Stand-Alone River Water Purification System Powered by Solar Photovoltaic Panels in Haiti

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***Abstract*—The paper presents the design of the application of a river water purification system using green technology, presented by solar photovoltaic (PV) panels, as well as the design of a water pumping system powered also by solar energy. This design presents a solution for the majority of the third world countries which have not only drinking water crisis, but electricity problems as well, and Haiti is one of these countries. This paper shows a complete study including health effects of drinking unsafe and contaminated water, environmental effects of powering the purification system by using conventional power plants as opposed to renewable energy, complete design of the project including pumping system and the PV panels that will power the purification and the pumping systems, financial study for the whole project, and a market analysis for Haiti.**

***Keywords*— Photovoltaic, purification system, reverse osmosis, river water, stand-alone.**

I. NOMENCLATURE

AC	Alternative Current
DC	Direct Current
PV	Photovoltaic
PVRO	Photovoltaic Reverse Osmosis
RO	Reverse Osmosis
SOC	State of Charge

II. INTRODUCTION

TheInstitute of Medicine panel - part of the National Academy of Sciences - suggests that the average human consumes roughly eight cups of water per day to maintain a healthy lifestyle [1]. In general, this doesn’t seem difficult to accomplish in most of the developed countries because running water is widely available, but it is a privilege rarely experienced by those in the developing world. In fact, the shortage of water is a growing concern in many parts of the world, though running water is available in developing nations but not exploited. It is ironic that such an issue could exist when over 75% of the Earth’s surface is covered by ocean and river waters. Through proper water purification, rivers and underground water can be a promising source of drinking water, which could adequately provide for the need of purified water [2].

It is expected that in 2025 at least 3 billion people, 43% of the world’s population, will have an insufficient water supply [3].In the other hand, the numbers today for Haiti are not encouraging since only 67% of Haiti population (48% for the rural areas) have access to drinking water, while the current global average is 86% [4].

Purification technologies can convert almost any water into potable water but they do require energy, mainly in the form of electricity. Thus, the water problem can also be seen as an energy problem since about one third of the world’s population, two billion people, is not connected to an electrical grid [5]. Most of them are cited in rural areas where is the highest needs of potable water, and since seawater, brackish water or freshwater of unknown quality are abundantly available but significant amounts of energy are required in order to make it suitable for drinking.

Purification of water using solar energy is a way to make water drinkable and usable for household activities. Using solar energy for water treatment has become more common as it is usually using low technology solution that works to capture the energy from the sun to make water cleaner and healthier for human use and consumption [6]. Most of the rural areas in third world countries don’t have enough electricity to run the purification plants. The same is for Haiti where only 12.5 % of the population have access to electricity “officially”, although the Ministry of Publics Works estimate that the coverage could be around 25% when irregular connections are considered, and it is 45% for its capital Port-au-Prince [7].This makes solar PV system more competitive than purification systems that use electricity generated by burning fossil fuels, which has severe environmental effects such as pollution, global warming, acid rain and health hazards associated with it.

In this paper, a design for a sustainable water purification system powered by solar PV panels will be presented. It will need around 39.6 kWh of electricity to purify 4,000 gallons of water per day. Beyond the environmental benefits, the system also competes with standard systems on the market. In this paper, a study will show the environmental and health effects of unsafe drinking water and of generating electricity from traditional thermal power plants as opposed to the use of renewable energy, especially solar energy. A design strategy for a small-scale PV powered sustainable system, able to supply a remote village with safe potable water, will be presented.The main cost factors for the system and an overall financial study, including costs of every component, installation cost, and payback period will be established.

Design of a pumping system is included also in this study. Haitian market analysis for the whole project will be presented, including the total installed cost, maintenance estimation and other costs, the selling pricesof the purified water per gallon, and the cumulative net incomes for the system.

III. ENVIRONMENTAL AND HEALTH EFFECTS

Consuming contaminated and unpurified water has a devastating health effects on humans, especially the young people. In other hand, using thermal power plants to generate energy affects the environment and many health problems are associated with it as well.

A. Effects of unpurified water consumption

According to a recent completed assessment published by the World Health Organization, 1.1 billion people around the world lacked access to "improved water supply" and more than 2.4 billion lacked access to "improved sanitation" as well. Widespread water-related diseases and deaths are very serious consequences of this failure. Water-related diseases are typically placed in four classes: waterborne, water-washed, water-based, and water-related insect vectors.

Waterborne diseases include those where transmission occurs by drinking contaminated water. These include most of the enteric and diarrheal diseases caused by bacteria and viruses, typhoid and over 30 species of parasites that infect the human intestines.

An estimated 16–33 million cases of typhoid fever occur annually. Its incidence is highest in children and young adults between 5 and 19 years old. These cases as of 2010 caused about 190,000 deaths up from 137,000 in 1990 [8].

Table 1 summarizes the most common diseases strongly related to unsafe drinking water, and more detailed study is shown in Appendix A.

TABLE I DISEASES RELATED TO UNSAFE DRINKING WATER [9]

Diseases	Estimated Morbidity (per year)	Estimated Mortality (per year)	Relationship of Disease to Water Conditions
Diarrheal	1,000,000,000	2,200,000 to 5,000,000	Strongly related to poor personal and domestic hygiene, unsafe drinking water
Dracunculiasis	150,000	-	Strongly related to unsafe drinking water
Poliomyelitis	114,000	-	Related to poor personal and domestic hygiene, unsafe drinking water

B. Environmental effects of generating electricity by burning fossil fuels

Thermal power stations contribute up to 69% of the world's energy production, see figure 1.They use coal, oil and natural gas as fuel to generate energy. Below,the environmental effects caused by producing electricity from thermal power plants are briefly discussed [10].

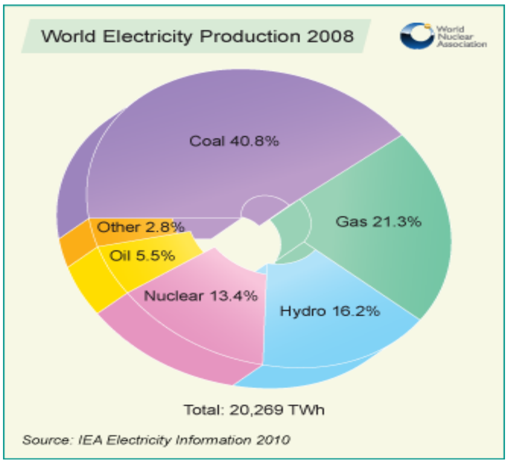

Fig. 1 World Electricity Production [11]

Environmental effects:

- Air pollution due to their consumption of thousands of tons of fossil fuels daily.
- Ground level Ozone (SMOG) and Black Carbon.
- Greenhouse gas emissions. In an average year, a typical coal plant generates 3,700,000 tons of carbon dioxide, 10,000 tons of sulfur dioxide (SO_2) and 720 tons of carbon monoxide (CO).
- Global Warming and Climate Change due to the increase in the greenhouse gas concentrations leading to raise the Earth's average temperature, influence precipitation and some storm patterns as well as raise sea levels [12].
- Respiratory Ailments due to SO_2 emissions.
- Water Environment due to using water slurry to take the ash from the power plant to a pond for disposal and the release of ash pond decant into the local water bodies.
- Land Environment due to the alkaline nature of fly-ash.
- Acid rain due to Nitrogen Oxides (NO_x) and Sulfur Dioxide (SO_2) emissions from the thermal power plants.

C. Benefits of using PV system as primary source of electricity

The major benefits in making use of solar energy are that the source is renewable, inexhaustible, and generally non-polluting. Additionally, solar energy tends to be synchronous with energy demands, and when deployed as distributed generation can reduce loads and congestion on utility distribution and transmission systems.

The generation of energy from sunlight does not contribute to noise, air, or effluent pollution, and does not result in the release of carbon dioxide into the atmosphere. Producing energy from solar offsets energy produced from other, typically fossil resources, and therefore reduces emissions that would otherwise be produced from those resources.

Stand-alone solar electric systems in remote locations are:

Affordable – Off-grid solar electric systems are now price competitive with alternative energy sources, such as operating diesel generators or installing utility electricity, as measured by dollars per kWh of energy generated.

Reliable – Unlike gas or diesel generators, or wind turbines, photovoltaic power systems have no moving parts and require little maintenance.

Flexible – Solar power systems can be designed in modules to meet specific requirements now. Add more capacity later with no equipment replacement as loads increase.

IV. Design of the River Water Purification System

In order to accomplish the design, many steps are taken. First, insolation and weather data are gathered in order to be able to have an accurate design for the PV systems. Second, the purification system is selected. Third, design the water pumping system from a river based on the water flow rate required and the actual dynamic head losses in the system. Lastly, PV panels, battery bank, charge controllers and inverter are selected and the PV systems are designed to power the purification system with the pumping system from a river.

A. Solar insolation and weather data for Haiti

In Haiti, only 25% of the population has access to the electric grid. Thus, an alternative energy source has to be used to supply the water treatment plan with the electricity needed [7].

In terms of solar, Haiti has a large amount of solar power generation potential. It has an average of 3115 hours of sunlight per year (of a possible 4383), with an average of 8h 31min of sunlight per day. In addition, 71.1% of daylight hours are sunny hours. The remaining 28.9% of daylight hours are likely cloudy or with shade, haze or low sun intensity.

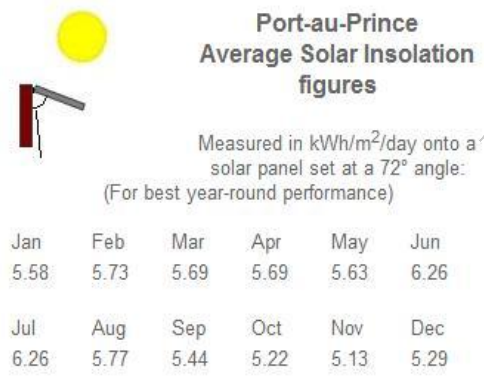

Fig. 2. Port-au-Prince average solar insolation data per day [13]

Comparing it with Boston-MA that has an average of 7h 29min of sunlight hours per day, or around 62% of the average daylight hours, this is 14% less than Haiti [14].

From figure 2, the average peak-sun-hours for Haiti can be extracted, and it is equal to 5.64 peak-sun-hours per day.

Figure 2 shows the average peak-sun-hours or the solar insolation for Port-au-Prince-Haiti measured onto a solar panel set at atilt angle of 18° from the horizontal for best year-round performance. The optimized tilt angle for best year-round performance is approximately equal to the latitude of the location, which is 18.5333° for Haiti [13].

This number is considered high and indicates that Haiti is a prime spot for solar energy generation. Comparing it with Boston-MA that has an average of 4.2 peak-sun-hours, which is 34% less than Haiti [15].

Table 2 summarizes the solar insolation and weather data for Haiti and compares it with Boston's data.

TABLE II SUNLIGHT HOURS AND PEAK-SUN-HOURS FOR HAITI COMPARED TO BOSTON

Sunlight hours/ Peak-sun-hours	**Haiti**	**Boston**
AverageSunlight hours (HH:MM)	08:31	07:29
Averagepeak-sun-hours(Hrs or kWh/m^2/day)	5.64	4.2
Average Temperature°C (°F)	28 (83)	11 (51)

B. Selection of the purification system

Nimbus Water Systems manufactures water treatment equipments for a wide range of applications. It has sold most of its portable units for many projects in Haiti to provide emergency water aid in the wake of the January 2010 earthquake and also to build long-term water infrastructure [16].

In this study the design was done for a system from Nimbus Company that can purify around 4,000 gallons per day. For an average consumption of 0.528 gallons (2 liters) per day per person, this system will be able to supply a community of about 7,570 people.

Many Nimbus systems are available that can purify 4,000 gallons of water per day which are. For this study, the CIV-8000, which can purify up to 8,000 gallons per day, seems to be the optimal option since it will be operating during the day-time for 12 hours only to supply the 4,000 gallons of purified water. Operating only during day-time will reduce the battery bank needed for the system, which would affect the total cost of the PV system. In addition, this system could be extended to supply the additional water demand for the future population growth of the community.

From the specification sheet of the CIV-8000 water purification system, the power needed will be 3.3 kW[17], the total energy needed will be 39.6 kWh per day to produce 4,000 gallons of purified water, and its cost is around $10,900 [18].

C. Design of the PV systems

After gathering the insolation data for Haiti, needed for the system's design, the design process is shown below of the PV system that power the pumping and the purification systems. In this project, SolarWorld SW 250W poly V2.5 is used since a polycrystalline is more efficient than monocrystalline panel in locations where temperature is relatively high like in Haiti.

1) For the water purification system

In order to generate 39.6 kWh per day to power the purification system, 36 panels will be needed, which would cost approximately 300 $/panel. The total number of PV panels required is calculated using the formula 1 [12].

Number, N_{PV}, of PV panels needed:

$$Npv = \frac{E}{Ppv * n * \eta * \eta^{\cdot}} \quad (1)$$

Where: E= Energy needed for the system to run (WH/day), here it is 39.6 kWh

P_{pv}= Power of the PV panel used (250 W)

n= Number of peak-sun-hours for Haiti, (5.64 peak-sun-hrs)

η = Efficiency of lead acid batteries, (85%)

$\eta^{\cdot}$ = Efficiency of the inverter, (90%)

For the battery bank, a 370 AH premium flooded battery 6 V (L16RE-B) optimized for renewable energy applications from Trojan Company is chosen. It works under challenging weather temperatures and has a 10-year life expectancy. To have a backup power for the water system for 8 hours (26.4 kWh), a total of 16 batteries are needed as a backup for the system when there are low solar irradiances, with a cost of 360 $/battery. The total number of batteries needed is calculated using the formula 2[12].

The number, N_{batt}, of batteries needed as a backup power for the system is:

$$Nbatt = \frac{E}{C*V*DOD} \qquad (2)$$

Where: *E*= Energy needed as backup for the system (WH), here it is 26.4 kWh (for 8 hrs)
C =Capacity of the battery used (370 AH)
V= Voltage of the battery used, (6 V)
DOD = Depth of discharge of the battery, (80%)

Figure 3 is an approximated simulation for the system. It shows the power needed by the purification system (running for 12 hrs per day), the power output of 1 PV panel, the power output for the 36 PV panels, and the behavior of the battery bank state of charge (SOC) during a typical day taking into consideration the energy losses of the inverter and batteries' efficiency.

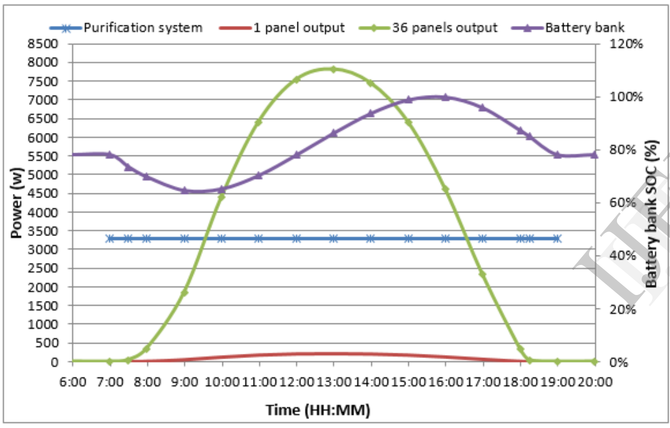

Fig. 3. Simulation of the system showing the power needed, the output of the PVs and the battery bank's behavior

Since the total number of batteries is 16 with 6 VDC each, the system will be 2 sets of 8 batteries with a total of 48 VDC each. And since the total power of the PV system is 9 kW, from MidNite, MidNite Lite Classic 200 is used. For 48 VDC system, 3 charge controllers are needed [19].

For the inverter, a 3-phase inverter is needed, 5 kW PanPower inverter is used to convert the power needed for the purification system from the battery bank.

Figure 4 shows a detailed drawing of the electric diagram and the wiring details of the PV system powering the Nimbus water purification system, including the PV panels, charge controllers, batteries, and the inverter.

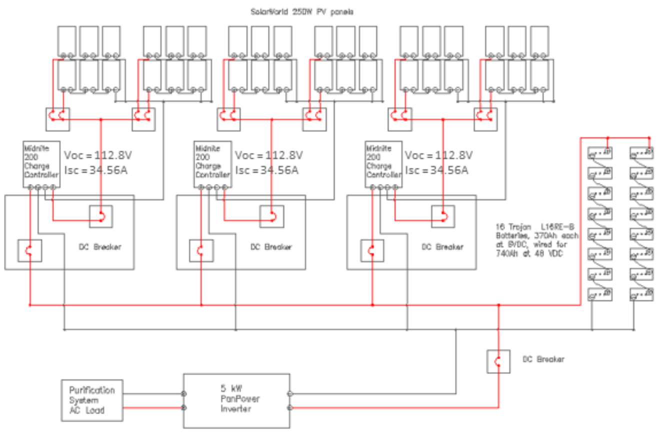

Fig. 4. Drawing of the water purification system showing the PV electric diagram and the wiring details

2) For the river water pumping system

First, and for the selection of the pump, Lorentz's company manufactures a wide range of maintenance free DC motor solar 4" submersible pumps. In order to select the appropriate solar pump, the total dynamic head loss in the pipes must be evaluated. For an assumption of 500 ft long 4" new steel pipes and 95 ft difference in elevation, the total dynamic loss for 18 gpm flow rate is approximately 95.2 ft [20]. Using PS600 C-SJ5-8 pump from Lorentz Company, and from its specifications sheet, the power required for the pump is around 0.65 kW to pump the water at 18 gpm with a total dynamic head loss of 95.2 ft [21].

So, to purify 4,000 gallons, the purification system needs around 8,000 gallons of contaminated water to be pumps and stored in a tank. For a flow rate of 18 gpm, the pump needs only around 7.4 hrs per day to pump 8,000 gallons. So, the total energy needed for the pump is:

$$E = 7.4\ hrs * 0.65\ kW = 4.81\ kWh$$

Second, for the PV panels, the same formula 1 is used to calculate the number of PV panels needed but without taking into account the efficiency of the inverter because the solar pump run on 48 VDC current. In order to generate 4.81 kWh per day to power the river pumping system, 4 SolarWorld 250W PV panels will be needed.

For the battery bank, a 130 AH premium deep cycle flooded battery 12 V (30XHS) is chosen. It is engineered to suit renewable energy application and to provide rugged durability and outstanding performance.

To have a backup power for the river water pumping system for 6 hours (3.9 kWh), and by using formula 2, a total of 4 batteries are needed as a backup for the system when there are low solar irradiances, with a cost of approximately 220 $/battery.

Figure 5 is an approximated simulation for the system. It shows the power needed by the pump (running for 7.4 hrs per day), the power output of 1 PV panel, the power output for the 4 PV panels, and the behavior of the battery bank during a typical day taking into consideration the energy losses due to batteries' efficiency.

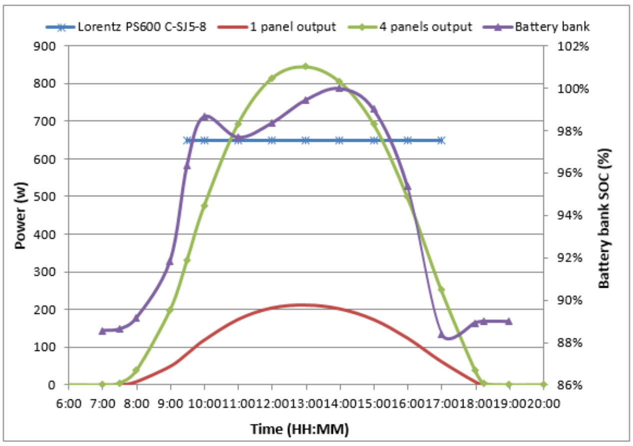

Fig. 5. Simulation of river water pumping system showing the power needed, the output of the PVs and the battery bank's behavior

Since the total number of batteries is 4 with 12 VDC each, the system will be 1 set of batteries with a total of 48 VDC. And since the total power of the PV system is 1 kW, from MidNite, MidNite Lite Classic 200 is used. For 48VDC system, 1 charge controller is needed [19].

Figure 6 shows a detailed drawing of the electric diagram and the wiring details of the PV system powering the river water pumping system, including the PV panels, charge controller and the batteries.

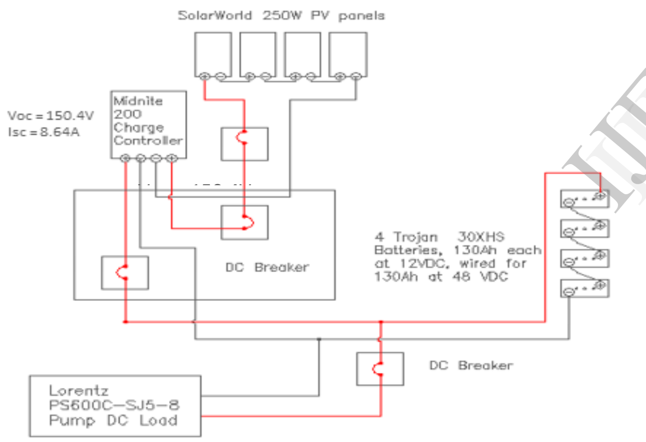

Fig. 6.Drawing of the river pumping system showing the PV electric diagram and the wiring details

Figure 7, shows a simulation of the water level variation in the tank where the river water is stored in prior to be purified, and the quantity of the potable water purified by the purification system, stored in a potable water tank and ready to be collected by the consumers.

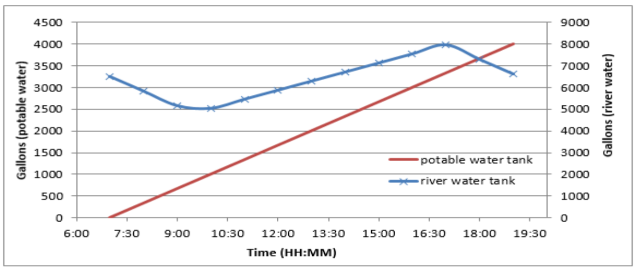

Fig. 7. Quantity of water pumped and purified for the purification system with river water pump

V. FINANCIAL PRESENTATION

In this paragraph, cost estimation of the whole purification system is determined and the payback period of the solar PV system will be calculated by using the cost of producing the electricity, by the Haitian electric grid, needed for the system to purify the required amount of water.

A. Costs of the system

The total cost of the purification system powered by photovoltaic solar panels is calculated by estimating the cost of each component as shown below in table 3, which comes out to be around $33,321.

TABLE IIICOST ESTIMATION OF PURIFICATION SYSTEM POWERED BY SOLAR PV

Component	Company of manufacturing	Cost (USD per item)	# of items	Total cost (USD)
Purification system (8,000 gpd)	Nimbus (CIV-8000)	10,900[18]	1	10,900
Batteries	Trojan 370AH (L16RE-B)	360[26]	16	5,760
Charge controller	MidNite Lite 200	700[27]	3	2,100
3-phase inverter	PanPower (48 VDC)	2,000[28]	1	2,000
PV panels	SolarWorld (250W poly)	285[29]	36	10,260
Potable water tank	Plastic tank (4,100 gallon)	2,301[30]	1	2,301
Total cost (USD)				**33,321**

The total cost of the river water pumping system powered by photovoltaic solar panels is calculated and shown below in table 4. It comes out to be around $16,975.

TABLE IV COST ESTIMATION OF RIVER WATER PUMPING SYSTEM POWERED BY SOLAR PV

Component	Company of manufacturing	Cost (USD per item)	# of items	Total cost (USD)
4" Submersible pump	Lorentz (PS600 C-SJ5-8)	2,600 [31]	1	2,600
Steel pipes	ASTM A500 Bare (4"x42')	500 [32]	12	6,000
Batteries	Trojan 130AH (30XHS)	190[33]	4	760
Charge controller	MidNite Lite 200	700	1	700
PV panels	SolarWorld (250W poly)	285	4	1,140
Water tank	Plastic tank (8,000 gallon)	5,775[34]	1	5,775
Total cost (USD)				**16,975**

B. Payback period of the PV systems

To calculate the payback period of the PV systems in Haiti, a US company, which was interested in the installation of such systems in Haiti, was consulted and a quotation for the installation cost in Haiti was given. The total cost of the PV system installed to power the purification system, including components and installation cost, is presented in table 5.

TABLE V TOTAL COST OF THE PV SYSTEM FOR THE PURIFICATION SYSTEM

Component	Company of manufacturing	Cost (USD Per item)	# of items	Total cost (USD)
Batteries	Trojan 370AH (L16RE-B)	360	16	5,760
Charge controller	MidNite 200	700	3	2,100
3-phase inverter	PanPower (48VDC)	2,000	1	2,000
PV panels	SolarWorld (250w poly)	285	36	10,260
Installation cost		1.5	9,000	13,500
Total cost (USD)				**33,620**

In Haiti, the cost of each watt hour of electricity produced by the electric grid company is around 0.23$/kWh [22]. This system consumes 39.6 kWh per day (12 hrs), or 14,454 kWh per year, and will cost $3,325 per year if it is running on the electric grid. The payback period of the installed price of the PV system is then calculated for Haiti, and is 10.1 years.

VI. Market Analysis

For the market analysis, many data for Haiti need to be determined and many studies are included.

Project description and outlook: Solar powered water purification systems are not yet widely used in Haiti, though, many purification systems from Nimbus Water Systems' products are in use there. It's expected that the demand in similar systems will double in couple years [16].

Target market needs and pricing: As mentioned before, 33% of Haiti population has no access to potable water, and only 25% has access to the electric grid. This indicates that the need of this type of purification systems are very helpful in Haiti where the problem is not only the lack of access to safe drinking water, but also the power outages and the lack of access to the grid. These two problems are solved by adopting the solar powered water purification system.

The need of the society must be identified. First, for Haitians, the taste of the water is important. This was an additional reason why a reverse osmosis purification system was chosen. The taste of water purified by a RO system is very good and first class [23]. Second, the cost of each gallon of water that Haitians can support has to be defined.

These local data and information and other following data about some estimated costs including cost of housing, labor salaries etc. have been obtained also from the company that was interested in installing this system in Haiti. The selling price of each gallon of purified water is $1 Haitian dollar in the major cities, which is equivalent to 0.1165 USD, and in the rural areas, the price is reduced to $0.4 Haitian dollar to help these communities in the need of water, which is equivalent to 0.0466 USD.

Size of the target market: For this system that purifies 4,000 gallons of water per day, and assuming an average of daily potable water consumption of 2 L/person (0.528 gal/person)[24], the daily number of people that are going to benefit from this system is around 7,570 person.

Future growth on the market: The growth of Haiti's population for the last five years is around 1.3 to 1.4% [25]. Thus, the growth on the market could be estimated and assumed to be equal to the population growth rate.

Total operating cost of the system: The total operating cost of the system should be estimated including maintenance, housing, racking for the PV, labor expenses etc.

Return on investment: Lastly, the return on investment is calculated and an estimation of the yearly benefits is presented.

A. *River water purification system*

The market analysis is divided into two parts. The first one is the analysis of the first year of operation of the system. It includes the purification system cost, the river water pumping system cost, racking for PV panels, housing for the systems, installation costs for the PV systems, pump and piping, and the labor salaries, which includes the salary of one guard staying on site to ensure the proper use and operation of the system. The second part of the analysis is for the successive years of operation after the first year. The two parts of the market analysis for the purification system with a river water pumping system is presented in tables 6 and 7, respectively.

TABLE VI MARKET ANALYSIS FOR FIRST YEAR OF OPERATION OF THE PURIFICATION SYSTEM WITH RIVER WATER PUMPING SYSTEM

Component	Cost (USD)	Yearly income (USD)
Purification system	33,321	-
Housing	8,000	-
Racking	9,250[35]	-
Pumping system from river	16,975	-
PV installation	15,000	-
Pipes + pump installation	15,000	-
Labor salary	18,000	-
Income for cities application (case1) ($0.1165/gallon)	-	170,090
Income for rural areas application (Case 2) (0.0466/gallon)	-	68,036
Total (USD)	105,546	-

TABLE VII MARKET ANALYSIS FOR THE SUCCESSIVE YEARS OF OPERATION OF THE PURIFICATION SYSTEM WITH RIVER WATER PUMPING SYSTEM

Component	Cost (USD)	Yearly income (USD)
Average yearly maintenance	11,904	-
Labor salary	18,000	-
Income for cities application (case1) ($0.1165/gallon)	-	170,090
Income for rural areas application (Case 2) (0.0466/gallon)	-	68,036
Total (USD)	29,904	-

Figure 8 shows the cumulative net income of the purification system with a river water pumping system for the 2 cases. First case is the application of the system in the major cities with higher selling price, and the second is the application in rural areas with lower rate. Both cases have an initial cost of $105,546 (negative value). The first case has a yearly income of $170,090. Its net income starts after around 10 months of operation and reaches $595,384 after 5 years. The second case has a yearly income of $68,036. Its net income starts after around 2.75 years of operation and reaches $85,114 after 5 years.

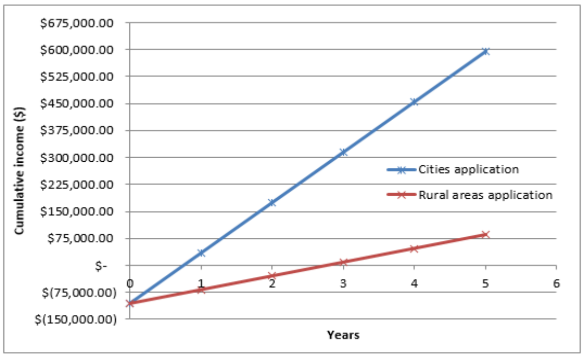

Fig. 8. Cumulative net incomes of the purification system with river water pumping system

VII. CONCLUSION

From this study, it is concluded that the PVRO purification system powered by photovoltaic panels in Haiti is:

- A need for the community since unclean water is one of the primary causes of illness and likely death, especially for infants and young adults, because many of them cannot afford the necessary medical treatment.
- Reliable since the solar energy is widely available in Haiti and more reliable than the national grid.
- Has no environmental and health effects compared to producing electricity from thermal power plants that run on fossil fuels.
- Cost effective and more reliable compared to the electric grid for all the areas in Haiti.
- Profitable for the investors who are interesting in investing in this type of systems and has a considerable return, especially if it is installed in the cities where the heavy population is cited and where the selling price of each gallon of purified water is $0.1165.

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