Localised Manufacturing of Solar-Powered Water Purification Systems for Rural Communities in South Africa: A Design Thinking Approach

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ABSTRACT

This paper examines the prospects of localised manufacturing of solar-powered water purification systems to solve water quality scarcity in rural communities in South Africa. The design thinking approach emphasises the importance of community engagement, modular system design, and sustainable partnerships in creating technically, economically, and socially viable solutions. The systems, which use solar technology for water purification, aim to reduce reliance on diesel-powered solutions and to promote environmental sustainability. Prototyping and iterative testing with local input ensure that systems meet specific community needs. The current study highlights challenges such as slow adoption rates, technical maintenance, and socio-economic impacts, and offers recommendations about local capacity building, simplified system designs, and integration with broader community infrastructure. The approach aligns with the United Nations' Sustainable Development Goals, particularly access to clean water, affordable energy, and sustainable communities. The study presents a model for replicable, community-centred innovation in resource-constrained environments.

OPSOMMING

Hierdie artikel ondersoek die vooruitsigte van gelokaliseerde vervaardiging van sonkrag-aangedrewe watersuiweringstelsels om waterkwaliteitskaarste in landelike gemeenskappe in Suid-Afrika op te los. Die ontwerpdenkebenadering beklemtoon die belangrikheid van gemeenskapsbetrokkenheid, modulêre stelselontwerp en volhoubare vennootskappe in die skep van tegnies, ekonomies en sosiaal lewensvatbare oplossings. Die stelsels, wat sonkragtegnologie vir watersuiwering gebruik, is daarop gemik om die afhanklikheid van diesel-aangedrewe oplossings te verminder en omgewings-volhoubaarheid te bevorder. Prototipering en iteratiewe toetsing met plaaslike insette verseker dat stelsels aan spesifieke gemeenskapsbehoeftes voldoen. Hierdie studie beklemtoon uitdagings soos stadige aanvaardingstempo's, tegniese instandhouding en sosio-ekonomiese impakte, en bied aanbevelings oor plaaslike kapasiteitsbou, vereenvoudigde stelselontwerpe en integrasie met breër gemeenskapsinfrastruktuur. Die benadering stem ooreen met die Verenigde Nasies se Volhoubare Ontwikkelingsdoelwitte, veral toegang tot skoon water, bekostigbare energie en volhoubare gemeenskappe. Die studie bied 'n model vir herhaalbare, gemeenskapsgesentreerde innovasie in hulpbronbeperkte omgewings.

1. INTRODUCTION

Localised manufacturing of solar-powered water purification systems for rural communities in South Africa could be effectively achieved through a design thinking (DT) approach [1]. This approach integrates community engagement, modular design, and sustainable partnerships [2]. The DT approach ensures that the systems are not only technically viable but are also socially and economically sustainable, thus addressing the unique needs of rural communities.

There are still homes in South Africa that rely on candles for illumination. About 5% of the entire South African population still depends on candles as their primary lighting source. This reliance equates to a substantial portion of the 16.6 million households in South Africa, highlighting a lack of access to the national electricity grid and indicating a need for solar energy [2].

The energy challenge in rural areas of South Africa affects the quality of water in rural communities across the country. Solar-powered water purification remains a viable option for achieving quality water in rural communities. To achieve a sustainable solar power energy generation system in rural communities, a DT approach would be indispensable to developing sustainable solutions [3]. The United Nations' Sustainable Development Goals (UNSDGs) underscore this current research.

Solar technology offers tremendous potential for addressing water purification needs [4]. By empathising with local users, the DT process allows a prototyping solution to be provided that creates systems that truly meet community needs; an empathetic DT process also helps to generate solutions with community involvement. It has often been observed that creating a solution to a community's needs without their involvement often leads to the waste of scarce resources and abandoned projects [5]. The DT approach leverages a flexible workforce, allows scalability, and potentially reduces operational costs compared with employing a full-time installation team. Design thinking has become a foundational methodology for developing solar water systems in rural South Africa. This human-centred approach has helped to create solutions that adequately addressed the needs of communities rather than imposing pre-conceived ideas. Table 1 focuses on recent studies on solar-powered water purification and DT.

Table 1: Previous studies on solar-powered water purification

Insight	Gap	Limitation	Ref
The study emphasises a DT approach to facilitate localised manufacturing of solar-powered water purification systems.	The paper highlights a slow uptake of solar water disinfection. There is a need for further research into the barriers to adoption and effective strategies to enhance user engagement.	The uptake of solar water disinfection is reducing, revealing a problem with increasing user adoption despite its potential benefits for safe drinking water access in rural areas.	[6]
The investigation highlights the importance of adapting technology to meet local needs and developing customer relations skills by understanding community requirements and logistical difficulties.	The need for improved community engagement indicates that previous projects were more of a giver–receiver relationship rather than fostering a true partnership with the community.	The team encountered problems related to the relationship with the community, which was initially more of a giver–receiver dynamic rather than a partnership.	[7, 8]
Production of modular components helps to meet communities' specific needs without requiring extensive expertise.	There is a need to develop user-friendly design methodologies that could simplify the configuration process for communities that lack technical expertise.	Designing a system for a specific location is difficult owing to the enormous number of design choices that are available and that require significant expertise.	[9]
The paper centres on establishing rural connectivity in South Africa through village operators, using wireless mesh network technology.	There is a lack of comprehensive analysis of the socio-economic impacts on the local communities of the connectivity provided by the village operators.	Remote villages lack infrastructure, which poses problems for the sustainability and resilience of the service.	[10]

Insight	Gap	Limitation	Ref
The exploration shows that providing clean energy and water through locally adapted renewable solutions, such as solar PV systems, can significantly drive socio-economic and sustainable development in off-grid rural communities.	The limitations of depending on a diesel-powered borehole pump for water supply include the high cost and the carbon footprint, leading to restricted opportunities for the development and growth of the village.	Limitations of relying on a diesel-powered borehole pump for water supply include the high cost and the unreliability of diesel fuel.	[11]
The paper discusses the implementation of autonomous, small-scale desalination systems for remote communities, emphasising renewable energy-powered membrane filtration.	Lack of real-world validation and consideration of practical operational factors in designing PV-powered water and energy systems for rural communities, which prior theoretical models often overlook.	The economic feasibility of installing classic centralised water and electricity systems in remote areas is limited owing to low population densities.	[12]
Solar energy-based low-cost rainwater purification system, which could inspire similar initiatives.	The paper does not address the long-term durability and maintenance requirements of solar-powered smart systems, which would be critical in ensuring their effectiveness in rural and underdeveloped regions over time.	The developed portable solar-powered purification system was tested only on a prototype scale, with limited capacity and performance data, and its long-term durability and effectiveness in diverse real-world conditions remain unverified.	[13]
The paper focuses on the design and manufacturing of a locally produced parabolic trough collector in Lesotho, emphasising indigenisation to enhance local economic benefits.	The study does not address potential scalability difficulties or the long-term sustainability of the manufacturing process in different regions of Africa.	The paper does not address potential economic or logistical problems that could arise in scaling up production or deployment in different regions in Africa.	[14]
The paper emphasises the importance of evaluating solar still designs based on function, quality, productivity, and cost, which could inform a DT process.	The paper does not address the long-term durability and maintenance requirements of the different solar still designs, which would be critical for implementation in rural settings.	Condensate drip-back was identified as a problem that would require using slopes.	[15]
The paper does not address the localised manufacturing of solar-powered water purification systems or a DT approach.	The feasibility study does not address the long-term impacts of climate change on groundwater levels.	Groundwater levels will need to be monitored to ensure the sustainability of the solar-powered groundwater pumping systems.	[16]

Despite previous innovations in the DT approach [6-16], it is clear that new research in design is needed to address the need for improvement, flexibility, affordability, sustainability, and best practices. This is what serves as the driving force behind this current study, which aims to contribute to the DT of sustainable solar-powered water purification in South Africa.

2. PRACTICAL STEPS IN SOLAR-POWERED WATER PURIFICATION SYSTEMS

2.1. Community engagement and co-design

The co-design process involves collaboration among designers, engineers, health and social scientists, and end users to ensure that the systems meet technical, economic, and social needs. This could be achieved through shared dialogue workshops and stakeholder engagement, which would be crucial for the acceptance and adoption of the technology in rural communities [17].

Engaging local communities in the design process helps to tailor solutions to specific cultural and environmental contexts, increasing the likelihood of successful implementation and long-term use. Figure 1 shows the modular solar water purification design that could be used in community engagement and interactive processes before the final architectural design.

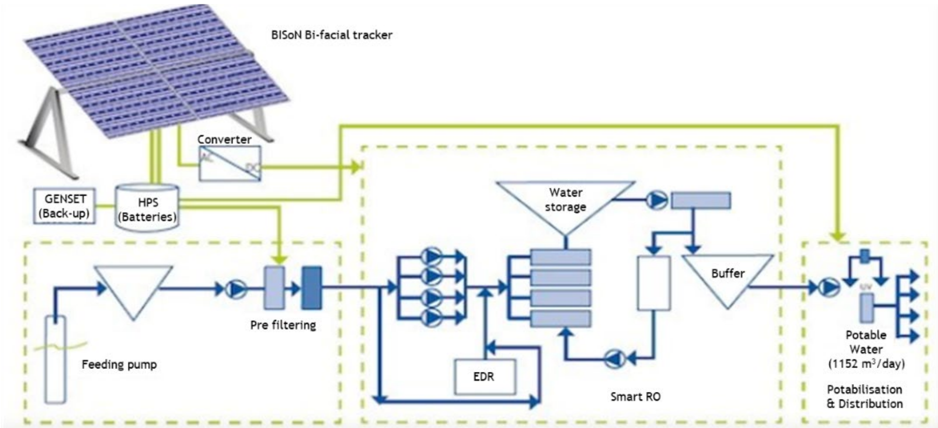

Figure 1: Schematic diagram of solar water purification system

2.2. Modular design and scalability

Modular design architecture allows for the creation of photovoltaic-powered reverse osmosis systems that are tailored to specific locations and water demands. This approach reduces manufacturing costs and enables non-experts to configure systems from modular components, making the technology more accessible to rural communities [18].

The scalability of solar-based water treatment systems, including solar pasteurisation and disinfection, provides an economical and sustainable solution that could be tailored to different community sizes and requirements around the world.

2.3. Sustainable partnerships

Establishing partnerships between local water-treatment experts, academic institutions, and rural municipal water treatment personnel could enhance the sustainability of water purification projects. Such collaborations would provide technical support and training, ensuring that the systems are maintained and operated effectively [19].

These collaborations have the potential to empower local stakeholders to oversee and maintain the water purification systems by promoting knowledge sharing and capacity building in the community. A thorough framework for creating localised water purification systems is provided by the DT approach. It is necessary to address issues such as the need for continuous technical support and the initial investment costs. Furthermore, combining solar-powered systems with conventional water treatment techniques could improve the general efficacy and acceptability of these technologies in rural areas.

A DT approach could achieve the localised manufacturing of solar-powered water purification systems for South African rural communities. This approach places a strong emphasis on community engagement, iterative prototyping, and user needs analysis – all of which are essential for creating long-lasting solutions in environments with limited resources.

2.4. Understanding community needs

Finding specific water quality problems and preferences through community engagement would guarantee that the solutions are pertinent and acceptable to the local culture. To learn more about the community’s current water sources and purification issues, surveys and workshops could be held [20].

2.5. Prototyping and testing

Developing inexpensive solar distillation equipment, such as double-glazed solar stills, enables real-world testing and improvements in response to community input. Prototypes can be iteratively tested in real-world settings to maximise usability and efficiency while guaranteeing that the systems satisfy regional environmental requirements [21]. Figure 2 shows the solar distillation modular design prototype.

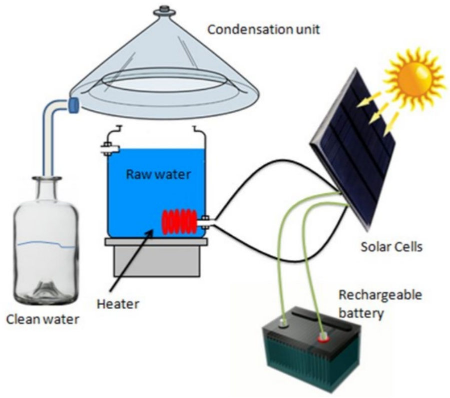

Figure 2: Prototype setup of solar distillation unit [22]

2.6. Implementation and training

Encouraging community members to run and maintain the solar water purification project promotes sustainability and a sense of ownership. Developing local manufacturing capacity could boost community resilience by lowering costs and generating employment.

Long-term success requires that issues such as initial funding, technical know-how, and continuing maintenance support be addressed, even though the DT approach provides an organised route to creating efficient solutions.

3. METHODOLOGY

3.1. Design thinking framework

The DT approach emphasises empathy, ideation, prototyping, and testing:

- Empathise: Engage with local communities to understand water-related difficulties, preferences, and constraints.
- Define: Identify critical pain points (e.g., high costs, maintenance difficulties, inconsistent water quality).
- Ideate: Brainstorm solutions, including solar-powered reverse osmosis, UV purification, and gravity-fed filtration.
- Prototype: Build low-cost prototypes with locally available materials.
- Test and iterate: Deploy pilot systems in target communities, gather feedback, and refine the design.

3.2. Rapid prototyping and iterative testing

Prototypes can be swiftly put together, tested on-site, and refined with the use of modular parts and straightforward building methods. This shortens the deployment time and enables ongoing adaptation in response to local feedback.

The DT process forms an iterative cycle that permits early solutions to be tested before fully understanding all aspects of the problem. This approach proves particularly valuable in addressing complex water problems that involve interconnected social, economic, and environmental factors [23].

4. STAGES OF FILTRATION

A five-stage water filtration system is excellent at eliminating a wide range of impurities, guaranteeing that the water is safe to drink. Five different filtration procedures are used in this system, each of which targets a particular kind of impurity.

Figure 3: Five stages of water filtration

I. Pre-filter stage: To get rid of bigger particles such as rust, sand, and dirt, this initial step usually involves a sediment filter. It prolongs the life of the downstream filters and keeps them from clogging. Larger sediments are removed by pre-filtration.

II. Carbon filter stage: To efficiently remove chlorine, volatile organic compounds (VOCs), and other substances that alter taste and odour, the second stage uses activated carbon. By eliminating organic compounds and chlorine, activated carbon filters enhance flavour and odour.

III. Reverse osmosis (RO) membrane: The central component of the filtration system (third stage). 95-99% of dissolved solids, including bacteria, viruses, and heavy metals, are eliminated by the semi-permeable RO membrane. RO membranes filter out dangerous impurities from water.

IV. Post-carbon filter stage: The water passes through a second activated carbon filter following its passage through the RO membrane. By eliminating any remaining impurities, this step further refines the water, improving its flavour, and the additional polishing ensures the water's quality.

V. UV filter stage (optional): A UV light stage is a component of certain five-stage systems that efficiently disinfects water by eliminating bacteria and viruses. Although this step is optional, it is especially helpful in areas where microbiological contaminants are a problem. UV protects against microbial contamination.

4.1. Maintaining a five-stage water filtration system

To ensure the longevity and efficiency of a filtration system, regular maintenance is key.

Table 2 shows the filter replacement programme.

Table 2: Filter replacement plan

Filter replacement schedule	Duration
Pre-filter and post-filter	6-12 months
Carbon filter	12 months
RO membrane	2-3 years, subject to water quality and treatment
UV Lamp	Follow manufacturer guidelines – typically every 12 months.

5. CONCLUSION

This study has discovered the potential to manufacture solar-powered water purification systems locally as a sustainable solution for rural communities in South Africa. Using a DT approach, it has emphasised community engagement, iterative prototyping, and modular design to ensure that systems are technically effective, economically viable, and socially appropriate. The findings highlight the importance of integrating local knowledge and co-design practices to foster user-centred solutions. Solar technology combined with a community engagement approach significantly enhances water quality and access, while promoting local economies through job creation and skill development. Nevertheless, difficulties such as the need for ongoing technical support, scalability, and resilience amid environmental changes must be addressed. Partnerships among local stakeholders, academic institutions, and NGOs would be crucial to ensure long-term sustainability. Furthermore, simplified system configurations and user-friendly designs could facilitate broader adoption. Generally, this approach should contribute to the advancement of the UNSDGs, particularly in providing clean water and affordable clean energy.

6. FUTURE PERSPECTIVE AND RECOMMENDATIONS

The localised manufacturing of solar-powered water purification systems holds significant promise for enhancing water security, public health, and economic resilience in rural South Africa. However, to realise this potential fully, several future directions and actionable recommendations should be pursued.

6.1. Future perspective

The long-term success of solar-powered water purification systems depends on community involvement. Beyond initial consultation, communities need to play a key role in co-design, implementation, and management to foster true ownership and sustainable use. Modular design has shown potential; further research is needed to streamline the configuration of systems for diverse communities with varying water needs and technical capabilities. Innovations in plug-and-play solutions could enable easier deployment and expansion. Solar-powered purification should not exist in isolation; linking these systems to rural electrification, education, and health infrastructure could create synergistic benefits that amplify community development.

Future designs must account for changing climatic conditions, including fluctuations in solar radiation and groundwater levels. Integrating monitoring systems and adaptive features would ensure long-term viability.

6.2. Recommendations

I. Establish local training programmes that equip community members with technical, managerial, and customer service skills to operate and maintain the systems. This would create jobs and promote resilience.

II. Implement rapid prototyping cycles with active community feedback loops to refine system design for cost, durability, and effectiveness in diverse local contexts.

III. Encourage collaborations between local water experts, universities, municipalities, and NGOs to provide continuous technical support, to share knowledge, and to drive innovation.

IV. Advocate for financial models and policy frameworks that lower the upfront costs for communities and ensure long-term sustainability, such as subsidies, microfinancing, or pay-as-you-go models.

V. Simplify system configuration and operation so that non-technical users could assemble, maintain, and adapt the systems. Intuitive design and clear documentation would be critical for widespread adoption.

VI. Explore emerging solar technologies (such as flexible solar panels or advanced batteries) and integrate them into purification systems to improve efficiency and reduce costs.

VII. Establish robust metrics to evaluate the social, economic, and environmental impacts of implemented systems. Continuous monitoring would identify areas for improvement and help to scale successful models.

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