Student Mall Sanitation Block at the University of Abomey-Calavi, Benin

Feasibility Study

ECI 289A -- D-Lab WASH

Sam Rodriguez, Daisy Guitron, Joe Wildman, Kylie Bodle

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Executive Summary

The University of Abomey-Calavi (UAC) Student Mall is currently in need of a sanitation resource. Dr. Charlene Gaba, a researcher at UAC, requested a study on the feasibility of installing a sustainable sanitation block (i.e. restroom) in the mall. She requested that the sanitation block utilize solar power, touchless sinks and toilets, and a rainwater catchment system for water supply. The following report assesses the feasibility of installing a sanitation block meeting these requirements and serving approximately 500 users per day. The sanitation block should also consist of two separate buildings, one per gender.

A rainwater catchment system is a feasible method of water collection for the sanitation block. There is sufficient rainfall in Abomey-Calavi to allow rainwater collection, and the method appears to be culturally appropriate for the area. However, rainwater catchment alone will not be sufficient to supply all the water needs of the restroom facility, and therefore the university will need to provide the majority of water supply to the restroom. Despite this, a rainwater catchment system designed as described in this report will provide approximately 4 m^3 of water to each restroom building each month, and will be sufficient for cleaning and as a partial supply for toilet flushing. The system will cost $5400 (US dollars).

The quality of the indoor environment should be maintained via a natural or hybrid ventilation system. This will ensure that air temperatures and humidity levels within the sanitation block are comfortable and will also prevent the spread of airborne diseases. Physical contact with surfaces can also be reduced via use of touchless faucets, toilets, and hand dryers. Paper towels are not recommended for hand drying as they create waste and are not sustainable. In total, the costs associated with indoor environmental quality are $2590.

An off-grid solar power system will provide the sanitation block with energy supply throughout the year. A comprehensive overview was conducted for solar photovoltaic systems and optimum tilt on solar panels. The number of solar panels needed for each facility is fourteen, a power rating of 200 watts each. The solar power system is sized to require 24 square meters of roof space and will provide 3,945 kilowatt hours annually. The total cost of the solar system is approximately $34,900.

Decentralized wastewater management will be obtained through utilization of an anaerobic baffled reactor and constructed wetlands system. This system will provide containment of the waste, thus preventing the spread of pathogens and other contaminants, and will also provide a measure of waste treatment. The system will cost approximately $3,300.

Altogether, installation of a sanitation block meeting the design requirements set by Dr. Gaba is feasible within the Student Mall portion of the UAC campus. The sanitation block will cost approximately $46,000 (not including labor), which is below our identified maximum capital cost of $100,000.

1. Introduction

The University of Abomey-Calavi (UAC) is the oldest university in Benin and has over 45,000 students [1]. UAC is located in southern Benin within the city of Abomey-Calavi, which has a population of 386,000 people [2]. The client for this study, Dr. Charlene Gaba, a researcher at UAC, has requested a feasibility study for a sanitation facility that will serve the campus mall area of UAC, which does not currently have a dedicated facility for guests and vendors. The sanitation facility, also referred to as a sanitation block, will be a free-standing building featuring a system that could showcase sustainable design practices for the University. This feasibility study provides an analysis of design options, financial evaluations, and recommendations for the project to proceed.

1.1 Background

Abomey-Calavi is located on the coast of Lake Nokoue in southern Benin. It is considered a suburb of the neighboring major city, Cotonou, which is the most populous city in Benin [2]. The climate in Abomey-Calavi is tropical, with an average annual temperature of approximately 27 degrees Celsius and annual rainfall around 1300 mm [4]. The gross national income per capita is approximately 860 U.S. dollars [33].

A study by the United States Agency for International Development (USAID) found that 28% of the urban population in Benin practices open defecation [35]. Although access to improved water sources is fairly high in Benin's urban areas--over 86%--the lack of access to safe sanitation, combined with high population growth, has resulted in the growing incidence of cholera infection in the area [3, 35]. Similarly, just 16% of surveyed households in Abomey-Calavi had a handwashing station or sink in their kitchen, and only 1.3% of homes had sinks near their toilets [35].

Approximately 56% of Benin's urban population has access to electricity, though supply can be intermittent [33]. Interest in solar energy utilization is growing in the area, and a study by UAC in 2018 recommended further investment in solar energy as a possible solution to the lack of energy supply throughout the country [34].

Altogether, the need for safe sanitation and reliable electricity indicates that a solar-powered sanitation block will be useful on the UAC campus. The amount of rainfall in the area also suggests that a rainwater catchment system could be utilized effectively to supply water for handwashing and/or toilet flushing.

1.2 Project Goal and Scope

The Four Lenses of Sustainability were used to assess pertinent sectors of each project aspect to maximize the value of the final project design. The Four Lenses consist of technical, social, environmental, and financial considerations. The project was broken into four sectors: water resources, indoor environmental quality, energy and solar power, and decentralized wastewater treatment. The lenses of sustainability related to each sector are discussed further in later sections of this report.

As requested by the client, this feasibility study assesses installation, operation, and maintenance of touchless bathroom faucets and toilets, a rainwater catchment system, and solar panels. Squat flushing toilets will be connected to a septic tank, which will require occasional cleaning, and therefore cleaning requirements were also considered in this study. Cultural and gender issues were also considered, and therefore gender-specific restrooms will be housed in separate buildings to ensure privacy. The rainwater catchment system will act as a backup to UAC water sources.

The students of the university, as well as any merchants that work at the student mall, were the target market for this project. The approximate number of users per day was estimated at 500. We assume that some users will require wheelchair ramps and handrails in order to access and use the sanitation block and therefore these features were also included in the project design.

2. Methodology

The development of the project framework utilized several methods to consider design factors related to existing market factors, the client's needs, and sustainability. The methods used in this feasibility study were a Strengths, Weaknesses, Opportunities, and Threats ("SWOT") analysis and an evaluative matrix. The following section discusses these analytical methods and their role in guiding the project.

2.1 SWOT Analysis

A SWOT analysis was first conducted to identify Strengths, Weaknesses, Opportunities, and Threats ("SWOT") associated with the sanitation block project. Strengths and weaknesses are internal factors associated with the project--for example, an internal strength associated with this project was that the land was already obtained and available from the university. Opportunities and threats are factors external to the project, such as competition, regulatory requirements, or possible weather risks. The resulting table is shown below (Table 2.1-1). This exercise was used to begin formulating design characteristics that might mitigate threats and weaknesses and capitalize on strengths and opportunities.

Table 2.1-1. **SWOT analysis**

Strengths	**Weaknesses**
- Land already acquired - Demand for sanitation - Many knowledge resources are available on alternative water systems design	- Touchless faucets can be unreliable - Financial resources are unknown
Opportunities	**Threats**
- Obvious need to improve hygiene/sanitation resources - Learning opportunity for students on sustainable, off-grid resources	- Sourcing material and hardware may be challenging - Maintenance requirements

2.2 Evaluative Matrix

An evaluative matrix was then used to define the objective functions associated with the sanitation block. Objective functions are aspects of the project that should be maximized or minimized. The target value and evaluation method associated with each function are listed in Table 2.2-1, as well as units of measurement ("Functional Unit"). Evaluation methods describe how each objective function will be analyzed. This matrix guided determination of the project attributes most important to the client.

Table 2.2-1. **Evaluative matrix**

Item No.	Objective Function	Functional Unit	Target Value	Quantitative / Qualitative	Evaluation Method
1.	Accessibility	Ease of access	100%	Qualitative	Review U.S. and Benin building codes
2.	Practice of proper hygiene	Number of people washing their hands after using the toilet	95%	Qualitative	Survey
3.	Availability of handwashing stations	Number of stations with clean water, soap, and handwashing stand	100%	Quantitative	Count number of hand washing stations in final design
5.	User experience	General comfort (smell, lighting, temperature)	8/10	Qualitative	Survey
6.	Battery energy storage from solar panels	kW-hr / day	1 kW-hr / day	Quantitative	Meter
7.	Water collected by rainwater catchment system	Cubic meters/year	100 m^3/yr*	Quantitative	Meter
8.	Capital cost	U.S. dollars	$100,000	Quantitative	Cost estimate
9.	Operation and maintenance costs	U.S. dollars	$1000/year	Quantitative	Cost estimate
10.	Ability to meet user demand	Number of stalls/each gender's building and wait time per visit	10 stalls/building, under 5 minutes wait/visit	Quantitative	Measure wait times during peak usage
11.	Septic tank capacity	Flow	3.5 m^3/day	Quantitative	Measure Flow

12.	Septic tank maintenance access	Number of access riser hatches (one access riser per compartment)	2	Quantitative	Count number of access hatches at installation
*Indicates relevant equations and calculations are provided in the next sections.					

3. Results and Discussion - Sectors

3.1 Rainwater Catchment

Water supply in Benin is managed by two governmental agencies: the National Water Supply Company and the General Directorate of Water. The National Water Supply Company (abbreviated SONEB in French) is responsible for water supply in urban areas [3]. According to the 2013 census, 86% of urban households have access to improved water sources [3]. An improved water source here means either water distributed by SONEB to houses or public taps, private boreholes, protected wells, rainwater, or protected surface water [3]. In rural areas, water supply is managed by the General Directorate of Water and 72% of rural households had access to improved water sources in 2013 [3]. Notably, the census did not consider contamination of these sources, and therefore it is possible that they are not safe for drinking [3]. For this reason, many households in Benin treat their water prior to drinking it by boiling, filtration, UV disinfection, or chlorination [3].

The four most common sources of water supply in Benin are public taps, boreholes, in-house taps, and unprotected wells [3]. Just 0.4% of the population, or about 40,000 people, use rainwater as a water source [3]. However, annual rainfall in the country ranges from 700-1300 mm, with annual rainfall in Abomey-Calavi on the higher end of the spectrum at approximately 1300 mm [3, 4]. A study by Obada et al. (2017) found that, though climate change is expected to decrease the number of wet days in Benin, the precipitation intensity is expected to increase, exacerbating flooding, erosion, and increasing sediment concentrations in water [5]. For this reason, in an urban area such as Abomey-Calavi, installation of a rainwater catchment system may help prevent excessive runoff from pavement and resulting degradations in water quality by collecting rainwater before it can reach the ground.

Likewise, though rainwater catchment is not a major water provision method in Benin, there are still many people using it and therefore presumably knowledgeable on its maintenance. Furthermore, installation of rainwater catchment systems is cheaper and less invasive than drilling a borehole [6]. Lastly, the frequency of households practicing water treatment prior to drinking their water indicates that the community in Abomey-Calavi is comfortable with and aware of the need to treat water before its use [3], which suggests that people will be aware of the need to treat captured rainwater. System designs exist that integrate UV treatment and/or chlorination with rainwater collection [7], and therefore systems of this type would likely be a good fit for use in the sanitation block if water is used for handwashing rather than solely for flushing toilets.

3.1.1 Sizing

The literature reviewed in Section 1 demonstrates that there is sufficient rainfall in Abomey-Calavi to allow a rainwater catchment system to function. The literature also suggests that a catchment system would be culturally suitable in the area. It was then necessary to determine if a sufficient volume of water could be collected from the roof of the sanitation block to justify the installation costs of such a system.

Water collection volume can be described by Equation 1 [6]:

$$Collection\ volume\ = Rainfall\ \times Efficiency\ \times Roof\ area \tag{1}$$

The average annual rainfall in Abomey-Calavi is 1300 mm [3, 4]. A collection efficiency of 85% is typically used in this calculation to account for losses due to evaporation, clogging, spillover, or other issues [6]. The volume of water needed for toilet flushing, handwashing, and cleaning was first determined to identify if it would be possible to collect enough volume for all water needs in the sanitation block. It was assumed that the sanitation block would be used five times per week and the average number of daily visitors would be 500. It was also assumed that the sanitation block would be cleaned five times per week at 10 L of water per cleaning per building, or 20 L total. These calculations are shown in Table 3.1-1.

Table 3.1-1. **Maximum water volume required to supply the sanitation block**

		Number of users per day	**Volume per day (L)**	**Volume per week (L)**	**Volume per year (m³)**
Water volume per handwashing (L) [27]	1.5	500	750	3,750	195
Water volume per toilet flush (L) [28]	4	500	2,000	10,000	520
Water volume per cleaning (L)	20	5*	100	100	5.2
**Note that this is the number of cleanings per week*				**TOTAL (m³)**	**720.2**

Based on a water volume of approximately 720 m³, the required roof area of the sanitation block would be over 700 square meters. This roof size is clearly larger than necessary for a sanitation block serving 500 people per day.

Assuming a building size of 3 m by 10 m, and therefore a more reasonable roof footprint of approximately 4 by 11 m, the resulting water volume captured per year is approximately 50 m³ per building, or 100 m³ total (assuming one building per gender, Table 3.1-2). This water volume is sufficient for cleaning, with remaining water available to partially supply toilet flushing or handwashing. We recommend that the remaining water be used for toilet flushing, rather than handwashing, in order to bypass the need for treatment and the costs associated.

Each restroom building should have an associated tank to collect water from the roof and store it for future use. Collection tanks are sized based on the following equation [6]:

$$V_t = V_{t-1} + Supply - Demand \tag{2}$$

where V_t is the water volume remaining in the tank at the end of each month, $V_{t-1}$is the water volume remaining from the previous month (starting with an empty tank), *Supply* is the rainfall volume collected, and *Demand* is the rainfall volume used. Using average monthly rainfall data in Abomey-Calavi (Table 4) and assuming that approximately 4 m³ of collected rainwater is used each month (as based on average monthly rainfall collection), the resulting maximum tank volume needed is approximately 15 m³ per building. Calculations are shown below. Note that we assume water collection begins in April, as this is typically the beginning of the rainy season.

Table 3.1-2. **Rainfall data and collection volume calculations**

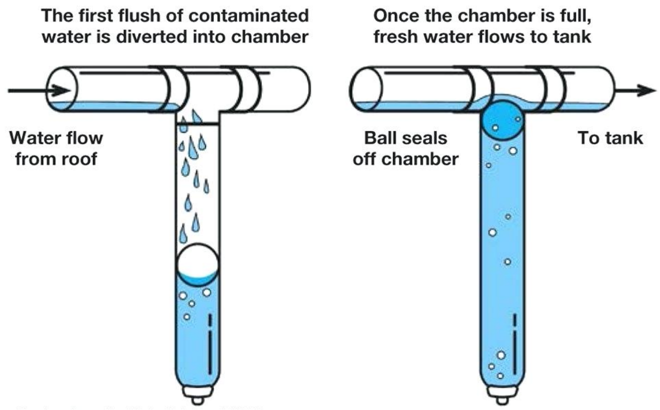
Month	Monthly Average Rainfall (mm) [4]	Collected Rainwater Volume (per building, m^3)*	Supply - Demand (m^3)	V_t (m^3)
April	137	5.1	1.1	1.1
May	196	7.3	3.3	4.5
June	356	13.3	9.3	13.8
July	147	5.5	1.5	15.3
August	64.9	2.4	-1.6	13.7
September	99	3.7	-0.3	13.4
October	126.7	4.7	0.7	14.1
November	41.4	1.5	-2.5	11.7
December	19.6	0.7	-3.3	8.4
January	9.2	0.3	-3.7	4.8
February	36.8	1.4	-2.6	2.1
March	73.8	2.8	-1.2	0.9
Total per building	**1307.4**	**48.9**		
Average monthly collection per building		**4.1**		

*Note that collected rainwater volume is based on roof area and catchment efficiency, and is equal to supply. Demand is assumed constant at 4 m^3 per month.

3.1.2 Maintenance

The rainwater catchment system will require a "first flush" diverter to prevent the initial flow of rainwater from carrying any debris on the roof into the storage tank. A first flush diverter should generally divert 4 L for every 100 square meters of roof [6]. In this case, that means the first flush should be designed to divert 1.4 L per building. A diagram of a first flush diverter is shown in Figure 1. One first flush diverter is typically used per building.

Figure 3.1-1. **First flush diverter** [29].



A first flush diverter should be emptied after large storm events to ensure that the system adequately traps contaminants. Diverters also exist that slowly drain over time, which eliminates the need for periodic drainage. A diverter of this type should still be checked on periodically to remove clogs and ensure proper function.

Gutters and tanks may require occasional maintenance or replacement. These should be checked periodically for leaks, cracks, or other problems. Likewise, tanks are likely to need annual cleaning to remove algae buildup or other contaminants [6]. This can be performed with shock chlorination using a chlorine tablet or with bleach [6]. A link to a rainwater catchment system maintenance guide is provided in Appendix B. Pumps, which will be needed to move water from the storage tanks to toilets for flushing, may also require occasional maintenance or repairs, which should be performed by local mechanics.

3.1.3 Costs

The rainwater catchment system will require gutters, piping, storage tanks, and a pump to move water from the tank to the toilets for flushing. Catchment system element costs are shown in Table 3.1-3. All costs were obtained from RainHarvest Systems [36]. We recommend that Tank Option 2, or two tanks (at 7.6 m^3 each) be used for water storage at each building, as this is the least costly option for water storage. Multiple tanks also provide redundancy should one tank require repair. Note that these costs do not include labor.

***Table 3.1-3.* Cost approximations for the rainwater catchment system**

Component	Unit Size	Dimensions (Diameter x Height, m)	Estimated Cost (USD)	No. of Units Required per Building	No. of Buildings	Total Cost (USD)
Tank Option 1	15 m³	2.6 x 3.25	$2,670	1	2	$5,340
Tank Option 2	7.6 m³	2.3 x 2.1	$900	2		***$3,600****
Tank Option 3	5.1 m³	1.8 x 2.2	$780	3		$4,680
Gutters (PVC)	11 m	NA	$180	2		$720
First Flush Diverter	1.4 L	NA	$40	1		$80
Pumps	140 L/min	NA	$500	1		$1,000
NA indicates not applicable. *Indicates this tank option was used in calculating the total cost.					**TOTAL**	**$5,400**

3.1.4 Rainwater Catchment Recommendations Summary

We recommend the following design for the rainwater catchment system:

- Approximately 4 m³ per month of water should be used by each building to ensure sufficient water is available in the storage tanks all year.
- Water should be used for cleaning and toilet flushing, as it will not be treated and therefore may not be safe for handwashing.
- Roof areas should be approximately 4 m by 11 m.
- Two 7.6 m³ storage tanks per building should be utilized for water storage.
- Backup water supply will be necessary, and therefore plumbing and connections to university water sources will be needed.

3.2 Indoor Environmental Quality

An understanding of building science and design can lead to a building with an indoor environmental quality that meets user needs, provides a healthy environment, and increases the quality of the surrounding area [8]. Building science is the field of study that optimizes building performance for user comfort, sustainability, and system energy efficiency [8]. Building design, on the other hand, is the engineering aspect of planning for future construction and uses building science. Together, building science and design are used to construct energy-efficient and comfortable buildings that benefit the UAC community, environment, and the university in general.

Based on the findings from the SWOT analysis and evaluative matrix, indoor environmental quality design should address mitigation of pathogen transmission, sustainability, ease of use, operation and maintenance, social acceptance, and cost effectiveness. The following discussion focuses on these fundamental requirements within the framework of the systems involved, and provides guidelines for further design.

3.2.1 Climate Control and Air Quality

Climate control within human-occupied facilities should be considered to ensure air quality conditions are conducive for facility functionality and do not create health issues, user discomfort, or problems for building operations. Controlling indoor relative humidity and temperature has a large impact on health conditions. Health hazards can result from the combination of high relative humidity and higher air temperatures. In Abomey-Calavi, the average annual relative humidity is 84% and the average daily high temperature is 30°C during the hot season. These levels of relative humidity and temperature can cause heat-related illnesses [32]. Additionally, high relative humidity levels are also associated with higher pathogen concentrations in indoor air, and therefore maintaining humidity levels between 40% and 60% can minimize adverse health effects caused by relative humidity [30, 31]. For these reasons, systems for ventilating airflow through the sanitation facility are necessary and are included in this feasibility assessment.

Facility ventilation is a primary factor in indoor air quality, impacting the comfort and respiratory health of building occupants. The rate of ventilation affects the transmission of respiratory illness, where more ventilation theoretically reduces respiratory illness rates by lowering the indoor air concentration of pathogens [9, 10]. The ventilation system for a building can be managed with active or passive systems, which are designed to maintain setpoints for air temperatures and relative humidity.

There are three types of ventilation systems: natural, mechanical, and hybrid systems. Natural ventilation relies on pressure differences, such as wind and buoyancy, to deliver fresh air into a building. Interior temperatures can be reduced by 3°C with interior air velocities of 49 m/sec. Natural ventilation also offers lower operational costs than to mechanical ventilation [14]. Disadvantages of natural ventilation include increased noise transmitted into the facility due to more openings in the building envelope and difficulty controlling airflow and insect vectors [11, 14].

Mechanical ventilation is achieved using motor-driven fans to exchange air. Mechanical ventilation operates on demand and is easier to design and install; however, it requires external power and a manual (e.g., an on/off switch) or automated control system (e.g., a relative humidity and temperature sensor) to operate. Hybrid control systems, using active and passive measures, may be more energy efficient but technologically complex [12, 14]. Aside from relative humidity control, the temperature within the facility should be maintained at no less than 20°C to maintain a comfortable environment [12].

Tables 3.2-1, 3.2-3, and 3.2-4 provide a predicted performance of natural, mechanical, and hybrid ventilation systems. Each ventilation system is evaluated based on assumed design time, construction cost, reliability, operation and maintenance (O&M), and power consumption. Scores are based on a 1 to 5 scale, where 1 predicts poor benefit to overall project feasibility, usability, capital and ongoing costs. A discussion of the feasibility of each ventilation system is provided below its respective evaluation table.

3.2.1.1 Natural Ventilation Systems

Table 3.2-1. **Natural ventilation system evaluation table**

Criteria	**Score** [1]	**Benefit** [3]	**Explanation**
Design time	3	Good	Time required to design building with low aerodynamic drag elements

Construction cost	3	Good	Low drag elements in building (doors, vents, with additional privacy considerations)
Reliability	3	Good	Air flow rate cannot be regulated on demand
O&M	5	Excellent	No O&M required
Power consumption	5	Excellent	No power consumption
Total Score	19		

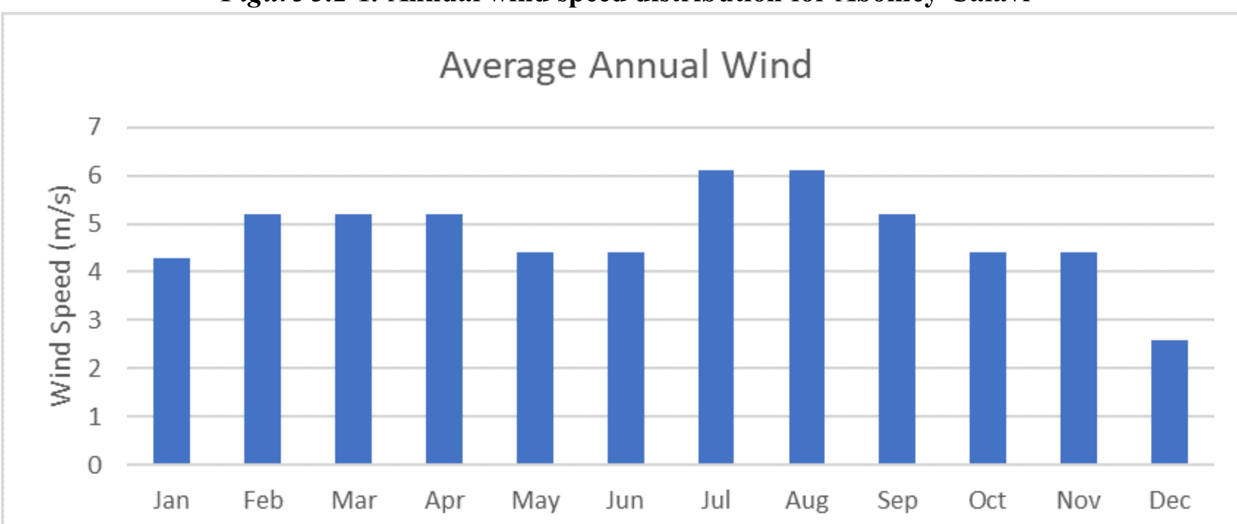
[1] A higher score means indicates lower impacts to the project feasibility
[2] O&M = operation and maintenance
[3] Benefit provided to project feasibility, usability, and cost.

Airflow through a building can be calculated with the following equation:

$$Q_{wind} = K * A * v,$$

where Q_{wind} = volumetric airflow (m^3/hr), A = area of a small opening (m^2), v = outdoor wind speed (m/hr), and K = coefficient of effectiveness [38]. The value of K ranges depending on the angle of incidence of wind hitting the opening, assumed to be the door, where at a 45° angle, K = 0.4 and at a 90° angle, K = 0.8 [38]. The average annual wind speed distribution was calculated to be 4.8 m/s using data collected from Figure 3.2-1 below.

Figure 3.2-1. **Annual wind speed distribution for Abomey-Calavi**



Data provided by: Atlantique Department, Benin. (n.d.).

The International Code Council recommends an airflow of 7,600 to 15,000 L/min-m^2, with respect to the floor area. Airflow entering individual sanitation buildings (Q_{wind}) was calculated using the parameters summarized in Table 3.2-2 and are compared against the design airflow, Q_{design}. Using the recommended unit airflow, the design airflow is 228,000 to 450,000 L/min, given a floor area of 10 m by 3 m per building. Q_{wind} was calculated with wind incidence at 45 and 90 degrees, providing airflows of 256,412 to 512,825 L/min, which are within the desired range of Q_{design}. In reality, Q_{wind} is likely less than the upper range of calculated airflow, as there will be pressure losses through the building. However, low drag elements such as labyrinth entrances will lower pressure losses and increase the overall airflow. These results indicate that natural ventilation would work for most of the year, but may be insufficient for colder months--though ventilation during these months is likely less critical for cooling purposes.

Table 3.2-2. **Natural ventilation air flow calculations**

Parameter	45° Wind Incidence to Opening	90° Wind Incidence to Opening	Units
A_{door}	2.2	2.2	m^2
K	0.4	0.8	[-]
v [1]	17,250	17,250	m^3/hr
Q_{wind}	256,412	512,825	L/min
$Q_{required}$ [2]	228,000 to 450,000		L/min
[1] Based on an annual wind speed of 4.8 m/s [2] Based on ICC specification of 7,600 to 15,000 L/min-m^2 (ICC Mechanical Code 401-402)			

Implementation of natural ventilation systems will likely require a longer design period than mechanical ventilation systems, as careful consideration must go into angling of the facility perpendicularly to the prevailing wind direction. Designs must also include low aerodynamic drag features, such as labyrinth entrances that use offset walls in the entry to provide privacy without requiring doors that would seal the building envelope. Natural ventilation system costs were estimated based on system components, such as labyrinth doors and ventilation grills.

To estimate the cost of materials for the labyrinth entrances, we assume that the labyrinth entrance of each building needs two 2.4 m by 1.8 m walls, having a total face area of 8.9 m^2. If each concrete block is dimensioned 0.15 m by 0.3 m (0.05 m^2), then 192 blocks would be required, costing ~$550 for each building, or $1100 for the entire facility. Ventilation grills are assumed to be $50 each, with each building requiring two, resulting in a total cost of $200 for the facility. All together, the cost of natural ventilation materials is $1300. This cost is only meaningful if compared against an option where the facility has regular hinged doors, priced around $200 total. The net additional cost of natural ventilation materials is then around $1100.

3.2.1.2 Mechanical Ventilation Systems

Table 3.2-3. **Mechanical ventilation system evaluation table**

Criteria	Score	Benefit	Explanation
Design time	4	Very good	Simple design
Construction cost	2	Poor	Mechanical (fan) and electrical (motors, sensors, wiring, controls)
Reliability	4	Very good	Proven reliability. Can be regulated on demand.
O&M	3	Good	O&M required for solar panels and batteries

Power consumption	3	Good	Likely enough power draw for additional energy costs for solar panels and batteries
Total Score	16		

The flow rate of fresh air into the building via mechanical ventilation is calculated with the following equation:

$$Q_{fan} = n * V,$$

where Q_{air} = volumetric airflow (m^3/hr), n = air change rate (h^{-1}), and V = volume of room (m^3) [43]. The design flow (Q_{air}) is 750 m^3/hr, assuming 15 air changes per hour and a single room volume of 10 m by 2 m by 2.5 m (50 m^3). The power required for the fan motor was calculated using standards provided by the International Code Council Section 401 and 403, American Society of Heating and Air-Conditioning Engineers (ASHAE) and American National Standards Institute (ANSI) in Standard 90.1-2007 [40, 41, 42]. The fan motor power for each building will be 425 W (1/2 horsepower, HP), or 850 W for the entire facility, to satisfy the design airflow requirements. The online market Alibaba lists upblast ventilators at $400 USD with fan motors rated for 1/2 HP. Inlet and exhaust vents are assumed to cost $200 for the entire facility. The total cost for mechanical ventilation is around $1000. A manual switch is recommended to control the fan, as this simplifies fan operation. The energy requirements associated with fans is included in *Section 3.3, Energy and Solar Power*.

3.2.1.3 Hybrid Ventilation Systems

Table 3.2-4. **Hybrid ventilation system evaluation table**

Criteria	Score	Benefit	Explanation
Design time	3	Good	Must design passive and active systems.
Construction cost	2	Poor	Mechanical (fan) and electrical (motors, optional sensors, wiring, controls), and low drag elements (ventilation grills)
Reliability	5	Excellent	Can be regulated on demand. Somewhat depends on environmental conditions for air flow.
O&M	4	Very good	O&M required for solar panels and batteries
Power consumption	3	Good	Likely enough power draw for additional energy costs for solar panels and batteries
Total Score	18		

A hybrid ventilation system is likely highly reliable, as it can utilize free wind power to ventilate each sanitation block building, lowering electricity costs. However, more time is required to design this system, as the mechanical and passive systems must be integrated. With a hybrid system, the fan motor can be down-sized to ⅓ HP (225 W), which costs less than the ½ HP motor and consumes less energy than the mechanical ventilation system. O&M requirements would likely also be less than those required by a mechanical ventilation system, since the fans would not need to run as often. A manual switch is recommended to simplify operation of the fan, otherwise a sensor detecting relative humidity and temperature can be used to switch on the fan. The cost to install the ventilation ductwork is minimal, since ductwork is limited to openings in the building envelope to the outdoor environment. However, the cost of hybrid ventilation must include the cost for the natural ventilation, plus the cost of a ⅓ HP motor ($250), summing to $1350. Table 3.2-5 below summarizes the total cost of the ventilation options but does not include installation costs.

Table 3.2-5. **Cost of ventilation systems for sanitation block**

Ventilation Options	Total Cost
Mechanical	$1000
Natural	$1100
Hybrid	$1350

[1] Costs from Alibaba.com

3.2.2 Lighting

The International Code Council specifies that indoor artificial light should provide an average of 107 lux over the area of the room at 30-inch (12 cm) height [44]. Natural lighting can be used during the day and artificial lighting can be used during low-light conditions [15]. During the day, sun tunnels can transmit sunlight through the roof to the floor below. LED lamps can provide low-light illumination and draw minimal power from facility solar-powered batteries. Sensors or manual switches can be used to turn on the LED lamps. LED lamps are about $12 each and each building will need about 10 lamps. Sun tunnels are $150 each and each building would need about 2. The total cost to provide indoor lighting for both buildings is $1,240.

3.2.3 Hand Hygiene

Reducing physical contact with surfaces in the sanitation facilities will lower pathogen transmission. For this reason, touchless faucets and hand dryers are recommended for hand hygiene. The cost of paper towels was evaluated assuming that 500 people visited the restroom five days per week, every week of the year, and 2 paper towels were used with each visit. The cost of a paper towel is around $0.01, so the cost to supply the sanitation facilities with paper towels each year is around $4,000. In contrast, an electric hand dryer from Alibaba is $75 each ($300 total for the sanitation facility) and costs about $120 per year to operate, assuming each hand dryer is 800 W, individuals spend 15 seconds drying their hands, the facilities receive the number of yearly visits described previously, and the cost of power is $0.20/kWh. Touchless hand dryers are strongly recommended for hand drying, since using paper towels costs $3,500 more per year. Touchless faucets cost roughly $75 each (prices from Alibaba) and the sanitation block will require four faucets, bringing the total cost of faucets to $300.

3.2.4 Recommendations

Although mechanical ventilation systems are the least expensive, when annual utility costs are considered, a natural ventilation becomes much less expensive. When taking into account system performance and user comfort, the hybrid ventilation system will likely out-perform other systems in the long term. If indoor temperature or humidity is too high, users could benefit from the hybrid system having both mechanical and natural ventilation, and utility costs would still remain low for the rest of the year. Additionally, in hot and humid climates, mechanical cooling is recommended when natural ventilation is the primary cooling mechanism [54]. For reliability and performance reasons, hybrid ventilation is recommended. The cost of the hybrid ventilation system plus other indoor components is $2,590. Figure 3.2.2 below is a depiction of a typical men's public restroom and shows the general layout of restroom fixtures such as hand dryers, sinks, and toilets. The women's restroom would be similar, but would have more stalls in place of urinals.

Figure 3.2-2. **Typical men's restroom layout**

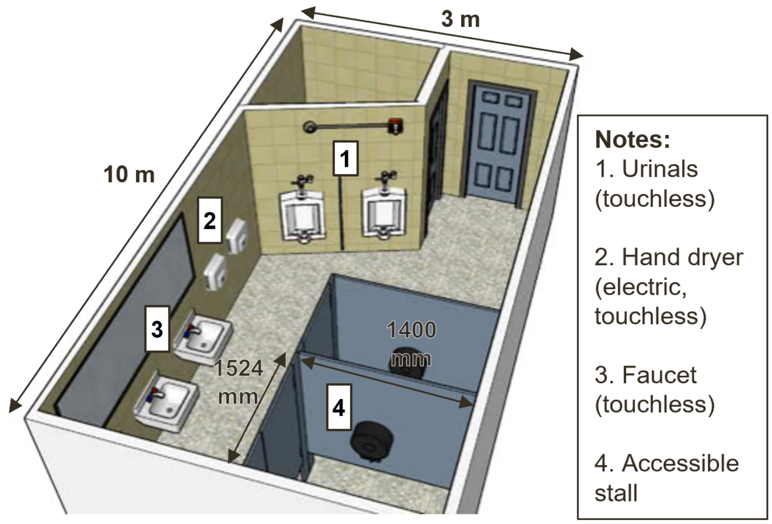


Image from SketchUp 3D Warehouse and may differ from report specifications.

3.3 Energy and Solar Power

Access to affordable and clean energy is the seventh of the United Nations Sustainable Development Goals. 640 million Africans still have no access to electricity, which is about 53% of the total population on the African continent [19]. Energy is a requirement for physical and socio-economic development for any community in the world. There is a need to promote and guarantee energy security, availability, and reliability to preserve any existing level of development and further new developmental strides for human comfort [5]. The purpose of this feasibility study, in respect to energy, is to provide the sanitation block with energy supply throughout the year via a solar system. A comprehensive overview was conducted for solar photovoltaic systems and optimum tilt on solar panels.

3.3.1 Photovoltaic System Types

There are different options for energy production, but for this particular feasibility study, photovoltaic (PV) panels were used to convert sunlight into electricity. This energy system requires solar panels, a stand-alone inverter, charge controller, battery bank, low voltage disconnect, and AC/DC circuits. The solar panels collect energy from the sun and turn it into electricity, which is passed through the inverter and converted into energy used to power the sanitation block [19]. This process is illustrated in Appendix A, Figure A2. A solar battery allows storage of excess solar electricity, which will be used when solar panels are not producing electricity--for example, at night, or during periods of dense clouds. Approximately half of each month in Benin is clear and sunny, with the other half slightly overcast; therefore solar power is well-suited to the area [23].

There are two types of solar systems: off-grid and on-grid. A comparison of the two is given in Table 3.3-1 [45]. This comparison shows that off-grid renewable electricity, particularly solar, can offer a wider range of modern solutions for enhancing access to energy in rural areas [46].

***Table 3.3-1.* Comparison of off-grid and on-grid solar systems**

Off-Grid Solar	On-Grid Solar
● Control over energy usage, reducing electricity consumption and making pollution-free renewable energy ● Independence from electrical utilities, power maintenance during utility outages and emergencies (such as hurricanes or thunderstorms) ● Remote areas with limited access to the electric grid are still provided with electricity	● Many utilities have net metering programs that pay for individual electricity production, which can lower overall electricity costs. This may cover the installation costs of an appropriately-sized solar and battery system ● Grid-interconnected solar is a more efficient use of the overall electricity system and community resources

In an urban area such as Abomey-Calavi, an off-grid solar power system may contribute to sustainable development in the area. Off-grid solar power systems allow full control of electricity production. Systems of this type are designed for peak electricity usage, rather than average electricity usage. Off-grid systems require more care and maintenance but can give a strong sense of independence.

To maximize electricity generation from solar panels, panels must be pointed in the direction that captures the most sun. There are a number of variables in determining the best direction. The simplest is to mount the solar panels at a fixed tilt and leave them stationary. However, the sun is higher in the summer and lower in the winter, which can affect how much energy is captured throughout the year. A study by Charles Landau found the fractions of energy collected under different scenarios and is summarized in Table 3.3-2. This table shows the effect of adjusting solar panel angles using a system at 40° latitude as an example (a system installed at a different latitude would result in different values) [47]. Each option is compared with the energy received by a panel pointed directly at the sun using a perfect tracking system.

***Table 3.3-2.* Effect of adjusting panel angles**

	Fixed	Adj. 2x/year	Adj. 4x/year	Ideal system
Percent of optimum	71.1%	75.2%	75.7%	100%

Table 3.3-2 demonstrates that adjusting panel angles four times per year allows slightly better energy collection, but this slight increase could be important if optimization of production in spring and fall is needed. Table 3.3-3 gives some examples of ideal summer, spring, and winter angles. In winter, a panel fixed at the correct angle will be relatively efficient, capturing 81 to 88 percent of the energy of an ideal

system [47]. In spring, summer, and autumn, capture efficiency is lower (74-75% in spring/autumn, and 68-74% in summer), because the sun travels a larger area of the sky in these seasons, and therefore a fixed panel cannot capture as much sunlight [47]. These are the seasons in which tracking systems can give the most benefit.

Table 3.3-3. **Ideal solar panel angles during different seasons and at different latitudes**

Latitude	Summer angle	Spring/autumn angle	Winter angle
25°	-1.3	22.2	46.3
30°	3.3	27.1	50.7
35°	7.9	32.0	55.2
40°	12.5	36.9	59.6
45°	17.1	41.8	64.1
50°	21.7	46.7	68.5

3.3.2 Electricity Consumption

This sanitation facility will harness solar energy to power toilets and sinks. Touchless faucets can save time and money and protect health. Germs and bacteria can last for a long period of time even with the most thorough cleaning routine; therefore use of touchless faucets can reduce the chances of germ transfer from surfaces to hands. The following devices will be powered using solar energy:

- LED light bulbs
- Touchless faucets
- Flushing squatting toilets
- Battery for energy storage
- Ventilation fan

A breakdown of energy consumption for each device is shown in Table 3.3-4 [51, 52]. The range varies from the smallest to largest power intake the device can handle. A range in power intake values exists as these values depend on the device model. The male sanitation block will utilize four urinals and three squat toilets, while the female building will require seven squat toilets.

Table 3.3-4. **Energy consumption of electric devices in the sanitation block for one facility**

Devices	**Quantity**	**Minimum**			**Maximum**		
		Power (watts)	Hours/ Day	(kWh/ day)	Power (watts)	Hours/ Day	kWh/ day)
Energy storage (battery)	1	4500	2.35	10.58	21,000	2.35	49.35
LED light bulbs	5	10	6	0.30	10	6	0.30
Touchless faucets (motion sensing)	2	0.036	6	0.00043	0.9	6	0.01
Flushing squatting toilets	3	2	6	0.04	4	6	0.07
Urinals	4	2	6	0.05	4	6	0.10
Ventilation fans	2	0	8	0	250	8	4.00
Total (kWh)		**10.96**			**53.83**		

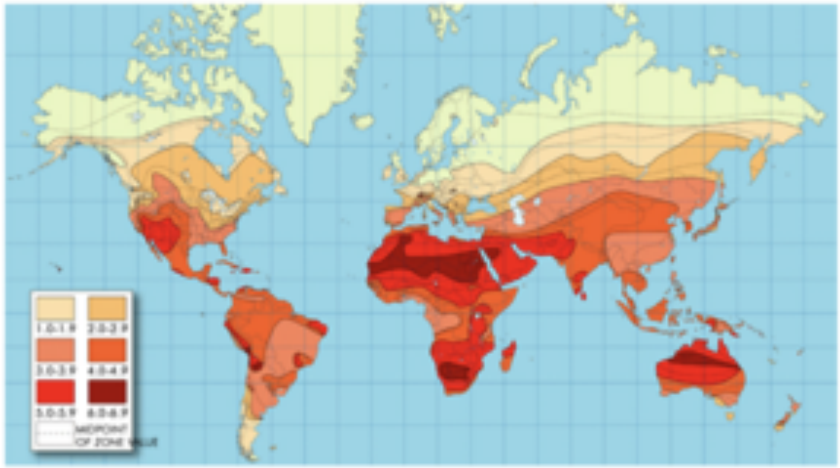
3.3.3 Sizing and Selection of Photovoltaics

To adequately size the PV system to the total sanitation block roof area of 88 square meters, the following parameters were needed:

- Monthly energy use
- Peak sun hours
- Max annual energy
- PV system capacity
- Module rates power

The amount of energy required depends on the devices used in the facility. Table 3.3-4 summarizes energy requirements for each device. While the amount of sunlight panels receive is important, a more accurate representation of the amount of energy the panels can produce is peak sun hours [48]. Figure 3.3-1 shows the world insolation map, which demonstrates the amount of solar energy in hours received each day during the worst month of the year [48]. For Benin, the peak sun hours range from 4 to 4.9 hours per day.

***Figure 3.3-1.* The world insolation map**



Solar panel outputs are shown in Table 3.3-5. Using the minimum and maximum watt-rated panel, and taking the average sun exposure per day, the energy collected by the solar panels can be estimated.

***Table 3.3-5.* Solar panel output for the one facility**

Parameter	Units	Minimum	Maximum
Rated power	Watts	200.00	400.00
Daily energy use	kWh	10.96	53.83
Monthly energy	kWh	328.78	1614.86
Annual energy use	kWh	3945.40	19378.37
Peak sun hours (PSH)	Hours	4.00	4.90

Referring to Table 3.3-5 and applying the formulas below, the off-grid PV system parameters were found (Equations 1-4 [53], Equation 5 [49]):

$$\text{Off-grid PV System Capacity (kWp)} = \frac{Daily\ Energy\ Use\ (kWh)}{Peak\ Sun\ Hours\ (hours)} \quad (1)$$

$$\text{Off-grid PV System Yield (kWh/kWp)} = \frac{Annual\ \ Energy\ Use\ (kWh)}{PV\ System\ Capacity\ (kWp)} \quad (2)$$

$$\text{Number of needed modules} = \frac{System\ Capacity\ (kWp)}{Module\ Rated\ Power\ (kW)} \quad (3)$$

$$\text{System Expected Output} = \text{PV System Capacity} * \text{PV System Yield} \quad (4)$$

$$\text{Space needed} = \frac{Roof\ Size\ (m2)}{10} * kWp \quad (5)$$

Two key values that describe PV systems are peak capacity, in kWp (kilowatt peak) and annual energy production per peak capacity, in kWh/kWp (kilowatt hours per kilowatt peak), corresponding to the equations above. Solar radiation of 1,000 watts per square meter is used to define standard conditions [49]. Using average hours of solar energy received each day during the worst month of the year (Figure 3.3-1), the resulting daily energy usage per building can be calculated and is shown in Table 3.3-6.

Table 3.3-6. **System design recommendations per building**

	Minimum	**Maximum**
Daily Energy Demand (kWh)	10.96	53.83
Off-grid PV system capacity (kW_p)	2.74	10.99
Off-grid PV system Demand (kWh/year)	3945.40	19378.37
Off-grid PV System Yield(kWh/ kW_p)	1440	1764
Number of PV modules needed	14	27

3.3.4 Solar System Costs

The energy system will require solar panels, a stand-alone inverter, charge controller, battery bank, low voltage disconnect, and AC/DC circuits. The energy system and facility elements are shown in Table 3.3-7 [52].

Table 3.3-7. **Energy system and facility elements costs for one building**

	Element	**Quantity**	**Minimum Cost ($)**	**Maximum Cost ($)**
Energy System	Solar panels	14	500	700
	Stand-alone inverter	1	200	1000
	Charge controller	1	20	100
	Low voltage disconnect	1	60	130

	AC/DC circuits	1	100	300
Facility Elements	Energy storage	1	8,500	15,500
	LED light bulbs	5	8	12
	Touchless faucets (motion sensing)	2	28	33
	Flushing squatting toilets	3	200	400
	Urinals	4	200	400
	Ventilation fans	2	40	100
	Total		**$ 17,456**	**$ 29,956**

3.3.5 Maintenance and Theft

Solar panels are very durable and should last around 25-30 years with no maintenance [55]. To preserve them to their maximum life cycle, panels should be washed two to four times per year to remove dirt and dust. This can be done using a garden hose from the UAC. This basic cleaning routine ensures that the sun can shine brightly on the panel, maximizing the amount of light available to turn into electrical power [55].

Solar panels are valuable and unfortunately can catch unwanted attention, especially in areas where they might not be common. While these solar panels might be covered under some sort of insurance policy, that will not recompense for the trauma of being a victim of theft. Thus, some security measures against theft should be taken. Some system owners use a rail and one way screws to lock all panels in an array to each other in such a way as to make removal of individual panels extremely difficult [50]. This would require the removal of a single very heavy row of panels. Factoring in the size of the panels, their transport would become almost impossible. This option would not have any additional costs. A second option would be chaining the panels together and adding some type of durable wire to make it harder for burglars to steal the panels.

3.3.6 Energy Recommendations Summary

- Off-grid solar power systems can ensure that people have electricity in a safe and reliable form.
- The tilt angle of the solar panels on the sanitation block should be adjusted four times per year (once per season) to optimize energy production.
- The solar power system is sized to require 24 m^2 of the 88 m^2 roof space. There will be 14 solar panels with a power rating of 200 watts each, providing a total of 3,945 kWh annually.

- The men's building will have four urinals and three squatting toilets and the women's will have seven squatting toilets. The total daily energy demand for both facilities is 21.92 kWh.
- The total cost for a solar power system for both buildings is $34,912.
- The solar panels will require cleaning approximately three to four times per year.

3.4 Decentralized Wastewater Treatment

One of the key goals of this project is to provide a restroom in the student mall area that demonstrates how to sustainably treat waste. Therefore, design alternatives were evaluated not only based on their performance, but also on their potential to act as a showcase of sustainable technologies. The technologies are called decentralized wastewater treatment systems because they are not connected to any centralized managed wastewater treatment system [62, 65].

Five alternatives are evaluated in a combination of primary and secondary treatment technologies. Conventional sewage treatment takes place in these two stages. A "primary" treatment stage involves sedimentation, filtration, and screening to remove floating objects, sand, and stones. "Secondary" treatment uses biological methods as well as aeration, oxidation, and filtration to properly decompose chemical contaminants in human waste.

3.4.1 Wastewater Management Alternatives

As of 2014, Abomey-Calavi only had one operating centralized wastewater treatment plant. Most households and commercial buildings in the area rely on septic tanks, as does the university [56]. The three primary treatment technologies proposed are all variations on septic tanks, and they include a holding tank, septic tank, and anaerobic baffled reactor. The secondary treatment options considered in this study include a constructed wetland or a drainage field. The five combinations of primary and secondary technologies are shown in Table 3.4.1, along with the variables used to evaluate them.

Table 3.4-1. **Decentralized wastewater treatment technologies**

	Vault	**Septic Tank + Drainage Field**	**Septic Tank + Constructed Wetlands**	**ABR + Drainage Field**	**ABR + Constructed Wetlands**
Capacity (m^3)	194.4	48.6	48.6	8.8	8.8
Foot Print (m^2)	97.2	46.68	45	49.9	21.22
HRT (days)	NA	1	1	2	2
BOD Removal	10%	25-50%	90%	790%	90%
Pathogen Removal[1]	0%	0%	5 log	0%	5 log

Sludge Removal Interval (years)	1	1	1	1	1
Maintenance	Periodic desludging	Periodic desludging	Periodic desludging + wetland health maintenance	Periodic desludging	Periodic desludging + wetland health maintenance
Total Capital Cost [2]	$10,798	$3,936	$3,950	$2,148	$1,977
Yearly Operational Cost[1]	$3,524	$811	$811	$160	$160

1) Kayombo et al. 2004 [60]
2) All costs have been modified by a contingency factor of 45%

3.4.2 Septic Tank + Drainfield

A septic tank is traditionally a vault or tank placed underground in which sewage is allowed to settle and then undergo a small amount of anaerobic digestion as it comes into contact with microorganisms [68]. The septic tank is a familiar technology to the University because they already operate multiple septic tanks on campus. A septic tank with a drainage field would have lower operating costs than a holding tank due to less frequent sludge vacuuming, but it will have a higher capital cost.

Drainfields consist of perforated pipes that send effluent out into gravel-filled trenches, where the effluent percolates out and then eventually makes it to the soil. Unfortunately, according to Massoud et al., septic systems only provide primary treatment, reducing BOD by approximately 25-50% and thus allowing released effluent to provide a possible source of contamination [18]. This could potentially be problematic as the university draws drinking water from a fairly high groundwater table.

3.4.2.1 Sizing

The septic tank and drainage field dimensions were calculated using Reed's method from the WHO *Guide to the Development of On-site Sanitation* [66] assuming a hydraulic retention time (HRT) of 24 hours, a user flow of seven liters (including flushing and handwashing), and 500 users per day. The resulting daily flow was calculated to be 3.5 m^3/day.

Septic tanks traditionally consist of a vault with two sections divided by a baffled wall. The first chamber is normally approximately two-thirds the tank volume and is where the majority of the settling occurs, while the baffle to the second chamber is to reduce the turbulence in the water to allow settling [68]. The working volume, or minimum HRT capacity of the tank, was found and added to the volume needed for maximum sludge accumulation using an accumulation rate of 25 liters per capita per year [66]. This resulted in a tank of approximately 49 m^3. The tank dimensions are shown in Table 3.4-2 and calculations can be found in Appendix B.

Drainage field design is dependent upon the site's soil condition and type. The soil in and around Abomey-Calavi is known to be gley, or very water-logged, and to contain a significant amount of coarse sand, which lead to the selection of an infiltration capacity of 50 L/m^2-day [59]. With this infiltration capacity, the wall area and depth of trench were chosen, leading to a design with two trenches each approximately 58 meters in series. Unfortunately, the waterlogged soil means that effluent making its way into the trenches might not infiltrate, thus creating a sanitation hazard in the form of a standing pond of wastewater effluent.

Table 3.4-2. **Septic Tank Sizing**

Parameter	Value	Unit
Volume Per User	7	L/person
Flow	3.5	m^3/day
Sludge Retention Rate	25	L/person/year
Max Capacity for 24 hr Retention	3500	L
Volume for sludge accumulation	25000	L
Working Tank Volume	29	m^3
Water Depth	1.5	m
Depth	1.8	m
Width	3	m
Length compartment 1	6	m
Length compartment 2	3	m
Total length	9	m
Designed Tank Volume	48.6	m^3

Table 3.4-3. **Drainage Field Sizing**

Parameter	Value	Unit
Infiltration	50	L/m^2-day
Wall Area	70	m^2
Depth	0.6	m
Length	116.7	m
Two trenches	58	m
Width	0.4	m
Volume of gravel	28.1	m^3
Area	46.68	m^2

3.4.2.2 Maintenance and Operation

Septic tanks require no start uptime, though no anaerobic digestion will occur in the first few months [68]. Maintenance will include periodic conservative desludging approximately every year. The drainage field maintenance is quite simple and consists of periodically checking for clogging in the gravel or in the pipes, which could lead to effluent flooding [66].

3.4.2.3 Cost Estimate

The septic and drainage field capital cost estimate does not include cost of construction and was estimated using the Engineering News Record's price for gravel, sand and cement and then multiplied by a factor of 45% for contingency. Operational costs for the septic tank are based on Hounkpe et al.'s 2014 case study on wastewater management in Cotonou, Benin [56]. Prices for desludging are based on the volume of truck used. For a smaller truck it costs \$75/ 6 m^3 and for a larger truck it costs \$150/ 12 m^3 [56]. The drainage field operations costs should be minimal, requiring only a check every time the ARB or septic tank is emptied.

3.4.3 Septic Tank + Constructed Wetlands

When dealing with the septic tank effluent, an alternative to a drainage field is a constructed wetland approach. According to Mekonnen et al.'s 2015 review of constructed wetlands in Africa, a horizontal constructed wetland can achieve approximately 80% efficiency in BOD removal [61, 64]. Constructed wetlands utilize an engineered version of a natural process to remove organic matter, suspended solids, pathogens and nutrients [60]. Vegetation and substrates provide treatment through biological and physical means such as microbial uptake and sedimentation [60]. The benefits of constructed wetlands include the ability to handle variable loads, cost effectiveness in comparison to mechanical treatment options and possible aesthetic and educational appeal [60]. The ability to handle variable loads makes constructed wetlands an ideal option for long periods when school is out of session and loading is greatly reduced. However, wetlands can be susceptible to climate changes and drought. The height of the water table and the topography of the area are also a factor when considering the necessary slope needed for treatment.

There are two main types of constructed wetlands: free water surface and subsurface flow. Free water surface flow has not been explored as an option due to its potential to attract unwanted vectors such as pests and insects, its potential to smell, contact with water column and need for intermittent loading [60]. Subsurface flow can either be horizontal or vertical. Horizontal flow utilizes an underground effluent pipe, while vertical pipes the effluent over the area of the wetlands [26, 60]. Horizontal flow was chosen due to the lack of need for a pump to lift the water above the surface.

Components for a constructed wetland include substrate, bed lining, piping, effluent tank and vegetation. Though the soil in Abomey-Calavi is very often water logged due to a high-water table, it does consist of coarse sand which has a high conductivity meaning there is potential for seepage [59]. Thus, it is recommended that the constructed wetlands be lined with an impermeable geosynthetic liner to prevent contamination. The choice of vegetation for a constructed wetland is dependent upon the local climate and preference is given to local species. Macrophytes are plants naturally found in wetlands and proven to aide in water treatment [63]. In 2009, professors from the University performed a study on a pilot constructed wetland using water from the university's septic tanks [57]. Deguenon et al. tested a vertical flow constructed wetland using locally-grown reeds called phragmites. The authors determined that, given a residence time of eight days, COD, BOD and TSS all reach local standards. This study is promising because it demonstrates knowledge within the University on constructed wetlands use and maintenance. The same type of reed is recommended for use in the constructed wetlands alternative, thus saving costs due to local availability.

3.4.3.1 Sizing

Reed's method for constructed wetland design was used to size the wetland [60, 67]. Sizing is based on a horizontal subsurface flow system, rather than the vertical pilot demonstrated by Deguenon et al. First the area of the wetland was calculated using a flow of 3.5 m^3/day. A septic tank influent BOD_5 of 444 mg/L was used based on the average BOD_5 found in Deguenon et al.'s septic tank data [57]. Assuming a BOD reduction of 30% across the primary treatment system gives a constructed wetland influent BOD_5 of 355 mg/L. Bringing the BOD down to the 30 mg/L, within the Benin wastewater standards, requires a wetlands area of 29 m^2 [57]. Sizing parameters can be found in Table 3.4-4 and more precise calculations can be found in the excel file in Appendix B.

Table 3.4-4. **Constructed Wetlands Sizing**

Parameter	**Value**	**Unit**
Depth	0.4	m
Porosity	0.4	
K_{20}	1.1	1/day
K_T	1.9	1/day
K_{BOD}	0.304	m/day
C_{in}	354.8	mg/L
C_e	30	mg/L
Surface Area	29	m^2
Conductivity K_f	0.0010	m/s
Slope (dH/dS)	0.01	
Cross-sectional Area	5	m^2

3.4.3.2 Maintenance and Operation

Constructed wetlands are relatively easy to maintain in comparison to other mechanical means of secondary treatment. The startup will require approximately 3 weeks to establish a proper microbial community, but after this time, if properly maintained this community will sustain itself. Maintenance will include keeping the banks free of weeds and overgrowth, checking the inlet and outlets for accumulation of solids to prevent clogging and watering during droughts as necessary [60].

3.4.3.3 Cost Estimate

The septic tank and constructed wetlands capital cost estimate does not include cost of construction and was estimated using the Engineering News Record's price for gravel, sand and cement and then multiplied by a factor of 45% for contingency. It is assumed that as in Deguenon et al.'s study, the plants can be sourced from the area, negating their cost [57]. Operational costs for the septic tank include periodic desludging costs derived from Hounkpe et al.'s 2014 study and the constructed wetlands will require minimal ground maintenance.

3.4.4 Anaerobic Baffled Reactor

An anaerobic baffled reactor (ABR) is much like a septic tank, but with more closely spaced chambers. The chambers force the water to flow up over a baffle and then constrict its flow down with another closely spaced baffle, forcing the water down into the sludge at the bottom of the tank [68]. In order to get settling the up-flow velocity must be less than that of the particles settling and in order to maintain this velocity a longer HRT is needed [66]. The extended time spent in contact with the sludge allows for greater contact time with anaerobic bacteria and a BOD removal rate of 70-95%, significantly better than that of the septic tank [68]. A schematic of an ABR can be seen in Appendix A, Figure A.3. Baffles make ABRs more compact than a septic tank, but the complexity adds cost. ABRs have better treatment than septic tanks and vaults, but they still produce effluent that is not safe, and it cannot handle the sludge accumulation like a holding tank, so either a drainage field or constructed wetlands.

3.4.4.1 Sizing

As of yet there are no standardized design criteria for an ABR so sizing was determined using Foxon et al.'s 2007 guidelines for implementing a hanging baffled ABR. Other manuals and equations for ABR design exist, such as in Sasse et al.'s 1998 *Decentralized Wastewater Treatment in Developing Countries* handbook [68]. Sasse et al.'s design utilizes a more complex design criteria, requiring information about the wastewater parameters that is not currently available [68]. It is suggested that if the project moves forward, data be collected on the University's wastewater characteristics to allow for a more fully developed design. For the purposes of the feasibility study, Foxon et al.'s ABR design criteria provide a sufficient estimate of ABR size [67].

The three most important criteria for ABR design are the up-flow velocity, hydraulic retention time and the number of chambers (3-6) [26]. The up-flow velocity in each chamber must be slower than the particle settling velocity and thus it is recommended that the up-flow velocity remain below 0.6 m/hr and a conservative HRT of 72 hours is recommended [67, 68]. Calculated dimensions for the ABR with settling tank are provided in Table 3.4-6. The calculations can be found in Appendix B in the excel sheet for easy adjustment should the client wish to change the design flow or other parameters.

An ABR will increase the BOD removal in comparison to a septic tank and thus will allow for the reduction in size of a consecutive constructed wetlands. Assuming a BOD_5 removal of 70% results in a constructed wetlands influent BOD_5 of 133 mg/L. A lower influent BOD_5 means the area of the constructed wetlands can be reduced to 18 m^2.

Table 3.4-5. **ABR Constructed Wetlands Sizing**

Parameter	**Value**	**Unit**
Depth	0.4	m
Porosity	0.4	
K_{20}	1.1	1/day
K_T	1.9	1/day
K_{BOD}	0.304	m/day
C_{in}	133.05	mg/L
C_e	30	mg/L
Surface Area	18	m^2
Conductivity K_f	0.0010	m/s
Slope (dH/dS)	0.01	
Cross-sectional Area	5	m^2
Width	12.5	m
Length	3.60	m
Inlet Gravel Zone	0.75	m
Outlet Zone	0.25	m
Treatment Zone	2.60	m
Volume of Gravel	18	m^3

Table 3.4-6 ABR Sizing

Parameter	**Value**	**Unit**
Flow	3.5	m^3/day
Settling Tank HRT	0.5	days
Settling Tank Required Volume	1.75	m^3/day
Settling Tank Length	0.5	m^3/day
ABR HRT	2.5	days
Working Volume	8.75	m^3/day
Peak Up-flow Velocity	0.58	m/hr
Design Up-flow Velocity	0.32	m/hr
Number of Compartments	4	
Hanging Baffle Clearance	0.2	m
Compartment Up-flow Area	0.45	m^2
Up-flow to downflow area ratio	2	
Compartment width to length ratio	3	
Total Compartment Area	0.7	m^2
Reactor Depth	2	m
Reactor width	1.8	m
Reactor Length	2.4	m
Volume	8.8	m^3
Sludge Accumulation rate	5	L/capita-year
Sludge Accumulation	1.1	m/year
Desludge Rate	0.8	years
Baffle Thickness	0.1	m
ABR Length	3.0	m

3.4.4.2 Maintenance and Operation

ABRs require a long startup period due to the need for the slow growing anaerobic bacteria to establish themselves and adjust to the wastewater characteristics [26]. Once the anaerobic bacteria are established, the reactor requires relatively little maintenance besides the periodic sludge vacuuming [68]. Tilley et al. recommend desludging the ABR when the sludge blanket reaches one meter in depth [26]. The maintenance period for the ABR is calculated using a sludge accumulation rate of 5 liters per capita per year. According to Reynaud's study on decentralized wastewater treatment systems in tropical zones, the sludge accumulation of ABRs is significantly reduced due to the added stabilization from a prolonged period in the anaerobic zone [58]. This results in a desludging rate of approximately once every year. During desludging it is important to leave some sludge in the bottom of the ABR to ensure some of the anaerobic bacteria remain alive and the tank does not have to acclimate again [68].

3.4.4.3 Cost Estimate

The ABR and constructed wetlands capital cost estimate does not include cost of construction and was estimated using the Engineering News Record's price for gravel, sand and cement and then multiplied by a factor of 45% for contingency. As with the septic tank it is assumed that as in Deguenon et al.'s study, the plants can be sourced from the area, negating their cost [57]. Operational costs for the ABR tank include periodic desludging costs derived from Hounkpe et al.'s 2014 study and the constructed wetlands will require minimal ground maintenance.

3.4.5 Holding Tank

Holding tanks are commonly utilized in Benin due to the high water table in the area and cost effectiveness [56]. While holding tanks do not require a drainage field, they do require more frequent desludging since there is no outlet for the waste. Holding tanks also have to be quite large, typically four times that of a septic tank, in order to accommodate the lack of an outlet [66]. A larger size and more frequent desludging makes a holding tank a more costly alternative in the present and in terms of operation. It should also be noted that Abomey-Calavi only has one operating wastewater treatment plant, which is frequently overloaded [56]. The frequent desludging associated with a holding tank would therefore contribute to this overloading problem, as the waste will need to be trucked to the plant.

3.4.5.1 Sizing

The holding is sized based on the WHO guidelines and is approximately 4 times the size of the septic tank [66]. Sizing parameters can be found in Table 3.4-7.

Table 3.4-7 **Holding Tank Sizing**

Parameter	**Value**	**Unit**
Volume	194.4	m^3
Depth	2.0	m
Width	3.0	m
Length	32.4	m
Length Compartment 1	21.6	m
Length Compartment 2	10.8	m
Desludge Rate	1	years

3.4.5.2 Maintenance and Operation

The holding tank will require periodic desludging approximately once every year, but the tank level should be monitored more frequently.

3.4.5.3 Cost Estimate

The holding tank capital cost estimate does not include cost of construction and was estimated using the Engineering News Record's price for gravel, sand and cement and then multiplied by a factor of 45% for contingency.

3.4.6 Overall Cost Estimate

Total capital and operating costs for each alternative are shown in Table 3.4-1. Costs were calculated using material unit costs shown in Table 3.4.2-1. Concrete costs were based on an assumed wall thickness of 20. A cost calculator has been made available in Appendix B.

Table 3.4.2-1. **Material costs for decentralized wastewater management**

Materials	Total Cost
Cement	$7/20kg
Gravel	$7/1000kg
Sand	$7/1000kg

[1] Engineering News Record and Alibaba.com

3.4.3 Recommendations

The lowest cost option is to implement an ABR for primary treatment followed by a constructed wetland. This option will provide the university with an efficient treatment system, as well an aesthetically-pleasing wetland to showcase sustainable decentralized treatment technologies. Constructed wetlands have been a topic of research at the university in the past and thus faculty have experience with the technology, opening up the opportunity for further research for students if the university permits.

4. Conclusions and Recommendations

In conclusion, installation of a sanitation block utilizing touchless faucets and toilets, solar power, and a rainwater catchment system for water supply appears feasible on the Student Mall portion of the UAC campus. The final project is estimated to cost a total of $44,879 US dollars and serve 500 users per day, at approximately five days of use per week and 52 weeks per year. A summary of recommendations for each project sector is provided below, and total costs are shown in Table 4-1.

Table 4-1. **Total costs for the sanitation block**

No.	Sector	Cost (USD)	Cost (West Africa CFA franc)
1	Rainwater Catchment	$5,400	3,154,572
2	Indoor Environmental Quality	$2,590	1,513,026
3	Energy and Solar Power	$34,912	20,394,892
4	Decentralized Wastewater Management	$1,977	1,154,924
	Grand Total	**$44,879**	**26,217,414**

4.1 Rainwater Catchment

- The rainwater catchment system is sized to provide 4 m^3 of water per month. This water should be used for toilet flushing or cleaning, as it will not be treated and therefore may not be safe for handwashing.
- Each restroom building will have two 7.6 m^3 water collection tanks associated with it. Each building will also have one first flush diverter, one pump to move water from storage tanks to toilets for flushing, and associated gutters. The total cost for a collection system for both buildings is $5400. Occasional maintenance of the pumps, first flush diverters, and storage tanks will be necessary.

- Backup water from UAC's distribution system is required to ensure the sanitation block has sufficient water supply all year. It is important to note that a rainwater catchment system meeting the size requirements discussed herein (two 4 m by 11 m roofs) is not capable of meeting the total water requirements of this sanitation block.

4.2 Indoor Environmental Quality

- For building ventilation, a hybrid system that primarily uses natural ventilation to provide fresh and cool air into the sanitation facility is recommended. A ⅓ HP motorized fan should be installed to provide additional ventilation and cooling when desired by facility users.
- Lighting of the facility should utilize as much natural light as possible during the daylight and use LED lamps in low-light conditions
- For hand hygiene purpose, we recommend installing touchless hand dryers, since their cost is much lower than the cost to supply paper towels. Touchless faucets are also recommended to reduce pathogen transmission.

4.3 Energy and Solar Power

- We recommend that the solar power system be off-grid in order to ensure the sanitation block has an independent, reliable power source.
- Solar panel angles should be adjusted each season to optimize energy production.
- The solar power system is sized to require 24 m^2 of roof space. There will be 14 solar panels with a power rating of 200 watts each, resulting in a total annual power supply of 3,945 kWh.
- The men's building will have four urinals and three squatting toilets and the women's will have seven squatting toilets. The total daily energy demand for both facilities is 21.92 kWh.
- The total cost for a solar power system for both buildings is $34,912.
- Solar panels will require maintenance three to four times per year.
- To prevent theft, use a rail and one-way screws to lock all panels to each other. This will make the removal of individual panels and the entire panel system extremely difficult.

4.4 Decentralized Wastewater Treatment

- We recommend that the university pursue a decentralized wastewater treatment system consisting of an ABR followed by a horizontal subsurface flow constructed wetland.
- Due to the abundance of reed plants in the area, we recommend that some of these plants are harvested to populate the constructed wetlands and thus eliminate the need to buy plants externally.
- The ABR will need desludging every year or when the sludge blanket exceeds one meter. Although it is not included in the cost, we recommend that the university investigate installing a monitoring system that will indicate when the sludge blanket approaches one meter and thus allow for servicing planning. It is important to note that the first two chambers of the ABR should never be vacuumed entirely, otherwise the reactor will have to go through an adaptation period to regrow its microbial population [60].

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6. Appendices

Appendix A - Figures:

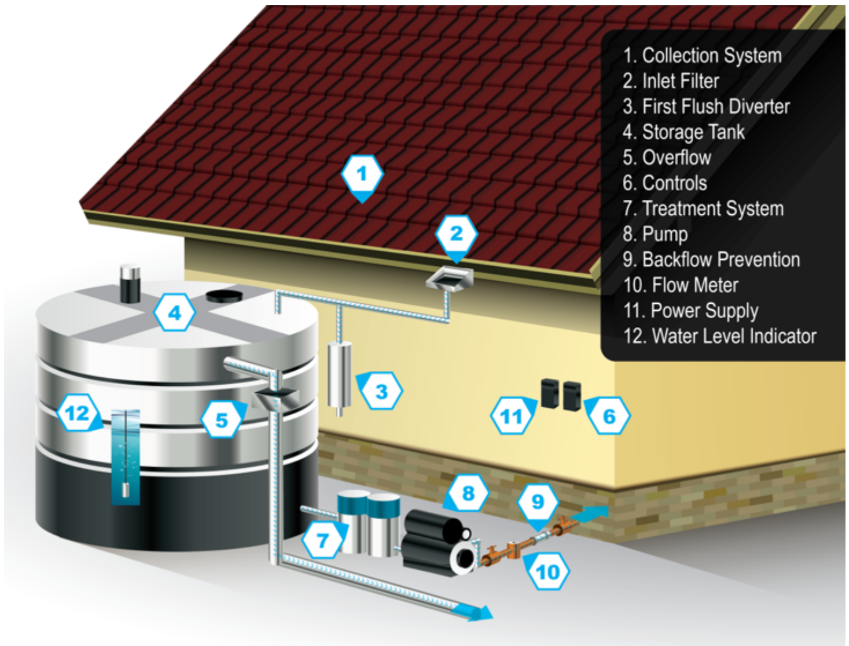


Figure A1. An example of a rainwater catchment system utilizing treatment prior to water consumption [7].

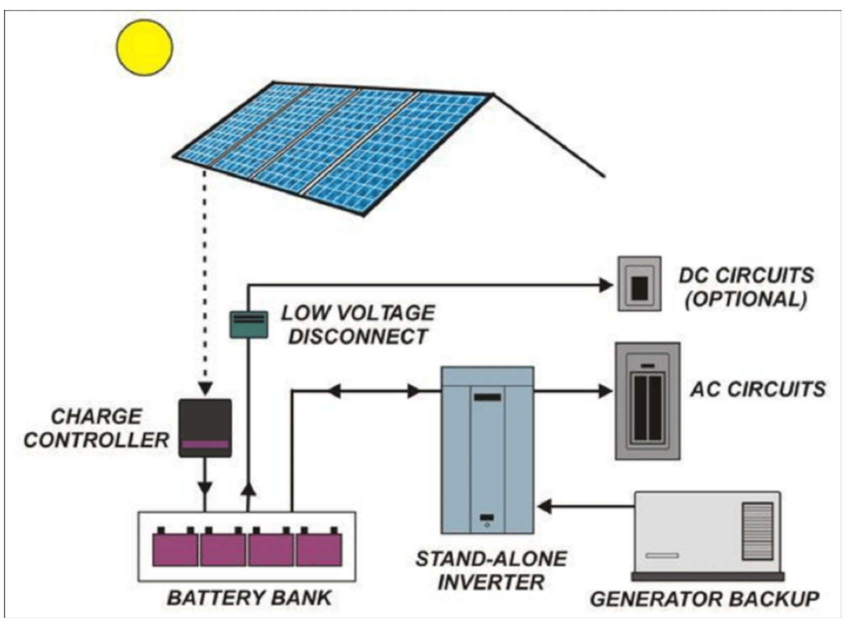


Figure A2. An example of a solar power system cycle [23].

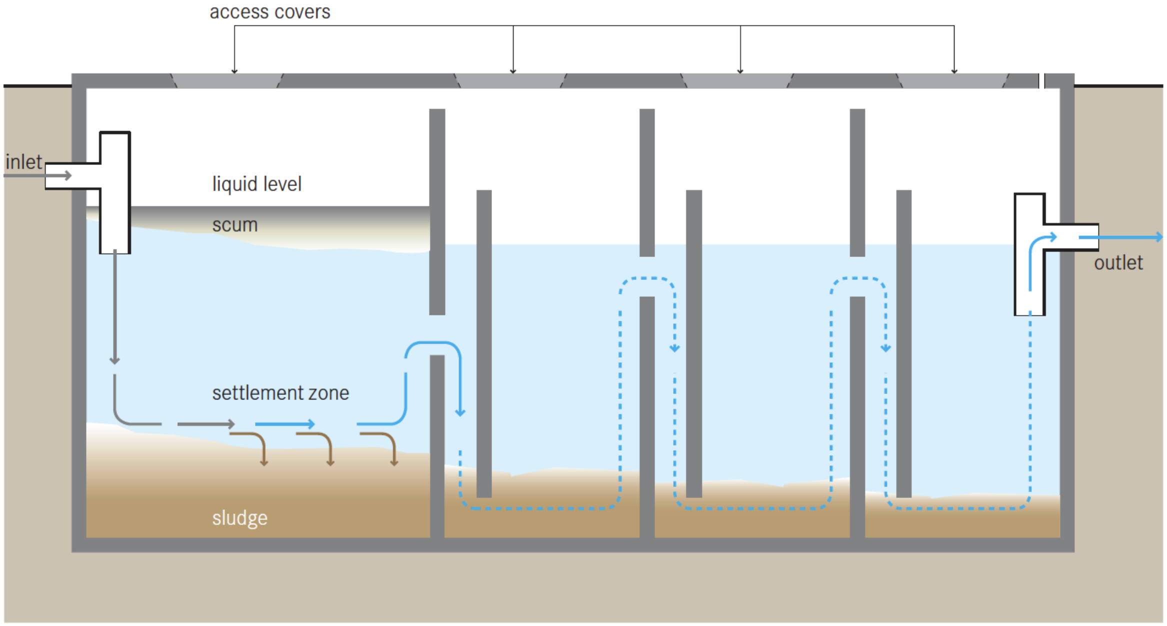


Figure A3. Depiction of an anaerobic baffled reactor [26].

National Weather Service
Heat Index Chart

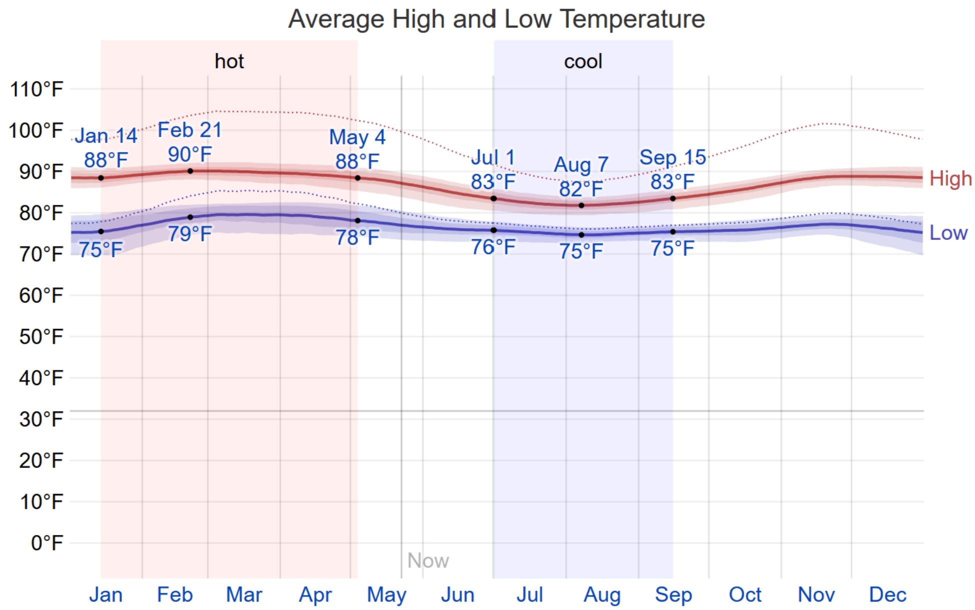
Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure and/or Strenuous Activity

Caution Extreme Caution Danger Extreme Danger

Figure A4. Heat index used for Indoor Environmental Quality Design [22].



The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures.

Figure A5. Abomey-Calavi average temperatures [22].

Appendix B - Attachments:

- Attachment 1 - Rainwater catchment system maintenance guide, provided here: https://www.radford.edu/content/dam/departments/administrative/Sustainability/Documents/Rainwater-Manual.pdf
  - This links to a comprehensive rainwater catchment system maintenance guide, compiled by the Cabell Brand Center and Radford University.
- Attachment 2 - Rainwater Catchment Calculator.xlsx
  - If monthly rainfall and building roof size are entered into this file, the resulting rainwater collection volume will be calculated. The storage capacity required will also be calculated.
- Attachment 3 - Energy_tables.xlsx
  - When the amount of power required by each device and its hourly usage are entered into this file, the total amount of energy required per day is calculated. Energy requirements per day and solar panel power ratings are then utilized to calculate the total output energy per building and the number of solar panels required.
- Attachment 4 – Wastewater Treatment Calculators.xlsx
  - In the Excel file are two tabs:
    - Sizing – calculator for sizing the different alternatives
    - Cost – cost of cement for the tank systems