after is high capital cost per unit of power, is the adjustment needed in distribution systems, how they are designed and operated in Puerto Rico, so that these can accommodate as many distributed energy sources as it is economically, technically, socially and environmentally viable.

Economic affordability of low income families is a social issue that must be addressed in the economic incentives that are required for these systems. Notice also that these numbers indicate that photovoltaic farms that compete with other renewable resources such as wind and biomass should have a lower priority. However, areas such as state highways, parking lots, etc could also be considered.

Another important consideration with PV technology deals with the way we build new structures, for example access to the roof from the electric distribution panels and the layout and use of space in the roof. Piping and air conditioning equipment, dish antennas and any structure over the roof can cast a shadow that limits potential use of PV in a rooftop.

### 1.3.5 Comments on eolic generation

Offshore wind farms offer a very high potential of electricity production in Puerto Rico. The two identified areas in the east coast (1,920 $km^2$) and south coast (825 $km^2$) can result in a total installed wind capacity of 13,725 MW. Even 10% of that area will result in 1,375 MW which is still a considerable amount.

Similar to ocean based technologies, wind is undergoing strong scrutiny from environmental and community groups. Wind farms are not only highly visible but could affect species such as bats and birds. However wind generation is a mature technology, proven around the World, and the most cost effective of the renewable generation options.

### 1.3.6 Comments on Fuel cell technology

Fuel cell technology had definite disadvantages versus faster growing technologies in the short, 1 to 5 years, and medium term range, 6 to 15 years. The relatively high price of hydrogen and natural gas is a very difficult hurdle to overcome especially in Puerto Rico.

## 1.4 Conclusions

Photovoltaic systems can have a dramatic impact at the residential level in Puerto Rico. During the day, enough electrical energy can be generated to displace fossil-fuel based generation equivalent to the residential load using dispersed residential PV systems. Irradiance variations are not a big issue for dispersed PV systems since it is unlikely under typical weather conditions, to have the whole Island under cloud cover.

PV technology is well understood, well known and commercially available.

Since rooftops provide ample space footprint is not an issue. Due to stringent land use limitations, it is not recommended to use land in Puerto Rico for large PV arrays. If and when storage technologies become a large-scale alternative, photovoltaic technology could even supply all electric energy in PR, even for large energy-intensive industries and commercial operations.

Higher capital cost is its main disadvantage compared to the other technologies.

Offshore wind farms offer a very high potential of electricity production in Puerto Rico and offer the advantage of no land use. Even with its higher capital cost off-shore wind remains attractive and competitive cost wise.

Its main draw back is their high visibility and the potential to affect species such as bats and birds if sites are not carefully chosen.

Wind generation is a mature technology, proven around the World, and the most cost effective of the renewable generation options.

Ocean waves have extraordinary potential and represent the largest, naturally produced, untapped energy resource for Puerto Rico. Its footprint is small and current cost lie between photovoltaic and wind.

Given the current development of wave energy conversion technology ***we recommend to perform pilot plant studies in Puerto Rico that includes actual ocean wave measurements and technology validation***.

Environmental, social and community concerns must be addressed in parallel with engineering developments for the sustainable use of ocean waves to produce electricity. Public policy, for licensing ocean space to harness its energy, must be developed.

Agricultural biomass, specifically from microalgae, has the potential to provide electric energy in excess of the 2006 electric energy demand of 20,600,000 MWh. Its impact could be even higher if we consider that biofuels are a source of **power <u>and</u> energy** not just energy.

Wind, ocean waves and solar photovoltaic are subject to fluctuations in the source of energy making them energy producers that require either energy storage, not necessarily in the form of electricity, careful and precise grid management to allow for continuous supply of electric power or both.

With reasonable footprint and cost agricultural biomass from microalgae to produce electricity merits further investigation. It does not constitute a short term solution to provide electricity since an inclusive debate on the "fuel vs. food", changes to the Puerto Rico´s Constitution and a major overhaul to the agricultural sector are needed in order to tap the potential benefits of using microalgae.

**We recommend wind, solar photovoltaic and ocean waves as the renewable resources/technologies to be targeted via Renewable Portfolio Standards in the immediate future. A clearly achievable use of only 10% of these resources will provide an estimated 115% of the 2006 electric energy demand.**

Finally, a common objection to the use of renewable energy resources is the electric grid interconnection issue. Electric grid integration and interconnection is a well studied area with a wealth of information and studies on how to deal with the technical challenges of taking advantage of renewable energy resources and an electric grid that was not originally designed for them.

This is not to say that we can indiscriminately interconnect distributed or renewable energy resources to our power grid. Operational limits, dependent on the utility's particular operating region, must be defined to keep the grid operating with the renewable resources and within its safety and operational restrictions.

**In Puerto Rico, with our abundant renewable energy resources, the question should be not how to best integrate renewable resources into the existing electric energy grid or other energy infrastructures, but how our existing infrastructures and practices should change or transition in order to allow maximum use of solar, wind, ocean and other renewable energy sources.**

The renewable energy potential is available, the technological know-how is present, but we need the will as a People and the inclusive and open dialogue spaces to reach historic decisions.

We need to stop thinking within the bounds of our disciplinary or sector limits, start considering the bigger picture and identify the connections and implications of our decisions into other areas or sectors. It is up to us, all Puerto Ricans, to make a stand for the future, a true social pact in which we do not wait for problems to be solved from the outside but solve the problems ourselves.