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THE PRINCIPLES OF SUSTAINABILITY SCIENCE TO ASSESS ALTERNATIVE ENERGY TECHNOLOGIES

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The emerging field of sustainability science recognizes the important role of technologies in reaching the conditional goals of sustainable development. Research in sustainable technologies requires transdisciplinarity to determine the resilience, adaptive capacity, and complexity of social-ecological systems to assess the potential of such technologies for increasing the carrying capacity and improving the resilience of social-ecological systems, or to assess the resilience of the technological system to demands from the social-ecological systems. This paper introduces a model to prioritize assessable sustainability performance indicators to manage alternative energy technologies following the principles of sustainability science. The model is based on the Kolb learning cycle, and thereby acknowledges the vital need for continual interaction between different entities and components of typical social-ecological systems, where specific technologies are to be introduced, to understand the key interactions within the sub-systems, also termed holons, that need to be assessed. The model is demonstrated with a case study in a rural village of South Africa, where an integrated alternative energy technological system was implemented. The application of the prioritized indicators is compared with the perceived overall performance of the technological system. The study confirms that an increased understanding of the principles of sustainability science may improve the assessment of sustainability performances of alternative energy technological interventions during the design stages of the technology life cycles. Further research is required to adapt conventional technology assessment methods and metrics; recommendations are made accordingly.

Keywords: Sustainable Development; Technology Management; Technology Assessment; Sustainability Science.

Introduction

The World Commission on Environment and Development (WCED, 1987) has described key conditions to achieve sustainable development. These conditions are:

- Economic growth that is significantly greater than population growth;
- Population size and growth that are in harmony with the changing productive potential of the eco-system;
- Changes in the exploitation of resources, direction of investments, orientation of technological development and institutions that are consistent with future as well as present needs; and
- Equitable access to resources so as to enable social growth.

The role of sustainability science (Kates et al., 2001) to address the exceptional challenge to meet these conditions in the sub-Sahara Africa region has been noted (Burns et al., 2006; Kates and Dasgupta, 2007); bringing practical solutions to sustainable development problems requires a transdisciplinary knowledge base and a holistic management approach (Klein, 2004). The New Partnership for Africa’s Development (NEPAD, 2005), adopted at the African Union Heads of States Summit in Lusaka, Zambia, in July 2001, recognizes that for sustainable development to take place, rural and urban communities should have access to innovations that accelerate development and provide new and effective solutions compared to those utilized previously. To this end, NEPAD aims to develop fully the available energy resources and to promote innovative, competitive, equitable and sustainable energy systems for various economic and social sectors across the continent. The NEPAD initiatives highlight the crucial role of technology for the sustainable development of the region; for long-term research much emphasis is placed on alternative energy technologies (AETs).

Conventional research in AET systems addresses fundamental and applied knowledge for the problems of sustainable development. These include the concerns of the efficiency of energy conversion from alternative energy sources and the efficiency of utilization as work, access to energy for development, and the reduction of global warming emissions (Kaygusuz and Sari, 2003). Success with these technical concerns is not enough as they do not address the complexity of social-ecological systems, i.e. the interactions between systems (Tsoutsos and Stamboulis, 2005). Sustainability science recognizes the negative and positive feedback loops associated with social-ecological systems and technology (Holling et al., 2002), and the role of technological life cycles to enhance the sustainability of complex social-ecological systems, i.e. concentrating on the design of devices and systems to produce more social good with less environmental harm (Kates, 2000). This paper subsequently investigates how the understanding of the principles of sustainability science may lead to the better management of technological systems. Specifically, the paper focuses on the implementation of AET systems in traditional communities in remote areas of Africa; energy infrastructure in remote villages is a key constraint to achieve the Millennium Development Goals (MDGs) in sub-Saharan Africa (Sanchez et al., 2007).

Technology life cycle management and associated evaluated systems

Technology is a way or ways of carrying through any economic purpose, and may be embodied in products and/or processes (Schilling, 1998). Technologies may exist as pure method or pure information; or they may be embodied in physical plant or machinery. Technology management (TM) addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies, in the form of product, process and infrastructure, which are needed to sustain the competitive advantage of regional sectors in accordance with the sector, regional, national and international sustainable development objectives (Brent and Pretorius, 2008). The TM process is conceptualized in Figure 1, the details of which are provided elsewhere (Brent and Pretorius, 2008). TM commences with idea generations, whereby ideas enter the wide end of a funnel and are then screened along the funnel using scientific and engineering performance criteria with the objective to identify, select and economically exploit innovations (Wheelwright and Clark, 1992). The first screening phase of the funnel, i.e. pre-feasibility and feasibility, occurs through a formal research and development (R&D) life cycle with idea, assessment, research and scale-up phases and associated decision gates, which are typical of R&D institutions (Swasdio et al., 2004). The final R&D decision is to commence, or not, with the development, implementation and exploitation (DIE) of the R&D output (Roelofse and Pretorius, 2003). Many tools and methods are applied in the DIE phases to support business-oriented decision gates to optimize and maximize the return on innovations (Roelofse and Pretorius, 2003). Through the market uptake cycle (Nieto et al., 1998) many different technological life cycles are associated with the innovation (Labuschagne and Brent, 2005), i.e. the life cycles of process and physical assets that manufacture or produce products and/or services, and the life cycles of the products and/or services themselves. A holistic understanding of the sustainable development implications during the market uptake cycle of innovations is required during the pre-feasibility and feasibility phases of the technology life cycle. Therefore, during these phases, adaptations of conventional technology assessment approaches (Pretorius and de Wet, 2000) are necessary and a number of statements have been made with regards to the ongoing development of relevant performance metrics (Geisler, 2002 in Brent and Pretorius, 2008):

- Technology is not judged by its existence alone, nor is its mere existence a sufficient condition for successful usage.
- We cannot evaluate technology unless and until we put it in the context of social (and environmental) and economic phenomena.
- Technology is not defined and evaluated by what it is, but by the criteria outside itself – by its actual and potential users.

It is suggested, from literature (Brent and Pretorius, 2008), that the principles or theories of sustainability science, and associated sustainability assessment methodologies (Singh et al., 2009), can be the foundation for the development of such performance metrics (see Figure 2 and Table 1) and thereby improve technology life cycle management practices in general. The focus for further investigation was how this generalization may manifest in and improve the management of alternative energy technologies (AETs), specifically in the traditional communities of remote areas of Africa.

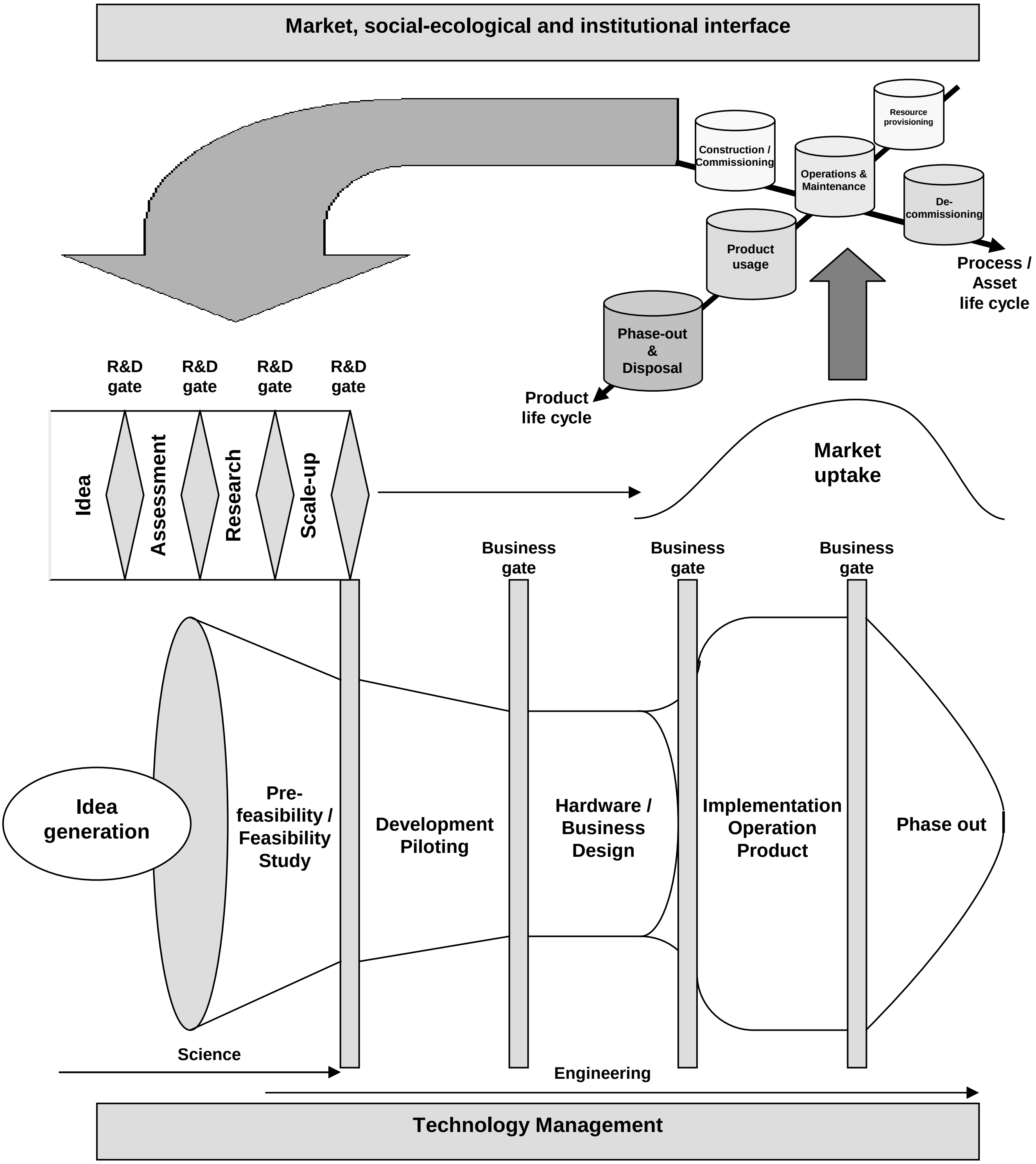
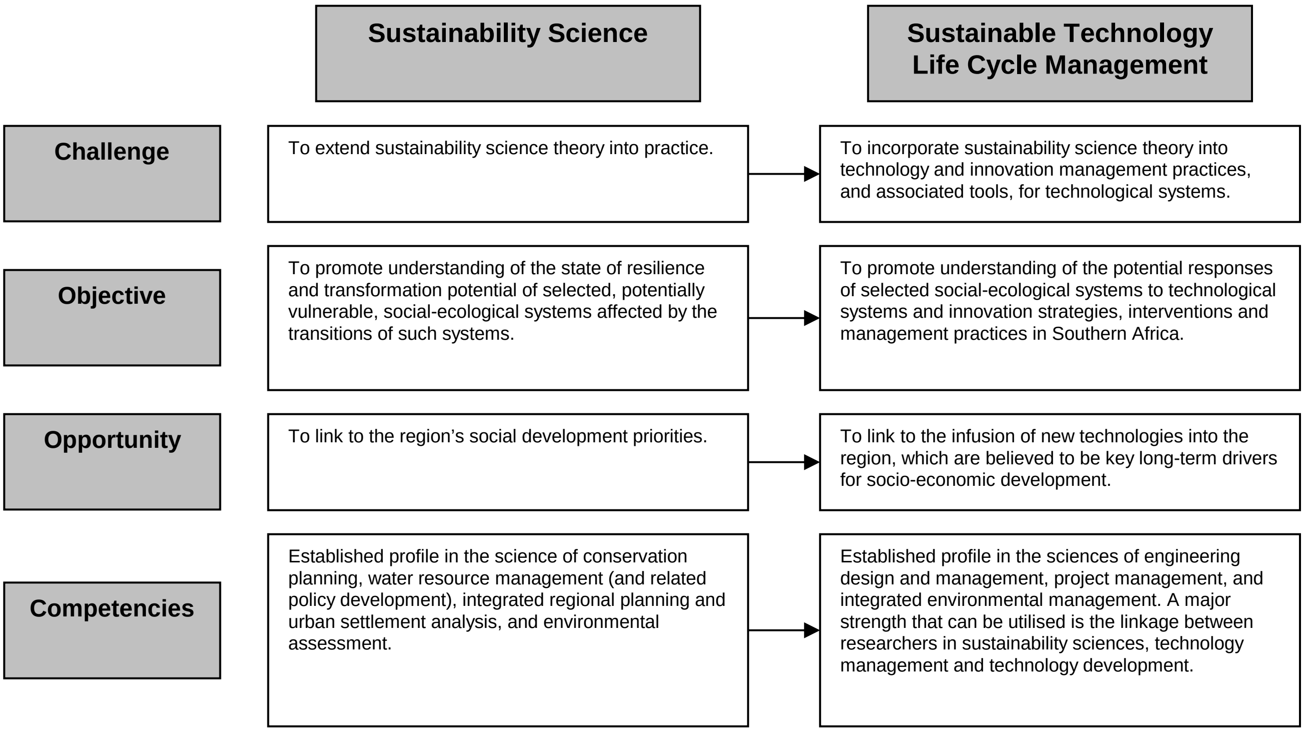


Figure 1. Technology life cycle interventions and associated evaluated systems (Brent and Pretorius, 2008)



	Sustainability Science	Sustainable Technology Life Cycle Management
Challenge	To extend sustainability science theory into practice.	To incorporate sustainability science theory into technology and innovation management practices, and associated tools, for technological systems.
Objective	To promote understanding of the state of resilience and transformation potential of selected, potentially vulnerable, social-ecological systems affected by the transitions of such systems.	To promote understanding of the potential responses of selected social-ecological systems to technological systems and innovation strategies, interventions and management practices in Southern Africa.
Opportunity	To link to the region's social development priorities.	To link to the infusion of new technologies into the region, which are believed to be key long-term drivers for socio-economic development.
Competencies	Established profile in the science of conservation planning, water resource management (and related policy development), integrated regional planning and urban settlement analysis, and environmental assessment.	Established profile in the sciences of engineering design and management, project management, and integrated environmental management. A major strength that can be utilised is the linkage between researchers in sustainability sciences, technology management and technology development.

Figure 2. The extension of the sustainability science field to technology management

Table 1. The specific theories of the emerging field of sustainability science that relate to performance metrics for technological systems

Theory	In the context of sustainability science	In the context of performance metrics of technologies
Transdisciplinarity	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[a].	Where: "successful transformation of technologies into marketable commodities requires knowledge and skills from a variety of different specialist fields of science and engineering"[b].
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[c]. 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)"[d]. 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[e].	The resistance and robustness of an integrated system against surprises, which includes risk-based measures and precautionary regulations[f]; the capacity to buffer change, learn and develop[g].
Complexity	From a biology perspective: "that understanding of how the parts of a biological	Deals with the study of complex systems, i.e. are composed of many

Theory	In the context of sustainability science	In the context of performance metrics of technologies
	system – genes or molecules – interact interact is just as important as understanding the parts themselves"[h]. From a natural systems perspective: "complex interactions of natural systems that are not chaotic"[i]. Furthermore, the growing appreciation of the need to work with affected stakeholders to understand the full range of aspects of any particular system[j].	interacting elements that interact in complex ways; and the ability to model complex interaction structures with few parameters[k].
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[l].	
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"[m].	

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Sustainable development indicators to improve the management of alternative energy technologies

Sustainable development indicators are viewed as a tool that can be used to direct and measure performances (UN CSD, 1995). The ideal is that these indicators are used to measure technological interventions in terms of the conditions and goals of sustainable development (see Figure 3) (Brent and Rogers, 2008). The consequence would be an extension to the concept of environmentally sound technologies (ESTs), i.e. those that have the potential for significantly improved environmental (and socio-economic) performances relative to other technologies (IETC, 2003).

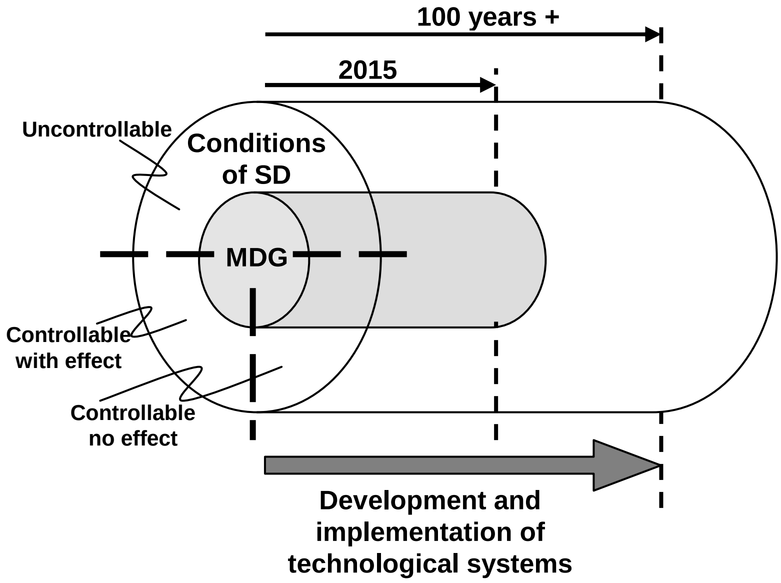

Figure 3. Technological systems aim to contribute to short-term Millennium Development Goals (MDGs) as a sub-set of the long-term conditions of Sustainable Development (SD) (Brent and Rogers, 2008)

The primary objective of the research summarized in this paper was to establish a model or method to prioritize assessable sustainability indicators for alternative energy technological systems that can be used upfront, in the technology management cycle, by designers and decision-makers of such technologies. The prioritization is based on hierarchy theory as it relates to sustainability science (Warren, 2005).

A model towards the prioritization of assessable sustainability performances of alternative energy technological systems

The proposed model to prioritize assessable sustainability indicators for alternative energy technological systems is illustrated in Figure 4. The approach initiates with a comprehensive set of sustainable development indicators that are deemed appropriate for the context of alternative energy technological systems under investigation. Only those indicators that are controllable by decision-makers in the context of the integrated technological systems, and specifically those that are expected, by the technological sub-systems analysts, to be effected through the implementation of the technological system (Figure 3), are considered further (#1 in Figure 4).

The remainder of the approach is based on the Kolb learning cycle of experience, reflection, conceptualization and planning (Kolb, 1984). First, the expertise of the technological sub-systems analysts, with the expertise of the sustainability economic, environmental, institutional and social sub-systems, also termed holons (Warren, 2005; Tsoutsos and Stamboulis, 2005), are used interchangeably through a sub-learning cycle to:

- 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.

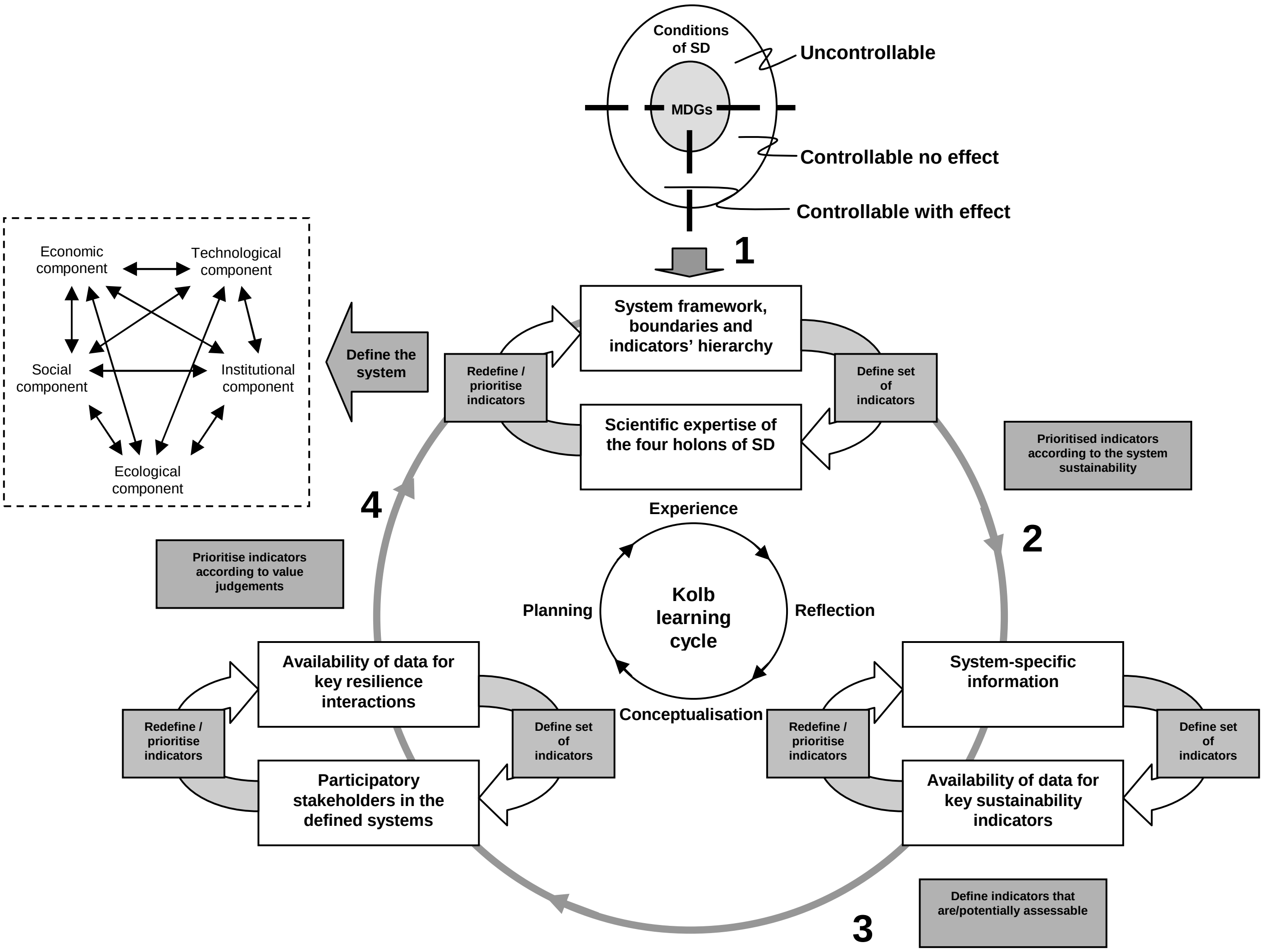

Figure 4. Proposed model to achieve prioritized assessable sustainable performance indicators

The outcome is an initial set of prioritized 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 expertise (#2 of Figure 4). The technology holon analysts then re-evaluate, through a number of sub-cycles, the site-specific information to determine which indicators are, or potentially, assessable for the specific technological implementation system under investigation (#3 of Figure 4). Thereafter, the different stakeholders of the technology-economic-social-ecological-institution system are engaged to highlight the key aspects of the integrated system to prioritize the indicators and identify aspects of the overall system that may not have been included in the initial set of indicators (#4 of Figure 4). Further learning cycles (2→3→4→2) are utilized to facilitate the transdiciplinarity prioritization of the key set of indicators. Finally, and considering that the market uptake of innovation (Brent and Pretorius, 2008; Brent and Rogers, 2008), the consideration of multiple technology-economic-social-ecological-institution systems at regional, national and international level may result in a different set of prioritized assessable indicators through a continuous learning process.

Materials and methods used in the research

The case study research methodology is described (le Roux, 2003) as a particular method of qualitative research that is an extensive examination of a singular instance of a phenomenon of interest and an example of phenomenological methodology. It is an account of problems and events in real situations. The type of case study that was used for this research can be described as a descriptive case study (Yin, 2003) because the objectives of this research rely on the current practice of alternative energy technological system implementation. The descriptive case study is an in-depth description of a situation for testing a particular theory (Page and Meyer, 2003), i.e. the principles of sustainability science, and specifically the introduced model to achieve prioritized assessable sustainable performance indicators.

A mini-hybrid alternative energy technological (AET) system case study

A mini-hybrid AET system that was implemented in Lucingweni Village, a traditional community with 220 households in rural South Africa, which is described in detail elsewhere (Rogers et al., 2007), was used as a case study. The power generation is exclusively renewable energy, i.e. Si Solar PV (560 units of 100 W nominal power output), Wind Turbines (6 units of 2.5 kW nominal power), and lead acid battery storage (~1300 kWh). The grid supplied a water pump and water filter system for improved drinking water, street lighting, a cellular phone tower, with each home having power for four lights, a cellular phone charger and a small television. There is no school or clinic in the village. A community centre was developed for communal uses of the power.

Indicators expected to be affected through the implementation of the technological system

As a point of departure all indicators of the MDG framework that are measured by the South African government, the main social, economic and ecological holons as described by the World Bank and the World Commission on Environment and Development (WCED), and associated institutional and technological indictors, were considered appropriate for such a renewable energy systems, and grouped under the following main criteria:

- Social criterion – Quality of life;
- Economic criterion – Stable economy;
- Ecological criterion – Preservation of biodiversity;
- Institutional criterion – Business viability; and
- Technological criterion – Sustainable technical system.

The conceptual criteria were mapped against practical issues to obtain comprehensive maps of potentially affected indicators through the implementation of the technological system (Rogers et al., 2007).

Initial set of prioritized indicators based on sustainability holon expertise

The maps of the holons were discussed with sustainability holon expertise, specifically researchers in the fields of economics, institutional governance, ecology and sociology. First, the individuals were requested to reflect on the holon directly applicable to their respective expertise and identify the most important indicators in the maps. The ranked priorities of each holon expertise was recorded (Rogers et al., 2007). They were then invited to comment on the maps of the other holons. The degree to which an indicator in a specific holon map interrelates with other holons was subsequently noted (Rogers et al., 2007). Thereby the complex interactions between the holons are emphasized.

Potentially assessable indicators based on site-specific information

The interviews with the sustainability holon expertise stipulated which indictors are assessable in the field. The basic comment was that if it is not measurable and assessable it is not an important indicator. The respective prioritized indicators were verified for possibility to assess with site-specific information during field observations by the technology analysts. It was ascertained that the prioritized indicators were indeed assessable from obtainable data.

Prioritized indicators based on stakeholders' perceptions

The holon maps with the prioritized set of indicators, as perceived by the sustainability holon expertise, were used to guide interviews with specific stakeholders of the integrated technological systems. These were:

- The municipality officials and ward council responsible for Lucingweni Village, i.e. the formal government structures. The individuals included the major; the speaker, and former local ward councilor for the village; the current ward councilor, which accompanied the technology analysts through the site investigations; maintenance managers and officials responsible for economic development in the municipality.
- The headman of the community of Lucingweni Village, i.e. the traditional leadership structure of the Xhosa people in the area. The interaction between the headman and the local ward councilor constitutes the linkage between the traditional and government structures at local and regional levels, and the traditional leadership structure is also represented in the national government.
- The ward committee, which are individuals that represent the communities of the villages in the ward and report to the local ward councilor.
- Two separate households in Lucingweni Village, one apparently poor and one representing a more affluent household.
- National government agencies responsible for the technical systems, i.e. the South African National Energy Regulator (NER) and the Department of Minerals and Energy (DME).

The aspects that were raised by the different stakeholders affected by the implemented technological system were recorded (Rogers et al., 2007). The national government agencies were also requested to prioritize their respective identified aspects. The overall priorities of the indicators are shown in Table 2. The highest priorities were assigned to those indicators that were ranked highest by the sustainability holon expertise and the government agencies, and also featured in the aspects raised by the different stakeholders.

Table 2. Overall prioritized assessable sustainability indicators for implemented technological systems

Indicator performance			Changes due to technological intervention		Unit	Remark
Holon	**Priority**	**Indicator**	**Designed for**	**Outcome after**		
Economic	**A**	PPP	none	None	US$/head/day	Purchase Power Parity; international benchmark of ability to meet basic needs with available resources.
	A	Gini	none	None	% income lowest quartile	Gini (share of poorest quintile in national consumption).
	A	Health	none	None	10 years of adult working life	World Bank model of health of adults for productivity; 0.4% productivity per 10 years life expectancy.
	B	Education	some	Some	years education working adults	World Bank model of education of adults for productivity; 0.5% productivity per year at school.
	C	Access to basic services	some	Some	no units	Basic services are required for productivity.
	B	Positive return on energy investments	Some	None	% return	Energy output of system > factor of energy cost of inputs; to ensure viable energy supplies.
	D	Affordability energy	yes	None	% of income/ disposable resources	Energy cost for users is affordable.
Institutional	**A**	Allocation and control of resources	some	None	Contracts	Allocation and control of resources. This is the indigent grant system that is controlled by the responsible authority.
	B	Legal protection for controls	none	None	contracts/working services	Legal protection to controls for resources. This is via contracts between the suppliers and the users.
	C	Access to credit	none	None	% of assets	This is via financial institutions that can use the assets as collateral for loans.
	C	Post Kyoto CO$_2$ eq. targets	none	None	tonnes CO$_2$ eq.	Post Kyoto targets for land use. Deforestation rates should be reduced.
	D	Access to basic resources	yes	3 months	national standards	Access to basic resources is guaranteed by the constitution, water and energy. Includes energy, clean water and sanitation.
Ecology	**A**	Biological community diversity	none	Some	acceptable trend	Resilience of ecosystem is indicated by trends in indicator populations for ecosystem type.
	B	Soil type maintenance (fertility)	none	None	acceptable trend	Resilience of ecosystem is indicated by trends in soil characteristics for soil type.
	A	Available natural energy resource	yes	Some	% of need	Natural resources must be available for conversion and the excess should reflect the efficiency and the need for stable supply.
Sociology	**A**	Jobs (ability to get food)	none	not direct	hours of saleable production work	Best indicator of ability to self support for basic needs.
	B	Nutrition	none	not direct	stunting of children	Best indicator of food quality that affects productivity and ability to learn.
	B	Life expectancy	none	not direct	Years	Best overall measure of resilience of social systems is average life expectancy.
	C	Literacy	yes	Yes	standard literacy test	Best overall indicator of ability of humans to improve productivity.
Technology	**E**	Increased productivity	none	None	% increase in production	Ability of energy system to assist production, e.g. electrical energy for means of production.

Discussion

The most important aspects were identified as the economic beneficiation from the technological intervention as expected by the community, and the community ownership of the technological system as expected by the lead implementing agency. From an economic and institutional perspective the community expected that they would receive a similar service, and performance, as provided by the national electricity grid. However, the capacity and reliability of the technological system proved insufficient to meet these expectations. For example, system instability resulted from the small excess between the planned supply of 272 kWh/day and the planned demand of 267 kWh/day. Also, the design of the system did not meet all the energy needs, e.g. a paraffin subsidy did not meet all the energy needed for heating and cooking purposes. The consequence was the ongoing reduction of indigenous forest in and around the village with ensuing degradation of the soil fertility. Finally, in practice, only 113 of the 220 households and associated street lights were connected to the mini-grid. The subsequent uncontrolled connections by the community resulted in system overload, disputes between all parties, and disconnections of power by the generator; the system stopped operating continually within one year of commissioning.

Overall the management of the technological intervention did not improve the conditions of the social sub-system in the rural village or meet any of the performance aspects raised by the stakeholders. The result was the breakdown of trust between the traditional societal structures and the formal government structures, and the technology developers.

The disregard at the design stage for almost all of the non-technical aspects had resulted in an overall unsustainable system. In other words, the case study emphasizes that in the pre-feasibility and feasibility phase of the technology life cycle a holistic understanding of energy needs and other expectations is crucial. If an integrated system is addressed as a whole then the overall resilience and adaptive capacity of all the sustainability aspects can be improved. Also, the system design needs to accentuate strategies for the technological intervention to ensure adaptive management of the integrated system in society.

Principles of sustainability science highlighted through the case study

The case study highlights the importance of the principles of sustainability science (see Table 1) to design and manage alternative energy technological (AET) systems:

- *Transdisciplinarity*. The different perspectives of experts and stakeholders on the aspects of sustainability are essential for the design stage. Thereby, technology designers can acquire a practical integrated understanding of the most important aspects and obtain agreement on the most important performance indicators for a type of technological intervention.
- *Resilience*. A key aspect to the sustainability of the integrated system is the trust between society and institutions, and technology developers and implementers. A breakdown of trust will result in society not accepting and adopting the technology intervention. Depending on the context, ecological and economic aspects may determine the resilience of the overall system to the technological intervention, e.g. the capacity of natural resources, and affordability.
- *Complexity*. Interactions between and within human and natural systems can result in misunderstanding and a mismatch between expectations and bio-physical and economic capacities. This complexity is likely to be poorly understood initially, and therefore deductive rather than inductive learning should direct technological design and intervention. Especially behavioural changes in the socio-economic, and the implications thereof for ecological systems, have high uncertainty.

- *Adaptive management*. AETs for electricity generation are relatively new to remote areas of developing countries. The management of a technology during and after intervention requires technical skills and understanding of equipment performance and economic benefits that are not readily available in this traditional context. Traditional social structures that need to support the technological intervention must be engaged to deal with the adaptive responses to changes in social values and eco-services.
- *Adaptive capacity*. The ability of the stakeholders to agree to experiment with alternatives to mitigate problems with sustainability aspects highlights the potential ability of the social system to learn and adapt to a technological intervention within the carrying capacity of the ecological systems and the technological capacity of the society over time. Alternative energy interventions should therefore provide flexibility for stakeholders to adapt to sustainability aspects within the constraints of the applicable social and institutional systems.

Implications for policy-making to promote alternative energy technologies

The literature frequently makes recommendations to governments about their responsibilities and the policies they should implement for long-term sustainable development (Winkler, 2006). However, because social-ecological systems are self-organizing their evolution rarely follows the paths intended by governments (Abel et al., 2006). Governments are not free to invest or establish institutions at will, but must take account of the political influence of all stakeholders to promote sustainable technology-economic-social-ecological-institution systems. The capacity of such systems to self-organize is the foundation of their resilience. Rebuilding this capacity at times requires access to external resources. Excessive subsidization can, however, reduce capacity. Cross-scale subsidization should end when self-organization becomes apparent, because cross-scale subsidization can increase the vulnerability of the broader system. A long-term perspective is essential, i.e. cross-scale relationships should in the long term be mutually sustaining, neither exploitative from above nor parasitic from below (Abel et al., 2006). Therein lays the challenge for policy-making related to the promotion of sustainable and adaptable AETs in social-ecological systems.

Conclusions and recommendations

The emerging field of sustainability science recognizes the role of technology to reach the conditions of sustainable development. Regional policies in sub-Saharan Africa place much emphasis on alternative energy infrastructure that are typically imported from developed countries. The research summarized in this paper set out to establish how the principles of sustainability science may manifest in and improve the management of alternative energy technologies (RETs). A case study was undertaken of a rural village in the Eastern Cape Province of South Africa where an alternative energy system was implemented.

A learning model (Figure 4) was introduced that provided a structured approach to prioritize assessable indicators for a specific type of technological intervention. It was found that the holon expertise are already knowledgeable about most issues in the field and much interaction with potential communities are subsequently not necessary, provided the holon expertise are familiar with the context where a technological intervention is planned. In this study only one learning cycle was completed. For new designed systems it is expected that multiple learning cycles will be associated with the phases in the technology life cycle (Brent and Rogers, 2008).

The complex interactions between the technological, economic, social, ecological, and institutional sub-system were demonstrated through the case study. The vulnerability of the overall system to issues such as trust and ownership was particularly highlighted. Such issues emphasize that transdisciplinarity understanding is required by AET (and other technology) designers to reduce uncertainty and improve the sustainability of technological interventions. Apart from technical aspects a holistic understanding of energy needs and implications, where a technology is to be introduced, is essential. The understating of implications or changes in the integrated system over time, in turn, could identify adaptive strategies for the management of AETs (or other technologies). The learning capacity of cultures in specific contexts, especially, is vital for the planning and decision-making of alternative energy systems. With such increased understanding it is envisaged that the sustainability performances of alternative energy technological interventions may be improved during the design stages, i.e. during the pre-feasibility and feasibility phases, and in the uptake stages, i.e. the transfer and adoption phases, of the technology life cycle.

Recommendations

The alternative energy system of the case study was found to be unsustainable. The failure of the integrated systems was found to be attributed 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 social, economic and institutional sub-systems.

For technology management in general, further research is therefore required to understand the complexity of social-institutional (and ecological) systems as they relate to technological systems to reduce the uncertainty for technology designers and decision-makers. For example, the means to measure and track trust and ownership within an integrated system. The development of resilience parameters and associated factors for the design of technological systems can then be undertaken. It is envisaged that such parameters and factors can be used for the development of technology assessment methods and metrics, as they are used in technology management practices. To this end, the modification of the widely used Technology Balance Sheet, Income Statement and Space Map analytical techniques are currently being investigated, with specific emphasis on the initial research and development phases of technology management (Brent and Pretorius, 2008).

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