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IDENTIFYING SUSTAINABLE SOLUTIONS FOR SANITATION, ENERGY, AND WATER NEEDS IN OFF-GRID INDIAN VILLAGES

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ABSTRACT
Food, energy, and water are the significant factors necessary for the social and economic well-being and prosperity of people, particularly to accelerate rural development. In order to attain sustainable development in off-grid villages, the issues associated with the Food-Energy-Water (FEW) nexus must be addressed with respect to social, economic and environmental aspects. SunMoksha, a socio-technical enterprise, has proposed a model that includes smart technical solutions or intelligent assets, such as, Smart AQUAnet™, Smart Nanogrid™, Smart MEZ™, etc., addressing food, energy and water needs in off-grid villages. Its development model allows for multiple sustainable solutions to be introduced into the rural community, to address specific needs as the community moves up in the development process.

In this paper, a method is presented to identify such sustainable smart solutions. The method involves the use of the dilemma triangle and Go/No-Go analysis to address the needs in off-grid Indian villages. We demonstrate the efficacy of the method by first identifying the key issues in an Indian off-grid village from the perspective of the FEW nexus using the dilemma triangle construct. A Go/No-Go analysis is used to select the best feasible solution from a set of possible solutions addressing the dilemmas and issues. Additionally, the needs for sanitation in the village is also considered in the analysis, keeping in mind the health and well-beings of the communities. The method is generic and will support stakeholders/decision-makers in identifying and selecting the best suitable solution from a set of potential solutions. The method is illustrated for an off-grid village to identify an intelligent asset to simultaneously address the sanitation, energy and water needs.

Keywords: Food-Energy-Water Nexus and Sanitation, Sustainable Rural Development, Dilemma Triangle, Go/No-Go Analysis, Microbial Fuel Cell Technology

1. FRAME OF REFERENCE
According to the 2011 Census of India, about 68% of people in India live in rural areas and villages. The majority of people in villages depend on agriculture as their main source of living. Many off-grid villages are situated in remote locations, which makes it difficult for people to have access to basic facilities. They have limited or no access to basic facilities such as water supply, electricity, schools, hospitals, toilets, etc. They depend on water from wells or tube wells for drinking, household and agricultural purposes. Sometimes, people have to walk long distances carrying water. At the same time, due to lack of facilities and awareness, unhygienic sanitation practices are prevalent in such villages, which adversely affects health and quality of life. Finding ways to improve the lives of people in villages with their participation is the key to self-sustaining socio-economic development. Education, entrepreneurship, physical infrastructure, and social infrastructure play an important role in developing rural regions. The development must be sustainable as the resources available are limited and human needs are always growing.

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According to the United Nations, sustainable development is a guiding principle for economic, environmental, and social development to meet 'the needs of the present without compromising the ability of future generations to meet their own needs' and an 'equitable sharing of the environmental costs and benefits of economic development between and within countries' [1]. Sustainable development is the organizing principle for meeting human development goals while simultaneously sustaining the ability of natural systems to provide the natural resources and ecosystem services upon which the economy and society depend[b]. According to the UN Agenda 2030, sustainable development is of comprehensive and universal and with the objective of being transformative. "Comprehensive" means that sustainable development should include economic, social and environmental dimensions. "Universal" implies that sustainable development not only complies with economic, social and environmental goals on the local scale, but global challenges also must be addressed by national governments and institutions, to enable suitable "transformative" changes in our ways of life [2].

1.1 Food-Energy-Water Nexus and Sanitation

Food, energy, and water are three central factors necessary for poverty eradication and the social and economic well-being and prosperity. The Food-Energy-Water (FEW) nexus is central for sustainable development [3]. The FEW nexus refers to the complex and inextricable interlinkages (synergies and trade-offs) that exist among the water, energy, and food sectors, in pursuit of balanced and sustainable development. Demands for these three are increasing due to increased population, economic instabilities, social discriminations, etc.

Unscientific agricultural practices are one of the main reasons for over-exploitation of water thereby causing water scarcity. Improper agricultural practices pollute groundwater and nearby surface water sources. Different processes involved in food production, namely, land preparation, fertilizer production, irrigation, sowing, using nutrients and fertilizers, harvesting, processing, and transportation of crops demand energy which is either limited or unavailable in off-grid villages. Also, a considerable amount of solid waste and wastewater are generated as a result of agricultural practices and human needs. Improper management of these wastes eventually causes soil erosion, land and water pollution and the outbreak of epidemics. The continuous growth of the same type of crops without proper replenishment of soil using organic fertilizers leads to a decrease in fertility of the soil resulting in low productivity. In order to attain overall socio-economic rural development, the issues and concerns with respect to food, energy, and water need to be addressed in a sustainable manner.

In addition to the issues related to food, energy, and water, another major problem faced by the people in off-grid villages is the need for proper sanitation. People may choose fields, bushes or other open lands for defecation due to traditional practices and lack of toilets [4]. Over 800 children under the age of five die every day from preventable diarrhea-related diseases around the world[c]. Water scarcity, poor water quality, and inadequate sanitation adversely affect the health, livelihood choices and educational opportunities of people in rural areas[d]. Therefore, people in rural areas must be empowered and made aware of the significance of proper hygienic practices. Facilities including toilets should be provided to ensure proper hygiene and sanitation. One of the targets of the UN sustainable development goals is to provide access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations by 2030[d]. In India, a cleanliness campaign named 'Swachh Bharath Abhiyan' (Clean India Mission) was launched in 2014 by the Government of India with the aim of 'clean India' by 2019[e]. Its objectives include the construction of household-owned and community-owned toilets thereby eliminating open defecation and improving sanitation. The government claims the mission as a massive success with about 92 million toilets built in rural areas.

The main challenge in rural areas is that access to toilets alone does not prevent open defecation and provide better sanitation. The people in rural areas must be educated about the health and environmental consequences of open defecation. The toilets and other sanitation systems should be maintained properly by facilitating proper sewage treatment and disposal. In order to ensure the proper functioning of sanitation facilities, an adequate amount of water and energy must be available. Water is required to maintain clean and hygienic toilets. Energy requirements are related to lighting bulbs inside the toilets, thus facilitating safe access to toilets at night. Therefore, in the context of off-grid Indian villages, the Sanitation-Energy-Water (SEW) nexus which includes the interlinkages between sanitation, water, and energy can be formulated similarly to the FEW nexus. The main elements of the FEW and SEW nexus are illustrated in Figure 1. By addressing the issues related to food, energy, water and sanitation, healthy and sustainable rural development is possible.

1.2 Social Entrepreneurs for Rural Development

One of the important concepts of sustainable socio-economic development in rural areas is social entrepreneurship. Social entrepreneurship (SE) is "an innovative, social value-creating activity that can occur within or across the non-profit, business or government sectors" [5]. The primary focus of SEs is to make a social contribution or social value. SEs encompass a variety of individuals with different backgrounds having social objectives with or without profit interests as their motivation [6]. The main difference between social entrepreneurship and business entrepreneurship is that social entrepreneurship focuses beyond simply generating a profit. SEs measure their performance based on the social, cultural or environmental positive impact that they make on society, yet earn profits to achieve financial self-sustainability.

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[b] Wikipedia, "Sustainable Development," Webpage: https://en.wikipedia.org/wiki/Sustainable_development, Accessed on: May 29, 2019.

[c] Water for South Sudan, "The importance of sanitation for all especially children", Webpage: https://www.waterforsouthsudan.org/wfss-blog-use/2016/4/13/the-importance-of-sanitation-for-all-especially-children, Accessed on February 23, 2020

[d] Sustainable Development Goals, "Goal 6: Ensure access to water and sanitation for all", Webpage: https://www.un.org/sustainabledevelopment/water-and-sanitation, Accessed on February 23, 2020.

[e] PM India, "Swachh Bharat Abhiyan", Webpage: https://www.pmindia.gov.in/en/major_initiatives/swachh-bharat-abhiyan/, Accessed on February 23, 2020.

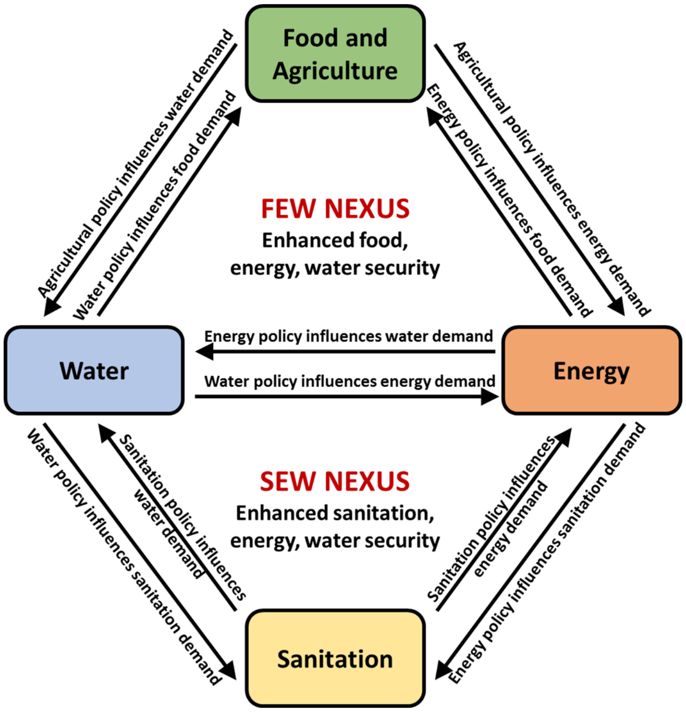


FIGURE 1: THE INTERFACES AMONG FOOD, ENERGY, WATER, AND SANITATION

SunMoksha is one such enterprise that develops and field-deploys clean and sustainable technology solutions in off-grid Indian villages[f]. SunMoksha's goal as a social enterprise is to improve the quality of life of people at the bottom of the economic pyramid. The development model of SunMoksha is based on a holistic systems approach as shown in Figure 2. The focuses in this development model are smart solutions, access to basic facilities like electricity, water, etc. and education, skill set development and microenterprises as depicted in the gears in Figure 2. SunMoksha's development process begins with interventions through smart technologies and assets that provide access to essential services and create livelihood opportunities. It trains local personnel during and after the deployment of the solutions and assets. The creation of livelihood and enterprise activities reduces the pressure on agriculture and creates an ecosystem for development for improved quality of life.

The different sustainable solutions provided by SunMoksha include, but are not limited to the following:

- Smart AQUAnet™: to deliver the appropriate quantity of water and nutrients to farms,
- Smart Nanogrid™: to supply the appropriate amount of electricity at the right locations,
- Smart MEZ™: to provide holistic and inclusive rural socio-economic development through technology intervention.

These smart interventions together with their efficient utilization creates an ecosystem for sustainable development and economic growth of the community, eventually creating Smart Villages.

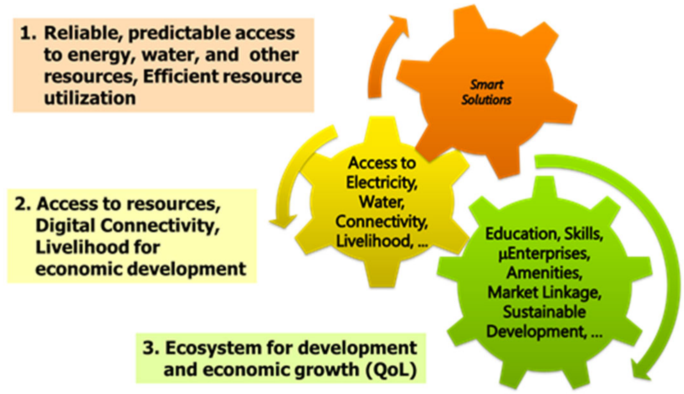


FIGURE 2: DEVELOPMENT MODEL BY SUNMOKSHA[f]

SunMoksha establishes robust technical solutions and sustainable development processes that can be rapidly deployed and scaled up in villages, especially in under-served and un-served communities. Value propositions are developed to address the Food-Water-Energy nexus, within the constraint of the P^3 – people (social), planet (environmental) and progress (economic) that leads to sustainable socio-economic development.

SunMoksha, as a socio-technical enterprise, plays a complex role in the sustainable socio-economic development of the rural community through smart technological interventions. These smart technology solutions are termed "***intelligent assets***" as they employ the advancements in technologies associated with the fourth industrial revolution, known as Industry 4.0[g]. These advanced technologies employ the potentials associated with the Internet of Things, Cloud-based Design and Manufacturing, Meters and Sensors, Machine Learning-based intelligent decision support, etc. We believe that the intervention of social enterprises and the intelligent assets they provide, which are anchored in a balanced approach to people, plant and progress, are essential for the overall sustainable development of rural areas in India, given the support offered by the Indian government to such initiatives[h]. The intelligent assets that we focus on in this paper include technological innovations, physical infrastructure, information and communication technologies, etc. that can be adopted in off-grid villages, thereby providing food, energy, and water security.

As mentioned earlier, SunMoksha provides different smart interventions such as the Smart AQUAnet, Smart Nanogrid, etc. for the overall sustainable development of rural areas. These interventions provide necessary solutions for the water and energy needs of people living in off-grid villages thereby improving agricultural productivity and food security. Depending upon the needs of people, the appropriate solution or intelligent asset can be adopted in the villages. For example, if an off-grid village in India does not have a continuous source of water for daily use, separate smart interventions can be made to provide them with water as well as electricity. In some cases, providing separate systems for water and electricity may not be affordable or sustainable. In such cases, an integrated system that

[f] SunMoksha Power Private Limited, "SunMoksha - Clean Technology and Sustainable Solutions," https://sunmoksha.com/, Accessed on: November 26, 2019.

[g] Industry 4.0 Drives the Sustainable Development Goals, Webpage: https://techpolicyviews.com/review-updates/2018/11/18/industry-4-0-drives-the-sustainable-development-goals/, Accessed on: May 31, 2019.

[h] Ministry of Corporate Affairs, "National CSR Portal," https://www.csr.gov.in/, Accessed on: December 27, 2019.

provides a sustainable solution for both water and energy needs simultaneously may be required.

The stakeholders/decision-makers identify the best feasible solution for a particular village based on the requirements and the conditions in that village. For that, the issues and challenges faced by the people and possible solutions addressing them must be identified. Therefore, there is a need for a systematic method to identify and select the best suitable and sustainable solution. The solution selected should address the requirements of the people in the specific village under consideration. In this paper, we present a generic method based on the dilemma triangle construct and Go/No-Go analysis for identifying dilemmas and selecting sustainable solutions addressing them. The method is demonstrated by identifying the sanitation, energy, and water needs in off-grid villages. An integrated system that can be adopted as a possible sustainable solution to address water, energy, and sanitation needs is proposed. The proposed system facilitates proper wastewater treatment and solid waste management, thereby improving the health and sanitation of the people in off-grid villages. For this, the major issues associated with the three drivers- people, planet, and progress are identified considering the general case of an off-grid Indian village. The problem considered here is defined giving emphasis to water and sanitation needs of those living in off-grid villages.

2. PROBLEM DEFINITION AND PROPOSED METHOD

As previously mentioned, food, energy, water, and sanitation are the significant factors necessary for social and economic prosperity. Therefore, in this paper, we focus on the possibilities of improving the lives of people by addressing their food, energy, water and sanitation needs and thereby attaining overall sustainable development. The fundamental problem addressed is:

> "*How to provide safe water to people while addressing the issues of water scarcity, energy needs, waste disposal, and land productivity in a sustainable, economical and environment-friendly manner and thereby improving the quality of lives of people?*"

In order to attain sustainable development in off-grid villages, the issues associated with FEW nexus and sanitation must be addressed with respect to social, economic and environmental aspects. Once the key issues are identified, the main focus is to propose sustainable solutions addressing the key issues and to provide people with opportunities for economic development, thereby providing them hope for a brighter future. The set of sustainable solutions identified needs to be further evaluated in terms of adaptability, applicability, and feasibility from the context of the off-grid village being considered. The best solution that satisfies the demands and wishes needs to be selected. The solution thus selected is accepted as a value proposition following a reality check by the stakeholders involved. A method to carry out these steps is presented next. The strength of this method is its generic nature. The same method can be applied for different domains where there are drivers with conflicting focus and issues. The outcome from this paper is a generic method using which human designers are able to identify, prioritize and select solutions for complex systems problems (such as FEW nexus, SEW nexus, etc.) that involve conflicting drivers and requirements.

Method to identify and select sustainable solutions (value propositions) for FEW and sanitation needs

"Dilemma triangle construct" is used to identify the major focuses for sustainable development from the perspective of food, energy and water and the issues associated with them [7]. The focuses and issues related to sanitation are included in the perspective of the water. The dilemma triangle construct can be used to identify dilemmas in a complex system that has three drivers with three or more goals. More details on the dilemma triangle method are available in [7] and [8]. Using this method, a decision-maker structures a problem to identify, prioritize and select solutions for complex problems. The novelty of the method presented in this paper is that it combines the dilemma triangle construct with go/no-go analysis. Our method improves the existing dilemma triangle method by facilitating a way for decision makers to identify, prioritize and select the best suitable solution from a set of possible solutions using go/no-go analysis. The complex system considered here is the food-energy-water nexus within an off-grid village in India. The steps involved in developing the dilemma triangle from the perspective of food, energy, and water are summarized as follows and are illustrated using Figure 3.

Step 1: Identify the key drivers – The main objective of decision maker using the dilemma triangle construct is to identify dilemmas and come up with sustainable solutions. Thus, the drivers are chosen in such a way as to consider the social, environmental, and economic factors, which are the three pillars of sustainability. Taking this into consideration, the drivers are selected as people, planet, and progress (P^3) respectively as shown in Step 1 in Figure 3. P^3 is identified as the key drivers based on the SunMosha's development model to ensure sustainable socio-economic development.

Step 2: Define the drivers in terms of focus and issues – The drivers are the major focuses for sustainable development and then the possible issues that may arise while trying to achieve the focuses are identified. The focus with respect to each driver is a statement/sentence emphasizing the goal of a social entrepreneur /decision maker for the particular driver (e.g., people, planet, progress), given a specific perspective (food, energy, water). The driver will vary depending upon the requirements of people and the goal of social entrepreneur. The possible dilemma triangles for food, energy, and water is shown in Figure 4. The dilemma triangle for water includes the focus and issues concerning both water and sanitation. In this paper, the primary focuses with respect to people, planet and progress and the probable issues in achieving the corresponding focuses are identified by considering the general scenario of an off-grid village in India, where agriculture is the major source of living. The issues are identified with respect to three drivers of sustainable development – Social (People), Environmental (Planet) and Economical (Prosperity or Progress) aspects.

Step 3: Identify the tensions and inter-perspective tensions – The issues identified for each focus in the three perspectives in Step 2 are compared to identify tensions and inter-tensions using a tension matrix. In a particular perspective, the issues which conflict in such a way that when we try to solve one issue, the

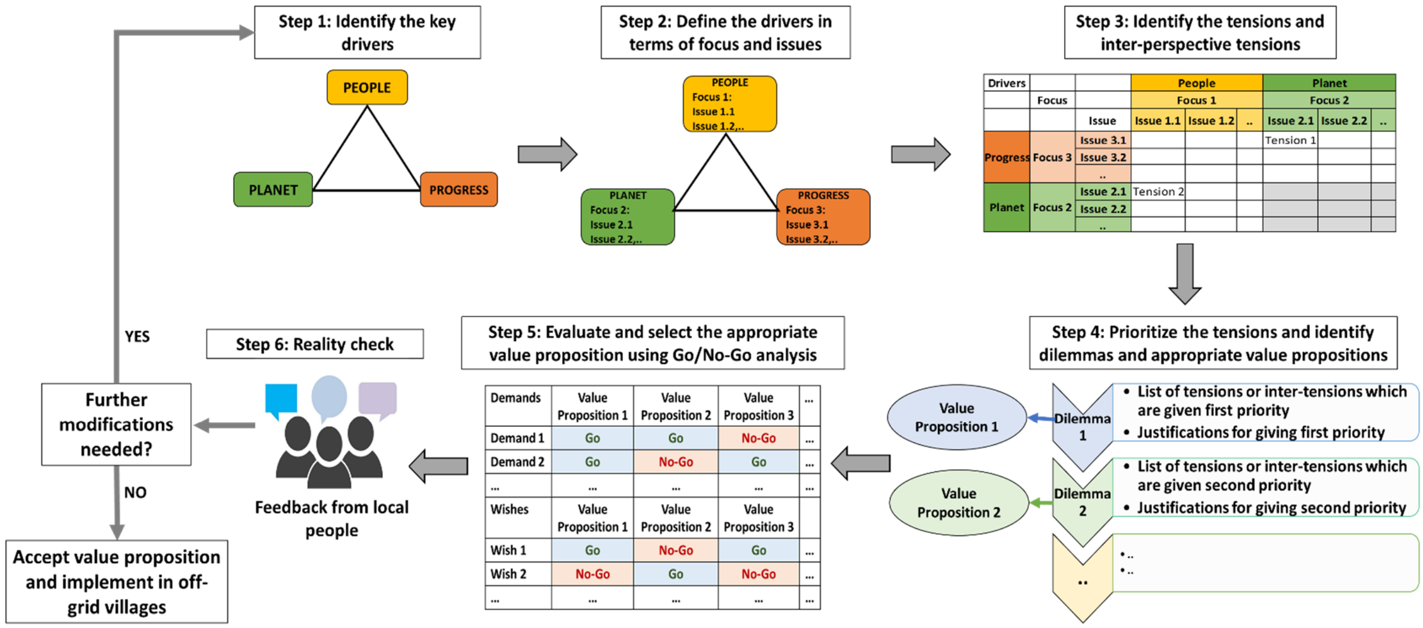


FIGURE 3: STEPS INVOLVED IN IDENTIFYING AND SELECTING VALUE PROPOSITIONS

other is impacted negatively, are identified as tensions [7]. The issues which conflict across different perspectives are identified as inter-tensions. The tension matrix identifying the key tensions from the perspective of water and sanitation is shown in Table 1.

Step 4: Prioritize the tensions and identify dilemmas and appropriate value propositions – The different tensions and inter-tensions identified in Step 3 are prioritized by giving weightage and consideration to the needs of the system considered. Here, the need for potable water and proper sanitation in off-grid Indian villages are given more priority than other needs. Based on the needs of the system, the dilemma to be addressed is identified and suitable value propositions are identified. The value propositions include technological or smart interventions like Smart AQUAnet^{TM}, Smart Nanogrid^{TM}, etc. provided by SunMoksha for the overall sustainable development of rural areas.

Step 5: Evaluate and select the appropriate value proposition using Go/No-Go analysis – The different value propositions identified in Step 4 are evaluated and analyzed considering their advantages and disadvantages using Go/No-Go analysis. Using Go/No-Go analysis, we are able to identify the most feasible solution out of the set of possible value propositions. The evaluation criteria for the Go/No-Go analysis are selected to determine the sustainability, adaptability and economic and environmental feasibility of the solutions. The demonstration of the applicability of Go/No-Go analysis is detailed in Section 5 of this paper.

Step 6: Reality check – In this step a reality check is carried out by the various stakeholders (which include social entrepreneurs, local government, village-level governing officials, local people, etc.) to identify the suitability and adaptability of the selected solution in the context of the off-grid Indian village under consideration. For this, stakeholders must be given awareness about the proposed solution/technology, its applicability, advantages, disadvantages and working principles. Based on their collective feedback, further modifications should be made to the proposed solution or the method, if necessary.

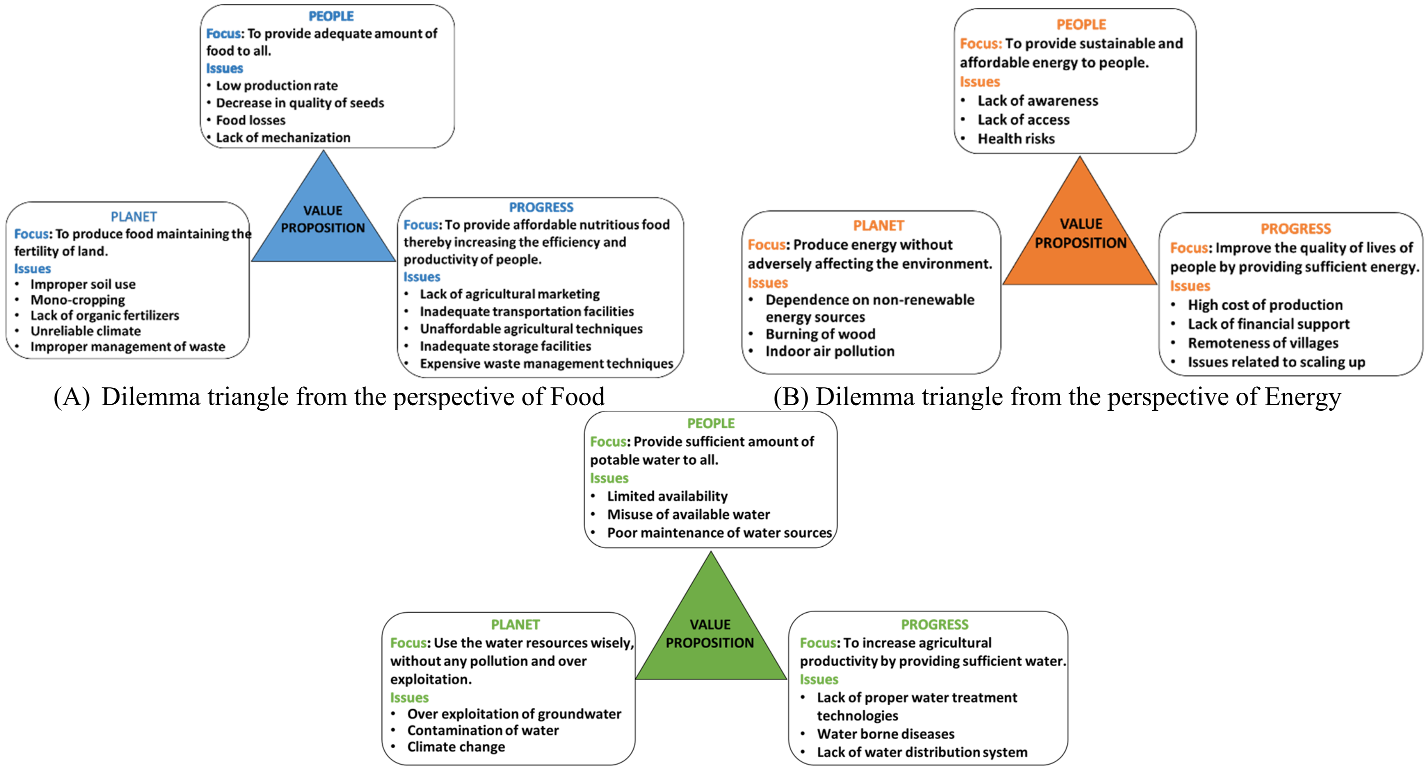
The feasible solution that best satisfies the requirements of the people in off-grid villages are accepted and will be implemented in that particular off-grid village. Safe (clean and potable) water is one of the basic needs for life. Hence, the issues concerning the need for clean water is given more priority in this paper. Treatment of water is essential for making the available water safe for people. Recycling the used water, after proper treatment using appropriate technologies, can be considered as a feasible solution to address the issues of water scarcity. The need for sustainable energy is also as important as clean water. The dependence on non-renewable resources must be reduced and technologies supporting renewable energy sources must be promoted. For improving the health and hygiene of the people, proper waste management techniques must be introduced. This will prevent the unhygienic practices that cause pollution and the outbreak of diseases. Giving importance to all the issues mentioned and prioritizing them, a comprehensive solution must be adopted and implemented in off-grid villages to attain sustainable development. The solution adopted must be sustainable, economic and environment-friendly and should provide hope and happiness to the people living there.

The requirements identified for defining and formulating the problem are as follows.

Requirement 1: A proper treatment facility to provide safe water to people.

Requirement 2: Address the issues related to solid waste and wastewater disposal.

Requirement 3: Meet the specific energy needs of the people using a self-sustainable intervention.



(A) Dilemma triangle from the perspective of Food

(B) Dilemma triangle from the perspective of Energy

(C) Dilemma triangle from the perspective of Water

FIGURE 4: DILEMMA TRIANGLES FROM THE PERSPECTIVES OF FOOD (A), ENERGY (B) AND WATER (C)

TABLE 1: TENSION MATRIX FOR WATER AND SANITATION

Drivers			**Progress**			**People**		
	Focus		To increase agricultural productivity by providing sufficient water.			Provide sufficient amount of potable water to all		
		Issue	Lack of proper water treatment	Water borne diseases	Lack of water distribution system	Limited availability	Misuse of available water	Poor maintenance of water sources
Planet	Use the water resources wisely, without any pollution and over exploitation	Over exploitation of groundwater				Tension		
		Contamination of water						
		Climate change						
People	Provide sufficient amount of potable water to all	Limited availability	Tension					
		Misuse of available water			Tension			
		Poor maintenance of water sources						

As discussed, for attaining self-sustainability in off-grid villages, the demand for clean water, sustainable energy, and waste management must be satisfied in an economic and environmentally friendly manner. To address this need, several challenges and gaps are identified, which include complicated and energy-intensive water treatment techniques, difficulties in wastewater disposal, the requirement of large areas for solid waste disposal, unavailability of environment-friendly energy production, etc. The major challenges and attributes for the solution identified are shown in Figure 5.

The scope of this paper is limited to addressing only two gaps: (i) a systematic method to address both water treatment and energy production simultaneously and (ii) a systematic method for the conversion of solid wastes into organic fertilizers. Thus, the primary question addressed is: *What are the working principles of an integrated self-sustaining system for water treatment, energy production, and waste management meeting the needs of people in villages in a sustainable, economical and environment-friendly manner?*

By proposing an integrated system for water treatment, energy production, and waste management simultaneously, in a sustainable, economical and environment-friendly manner that involves the participation, collaboration and contribution of villagers, the overall development of off-grid villages is possible.

3. PROPOSED SOLUTIONS FOR FEW AND SANITATION NEEDS

Constructed wetlands, bioenergy, solar photovoltaic cells, thermal hydrolysis, and microbial fuel cells are some of the possible technologies that can be used to address both water and energy needs simultaneously. All these solutions have advantages and limitations in order to be implemented in an off-grid village, see Table 2.

The different possible solutions are evaluated based on their sustainability, applicability, and adaptability in off-grid villages using Go/No-Go analysis. The criteria for evaluation are selected to determine the feasibility of the identified solutions. The Go/No-Go matrix used for the evaluation is shown in Table 3. The demands in the matrix represent the mandatory characteristics required for the possible solution and the wishes represent those characteristics that are desirable but not mandatory. The solution which has more "Go" is selected as best feasible from the set of possible solutions. The demands and wishes for the analysis are defined in the context of solutions addressing sanitation, energy, and water needs of the people in off-grid villages. The description of each criterion used for the analysis is shown in Table 4.

Based on the analysis of advantages and disadvantages of the above-mentioned technologies, thermal hydrolysis and microbial fuel cell technology are potential solutions to simultaneously address the need for proper wastewater treatment, reduction of solid waste and energy production. However, high temperature and pressure requirements of thermal hydrolysis make it less suitable for implementing in rural off-grid communities. On the other hand, microbial fuel cell technology can be set up using less expensive materials and can be considered as a relatively viable solution for addressing the sanitation, energy, and water needs of people in off-grid villages. The justification for selecting microbial fuel cell technology from the set of potential solutions is given in Table 5. The justifications for not selecting the other solutions are beyond the scope of this paper and are not included.

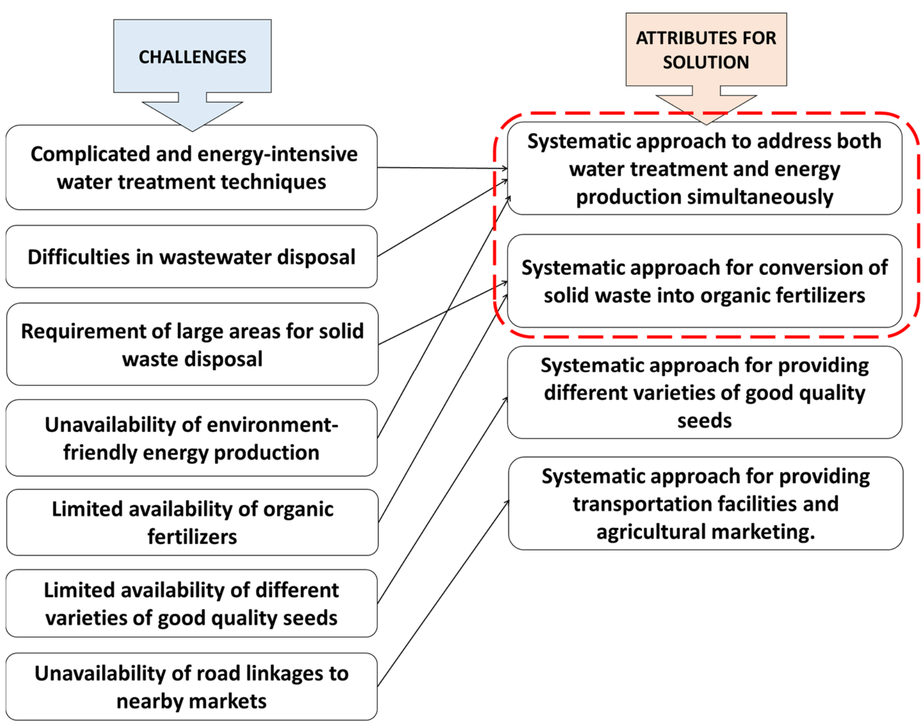


FIGURE 5: CHALLENGES AND ATTRIBUTES FOR THE SOLUTION

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TABLE 2: ADVANTAGES AND DISADVANTAGES OF SOME OF THE POSSIBLE SOLUTIONS CONSIDERED

POSSIBLE SOLUTIONS	PROS	CONS
Constructed wetlands [9]	• Man-made constructed systems, treat wastewater without any additional energy or chemical input. • Cost-effective and environment-friendly treatment. • Reuse of treated wastewater for irrigation and/or other purposes.	• Require a large land area. • Need preliminary treatment before wastewater can be treated by the system. • Need higher retention time and may cause problems with pests. • Addresses the issue of wastewater disposal only.
Bioenergy[i]	• A reliable source of renewable energy derived from biological sources. • Fuel is a by-product, residue or waste product from agriculture, animal husbandry or forest.	• Energy content derived from biomass is small. • Uses a lot of wood from natural forests which can lead to deforestation. • The cost of harvesting, extracting, transporting and handling biomass is high. • Addresses the issue of energy needs and solid waste disposal.
Solar Photovoltaic Cell[j]	• Electricity produced by solar cells is clean and silent. • PV systems do not cause air or water pollution, deplete natural resources, or endanger animal or human health.	• Solar energy has intermittency issues. • Solar energy storage is expensive and requires space. • Addresses the issue of energy needs only.
Thermal Hydrolysis [10]	• Serves *three* purposes: wastewater treatment, reduction of waste byproduct (sludge) and production of biogas. • Sludge is heated and compressed in large vats.	• Temperatures required range from 160 to 165 degrees Celsius • The pressure required ranges from high pressure 7 – 11 or 12 bars. • The method is expensive and practically not possible in off-grid villages.
Microbial Fuel Cell [11]	• Performs three functions simultaneously. • Uses bacteria to clean wastewater. • The byproduct of the bacteria's consumption of wastewater sludge is charged electrons that can be converted into electricity. • Can be set up using less expensive materials.	• Power produced from a single MFC unit is limited. • Can be used only for powering devices that have low power needs.

TABLE 3: GO/NO-GO ANALYSIS MATRIX

DEMANDS	CONSTRUCTED WETLANDS	BIOENERGY	SOLAR PHOTOVOLTAIC CELLS	THERMAL HYDROLYSIS	MICROBIAL FUEL CELL
Address water needs	No-Go	No-Go	No-Go	Go	Go
Address energy needs	No-Go	Go	Go	Go	Go
Address wastewater disposal	Go	No-Go	No-Go	Go	Go
Self-sustainable	Go	No-Go	No-Go	No-Go	Go
Practically feasible in off-grid villages	Go	Go	Go	No-Go	Go
Consistency	Go	No-Go	No-Go	No-Go	Go
Cost-effective	Go	Go	Go	No-Go	Go
WISHES	**CONSTRUCTED WETLANDS**	**BIOENERGY**	**SOLAR PHOTOVOLTAIC CELLS**	**THERMAL HYDROLYSIS**	**MICROBIAL FUEL CELL**
Easy maintenance	No-Go	Go	Go	No-Go	No-Go
Less land requirement	No-Go	Go	No-Go	No-Go	Go
Address water and energy needs simultaneously	No-Go	No-Go	No-Go	Go	Go

[i] Energy Alabama, "Pros and Cons of Bioenergy", https://alcse.org/pros-and-cons-of-bioenergy/, Accessed on May 29, 2019
[j] Renewable Energy World, "Advantages and Disadvantages of Solar Photovoltaic – Quick Pros and Cons of Solar PV", https://www.renewableenergyworld.com/2012/12/19/advantages-and-disadvantages-of-solar-photovoltaic-quick-pros-and-cons-of-solar-pv/#gref, Accessed on May 29, 2019.

TABLE 4: DESCRIPTION OF THE CRITERIA FOR GO/NO-GO ANALYSIS

DEMANDS	CHARACTERISTICS OF THE POSSIBLE SOLUTIONS
Address water needs	The solution should be capable of addressing the water needs of the people in off-grid villages. The solution should facilitate the treatment of water for making the available water safe for people.
Address energy needs	The solution should completely/partly address the energy needs of the people in off-grid villages.
Address wastewater disposal	For improving the health and hygiene of the people in off-grid villages, the solution should facilitate proper wastewater disposal/treatment.
Self-sustaining	In the context of off-grid villages, a solution is considered self-sustaining if it addresses sanitation, energy, and water requirements without a need for interventions from external sources.
Practically feasible in off-grid villages	The solution set up using easily available, environment-friendly materials and easily operated can be considered practically feasible in off-grid villages.
Consistency	The solution should address the issues without any intermittencies.
Cost-effective	In the long term, the solution should be economically productive.
WISHES	
Easy maintenance	The solution is desired to have no or less maintenance.
Less land requirement	The solution using less land/space for installation and operation is desirable.
Address water and energy needs simultaneously	The solution is desired to address both water and energy needs simultaneously.

TABLE 5: JUSTIFICATION FOR GO/NO-GO ANALYSIS – MICROBIAL FUEL CELL

DEMANDS	MICROBIAL FUEL CELL	JUSTIFICATION
Address water needs	Go	Microorganisms in the microbial fuel cell consume the impurities in wastewater and provide relatively clean water. This water can be used for agricultural purposes or can be treated further for domestic uses, thereby addressing water needs.
Address energy needs	Go	Microbial Fuel Cell is a device that converts chemical energy into electrical energy by the action of microorganisms. They are used for power generation applications that require only low power, see [12].
Address wastewater disposal	Go	Different types of wastewater including domestic wastewater, agricultural wastewater, etc. can be used for deriving energy using microbial fuel cell technology, thereby addressing the issues of wastewater disposal, see [15] and [16].
Self-sustainable	Go	MFCs are energy-positive based on their low energy consumption and direct electricity generation, see [15]
Practically feasible in off-grid villages	Go	MFCs can be set-up using less expensive and environment-friendly materials that are easily available making this technology suitable for off-grid villages, see [16]
Consistency	Go	MFCs can be operated as long as wastewater is available. There are no issues of intermittencies.
Cost-effective	Go	Although the initial setup cost of conventional MFCs may be high, energy-efficient, low-cost and cost-effective modifications are possible, see [17–19]
WISHES	**MICROBIAL FUEL CELL**	
Easy maintenance	No-Go	There are chances of accumulation of ions on the proton exchange membrane, thereby reducing the performance of MFCs. Periodic inspection and maintenance may be required, see [21] and [22]
Less land requirement	Go	MFCs do not require extensive areas for operation. The size of the set-up depends upon the amount of wastewater to be treated, the energy produced, etc.
Address water and energy needs simultaneously	Go	MFCs utilizes microorganisms to convert organic matter present in wastewater into electrical energy. During this process, both clean water and energy are produced simultaneously.

4. MICROBIAL FUEL CELL TECHNOLOGY

A Microbial Fuel Cell (MFC) is a device that converts chemical energy into electrical energy by the action of microorganisms [11]. Applications of MFCs include power generation, wastewater treatment, hydrogen production, etc. MFC consists of an anode chamber containing an anode and a cathode chamber containing cathode. These chambers are separated by a proton exchange membrane. Microorganisms at the anode oxidize the organic matter generating protons and electrons. Protons pass through the membrane to the cathode and the electrons pass through the anode to an external circuit to generate current. Protons and electrons reaching the cathode chamber react with oxygen to form pure water[k].

The schematic representation of a conventional MFC is shown in Figure 6. A mediator (chemicals like methylene blue, natural red, thionine, etc.) is used to transfer electrons from the bacteria in the cell to the anode[k]. Modifications can be done to conventional MFCs to improve the performance and make the system economical and cost-effective. Mediator-less MFC uses electrochemically active bacteria (*Shewanella putrefaciens*) to transfer electrons directly to the electrode so that the use of hazardous chemicals in MFCs can be eliminated [22]. The power output generated from an individual MFC unit is insufficient for most practical applications, therefore to increase power, the series configuration of individual MFC units needs to be implemented into a stack [23]. MFC stack designs can be adopted where several cells are connected in series and/or in parallel in order to achieve the desired voltage and current and, ultimately, power. In Table 6, a literature search on microbial-fuel cell-based technologies and applications are presented.

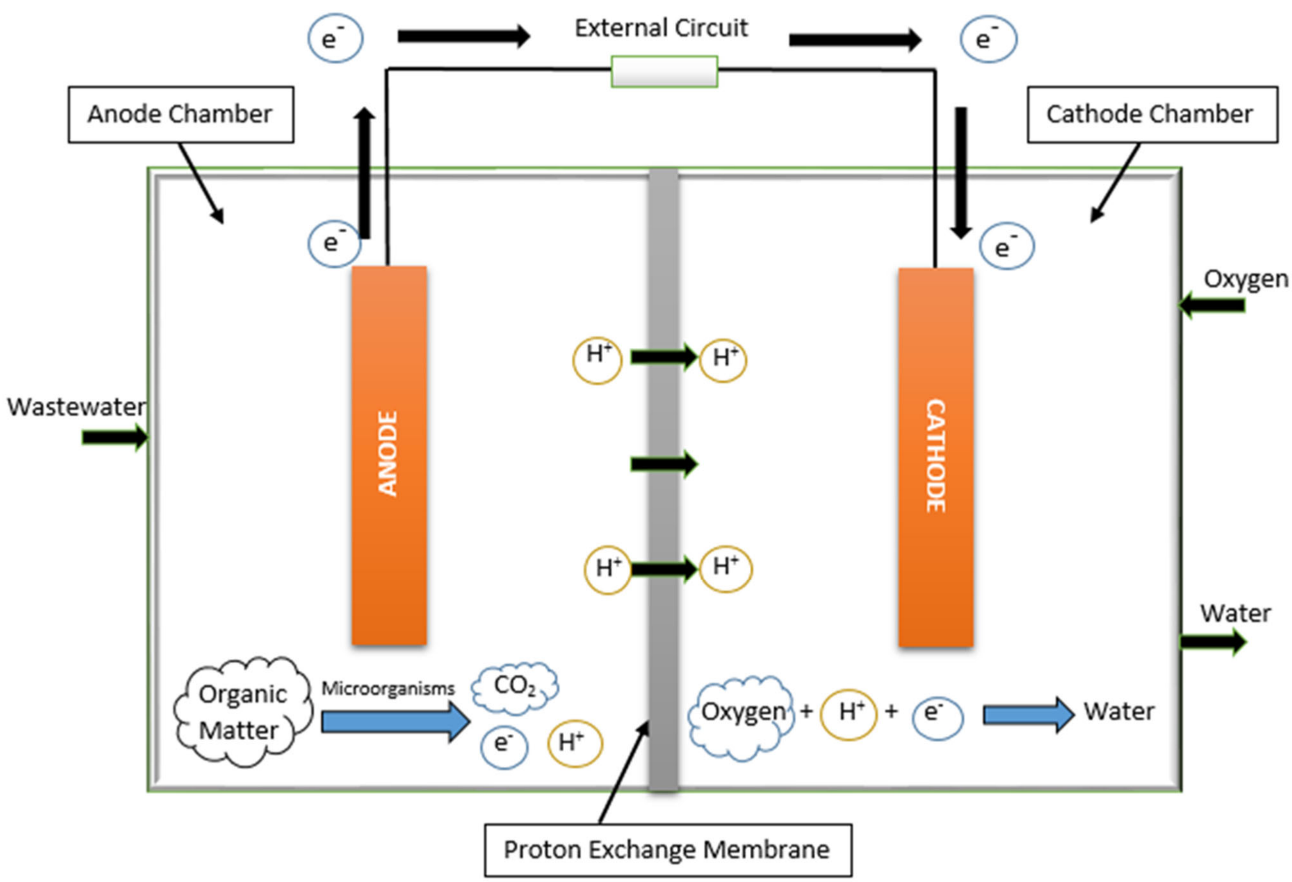

FIGURE 6: SCHEMATIC REPRESENTATION OF A TYPICAL MICROBIAL FUEL CELL

[k] Alternative Energy, "What are Microbial Fuel Cells," Webpage: http://www.altenergy.org/renewables/what-are-microbial-fuel-cells.html, Accessed on: May 29, 2019.

TABLE 6: MICROBIAL FUEL CELL-BASED TECHNOLOGIES – LITERATURE SEARCH

Topic	Reference	Application Details
A microbial fuel cell–membrane bioreactor integrated system for cost-effective wastewater treatment	Wang and co-authors [17]	• MFC–MBR integrated system for simultaneous wastewater treatment and energy recovery. • Low-cost materials were used for reactor construction. • The influent flow rate was 2.33L/hr. • Average current of 1.9 ± 0.4 mA achieved over a period of 40 days. • Maximum power density of 6.0W/m^3.
Low-Cost, Single-Chambered Microbial Fuel Cells for Harvesting Energy and Cleansing Wastewater	Ashutosh Patra [18]	• MFCs were constructed from cheap alternatives to traditionally used, expensive Nafion® membranes. • A novel electrode-membrane-cathode assembly was shown to produce 4.33 times the amount of energy per dollar than the typical current laboratory MFC. • Current and potential of 0.78 mA and 0.59 V respectively were generated by a 9 cm^2 anode.
Pee power urinal – microbial fuel cell technology field trials in the context of sanitation	Ieropoulos and co-authors [13]	• Demonstrated the feasibility of modular MFCs for lighting. • A mixture of activated sewage sludge and fresh urine was used for treatment. • Total liquid capacity of the system was 25 liters. • Field trial consisted of 288 MFCs (8 modules with 36 MFCs in each) generating 75 mW (mean), 160 mW (max) with 400 mW when the lights were connected directly without supercapacitors.
Continuous electricity production from artificial wastewater using a mediator-less microbial fuel cell	Moon and co-authors [24]	• MFC was optimized in terms of MFC design factors and operational parameters for continuous electricity production using artificial wastewater. • Highest power density of 0.56 W/m^2 was achieved with wastewater fed at the rate of 0.53 ml/min at 35°C.

A microbial fuel cell can be adopted as a technique for simultaneous wastewater treatment and energy production. For achieving self-sustainability, an integrated system for water treatment, energy production, and waste management for villages in a sustainable, economical and environmentally friendly manner is required. A possible approach involving a microbial fuel cell that can be implemented in an off-grid village for addressing the issues of water treatment, energy needs, and waste disposal is presented schematically in Figure 7. In addition to microbial fuel cells, the integrated system incorporates different systems/technologies such as a primary settling tank, composting system, filtration/disinfection system, etc.

The wastewater generated from households includes wastewater from kitchens, toilets, cattle housing, etc. Low strength wastewater can be directly fed into the MFC system. A primary settling tank is incorporated for separating the solid contents in high strength wastewater before feeding into the MFC system. Wastewater reaching the MFC system is treated using microorganisms and electricity is generated. Electricity generated can be used to power small LED lights in toilets or can be stored in rechargeable batteries. Treated water from the MFC can be reused for household or agricultural applications where clean water is not required. Also, water from the MFC can be further treated using filtration or disinfection to get more clean water, if needed. Settled solids from primary settling tank and solid wastes from kitchens, animal wastes, straw, etc. decompose in a composting system to form compost. Compost is rich in nutrients and can be used as an organic fertilizer.

The proposed integrated system is developed to address the three requirements, namely, water, energy, and sanitation needs, as mentioned below.

Requirement 1: Provide safe water – By integrating microbial fuel cell and filtration/disinfection technologies, safe and clean water can be obtained.

Requirement 2: Address energy needs – A microbial fuel cell converts chemical energy from organic matter into electrical energy, which can be utilized for lighting small bulbs or stored in rechargeable batteries.

Requirement 3: To address sanitation needs – Addressing sanitation needs include taking care of both wastewater and solid wastes. A microbial fuel cell facilitates the treatment of wastewater by the action of microorganisms. Solid wastes generated are converted into useful compost with the help of the composting system. Therefore, by integrating the MFC and composting system, the sanitation needs of the people can be addressed.

The integrated system is a self-sustaining solution as the above-mentioned requirements are addressed without any external intervention. Electricity is produced using wastewater generated within the system (kitchen, toilets, etc.) and this electricity is used within the system (lighting LED bulbs in toilets) itself. Also, the clean water obtained during this process will return into the system.

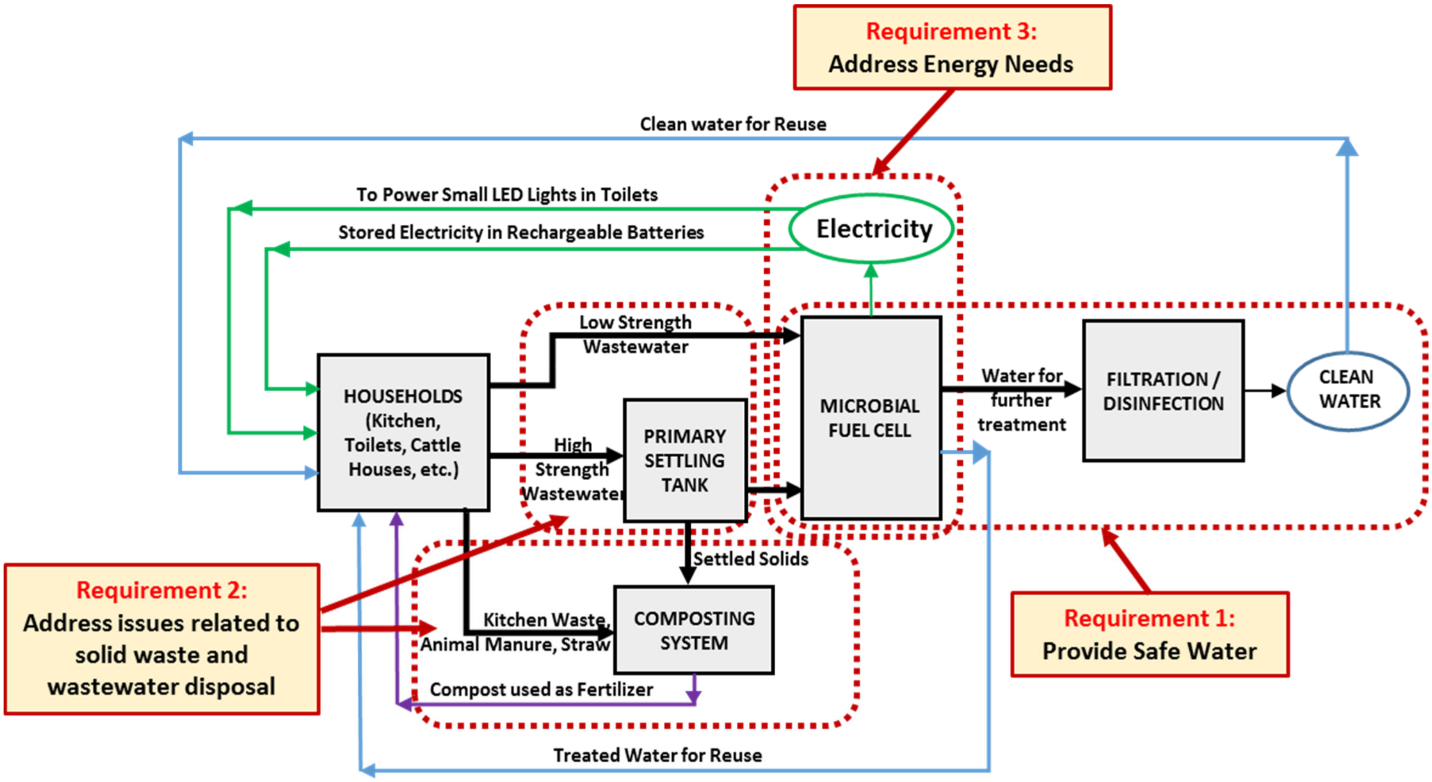

FIGURE 7: PROPOSED SOLUTION - AN INTEGRATED SYSTEM FOR WATER TREATMENT, ENERGY PRODUCTION, AND WASTE MANAGEMENT, SIMULTANEOUSLY.

5. SUSTAINABILITY 4.0 – SPECULATING ON THE FUTURE

Sustainable rural development is not a simple technique that can be achieved by a particular organization or social entrepreneur alone. It requires multiple partnerships from different sectors of science and technology. The possible solution proposed in this paper involves technologies that require academic, industrial and governmental support. The various techniques mentioned in the method should be adapted for an off-grid village. The characteristics and needs of each village will be different from each other. The primary step towards achieving sustainable rural development is to gather information about the actual issues and demands of the people in the village under consideration. For this, social workers, non-governmental organizations (NGOs) or volunteers from similar organizations have to meet the people in person and understand the socio-economic and environmental conditions of the village.

The next step is to design the solution in such a way that it meets the needs of people in a sustainable, economical and environmentally friendly manner. Modifications for the proposed design must be done to make the solution adaptable for the specific village, which is possible only with the help of researchers and academic institutions. Collaborations from different industries and manufacturing enterprises are necessary for producing and processing the required technology. Capital investment and financial backing is another essential factor required for making sustainable rural development possible. The expansion of e-tools in rural areas will enable villages to become more agile, make better use of their resources as well as improve the quality of life of rural residents [25]. Once an off-grid village is given access to electricity, the next step to becoming a smart village is by providing internet connections. The Internet of Things (IoT) is the future of communication and technology. It is the extension of internet connectivity into physical devices and everyday objects[l]. With the help of IoT, smart villages can adopt sophisticated technologies for improving agriculture, health, environment, water treatment, waste management and safety [26].

Sustainability 4.0, or the fourth sustainable revolution, involves the innovations like automation, intelligence, and data exchange in sustainable technologies. This is supported by the technologies associated with Industry 4.0. Sustainability 4.0 is characterized by the use of technologies like the Internet of Things for achieving sustainability and for conserving the environment[m]. In the near future, the trend in technology developing enterprises will be in exploring the combined possibilities of sustainability 4.0 and industry 4.0. The technologies of industry 4.0, e.g., artificial intelligence, machine learning, etc., will be utilized to attain sustainable development goals. Technology companies should consider both business and environmental goals simultaneously to stay productive and efficient. The integration of intelligence in production machinery and across the supply and distribution chain has great potential to reduce pollution, wastage, and emissions - contributing to

[l] Wikipedia, "Internet of Things," Webpage: https://en.wikipedia.org/wiki/Internet_of_things. Accessed on: May 31, 2019.

[m] Manoukian, J.-G., "Industry 4.0 Meets the 4th Wave of Environmentalism," Webpage: https://enablon.com/blog/2018/06/28/industry-4-0-meets-the-4th-wave-of-environmentalism, Accessed on: May 31, 2019.

sustainable industrialization through innovation[n]. The possible technologies and innovations needed for sustainable solutions are shown in Figure 8. These include data analytics and data-driven methods to capture information and knowledge; knowledge-based platforms for storage and reuse of knowledge; automation technologies that facilitate sustainable manufacturing and supply chains; cloud-based technologies that facilitate instant communication, sharing and collaboration; dematerialization to reduce the amount of resources for production, packaging, transportation along with reuse and recycling technologies; intelligent resources, sensors, and smart products that support human decision making, machine learning, and artificial intelligence to process information thereby supporting human decision making.

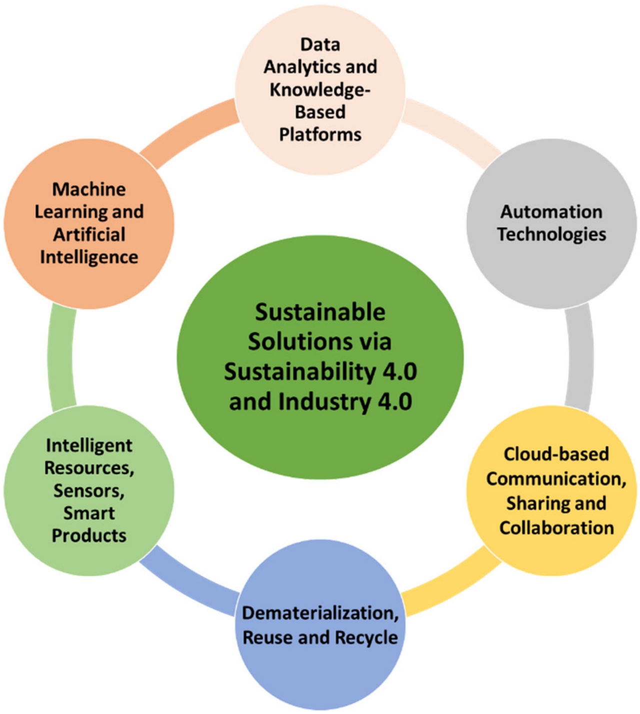

FIGURE 8: SPECULATING THE TECHNOLOGIES AND INNOVATIONS FOR SUSTAINABLE SOLUTIONS VIA SUSTAINABILITY 4.0 AND INDUSTRY 4.0

By leveraging these innovations and technologies, business enterprises, technology companies, social entrepreneurs, and leaders can raise the bar for sustainability to align business, social, economic and environmental goals. Industry 4.0 technologies like cloud-based design and manufacturing [27], and Fourth Wave innovations [28], can support these efforts by sharing valuable data, information, knowledge, and resources instantly. This paves way for open innovation and powerful collaboration among partners from industry, advocacy groups, and the communities thereby facilitating a cost-effective co-creation of value.

6. CLOSING REMARKS

In this paper, a method is presented to identify and select sustainable solutions addressing food, energy and water needs in off-grid Indian villages. The dilemma triangle construct and Go/No-Go analysis is incorporated in the method to help stakeholders/decision-makers in identifying and selecting sustainable solutions. The method presented here is generic and can be adapted to different domains addressing different issues.

In this paper, the efficacy of the proposed method is demonstrated by identifying the key FEW issues in an Indian off-grid village using the dilemma triangle construct. Using Go/No-Go analysis, the best feasible solution from a set of possible solutions addressing the dilemmas and issues is identified. Using this method, we propose an integrated system based on microbial fuel cell technology as an intelligent asset for simultaneously addressing sanitation, energy, and water needs in off-grid villages. Microbial fuel cell technology is a promising sustainable energy alternative with simultaneous water treatment and electricity generation. Villagers can be empowered to use the integrated system and exploit the advantages of MFC technology in terms of carrying out water treatment, energy production, and waste management simultaneously and thereby attain self-sustainability. By establishing a healthy and self-sufficient village, we are able to provide hope and happiness to the people living there. We expect that the challenges associated with achieving this goal can be overcome by the joint support and partnership with academic institutions, industries and other government and non-governmental organizations. Also, using Sustainability 4.0 and Industry 4.0 technologies, technology companies can scale sustainable solutions making socio-economic and environmental partnerships more productive, measurable, open, and collaborative.

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DISCLAIMER

In this paper, the authors try to address the sanitation, energy, and water needs of people in off-grid Indian villages. The focus and issues for constructing the dilemma triangle are identified based on these requirements as provided by SunMoksha, a social technical enterprise that operates in Indian off-grid villages addressing the needs of the people there. The authors do not intend to promote SunMoksha or its products. SunMoksha is considered as an example of a social enterprise for which the proposed method will be of value.

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