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Father Verspieren and Mali Aqua Viva: Lessons learned from fighting drought and poverty with photovoltaic solar energy in Africa

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ABSTRACT

Almost fifty years after the first installations, I identify the main lessons learned from fighting drought and poverty in Africa with direct solar-powered pumps thanks to Father Bernard Verspieren and Mali Aqua Viva. Six main findings and three main recommendations emerge from the present analysis. They are of direct relevance to all Africa's countries whose population has gone from 438 million in 1977 to 1,308 million in 2019, with about 600 million still having no access to electricity. In place of "awareness campaigns" and extraordinary courses held by international organizations, I recommend to establish national solar energy institutes whose task will include the education of solar energy professionals giving practice-oriented workshops on solar-powered drip irrigation and rainwater harvesting throughout each Africa's country. Said education will critically include the economic and social aspects of distributed "generation" of energy and water from sunlight and rainfall.

Keywords:
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Solar energy in Africa
Rainwater harvesting
Solar pump

1. Introduction

The achievements of Father Bernard Verspieren in fighting drought in Mali in the mid 1970s pioneering the use of the first electric pumps powered by photovoltaic (PV) electricity has been recounted by Perlin in a seminal book on the history of solar PV energy first published in 1999.[1]

Detailing how Verspieren started a solar water pumps programme for Mali using a direct (battery-free) PV-powered water pump first developed by Roger, a physicist at the University of Lyon, and Campana, an undergraduated student who first had the idea to couple directly PV modules and the water pump, Perlin identifies the key factors that made the Mali's programme a model project for developing countries.[1]

Said factors were financial participation by the users and the creation of a highly skilled and well-equipped maintenance workforce.[1]

Today, advanced textbooks[2] detail the specification of PV pumping systems in agriculture, whereas the $1 billion (in 2018) global solar pumps market is estimated to grow at over 12% annual growth rate between 2019 and 2027.[3]

However, very few scholarly studies in the scientific literature have been devoted to the achievements of Father Verspieren in Africa. For example, a search on Google Scholar with the query "Father Bernard Verspieren" as of late February 2020 returned only eight (8) results. The only brief account returned by the aforementioned online search is a two-page account authored by Perlin in 2001.[4]

Another book[5] provides an industrial perspective on the achievements of Verspieren with solar-powered pumps. Therein Varadi, a pioneer of the solar PV industry, recounts for example how the first solar pumps developed by the French water pump company following the work of Roger and Campana originally used PV modules manufactured in North America (and subsequently assembled in France by a joint venture company).[5]

In this study, I identify the main lessons learned from fighting drought and poverty in Africa with direct solar pumps thanks to the pioneering efforts of Father Bernard Verspieren and Mali Aqua Viva.

After a brief review of the scientific and technology achievements that led to the introduction of the first direct solar pumps, I discuss the subsequent impact of solar-powerd water pumps on Africa and the lessons learned. The findings and the recommendations emerging from the present analysis are of direct relevance to all Africa's countries whose population has gone from 438 million in 1977 to 1308 million in 2019, with about 600 million still having no access to electricity.

2. Technology and practical use-driven innovation

Today, solar pumps powered by PV modules are equipped with an electronic controller using the Maximum Power Point Tracking (MPPT) electronic technology. Often, the same controller provides real-time monitoring of the borehole water levels, storage tank levels, and pump speed.[3]

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In the second half of the 1970s the MPPT electronic technology was not yet available, and Roger solved the scientific challenge to directly connect the permanent magnet electric motor powering the pump directly to the PV array, and the pump to the water well. Both sunlight and borehole water levels, indeed, vary during the day and seasonally.

In 1979 Roger published the theory the interaction of photovoltaic arrays with direct current motors as a function of the load leading to "very simple and reliable installation" that "must start in the morning with no external intervention".[6]

Figure 1. Father Verspieren dedicates the first Mali Aqua Viva Project in Mali, 1978. [Photo courtesy of John Perlin, *Let It Shine: The 6000-Year Story of Solar Energy*, 2013].

Since April 1976, Roger's team was monitoring the performance of a 0.5 kW solar pump consisting of an immersed centrifugal pump connected to a surface direct current motor through a 10 m shaft.[7] Installed in the South Corsica mountains to supply extra water to a sheep ranch, the pump was able to extract a large amount of water "enough to raise 200 sheep as well as pigs and poultry plus a market garden".[8] Since then, wrote Perlin more than twenty years later, "those seriously interested in solar water pumping ventured through the challenging Corsican terrain to see the apparatus at work".[1]

Amid them was Father Verspieren who commissioned two such pumps to be installed in Mali. The one installed in late 1977 and inaugurated in the village of Nabasso in February 1978 (Figure 1), was able to produce 30 m^3 of water per day "to the wonder and joy of the 2000 parched folk so that they can keep 800 sheep and raise…vegetable patches on land formerly barren for most of the year".[8] Water abstracted from the well was collected in a storage tank and made freely available to villagers.

Two years later, talking as invited speaker to the delegates of the *Photovoltaic Solar Energy Conference* in Cannes, France, Verspieren emphasized how:

> «I would say that for me the question of the cost is secondary. What matters above all is the reliability from which it depends the viability of our populations. I speak to you with full knowledge of the facts, because I currently have in my project sixteen pumps in activity, that is to say 21,800 Watts outgoing daily a total of 1,500 m^3/day.

> «Sometimes the enemies of photovoltaics, when they visit our stations pumping, ignoring the cause of the failures, attribute to the PV modules failures that actually come from the pump part (plugged strainer, deteriorated bearings, sometimes also breakdowns are caused by deficiencies in the drilling system).

> «We do everything to enlighten them but all technicians are not honest and the slander is international».[9]

In other words, in two years only the drilling company (Mali Aqua Viva) established by Verspiaren in 1974 following a request of Mali's government had already installed 16 solar pumps powered by PV arrays whose overall peak power did not reach 22 kW and still were producing (extracting) 1.5 million L of water per day.

At the same conference Verspieren reported how the laminated plastic surface of solar modules exposed to sun, wind and sand in the Sahel quickly deteriorated, calling the solar industry to develop new PV module coatings capable to resist under the demanding weather conditions of semidesertic Sahel.[9]

"The engineers responded by developing a more rugged design and more durable moulded glass panel which more completely sealed the cells and their connections from contaminants".[10] "This shows", emphasized social anthropologist Cross thirty years later "how scientific and technical knowledge that was critical to the development of the conventional silicon-based solar photovoltaic module… was produced not in the laboratories spaces of Europe and North America but in field laboratories across the non-western world".[10]

In late 1981, reviewing the state of the art of water and photovoltaics for developing countries with over 200 solar-powered pumps installed across the world (and mainly in Africa's Senegal, Mali and Niger), Roger could conclude that in light of progress occurred in the previous five years, photovoltaic pumps were competitive with diesel engines for powers of up to 5 kW.[11]

In the same study Roger noted how in Corsica the solar pump installed in 1976 showed a high degree of reliability with "no break in the water supply observed during the years that have elapsed".[11]

3. The impact on Africa and lessons learned

Critics of the first solar pumps installed in Nabasso readily identified in the high upfront cost their main drawback. Verspieren was aware of the problem and addressing the audience of the Cannes conference in 1980 said:

> «Many criticize our installations claiming that the investment is too large, and this because they calculate the price of one cubic meter of water on a one-year basis. This is a wrong calculation because we think we can maintain our installations for 10 years, given that the manufacturers guarantee the system for 5 years».[9]

New PV modules coated with tempered glass using new sealing resin were shortly made available by the early PV industry. Eventually, some 125 solar pumps were installed and managed by the Mali's company.[12]

The approach followed by Verspieren for which each village had to co-finance and self-maintain their own solar pumps turned out to be successful.[1] Within 1986 Mali Aqua Viva replaced all the pumps with shaft-free, self-lubricating immersed pumps with motor in stainless steel and the pipe carrying the water in plastic.[1]

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The new pumps, powered by alternate current produced by a small inverter placed above the well, required maintenance every 2.5 years, whereas the previous pumps required 6-to-10 maintenance visits per year.[1]

The only problem encountered was the frequent theft of solar modules after 1997.[12]

The achievements fighting water scarcity in Mali were known in Europe since the early 1980s. The European Commission funded in 1986 the first round of the Regional Solar Programme to install solar-powered pumps in rural areas of Burkina Faso, Cape Verde, Guinea Bissau, Mauritania, Senegal, Mali, Chad, Niger and Gambia. Eventually, three million people gained access to drinking water between 1986 and 2007 thanks to the 1,091 solar-powered pumps installed in the course of the two rounds of the Programme (626 in the first round, and 425 in the second).[13]

The provision of said systems was largely due to the pioneering efforts of Father Verspieren. Even the approach followed when installing the systems for free was similar to that pioneered by Verspieren because the villagers had to bear the operation (*i.e.*, maintenance and surveillance) costs.[13]

Eventually some 30 per cent of the PV modules installed during the European-funded programme were stolen. Only in Senegal as of 2005 some 15 per cent of solar panels installed in the country were stolen, leading country's officers to conclude that "before going ahead with investments in equipment, it is essential to secure solar installations".[14]

Figure 2. One of the first Mali Aqua Viva solar pumping system in Mali, late 1970s. [Photo courtesy of John Perlin, *Let It Shine: The 6000-Year Story of Solar Energy*, 2013].

It is enough to visualize pictures of the early installations in Nabasso (Figure 2) to notice that the solar-powered pump was indeed fenced. Similarly, a video on *Teriya Bugu* centre for rural development founded by Verspieren shows how in 2000 all the PV modules of a relatively large installation next to a river from which water was abstracted to irrigate fruit trees and for aquaculture were welded, surrounded by fencing and guarded night and day by villagers.[15]

4. The key need for education

Verspieren, who prior to becoming a priest had studied agricultural engineering in France, understood the need to educate and train a local maintenance staff to ensure proper functioning maintenance of the solar-powered pumps.

Hence, at a time when education on solar energy and applied photovoltaics was rare even in Europe or in North America, he asked the solar water pump manufacturers to locally train selected villagers. Forty years later training was still recognized of fundamental importance by the Food and Agriculture Organization (FAO) organizing a workshop on solar powered irrigation in Kigali, Rwanda, with several companies showcasing solar powered irrigation systems and the financial solutions for their uptake.[16]

In the same country (Rwanda), for instance, a farmer using a solar-powered water pump to irrigate a 8 ha crop field after installing the solar pump in 2016 saw the harvest of beans to go from about one tonne of beans per ha to 2.5 tonnes of beans per ha (+150%).[17]

Showing evidence of the ongoing adoption of solar-powered pumps throughout Africa, just one solar pump company based in South Africa between 2009 and 2019 supplied more than 3,000 solar pumps to farms in South Africa, Botswana, Lesotho, Malawi, Mozambique, Namibia, Zimbabwe and Zambia.[18]

In a 2018 overview of solar-powered irrigation, the FAO emphasized how the technology would pose a risk to water wells depletion, recommending to include solar-powered irrigation in curricula for agricultural extension services, irrigation managers, technicians and technical government staff.[19] The agency of the United Nations recommended in the same report to launch new courses to train farmers on more water-efficient irrigation methods, cropping patterns and soil management.[19]

To prevent any water depletion risk it is enough to use the solar-powered irrigation systems to pump water harvested during the yearly rainfall,[20] and to systematically use highly efficientt and effective drip (micro) irrigation.

Hence, in place of "awareness campaigns" and extraordinary courses held by international organizations, I recommend to establish national solar energy institutes whose task will include the education of solar energy professionals giving practice-oriented workshops on solar-powered drip irrigation and rainwater harvesting throughout each Africa's country.

Said education will critically include the economic and social aspects of distributed generation of energy and water from sunlight and rainfall, providing practically-relevant information with the aid of visual references for each concept and technology illustrated. Hence, for example, a typical workshop on "Rainwater harvesting and solar-powered irrigation" (Table 1) will incorporate Africa's case studies and real technologies presented by by farmers already using solar irrigation and by industry's practitioners.

In order to make learning personal and effective, the number of attendees per workshop should be limited to 15 and answer all key practical and relevant questions. As put it by Steinert, active participation via questions and group discussion is one key ingredients of any successful workshop.[21] A group size exceeding the 15 threshold makes active participation less feasible since it becomes increasingly difficult for trainers to manage questions and make the training personal.

Furthermore, in agreement with today's expanded approach to education in solar energy[22] and with the key adult learning principle of motivation to learn,[23] the workshop will critically include economic and financial aspects of rainwater harvesting, water management and solar-powered irrigation as central aspects of the training programme.

Table 1. "Rainwater harvesting and solar-powered irrigation" Workshop

Structure	Environment	Materials
Day 1 (6 h) in classroom (answer all key questions via an ordered sequence of presentations properly illustrated)	Identify and prepare well-suited learning space in which participants can all see each other	Workshop slides in digital formats shared with the attendees
Day 2 (6 h) in classroom (3 h with external educators, *i.e.*, practitioners of the technology from industry and from farms)	Identify and make available functioning technical equipment (e.g., PC, projector, pointer, etc.)	Handouts with instructions and visual references for each activity
Day 3 Visit to a farm using the methods	Transfer to a selected farm with visit to the solar irrigation and rainwater harvesting systems followed by discussion	Share key insights, and goals accomplished via pictures, videos and e-mails

5. Lessons learned and recommendations

Reviewing the achievements with solar-powered pumps and solar-powered irrigation started by Father Bernard Verspieren in Mali in the late 1970s teaches six main lessons of general validity for all Africa's countries.

First, at a time when the price of photovoltaic modules exceeded $13/W (between 1975 and 1978 the solar cell module price dropped from about $35/W to $13/W)[24] and their supply was restricted to a few companies with a yearly global production output limited to 100 kW, their use to power directly connected pumps was found to be more convenient than diesel-powered pumps for powers up to 5 kW.[11]

Second, as early as of 1980 Father Verspieren was reporting about "enemies of the photovoltaic technology" wrongly ascribing to PV solar cell and module failure problems that were instead due to pumps.[9]

Third, as already noted by several scholars,[10,1] Verspieren's analysis of the problems encountered by the PV modules in the solar-powered pumps initiated key advances in the manufacture of solar modules which led to a first dramatic extension of their longevity, and thus to a significant reduction in the cost of solar electricity during the module lifetime.

Fourth, at a time when the internet did not exist, Father Verspieren understood the importance of communicating the results of his community's efforts to all the stakeholders across the world. He travelled to international conferences in Europe and elswhere, and disseminated the outcomes of an initiative that otherwise would have remained unknown to most outside Mali.

Fifth, long before than the relevance of social science to energy research was acknowledged,[25] Verspieren understood the importance of the social involvement in the uptake of a new energy technology until then completely unknown to its users. Hence, he required villagers to be responsible for the maintenance and surveillance of the solar pumps, *and* to share the financial costs of the new systems. Accordingly, all solar pumps were considered by the local population of high social and economic value, fenced and guarded against theft, a cultural and social trait that plagues solar PV installations across Sub-Saharan Africa still today.[26]

Sixth, a large part of the water abstracted from boreholes with the aid of the solar-powered pumps was used for productive purposes, namely for irrigating agricultural crops and even to make bricks. This, noted Verspieren in 1980,[9] led to economic growth and prevented villagers from abandoning their village or become unemployed.

Since the uptake of the first direct solar pumps in Mali, Africa's population has gone from 438 million in 1977 to 1,308 million in 2019. Yet, about 600 million people in Africa still had no access to electricity by the end of 2019, when only 5 GW of solar PV were installed across the whole continent.[27]

This makes Verspieren's pioneering efforts of direct and practical relevance to virtually all African countries.

Today, indeed, mainstream 60 cell modules of peak power between 275 and 295 W are twice more efficient than in 1977, and sell at about $0.25/W,[28] whereas the yearly production of solar cells exceeds 120 GW.

Three major recommendations follow therefore by the present analysis.

First, each Africa's country should establish its own national solar energy institute, whose tasks need to include the continuous provision of practice-oriented education aimed to reach farming companies and rural families for the widespread adoption of PV technology and rainwater harvesting to meet their energy, water and irrigation needs. We have shown elsewhere how this can be done creating public research centres capable to provide more useful research, education and policy advice in the fields of solar energy and of the bioeconomy.[29]

The benefits of establishing a national solar energy institute training a large number of young professionals in today's solar energy science and technology will rapidly overcome the costs through *i*) the financial savings of families, firms and government administrations self-generating energy though low cost and well installed solar energy technology, as well as through *ii*) enhanced crop yields thanks to low cost and highly efficient solar-powered drip (or micro) irrigation eventually generating significantly greater income for farmers.[30]

In the educational programs proposed in this study such benefits should be clearly discussed, providing details about the current cost of solar pump projects relative to the alternatives. For example, a study reporting the annual outcomes of three 0.5 ha solar-powered drip irrigation systems installed in northern Benin villages as of late 2007, when the price of PV arrays was around $9,000/kW, found a payback time of 2.34 years.[30] However, the payback time decreased to 1.76 years and the internal rate of return (IRR) increased to 64% for PV arrays selling at $3,000/kW.[30] As mentioned above, today's mainstream PV modules sell at $250/kW.[28]

Second, the uptake of solar-powered irrigation systems should take place along with the uptake of rainwater harvesting and efficient water utilization (including drip irrigation) practices.[20]

Third, aware that utility-scale electricity production via PV modules coupled to energy storage systems (ESS) based on Li-ion batteries has lately become competitive with centralized thermoelectric generation,[31] Africa's policy makers aiming to support industrial development should focus investments on PV technology coupled to ESS, and local energy distribution grids.

As to the "*ennemis du photovoltaïque*"[9] doubting today about its technical and economical feasibility -- as their ancestors did in the late 1970s after visiting the first solar-powered pumps in Mali -- updated education in solar energy of young professionals from companies and other sectors of the civil society based on the same "practical and relevant information" invoked by Steinert[21] will overcome obstacles and open the route to general uptake of solar energy for all end energy uses.

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References

1. The book was re-published in 2002: J. Perlin, Father Verspieren Preaches the Solar Gospel In *From Space to Earth - The Story of Solar Electricity*, Harvard University Press, 2002; pp. 103-124.

2. I. Yahyaoui, *Specifications of Photovoltaic Pumping Systems in Agriculture*, Elsevier, Amsterdam: 2017.

3. Transparency Market Research, *Solar Pumps Market (Product Type: Submersible Pumps, Surface Pumps; Operation: AC Pumps and DC Pumps; Application: Agriculture, Drinking Water, Municipal Engineering, and Others) - Global Industry Analysis, Size, Share, Growth, Trends, and Forecast, 2019-2027*, Albany, NY: 2019.

4. J. Perlin, The French Connection: The rise of the PV water pump, *Refocus* **2001**, *2*, 46.

5. P. F. Varadi, *Sun Above the Horizon*, Pan Stanford Publishing, Singapore: 2014; pp. 199-201.

6. J. A. Roger, Theory of the direct coupling between d. c. motors and photovoltaic solar arrays, *Solar Energy* **1979**, *23*, 193.

7. D. Campana, A. Castiel, A. Perez, J. A. Roger, C. H. S. Dupuy, P. Lavit, M. Lepert, Realization and testing of a pumping system powered by solar cells, *Solar Energy: Proceedings of the Unesco/WMO Symposium*, Geneva, 30 August - 3 September 1976; WMO No.477, 611-620.

8. *New Scientist*, 20 April 1978; p.208.

9. Father B. Verspieren, The Application of Photovoltaics to Water Pumping and Irrigation In Africa In *Photovoltaic Solar Energy Conference*, Cannes, France, 27-31 October 1980, W. Palz (Ed.), Springer, Dordrecht: 1981.

10. J. Cross, History, Science and Society, *Low Carbon Energy for Development Network Symposium*, Loughborough University, 4-5 April 2012. See at the URL: https://solarassemblage.wordpress.com/2012/04/10/76/ (last accessed April 2, 2020).

11. J. A. Roger, Water and photovoltaics in developing countries, *Solar Cell.* **1982**, *6*, 295.

12. Oullins Mali Aqua Viva, Bernard Verspieren, 13 February 2011. See at the URL: www.oullinsmali.fr/bernard-verspieren (last accessed April 2, 2020).

13. W. Palz, Solar Power for the World In *Power for the World*, W. Palz (Ed.), Pan Stanford Publishing, Singapore: 2011; p.101.

14. A. Faye, Energy-Senegal: Theft Casts a Shadow Over Solar Programmes, *Inter Press Service*, 27 January 2006.

15. P. Rapay, *Le Père aux quatre vies*, Teriya Bugu, 2000. See time 17:07 (m:s) in the video online at the URL: https://teriyabugu.com/qui-sommes-nous/histoire (last accessed April 2, 2020).

16. Food and Agriculture Organization of the United Nations, *Solar powered irrigation in Eastern Africa: from technology to up-scaling*, 7-11 November 2017. See at the URL: www.fao.org/in-action/water-for-poverty-in-africa/events/events-details/en/c/1047319 (last accessed April 2, 2020).

17. E. Ntirenganya, Rwanda: Solar-Powered Irrigation Sees Farmers Double Their Yield, *allAfrica*, 17 November 2017. See at the URL: https://allafrica.com/stories/201711140229.html (last accessed April 2, 2020).

18. Olivia Energy Solutions, Bloemfontein, South Africa. See at the URL: www.oliviaenergy.co.za/index.php/products/solar-water-pumping-systems (last accessed April 2, 2020).

19. Food and Agriculture Organization of the United Nations, *The benefits and risks of solar-powered irrigation - a global overview*, FAO, Rome: 2018.

20. R. Ciriminna, M. Pecoraino, F. Meneguzzo, M. Pagliaro, Expanding the Distributed Generation Concept: Toward Decentralized Energy and Water Supply, *Global Chall.* **2018**, *2*, 1800006.

21. Y. Steinert, Twelve Tips for Conducting Effective Workshops, *Med. Teach.* **1992**, *14*, 127.

22. R. Ciriminna, F. Meneguzzo, M. Pecoraino, M. Pagliaro, Rethinking Solar Energy Education on the Dawn of the Solar Economy, *Renew. Sust. Energ. Rev.* **2016**, *63*, 13.

23. O. Gom, Motivation and Adult Learning, *Contemporary PNG Studies* **2009**, *21*, 17-25.

24. L. Rosenblum, W. J. Bifano, G. F. Hein, A. F. Ratajczak, Photovoltaic power systems for rural areas of developing countries, *Sol. Cell.* **1979**, *1*, 65.

25. B. K. Sovacool, S. E. Ryan, P. C. Stern, K. Janda, G. Rochlin, D. Spreng, M. J. Pasqualetti, H. Wilhite, L. Lutzenhiser, Integrating social science in energy research, *Energy Res. Soc. Sci.* **2015**, *6*, 95.

26. E. C. X. Ikejemba, P. C. Schuur, Analyzing the Impact of Theft and Vandalism in Relation to the Sustainability of Renewable Energy Development Projects in Sub-Saharan Africa, *Sustainability* **2018**, *10*, 814.

27. International Energy Agency, Africa Energy Outlook 2019 In *World Energy Outlook*, Paris: 2019. See at the URL: www.iea.org/reports/africa-energy-outlook-2019 (last accessed April 2, 2020).

28. M. Schachinger (pvXchange.com), Module Price Index February 2020: Remove the cap to sure up PV sector, *pv-magazine*, 2020. See at the URL: www.pv-magazine.com/module-price-index (last accessed April 2, 2020).

29. M. Pagliaro, F. Meneguzzo, *Que faire?* A Bioeconomy and Solar Energy Institute at Italy's Research Council in the Context of the Global Transition to the Solar Economy, *Chem. Eur. J.* **2017**, *23*, 15276.

 doi:10.20944/preprints202002.0298.v3

30. J. Burney, L. Woltering, M. Burke, R. Naylor, D. Pasternak, Solar-powered drip irrigation enhances food security in the Sudano-Sahel, *Proc. Natl. Acad. Sci. U.S.A.* **2010**, *107*, 1848.
31. M. Pagliaro, Renewable energy systems: Enhanced resilience, lower costs, *Energy Technol.* **2019**, *7*, 1900791.