Paper ID APEN-MIT-2019_242
Applied Energy Symposium: MIT A+B
May 22-24, 2019 • Boston, USA

Survivable Nanogrid through Jointly Optimized Water and Power: The Case of Texas Colonias

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Abstract— **This paper studies a distinct perspective of a nano-grid to provide water needs at a survivable level for people with limited access to both electricity and drinkable water. It is shown that by considering the essential requirements of colonias, a portable treatment facility supported by a few photovoltaic (PV) panels and water storage tanks can provide the bare minimum living standards. This set up is defined as the survivable nanogrid. Given the primitive conditions, the proposed sizing and operation of the nanogrid leverages the flexibility of water filtration energy needs to compensate the fluctuating solar PV generation. The case study based on a water samples and historical weather data for targeted colonias in Texas suggests the unique benefits of joint optimization of both energy and water needs. It is shown that power generated by as little as 20 PV panels in each colonia can provide drinkable water for as many as 200 people in a sustainable and cost-effective manner. This finding is potentially generalizable towards for many other under-developed remote communities.**

Keywords—nanogrid, water treatment, water-energy-nexus, colonias.

I. INTRODUCTION

Access to potable water continues to be a global concern. With global population projected to increase from 7.7 billion to 8.6 billion by 2030 [1], demand for safe drinking water will inevitably increase. In addition, climate change and groundwater depletion are diminishing future freshwater supplies [2].

The World Health Organization (WHO) defines safe drinking water as water that has no significant risk to a consumer's health over their lifespan [3]. In 2015, it was estimated that 663 million people lacked access to an improved source of water. Instead, they captured water via unimproved sources such as unprotected wells and springs, surface water, and tanker truck water [4]. Additionally, the most vulnerable countries which experience low coverage of drinking water from improved sources are of the 48 least developed countries in the world by United Nation's standards. These countries are mostly found in sub-Saharan regions [4]. Despite continuous efforts and improvements in water/wastewater infrastructure planning and construction, there is still a need for providing temporary solutions to these communities.

In addition to water needs, reliable electricity supply is also an essential part of human societies in the 21st century. The United Nation addressed this need in its no. 7 Sustainable Development Goal [5]. Thus, electricity is essential and directly related to the safety and well-being of today's society.

In this paper, we identify a case along the Texas-Mexico border where approximately 73,000 people living in vulnerable colonias or rural Hispanic communities are without sustainable access to improved sources of water, despite proximity to developed municipalities with proper infrastructure and potable water.

While this paper focuses on the case study mentioned, the method and application can be generalized to any region without access or with low access reliability for minimum living standards of safe drinking water and electricity.

Conventionally, a centralized grid serves electricity to populations living in a city. This entails a large capital investment and long-term planning horizons. Due to the unique condition of Texas colonias, a minimum supply of electricity was considered in this paper with the priority given to the water needs.

The paper is organized as follows; Section II defines the problem being solved in this paper, Section III discusses the water filtration process and its connection to costs, Section IV describes the design process and results are discussed in Section V. Conclusions and future work of this research are presented in section VI.

II. PROBLEM DEFINITION

Colonias are distributed in geographically diverse locations away from the urbanized world and generally contain a low number of inhabitants. This supports justification for a decentralized and partially mobile water filtration and electricity supply units. These water units are intended for emergency situations or temporary supply of minimum living standards.

In addition, this alternative is more practical for emergency situations due to guidelines, requirements, and regulations for mobile units. As a result, this study focuses on providing a mobile treatment unit as a temporary solution that meets the demands for safe drinking water, and electricity through solar nanogrids. The nanogrids are implemented to 1) provide required energy to perform the needed filtration process for potable water and 2) supply minimal needs of electricity to the customers.

Here, the logic behind deciding different strategies for water treatment is discussed. Then the deciding factors for the sampled water from these colonias are reported, and finally the filtration strategy and the nanogrid design are assessed in detail.

Different approaches are taken for solar powered desalination. Photovoltaic powered reverse osmosis (PV-RO) is the most studied and investigated aspect in recent studies [6-7]. The studies are based on the use of reverse osmosis (RO) membranes for water desalination to attempt high removal of dissolved ions and contaminants.

However, nanofiltration (NF) membranes can be used as an alternative to RO membranes in brackish water treatment systems with efficient removal of many multivalent ions and water contaminants as well as less energy requirements. To minimize energy requirements, NF membranes are studied and tested for the level of treatment and removal of targeted contaminants from the water sample.

Several investigations and reports were conducted to assess the water quality of the sampled surface and groundwater resources in order to design and install feasible water supply solutions. One of the issues, in addition to the salinity of those brackish surface and groundwater resources, is the high concentration of arsenic. The maximum contaminant level (MCL) of arsenic for drinking water is set to 10 ppb (parts per billion), according to national primary drinking water standards set by the US Environmental Protection Agency (EPA) [8].

Despite high desalination energy requirements, solar powered desalination through NF motivates the design and use of a mobile decentralized unit to satisfy energy requirements and water needs.

III. METHODOLOGY AND LAB SETTINGS

To provide a solution for water necessities in Texas colonias, water samples were collected from a well in the colonia Campacuas and an unnamed canal that runs by the colonia Wes-Mer in Hidalgo County. In addition, water was sampled from a well in San Isidro in Starr County; all three water sources are in South Texas near the United States-Mexico border as seen in Figure 1. These sources were chosen because the colonias reside in two counties in Texas with high concentrations of colonias. Thus, the characteristics of their locations made Well Campacuas, Canal Wes-Mer, and San Isidro Water Well potentially suitable sites for mobile treatment systems planning. The water samples were received in plastic containers and stored immediately in 4 °C refrigerators until analysis.

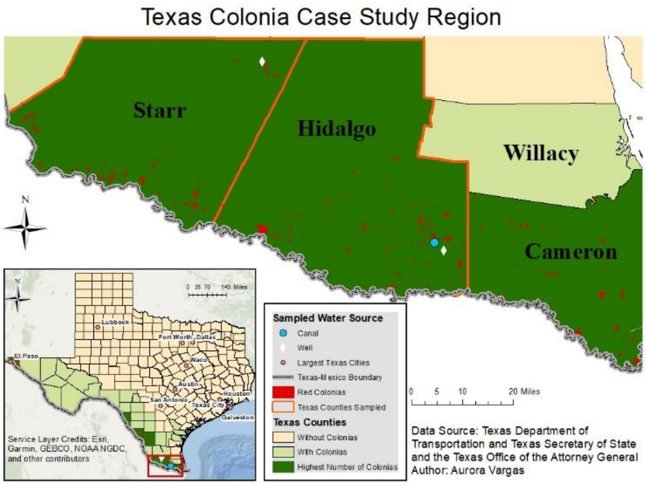

Figure 1. Texas colonia case study counties with identified ground and surface water samples.

A. *Characterization of water samples*

Water samples, i.e. samples as received before treatment, were characterized by elemental concentration via inductively coupled plasma mass spectrometry (ICP-MS), bacterial count via Heterotrophic Plate Count (HPC), protein concentration via modified Lowry assay kit (Thermo Fisher Scientific, Waltham, MA), conductivity, total dissolved solids (TDS), and pH. Some of these analyses were carried out for the membrane-treated water samples as well. These analyses were important in understanding the composition and organic/inorganic contents in water samples, comparing to the current regulations and also to understand the treatment needs and the effects on membrane performance. All regulatory information for drinkable water was taken from EPA primary and secondary drinking water regulations, which are typically enforced and monitored in drinking water systems that are delivering safe water quality for human consumption.

B. *Membrane filtration experiments*

After defining filtration needs, and based on preliminary experiments, NF270 membranes were tested for filtering the water samples in two different settings. The first type was by utilizing a dead-end filtration system using a stainless-steel stirred cell for dead-end filtration. Membrane coupons were cut to 17 cm^2 circles and placed inside the module with an active filtration area, area of membrane exposed to water, inside the module of 14.6 cm^2. 100 mL of water sample was added, and 15 ml was filtered to have a recovery of 15% at pressure of 70 psi (4.83 bar). Experiments were triplicated for each water sample. The main objective of experimenting with this system was to test the removal efficiency of ions and contaminants in water samples by the NF270 membranes. Prior experiments, clean membranes were tested in the same system with 2000 mg/L Na_2SO_4 to check the integrity of membranes and compare it with manufacturer technical information. ICP-MS, conductivity, and pH were measured for the filtered samples.

The second type of filtration experiments was crossflow filtration. For crossflow experiments, SEPA CF system (Sterlitech, Kent, WA) was used, with an active membrane area of 139 cm^2. Feed flow, permeate flow, and pressure were monitored throughout the experiments using LABVIEW software (National Instruments, Austin, TX). Total recycling mode was used for those experiments, so both concentrate and permeate were continuously returned to the system as feed. All sensors were calibrated and checked before commencing the experiments. Prior to filtration of collected water samples, membranes were tested for pure water permeability to draw the relationship of flux response to pressure change. Then, 1 g/L of Na_2SO_4 was circulated in the system for membrane setting, and this setting continued until stabilization of the system. Following membrane setting, Well Campacuas water was used as the feed water. The Well Camapcuas sample was chosen due to having high conductivity and showing the lowest flux in dead-end system experiments, as well as being abundantly obtainable.

Crossflow experiments were designed to be run in two modes. The system was cleaned and new membranes were used in each mode. The first mode was run by changing the pressure profile in a way simulating how the solar energy profile changes throughout the day. The second mode was based on fixed pressure of 70 psi (4.83 bar).

The pressure profile for the first mode was selected to simulate how the solar energy profile change for the median day of the studied annual data. In other words, we set the maximum and minimum pressure limits to 100 psi (6.89 bar) and 20 psi (1.38 bar), respectively, based on lab system maximum and minimum pressures that would permit flow within system capability and sensor detection accuracy. Then we proportionally correlated the solar energy data to the pressure. The solar energy profile of the median day and the correlated pressure profile for the experiment are shown in Figure 2. Power consumption was monitored throughout crossflow experiments to understand and estimate relationships of power consumption with pressure or flux change for ultrapure water and tested water sample. The device that monitored the power was a reprogrammed WEMO switch that is commercially available. The reprogramming objective was to change the sampling rate of the available switch and gain higher sampling resolution.

C. Cost Estimation

To address the cost estimation of the investment strategy, we considered pertinent inputs in the acquisition, building, installment, and execution of the mobile solar powered water filtration unit. The immobile inputs for the proposed unit include all water storage tanks, pumps, and solar panels. Table 1 subtotals the separate costs required for each colonia to have their own stationary solar power grid and water collection. It also gives an overall total cost which includes each colonia's separate infrastructure costs along with the shared cost of the mobile water filtration unit and membranes. We also included the cost of transporting the unit between colonias. The American Transportation Research Institute (ATRI) creates an annual report stating the marginal costs of a motor carrier. The marginal costs include both vehicle based (fuel, truck/trailer lease or purchase, repair and maintenance, truck insurance premiums, etc.) and driver based (wages and benefits) costs. In 2017, the average marginal cost per mile driven was $1.691 [9]. Also, the average distance between colonias is 11 miles. The trucking price and average distance were used in the cost analysis in Table 1.

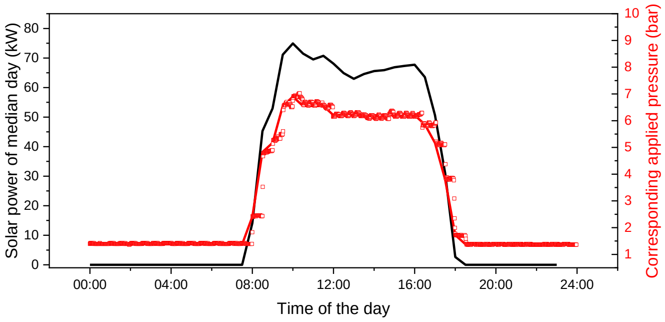

Figure 2. Solar power profile for a median day of the year, and its corresponding pressure profile for variable pressure mode experiment. The lines represent calculated solar power and pressure profiles, whereas the cube shaped points are actual readings of pressure profile from the experiment.

Table 1: Cost of providing colonias with individual infrastructure and shared water purification unit.

Product	Manufacturer	# of Units	Cost per Unit	Price ($)
Solar Panels SLA-M 300W	Silfab Solar	19	228.00	4,332.00
Solar Panel Installment	Silfab Solar	1	8,448.00	8,448.00
Battery Bank	Discover	1	28,932.00	28,932.00
Utility Pump	AquaPro	40	162.00	6,480.00
Tank (525 gal)	Norwesco	2	679.00	1,358.00
Tank (5,000 gal)	Norwesco	12	2,400.00	28,800.00
Tank (17,000 gal)	Chem-Tainer Industries	2	1,284.00	2,568.00
Plat (sq meter)	Texas Farm Bureau	262	0.63	165.35
Avg Trucking Cost (mile)	ATRI	10,400	1.691	17,586.40
			Cost per Colonia	**$98,669.75**
			Subtotal for two Colonias	**$197,339.50**
NF270-4040 (4")	FilmTec	21	317.00	6,657.00
Water Filtration Unit	Lenntech	1	13,310.00	13,310.00
			Total for two Colonias	**$217,306.50**

Prices and product life estimates for the NF membranes, desalination unit and solar panels were given via quotes. All other prices and product life estimates were determined through online sources. The cost of infrastructure for each colonia is approximately $98,669.75 with $197,339.50 being the total cost of infrastructure for two colonias. In addition to that cost, two colonias will be sharing a water filtration unit along with the required NF membranes. Thus, the total cost of the project is $217,306.50 for two colonias of approximately 200 people with product replacement included for a life of 20 years.

D. Optimization formulation

The main investment cost is on the number of solar panels needed to be installed. A simple optimization formulation for this problem can be seen in (1), where $x \geq 0$ is the number of solar panels and $s[w]$ is the conversion coefficient for solar forecast for week w and $d[w]$ is the kWh demand for electricity for this week. w in (1) can vary for the duration of data availability. In this study we performed the study over a year span so $n = 52$. Basically, in (1) we penalize both over investment and underinvestment in the installed solar infrastructure.

$$\min_{x} \; z = \sum_{w=1}^{n} |s[w]x - d[w]| \qquad (1)$$

To find s[w], we first need to connect the solar properties and then convert them to kW. In (2) GHI is Global Horizontal, DNI is Direct Normal, and DNI is Diffuse Horizontal. $\propto$ is the angle of solar panel deviation from the nominal angel available in the datasheet of manufacturer. In this case study we assumed $\propto = 0$.

$$GHI = DNI \times \cos(\propto) + DNI \qquad (2)$$

After finding GHI, and selecting the vendor of solar panel, k_v in (3) can be found from the characteristics of the panel and $s[w]$ can be achieved.

$$s[w] = k_v \times GHI \qquad (3)$$

In this report, we used datasheet of [2] in our study. Since it was assumed that water treatment facility will move every 7 days between colonials, we used weekly resolution for this analysis, and it can be extended or shortened to any other number of days. The unit of $s[w]$ in (1) is $kWh/panel$.

To find weekly demand for electricity, $\boldsymbol{d[w]}$, three separate needs was considered as below:

- Run the filtration unit for 6 days to store filtered water quantity enough to provide 30 liters per person per day for two weeks. (the filtration unit is mobile and shared between the two colonias, and every week, one day will be consumed for transporting and connecting/disconnecting the unit), $d_f[w]$ in (4)
- Provide essential electrical needs of households including lights, cooking, refrigeration and charging needs, $d_n[w]$ in (4)
- Pump the water to a 10 feet high storage tank, $d_p[w]$ in (4)

The implicit assumption in our current design sends any excess energy at any time to the battery and uses it when needed. Therefore, we used summation of all these consumption over a week without considering temporal variations. Another implicit assumption is not considering losses in the battery charge and discharges. (Any inputs on how to make these two points closer to reality is welcomed.)

$$d[w] = d_f[w] + d_n[w] + d_p[w] \qquad (4)$$

The unit of $d_f[w]$ is also kWh therefore a coefficient is needed to change the water needs to electricity demand for the purpose.

The electricity consumption needs were estimated based on essential living condition electricity. Lighting for safety and community communication at nights. Cooking and refrigeration for nutritional needs and electricity for charging cellphones or any rechargeable battery for also safety and psychological needs. The needs for electricity for lighting is slightly higher in winter since the length of dawn to dusk is higher.

The third part of electricity needs is for pumping water to the storage tanks for pre-treatment and post-treatment.

IV. SOLAR PANNEL SIZING TO PROVIDE SURVIVABLE CONDITIONS

After a thorough discussion on the technical and socio-economic hurdles of water filtration procedures in Section II, we move to the nanogrid design in this section. We discuss how the objective in our method varies from a typical Micro/Nano grid objective and we list the approach we chose to resolve such a problem.

Electricity supply reliability for residential use is the key concern for a typical nanogrid design plan. To address that, one provides redundant supply sources for electricity with a meshed grid structure. Therefore, if one or more pieces of equipment in the system fails or the generation faces a scarcity, customers may not be affected and they will undergo a satisfactory provision of electricity over the year for all weather scenarios.

For the case of a PV integrated grid, battery storage and supported by a grid are two possible sources that the nanogrid can rely on in case of an interruption or scarcity in the generation. For the battery, sizing is a big issue affecting the investment cost and the need for more space to operate. To use the grid, more lines and infrastructure are needed to make the connection to the grid.

While these approaches look captivating, their operation costs tend to be inevitably high due to the cost of reliability. But reliability might not be the big concern in some circumstances.

When reliability is not the main objective, like in this case study, these constraints can be relaxed to achieve a much more viable solution to provide a survivable living condition. The top priority for such approach is constant water supply plus some essential electricity usages. Such design needs some inputs, settings, and outputs. An illustration of it is shown in Figure 4.

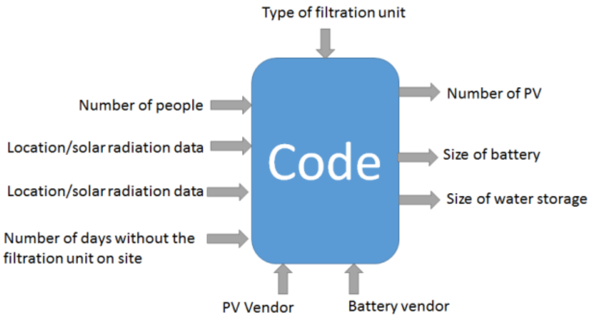

Figure 3. Inputs and outputs to the decision making process.

The first input to this design comes from the field study and water sampling. This is due to the fact that as will be seen later, water filtration carried the highest priority in our approach to provide survivable living condition.The type of available water in the designated location can impose significant changes in the filtration strategy and therefore power consumption. The second parameter is the number of people living in the area our design is being performed at. Each person needs a minimum number of liters per day so this input parameter directly affects the scale of design. Solar radiation data for a particular location is also another input parameter. Data was pulled from the National Solar Radiation Data Base (NSRDB) by the National Renewable Energy Laboratory (NREL) [10].

V. Results

NF cross-flow experiments within two testing modes, run according to solar energy data, were modeled off the power profile for the median day**.** Applied pressure was adjusted to follow the trend of this power profile and resulting changes in power and fluxes were observed. The ratio of flux/pressure did not change in the same significance as opposed to fluxes or pressure individual changes. Power largely followed the trend of the power profile but did not experience as significant increases as did water production. The power rose by a factor of 2.9 with the increased pressure after hour simulating 8:30 AM, whereas the rate of water production increased by a factor of 5.5. Water production was much more significant during hours simulating the period between 8:30-18:00, the time when the most energy can be harnessed from the sun. During this 9.5-hour period, permeate (treated) water volume increase 3.5 times the volume of water permeate that was produced during the other 14.5 hours of the day.

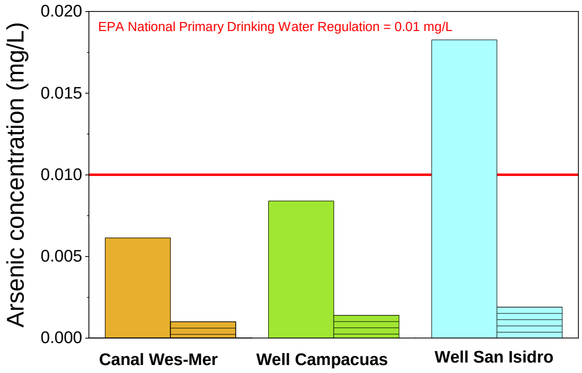

Figure 4. Arsenic concentrations for raw (solid columns) and NF treated (dashed columns) water samples. Water quality parameters and comparison with EPA drinking water requirements.

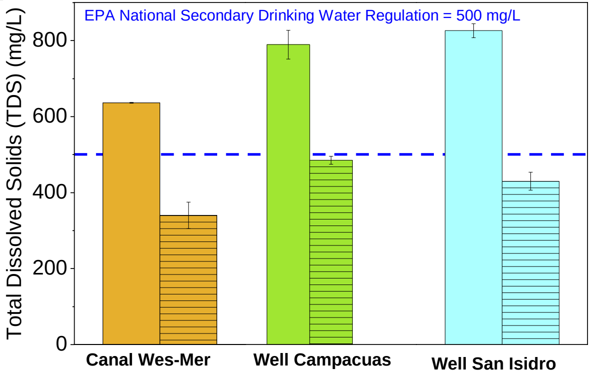

Figure 5. Total Dissolved Solids (TDS) of raw (solid columns) and NF treated (dashed columns) water samples.

While the variable pressure experiments have significant importance in simulating conditions responding to variations in available energy, the constant pressure experiments can highlight other benefits in understanding the system performance and membrane susceptibility to fouling. The constant pressure (70 Psi) experiment showed that Flux/pressure ratio reduced by approximately 2.2% and 6.6% after 24 and 120 hours of continuous running, respectively, as compared to the ratio after 1 hour of filtering the Well Campauas Water Sample. Power was also monitored and showed no significant overall changes. However, some repeated fluctuations were observed in recorded power, which could be correlated with the small fluctuations in pump running. In general, the volume of filtered water in constant pressure experiment was more than that in variable pressure experiment.

The ultrapure water runs for these experiments showed strong correlations between pressure, flux, and power. Those relationships were fitted, and the fitting equations were used to estimate some of the parameters and calculations for scaling-up lab scale experiments to pilot scale or a scale applicable for this case study.

A. Water quality discussion

All three untreated water samples showed conductivity and TDS measurements less than 1700 µS/cm and 850 mg/L, respectively, based on probe measurements. The sample with the highest conductivity was the Well Campacuas water sample. All the water samples before filtration showed TDS and HPC values higher than the set values by EPA drinking water regulations. In general, the tested water samples revealed that arsenic was the only element, among the elements that were analyzed by ICP-MS, with concentrations near or above the primary drinking water standards. Untreated Well Campacuas, Canal Wes-Mer, and Well San Isidro samples had HPC concentrations of 16,000 cfu/mL, 940 cfu/mL, and 15,000 cfu/mL, respectively, no colonies were detected in the permeates from any of the three sources. All treated water samples yielded arsenic and TDS concentrations below the EPA standards for drinking water as shown in Figure 4 and Figure 5. Therefore, the NF270 membrane was enough in treating those water samples and delivering quality of water that meets current regulations.

UV scans to detect natural organic matter (NOM) showed absorbance values of 0.021 for the Well Campacuas permeate, 0.013 for the Canal Wes-Mer permeate, and 0.022 for the Well San Isidro permeate. TOC analysis showed 42% rejection of organic carbon in Well Campacuas water, 68.8% in Canal Wes-Mer water, and 29% in Well San Isidro water. Well Campacuas had a TDS removal of 47.85 ± 4.08% , Canal Wes-Mer had 46.54 ± 5.48 % TDS removal; and Well San Isidro had the least TDS removal, with 38.38 ± 3.78% removal. This difference in removal can be explained by the concentration of salts in each sample (Data not shown in this report). In all, Well San Isidro experiences the least TDS removal, as a percentage of its initial value, due to a larger fraction of its salt content being monovalent. Well Campacuas experiences the most significant drop in TDS values, due to the high concentration of easily removable divalent salts. Canal Wes-Mer shows the lowest final level of TDS due to its lower initial levels of both total salt concentration and monovalent salt concentration.

While fouling was not investigatd in this study, it is worthy to highlight the possible membrane foulants and suggestions for chemical cleaning Based on current available knowledge regarding NF270 membranes fouling analysis [11]. Groundwater sources are more saline than the surface water and is evident against the higher TDS for the raw water. In addition, the organic content of the surface water used in this study is higher than that of the ground water feed sample, which can be seen in the TOC and UV absorbance results. Therefore, it can be expected that the surface water can cause more organic or biological fouling than the groundwater samples.

B. *Optimization results*

The results of running the optimization in Figure 3 for two different water treatment approaches and supporting electricity for other needs are shown in this section. The results are presented for different weeks of the year using south San Antonio solar radiation data. The number of inhabitants in each household was assumed to be 8 with 25 households existing in an average colonia size of 200 people.

The simulation results are shown in Figure 6 and Figure 7. As the figures show, the dominating need is for surface and number of PV panels is for household electricity consumption. A tradeoff between needs for electricity for water treatment and household electricity is observed.

One result worth emphasizing is that except for a few weeks with significantly low solar radiation, which resulted in a spike is the number of solar panels, for most cases 20-30 panels can address all needs requiring a 40-60 m^2 space. Understandably this approach carries some risks with respect to reliablilty. However, it is guaranteed that there will be enough electricity for water treatment alone under all scenarios. Therefore, in the case that occasional curtailment of household electricity is allowed and being treated as a soft constraint, it can be a good way to save space and money.

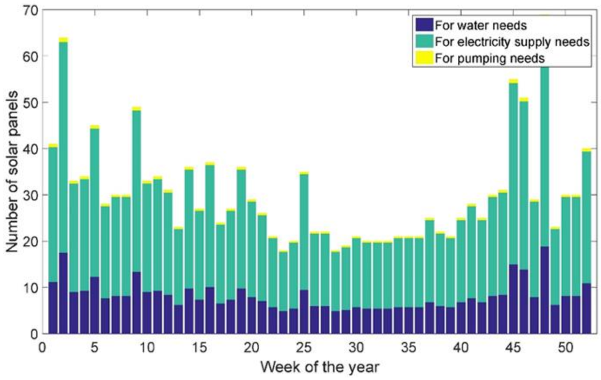

Figure 6 Area needed for solar plant of 200 people living in a colonia for weekly solar radiation scenarios: case of industrial water filtration.

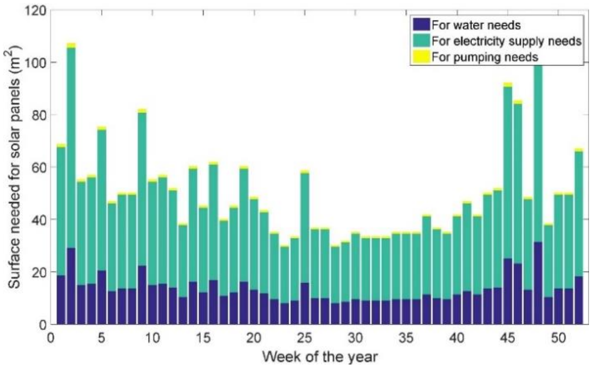

Figure 7 Area needed for solar plant of 200 people living in a colonia for weekly solar radiation scenarios: case of industrial water filtration.

VI. CONCLUSIONS

The focus of this paper is to provide a potential solution to a real-world problem. The focus of this paper is not providing the best water or electricity or in general living condition for the people under study. The purpose of this paper is to design the least cost condition for Texas colonias to survive while they reside in a location without safe water access.

All design parameters are focused on this core intention. It was shown a limited investment supported by adequate design could provide a sustainable water supply for these regions.

The idea of this paper can be extended in multiple directions. Our future work includes formulating the problem in a chance-constrained program to provide the risk of water shortage rigorously.

The design parameter will include battery storage sizing and water tank sizing. If the targeted colonia is close to a substation, historical LMP analysis can reveal the potential of energy arbitrage possibility for a battery energy storage facility. Based on the circumstance, even without colonia in place, e.g., if the colonia location moves in future, PVs supported by storage provide a unique facility to sell energy to the grid when the prices are high and charge batteries when prices are low. An extension currently being pursued includes a life cycle analysis comparison of CO_2 emissions from the proposed unit compared to the emissions of single use water bottles and water vending machines in the colonias. Topics mentioned above are the authors targets for the extension of this manuscript to be submitted to the Applied Energy journal upon acceptance.

ACKNOWLEDGEMENT

This research was supported by funding from Texas A&M University water seed grant initiative.

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