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A conceptual framework for energy technology sustainability assessment ☆

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ABSTRACT

Technology assessment has changed in nature over the last four decades from an analytical tool for technology evaluation, which depends heavily on quantitative and qualitative modelling methodologies, into a strategic planning tool for policy making concerning acceptable new technologies, which depends on participative policy problem analysis. The goal of technology assessment today is to generate policy options for solutions of organizational and societal problems, which, at the operational level, utilize new technologies that are publicly acceptable, that is, viable policy options. This study focuses on the development of a framework that incorporates a technology assessment approach, namely, system dynamics, within the broader scope of technology development for sustainability. The framework, termed system approach to technology sustainability assessment (*SATSA*), integrates three key elements: technology development, sustainable development, and dynamic systems approach. The article then demonstrates the framework of incorporating the system dynamics methodology in energy technology assessment theory and practice within the context of sustainable development. The framework provides for technology sustainability assessment, which, in turn, can guide the promotion of sustainable energy technologies at a policy level. In addition, it can assist technology developers in understanding the potential impacts of a technology, hence enabling them to reduce technology transfer risks.

Introduction

Technological development has long been a key driver in the energy sector (Sagar and Holdren, 2002). Technology development is regarded as an interaction of the technology with the system in which the technology is embedded (Hekkert et al., 2007). Technology development not only has the potential of providing the advantage of economic growth and societal benefits but can also facilitate in minimizing the negative effects on the natural environment. The relation between the environment and technology is, however, complex and paradoxical (Grübler, 1998; Grübler et al., 2002). Firstly, technologies use resources and impose environmental stress. On the other hand, technologies can also lead to more efficient use of resources and less stress on the environment. The latter approach is referred to as sustainable technology development (Weaver et al., 2000). Since sustainable technology development is not autonomous, its management is necessary.

One of the important disciplines in technology management is technology assessment (TA), which has evolved over the past four decades (Tran and Daim, 2008). TA enables the evaluation of the aggregate technology capability and facilitates strategic technology planning. Although TA does not necessarily provide policy makers and managers "*the answer*", it may improve the odds that the maximum benefits of technology will be achieved (De Piante Henriksen, 1997). TA can reduce the risks inherent in the competitive process by providing information in support of decision making and can be important in determining research and development direction, new technologies adoption, incremental improvement in existing technologies, level of technology friendliness, 'make or buy' decisions, optimal expenditure of capital equipment funds, and market diversification (De Piante Henriksen, 1997).

While TA has found value in many technology-related problems, there is still a strong need of finding more effective methods of assessment (Tran and Daim, 2008), especially in Africa. This is because TA does not feature in many African government policies (Musango and Brent, 2010). In South Africa, however, a Technology Innovation Agency (TIA), which is a state-owned body, was recently established (IT News, 2009). The agency has three critically important objectives (Engineering News, 2007; Technology Innovation Agency Act of 2008, 2008). Firstly, it is to stimulate technology development; secondly, to stimulate the development of technological enterprises; and, finally, to stimulate the broader industrial base. However, without a formal comprehensive or well-integrated TA tool to evaluate sustainability of any technology, the policy makers, technology designers, and decision makers are faced with difficulty in terms of the appropriate technology options for the country.

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Providing support for the development of sustainable energy innovations therefore remains a difficult task for decision makers with a need to influence the course of technological change.

This article therefore develops a conceptual framework of a systems approach to technology sustainability assessment (*SATSA*) with an aim of providing an improved assessment practices model for renewable energy technologies in developing countries. The framework can also ensure that technology development projects incorporate a broader range of considerations for achieving the desired sustainability performance. Through the framework, the basis of using system dynamics modelling as a means for technology sustainability assessment is explored, and the guiding steps for model development are provided using renewable energy technologies as a case.

Proposed conceptual framework

Fig. 1 provides a schematic representation of the proposed conceptual framework for technology sustainability assessment. The aim of the framework is to demonstrate the linkages between the key elements that are proposed as important for improved technology sustainability assessment practices. These are technology development, sustainable development, and dynamic systems approach. Pairing these elements renders the understanding of sustainable technology development, technology assessment, and sustainability assessment. On the other hand, integrating the three elements provides the foundation for *SATSA*.

Technology development

Technology has affected society and its environment in a number of ways. In many societies, technology has facilitated the development of more advanced economies, such as the current global economy, and the rise of a leisure class. However, many technological processes produce unwanted by-products, such as pollution, and deplete natural resources, both to the detriment of the natural environment. Also, various implementations of technology influence the values of a society and new technology often raises new ethical questions (see Text box 1 for an illustration).

The last 300 years have experienced more momentous technological changes than any other period and is considered as the "*age of technology*" (Grübler, 1998). Anthropologists, historians, and philosophers were the first to have an interest in understanding the role technology plays in shaping societies and cultures. Individuals from other disciplines such as economics only followed later to study technological change (Rosegger, 1996). Thorstein Veblen and Joseph A. Schumpeter pioneered the thinking on technology. Veblen (1904, 1921, 1953) was the first to focus on the

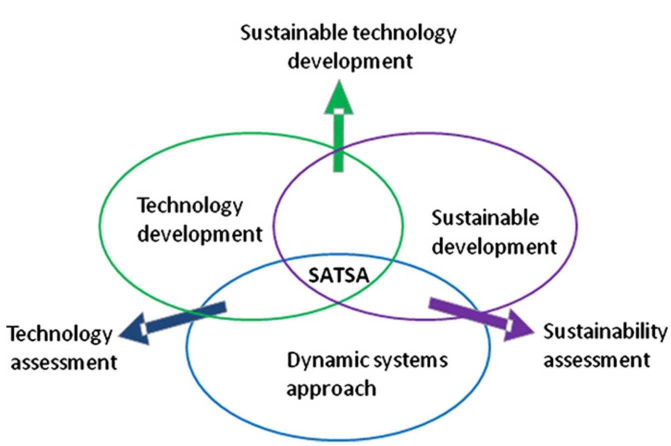

Fig. 1. Schematic representation of a systems approach to technology sustainability assessment (*SATSA*).

Text Box 1
An illustration of the effect of technology on society and environment.

From fossil fuel to renewable energy technologies.
Fossil fuels such as coal, natural gas, and crude oil have contributed to the sophistication of the society for many decades. However, these energy technologies have posed the unintended effects. Burning of oil and coal for all these decades led to greenhouse gas emission to the atmosphere that exceeds the earth's absorptive capacity. The world is at crossroads in determining the future energy technology development. Renewable energy, such as wind, solar, wave, tidal, and geothermal provide an alternative pathway for sustainable energy development. Thus, the choice between fossil fuel and renewable energy technologies poses ethical questions.

interactions between humans and their artifacts in an institutional context and to regard technology as part of material and social relationships. Technology was deemed to be developed and shaped by social actors while at the same time shaping social values and behavior.

Schumpeter (1911), in turn, considered the sources of technological change as endogenous to the economy. This is well illustrated using Schumpeter's waves (see Fig. 2), whereby the duration in which the utilization of new technology knowledge influences the characteristics of economic development decreases. Technological change thus arises *within* the economic system as a result of newly perceived opportunities, incentives, deliberate research and development efforts, experimentation, marketing efforts, and entrepreneurship (Grübler, 1998).

Currently, numerous technology studies acknowledge the feedback loops affecting technology development and a common conclusion that technology development is neither simple nor linear is shared. Grübler (1998) identifies four important characteristics of technology development that are relevant in guiding the development of the improved technology sustainability assessment; these are *uncertainty*, *dynamic*, *systemic*, and *cumulative*.

Technological *uncertainty* arises due to the existence of a number of solutions to achieve a particular task. It is thus uncertain which of these solutions might be the "*best*" when all economic, social, technical, and environmental factors are taken into account. *Uncertainty* also exists at all stages of technology development, from the initial design choices to success or failure in the market place. Secondly, technology is *dynamic* implying that it exhibits an s-curve as it changes over time as a result of improvements or modifications. Plotting the performance of a technology against the cost of investment initially shows a slow improvement, which is then followed by an accelerated improvement and finally diminishing improvement, as shown in Fig. 3. The factors contributing to the *dynamic* nature of technologies is due to either (i) the new inventions or (ii) continuous replacement of capital stock as it ages and economies expand. Technology development is *systemic* and cannot be treated as a discrete, isolated event. The interdependence of technologies causes enormous difficulties in implementing large-scale changes. The mutually interdependent and cross-enhancing "socio-technical systems of production and use" (Kline, 1985) cannot be analyzed in terms of single technologies. This should be considered in terms of the mutual interactions among the concurrent technological, institutional, and social change. Finally, technology change is *cumulative* and builds on previous experience and knowledge.

Although the technology development characteristics discussed above are recognized in the literature, two fundamental features are still largely ignored by macroeconomic (Grübler, 1998) and other models. These are (i) evolution from *within* and (ii) the inherent dynamic and non-equilibrium nature of technological change, which the static and equilibrium models fail to capture.