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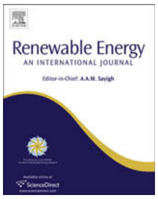

Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context

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ABSTRACT

The investigation summarised in this paper applied a sustainability assessment methodology on a renewable energy technological system in a rural village project that was commissioned by the South African Department of Minerals and Energy. The project comprised of wind, solar and lead-acid battery energy storage technologies that were implemented as a mini-hybrid off-grid electrification system for the village. The sustainability assessment methodology predicts the outcomes of such interventions by way of a learning model using discipline experts in the fields of economics, sociology, ecosystem sustainability, institutional governance, and the physics and chemistry of energy conversion processes. The comparison of the project's outcomes with a South African sustainable development framework shows that the specific village renewable off-grid electrification system is not viable. The main reason is that charges for electricity supply costs in village grids are too high for available subsidies; the economies of scale for renewable energy supply technologies favour national grids. The failure of the integrated system may also be attributable to the complexity of the social-institutional sub-system, which resulted in uncertainty for project planners and system designers, and the lack of resilience of the technological system to demands from the socio-economic and institutional sub-systems. Policy-related recommendations are made accordingly.

1. Introduction

The South African governance system is developing national measures of sustainability. For example, the Millennium Development Goals are pursued to reduce widespread poverty by 2015 [1]. The post Kyoto 2012 commitments to low-carbon technologies to mitigate the effects of climate change are based on renewable energies, which are to be supported by a carbon tax [2]. In terms of mitigation, the application of (energy) technological innovation to meet the objectives of sustainable development and the conditions for sustainability has been stressed [3–5]; a model, based on the principles of sustainability science (see Table 1), has been developed that can be used to assess the sustainability of such technologies (see Fig. 1) [5]. The model integrates:

- A life cycle perspective [4] and systems thinking, i.e. systems provide feedback loops and are self-correcting [6].
- Learning methods for the management of information in the paradigm of sustainable development [5].
- Conditions for sustainability to reduce the complexity of systems by clarifying the magnitude of cause and effect on systems, so that priorities can be allocated [5].
- Technology innovation and what is feasible within constraints of time, finances and institutions [3,4].

The model to prioritise assessable sustainability indicators for renewable energy systems initiates with a comprehensive set of sustainable development indicators that are deemed appropriate for the context of integrated renewable energy technological systems under investigation. Only those indicators that are controllable by decision-makers in the context of an integrated technological system, and specifically those that are expected, by the technological sub-system analysts, to be effected through the implementation of the technological sub-system, are considered further (#1 in Fig. 1).

The remainder of the approach is based on the Kolb learning cycle of experience, reflection, conceptualisation and planning [7]. First, the expertise of the technological sub-system analysts, with the expertise of the sustainability of the economic, environmental,

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Table 1
Specific theories of the emerging field of sustainability science that relate to sustainability performance indicators for technological systems [5].

Theory	In the context of sustainability science	In the context of performance indicators of technologies
Trans-disciplinarity	The result of a coordination of disciplines such as science and laws of nature; technology and what is achievable; law and politics and what is acceptable to social systems; and ethics of what is right and wrong beyond the bounds of society.	Where: "successful transformation of technologies into marketable commodities requires knowledge and skills from a variety of different specialist fields of science and engineering".
Resilience	A system's ability to bounce back to a reference state after a disturbance and the capacity to maintain characteristic structures and functions despite the disturbance. Where: "ecological resilience is the amount of disturbance that a system can absorb before it changes state. Ecological resilience is based on the demonstrated property of alternative stable states in ecological systems. Engineering resilience implies only one stable state (and global equilibrium)". Further: "a resilient ecosystem can withstand shocks and rebuilds itself when necessary. Resilience in social systems has the added capacity of humans to anticipate and plan for the future". Resilience is conferred in human and ecological systems by adaptive capacity.	The resistance and robustness of an integrated system against surprises, which includes risk-based measures and precautionary regulations; the capacity to buffer change, learn and develop.
Complexity	From a biology perspective: "that understanding of how the parts of a biological system – genes or molecules – interact is just as important as understanding the parts themselves". From a natural systems perspective: "complex interactions of natural systems that are not chaotic". Furthermore, the growing appreciation of the need to work with affected stakeholders to understand the full range of aspects of any particular system.	Deals with the study of complex systems, i.e. is composed of many interacting elements that interact in complex ways; and the ability to model complex interaction structures with few parameters.
Adaptive management	Or adaptive resource management (ARM) is an iterative process of optimal decision-making in the face of uncertainty, with an aim to reducing that uncertainty over time via system monitoring.	
Adaptive capacity	"As applied to human social systems, the adaptive capacity is determined by: • The ability of institutions and networks to learn, and store knowledge and experience. • Creative flexibility in decision-making and problem solving. • The existence of power structures that are responsive and consider the needs of all stakeholders. Adaptive capacity is associated with r and K selection strategies in ecology and with a movement from explosive positive feedback to sustainable negative feedback loops in social systems and technologies".	

institutional and social sub-systems, also termed holons [8], are used interchangeably through a sub-learning cycle to [5]:

- Define a specific system, as a framework, in terms of technology–economic–social–ecological–institution interactions, including the boundaries of the system, and important resilience considerations; and
- Establish a hierarchy of controllable indicators that may be affected in terms of their respective importance to ensure the sustainability, as defined by the concepts of Table 1, of the investigated technology–economic–social–ecological–institution system.

The outcome is an initial set of prioritised indicators for each of the technology, economic, social, ecological, and institutional sub-systems or holons according to the overall system sustainability, as perceived by the sustainability expertises (#2 of Fig. 1). The technology holon analysts then re-evaluate, through a number of sub-cycles, the site-specific information to determine which indicators are, potentially, assessable for the specific technological system under investigation (#3 of Fig. 1). Thereafter, the different stakeholders of the technology–economic–social–ecological–institution system are engaged to highlight the key aspects of the integrated system to prioritise the indicators and identify aspects of the overall system that may not have been included in the initial set of indicators (#4 of Fig. 1). Further learning cycles (2 → 3 → 4 → 2) are utilised to facilitate the transdisciplinarity prioritisation of the key set of indicators. Finally, and considering the market uptake of innovation [9], multiple technology–economic–social–ecological–institution systems at regional, national and international levels may result in different sets of prioritised assessable indicators through a continuous learning process.

The main objective of the investigation summarised in this paper was to apply the introduced model on a rural mini-hybrid off-grid electrification system to determine the sustainability performance of such systems in the African context. Thereby policy makers may be informed as to the key aspects that drive the sustainability of mini-hybrid off-grid renewable energy systems.

2. Application of the model on an implemented renewable energy technological system

Supply of energy for basic needs is an assumption for sustainable development of the South African National Department of Minerals and Energy (DME) [10]. Household electrification and an energy grant of R 55 (~€5) per household per month are administered to local municipalities by the Department of Provincial and Local Government (DPLG). In rural areas up to 84% of households can qualify for this grant [11]. In 2003 the DME embarked on a renewable energy project in the OR Tambo municipality Lucingweni Village in the Eastern Cape Province, which was used to test the viability of renewable energy for locations not accessible to the national grid; the introduced model (of Section 1) was applied to the Lucingweni case study [3,5].

2.1. *Scope of the study*

The boundaries of the case study were set at the borders of Lucingweni Village with its four neighbouring villages and a nature reserve; the details of the case are described elsewhere [3,12]. The time period for the case study was from September 2004 to January 2007. The boundaries and key elements have been described for the following sub-systems [3]:

- Socio-political – the five villages and the region that is controlled by a traditional, cultural government system.
- Socio-ecological – the area used by the villagers of Lucingweni for their ecological services.
- Socio-economic – the same as the socio-political sub-system with the nature reserve and an associated tourist camp that is a source of employment, including the economic services that are provided as part of the non-traditional government system, i.e. a clinic and school, through the Eastern Cape Parks Board of the South African government.
- Technological – the area to which the power lines are extended. This is a subset of the Lucingweni village.