Systems dynamics modelling to assess the sustainability of renewable energy technologies in developing countries

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Abstract

The 'water-energy nexus' is now receiving more attention as policy- and decision-makers grapple with measures to enable the transition to a sustainable, low-carbon economy. South Africa, in particular, finds itself in a polycrisis in terms of dealing with economic development, to alleviate poverty, within water and energy constraints. In the Western Cape Province of the country, desalination is suggested as one solution to the water shortage crisis, but the critical issue is that of energy supply, and the related cost implications, for water supply; concentrated solar thermal technology options are currently considered. In this paper a systems dynamics approach is used to assess the sustainability of these types of renewable energy technologies. The objectives of the paper are thus twofold. Firstly, the paper demonstrates the potential suitability of system dynamics modelling to inform policy- and decision-making in the developing country context. Secondly, the paper highlights the sustainability issues that must be addressed appropriately if concentrated solar thermal, and other renewable energy systems, are to be used in developing countries at the scale of desalination. Recommendations are made accordingly to improve the analysis, and its usefulness, to utilise this technique effectively in the future.
Keywords: systems dynamics, technology assessment, technology strategy, technology policy, Africa.

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1 Introduction

The concept of sustainable development, which includes, among others, energy security, environmental protection, and mitigation of and adaptation to climate change, is placing a special responsibility on technology policy and use in individual sectors of the economy. Increasingly, technology strategies and options will have to account for national development targets and for steering the economy in a sustainable (green) direction [1]. Framing and modelling technology policy is becoming a critical capability in the domain of science and technology in order to better represent and understand the connections between determinants, decisions and consequences [1].

Many studies are recognizing the potential of renewable and alternative energy technologies to contribute to sustainable development [2, 3]. However, the development of renewable and cleaner energy technologies still involves interactions with the environment. For instance, renewable energy options require natural resources for their development, but may have the potential to reduce impacts on other natural resources. Renewable energy also has a social function in human lives, and interactions may be established between technology development and applicable social systems. To this end, the development of renewable energy technologies involves diverse actors including policy makers, technology developers/investors, assessment practitioners, and the community that would be involved in establishing the technologies, to name a few. These factors display the complex system that constitutes renewable energy technology development, which, some have argued [3], may undermine the achievement of sustainable development. Thus, renewable energy technology management and planning is imperative.

Technology assessment is an important component of the effective management of technology [4, 5] and occurs in initial technology life-cycle phases [6]. A summary of the development of technology assessment over the last four decades has been provided [7]. The emergence of organised technology assessment, as a formal procedure, was, first and foremost, an attempt to predict the unintended negative consequences of technical innovations in the market uptake cycle of technologies [6] to facilitate more adequate policy-making. An expectation of technology assessment was that it should reveal the future consequences of new technology that otherwise would not have been recognized [7]. With respect to renewable and clean energy technology development, some studies acknowledge the need to analyse the development as a complex system [8–10]. Thus, the approach to use in assessing the renewable and alternative energy technology development for sustainability will need to be in a position to account for the assumptions regarding sustainable development [4–6]. This includes the economic, social, environmental and other changes that might influence its development towards the desired sustainable path. The system dynamics approach provides the potential for such a technology sustainability assessment [5, 9].

1.1 System dynamics and its application in the energy sector

System dynamics is among the tools and methods that are recognized for technology assessment [11, 12]. It is an interdisciplinary and transdisciplinary approach that is based on the theory of system structures [13]. System dynamics represents complex systems and analyses their dynamic behaviour over time [14]. The approach has gained popularity due to its focus on the structure and its flexibility, and its potential as an intermediate level tool in technology assessment is recognized [15].

Several studies have been undertaken in the past to address the issues of climate change, alternative and renewable energy, and sustainable resource utilisation, using system dynamics modelling as a tool. For example, at a macro level, the system dynamics approach has been used to develop practical policies, and promote appropriate regulatory regimes for policy-makers, to address climate change issues [16]. The global agricultural and biomass development has been modelled through such an approach [17]. Similarly, the carbon cycle and electricity generation from energy crops has been modelled and simulated [18]. At a micro level, a system dynamics approach has been applied to assess and measure the factors that contribute to or impede the development of efficient, viable, an appropriate access to energy services in remote rural areas [19].

Based on a review of these, and other, applications [4], a conceptual framework of a systems approach to technology sustainability assessment (SATSA) has been developed [5] with the intention to improve sustainability assessment practices for renewable energy technologies in emerging markets. SATSA aims to demonstrate the linkages between key elements, namely, technology development, sustainable development, and dynamic systems approach that are suggested as vital for improved practices of sustainability assessment of technologies. These elements, in combination, provide the understanding of sustainable technology development, technology assessment, and sustainability assessment and form the basis for SATSA (see fig. 1).

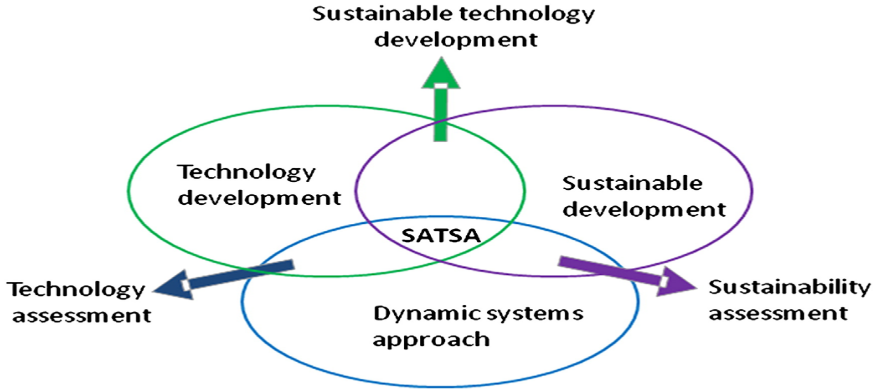

Figure 1: The SATSA framework [5].

1.2 South Africa and its sustainability polycrisis

South Africa finds itself in a polycrisis in terms of dealing with economic development, to alleviate poverty, within water and energy constraints (see fig. 2).

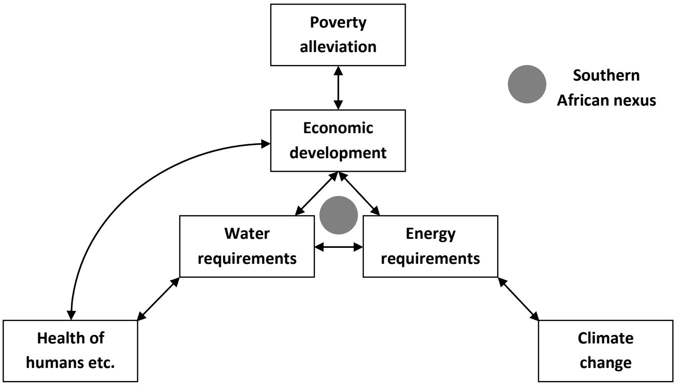

Figure 2: The Southern African polycrisis [20].

Due to its scarcity, much of the water has been allocated and the region has lost its dilution capacity, so all pollutants and effluent streams will increasingly need to be treated to ever higher standards before being discharged into communal waters or deposited in landfills. The spatial development pattern of the region is also unique in that all of the major centres of economic development, and thus cities and urban conurbations, are located on watershed divides. It now means that effluent return flow out of these major industrial and urban conurbations is a major threat to future economic development, simply because the quality of the water is so degraded that it becomes unfit for human, ecosystem and industrial consumption. All these (water) issues are exacerbated by historic legacy that remains to this day; service delivery to treat water and waste, and supply suitable water is now a recognised problem in the public sector with a propensity to become more complex over time.

At present, the region relies heavily on coal as feedstock; the carbon intensity of energy supply, and therefore of the related products from the region, is high. The reliance on coal also has dire consequences for water resources in the region in terms of water use and impacts on water quality. In South Africa, the industrial sector currently comprises 41% of the total energy use and 53% of the total electricity demand of the country. Within the industrial sector mining, iron and steel, non-ferrous metals and non-metal minerals together constitute 59% of energy and 66% of electricity consumed in the industrial sector, with smaller-scale industries collectively accounting another 25% and 22%. It is here that renewable energy systems can make a direct contribution to address the government imperatives of stimulating economic growth coupled with industry development and (labour-intensive) employment creation, improving energy security and access, and addressing climate change, whilst also addressing some of the other societal problems related to water. In particular, desalination with solar systems is now considered, not only of sea water to meet coastal water demands, but also of polluted inland water, which could lead to more carbon-neutral locally-supplied water.

1.3 The Western Cape Province – policy context and challenges

The Department of Economic Development and Tourism of the Western Cape Province (see fig. 3), highlights a number of policy-related challenges [22]:

- There is a potential for Western Cape Province to distinguish itself from the national energy system and establish greater energy independence and be a major role player in the country's energy landscape. This is the economic priority for the Province that will require more than reconciling supply and demand, but address structural reform of the economy to make it more competitive, labour-intensive and equitable. The Province has subsequently developed a Sustainable Energy Policy, of which a Renewable Energy Plan of Action is an integral part. The plan sets a target of producing 15% of the Province's energy from renewable energy sources by 2014. One of South Africa's national priorities is economic growth and employment creation. Renewable energy should be central to achieving this national imperative and the Province should embrace this opportunity to develop its economy and society on the base of a healthy renewable energy regime.
- The Western Cape Province is served by a complex water supply system comprising of six dams, pipelines, tunnels and distribution networks; some elements of the water system are owned and operated by the national Department of Water Affairs and Forestry and some by the City of Cape Town. It is expected that water demand in the Province will exceed supply by 2019, and possibly even earlier if water availability diminishes because of climate change and if water conservation measures in Cape Town should not be as successful as envisaged. A number of additions to the system, such as the heightening of dams, are considered, as well as seawater desalination in order to cope with rising demand. The latter was emphasised by the Minister of Water Affairs in her National Assembly budget vote speech of 2010: "*desalination has become the preferred purification option in terms of both cost benefit and the flexibility of application*".

1.4 Objective of the paper

The critical issue with the desalination strategy is the energy requirements of the process and the associated cost implications for water supply. Thus, given the policy objectives of the Western Cape Province, as well as the solar resource in the Province (see fig. 3), concentrated solar thermal (CST) is an energy technology option, as is highlighted in a recently completed Solar Energy Technology Roadmap for South Africa [21]. In this paper the SATSA framework is used to assess the sustainability of these types of renewable energy technologies, with the primary objective to ascertain the critical sustainability issues that must be addressed appropriately if concentrated solar thermal systems are to be used for the purposes of desalination. Thereby the best technology strategy policies to meet the long term water and energy needs of the Western Cape Province can be formulated by assessing the medium- to long term interactions between society, its water and energy related technologies, sectors of the economy, and the environment that ultimately limits the growth of water and energy resource use in the Province.

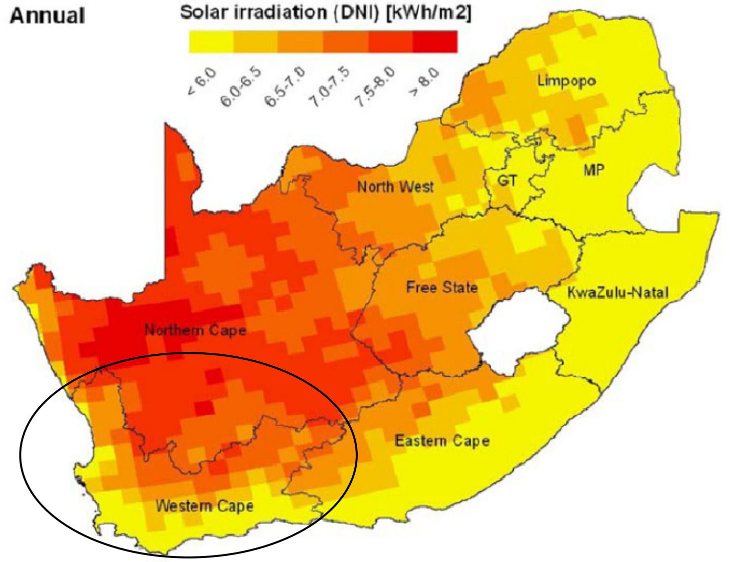

Figure 3: Average daily direct normal irradiation (DNI) for South Africa [23].

2 Contextualising the technology policy formulation in the Western Cape Province

Technology policy is a complex issue irrespective of the specific technology and/or the policy context at hand. The dynamic complexity arises from the interactions among system components that form the basis of technology policy planning [1]. Without a structured formulation process, policies may produce only short-lived benefits while in the long run challenges become severe [1]. Fig. 4 shows a point of departure for technology policy formulation.

The elements shown in fig. 4 are generic and pertain to technology policy and development across any domain of activity, sector, and/or technology. These feature (i) overarching goals and objectives, (ii) essential actors and resources, (iii) dynamics of conversion of intent into action, (iv) the imperatives of skill and capacity-building, and (v) the actual implementation factors [1]. In terms of the Western Cape Province case the characteristics of the modal elements are as follows:

1. Specific Technology Priorities – the Province has made commitments to producing 15% of its energy from renewable energy sources by 2014, reduce

its CO_2 emissions in line with the country's ambitious Copenhagen targets of 34% by 2020, create jobs, and augment water supplies through desalination in order to cope with rising demand.

2. Strategy Design and Coordination – to meet future demands for energy the Province must consider renewable energy sources in the mix of all available energy resources in the Province. Concentrated solar thermal (CST) systems are well suited for semi-arid like areas such as the Western Cape Province. Building a CST plant adjacent to the desalination plant will generate significant benefits, such as energy savings, provision of fresh water, cost savings and environmental gains, but the need exists to ensure that all the resources that are required to build and operate CST and desalination plants are readily available, and that they can be effectively integrated in the social-ecological systems of the Province.
3. Skills and Capacity Building – the resources that are required include, among others, people, institutional support, infrastructure, and finances; these are key inputs that necessitate skills and capacity building in the Province. Human resources will be needed to design, build, and operate the plants. The financial resources must be secured through the funding of various public-private schemes. In addition, access to the latest CST technologies and processes to produce solar energy is needed – this can be achieved by building local capacity in solar thermal energy, including local capacity for research and development, or through continuous partnerships with other countries, such as Spain, Germany, Israel, Australia, and the United States.
4. Sustainable Technology Strategy – physical conditions and the cluster of variables known as "carrying capacities" can be limiting factors to the development of solar technologies; it is useful to determine what is needed to sustain solar energy use and economic performance. Carrying capacities impose constraints, such as limited land because solar technologies require large physical space, and other possible limiting factors.

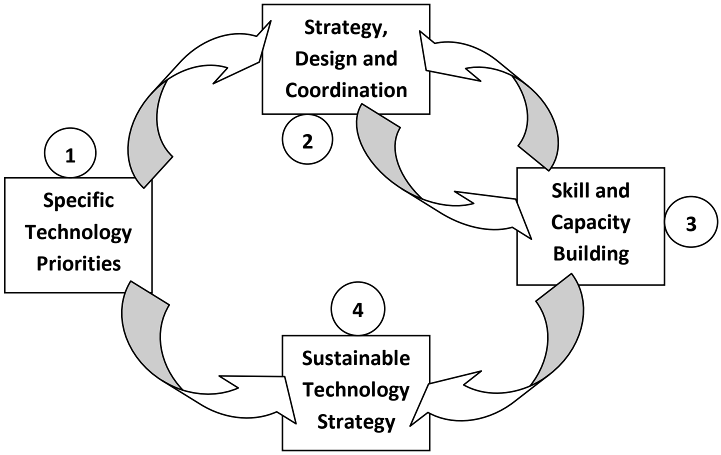

Figure 4: Modal elements of technology policy formulation [1].

The above captures most if not all of the key variables and decision points. Fig. 5 then maps out the logic of technology policy formulation in the Western Cape.

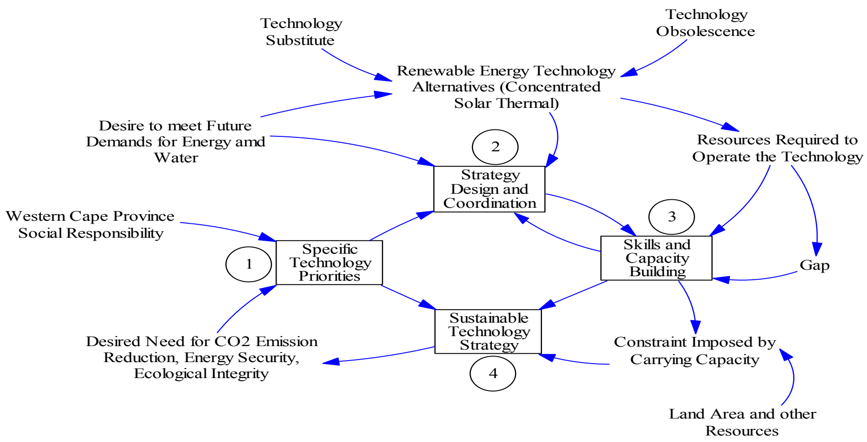

Figure 5: Mapping the logic of technology policy formulation in the Western Cape Province.

3 Application of the SATSA framework to the Western Cape Province case

SATSA, as a framework for assessing the sustainability of technologies, aims to assist policy- and decision-makers to understand, holistically, the ways in which technological systems function and the consequences that may follow as a result of the interconnectedness of system components [5]. In other words, changes happening in one part of the system may consequently induce changes in other parts. The initial step in system dynamics modelling, which underpins the SATSA framework, is then to determine the system structure consisting of positive and negative 'cause and effect' relations between system components.

3.1 Causal relations

The long-term competitiveness of the economy of the Western Cape Province is dependent on decisions taken on energy and water policy in the medium to long-term. Consequently, the success or failure of energy and water policy initiatives or strategic plans by the Western Cape Province is largely dependent on whether the policy- and decision-makers truly understand the interaction and complexity of the system they are attempting to influence [24]. Considering the size and complexity of the systems, with related challenges, that public decision makers must manage, it is not surprising that the "intuitive" or "common sense" approach to policy design often falls short, or it is counter-productive, to the desired outcomes [24]. Such complex systems/problems that decision makers often grapple with are possible to find solution(s) to if one begins to analyse systems/problems dynamically and holistically, namely by first examining the patterns of behaviour that real-world systems exhibit, and then discussing the structure that causes such patterns to emerge. Fig. 6 presents the causal loop diagram showing the causal relations (dynamics) of energy and water technology policy of the Western Cape Province.

3.2 Feedback dynamics

Fig.6 highlights four key feedback loops that can be used to explain variations in success regarding policy challenges in the Western Cape Province. Loop B1 shows the intended policy of using desalination technologies to augment water supplies in Western Cape Province. That is, pressure to invest in desalination technologies due to widening water deficit increases leading to actual investments in desalination technologies. That increases the resources required to design, build and operate these technologies. Over time, the investment made increases the uptake level of desalination technologies leading to improved economic growth. Similarly, loops B2 and B3 present the economic rationale for investment in renewable energy technologies, particularly concentrated solar thermal (CST) technologies. Finally, loops R1 and R2, present the second order effect of both desalination and renewable energy technologies – that is continuously building the skill and capacity to operate the technologies and allowing for further desalination and renewable energy technologies – thus achieving provincial priorities of meeting demands for water and energy.

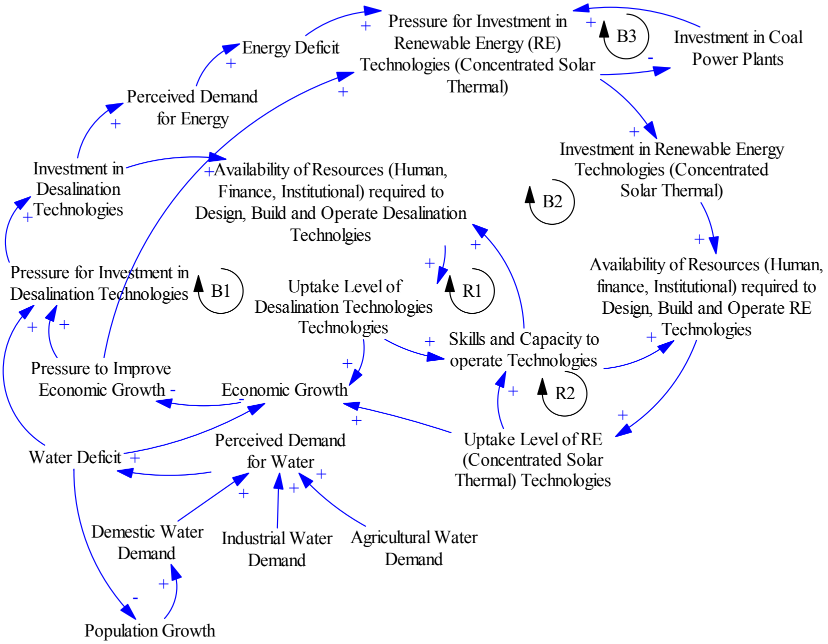

Figure 6: Casual loop diagram of the Western Cape Province case.

An important issue to consider with a system dynamics approach is that of the delay between feedback loops that can undermine change if significant enough [1]. For example, the investment in renewable energy technologies may lead to security of energy supply and increased use of renewable energy in the Western Cape's primary energy mix, but lead to a delayed economic growth due to minor progress in economies of scale because vested interests still pursue coal projects and deliver electrical energy at prices that renewable energies cannot compete. As a result job creation from the renewable energy sector is negatively affected leading to a possible abandonment of a good strategy.

4 Conclusions and recommendations

This paper introduces the systems approach to technology sustainably assessment (SATSA), as a means to analyses technology policy options for the 'water-energy nexus' that is faced in many developing countries, and especially in South Africa. The SATSA framework is applied to the Western Cape Province of the country as a specific case, where a combination of concentrated solar thermal (CST) and desalination technologies is considered.

As a first phase of the analysis, the key elements for technology policy formulation are defined, in terms of Specific Technology Priorities, Strategy Design and Coordination, Skills and Capacity Building, and Sustainable Technology Strategy. Also, the initial step of system dynamics modelling that underpins the SATSA framework, is taken in terms of determining the system structure based on the defined key elements. The initial analysis highlights the importance of investment behaviour (balancing loops) and the building of skills and capacity (reinforcing loops) as the main components of the system that must be addressed in the formulation of appropriate technology policy. However, what is not clear from the first phase of the analysis, is the extent of the relationships of the main components; this constitutes the next phase – the stock and flow analysis that is required to provide a unique insight into the behaviours in the system. Also, the next phase will clarify an uncertainty that has been highlighted in the initial analysis; understanding the key time delays in the complex system and aligning policy to accommodate delays as a necessary governance function.

Apart for taking the modelling to the next step, to refine the analysis of the CST and desalination combination in the Western Cape Province of South Africa, the usability of the system dynamics technique, for policy- and decision-makers, also requires further investigation. This research is ongoing in the South African energy sector.

References

[1] Choucri, N., Mistree, D., Haghseta, F., Mezher, T., Baker, W. & Ortiz, C., Mapping sustainability: Knowledge e-networking and the value chain. *Alliance for Global Sustainability Bookseries*, **11**, 2007.

[2] Silva Lora, E.E., Escobar Palacio, J.C., Rocha, M.H., Grillo Renó, M.L., Venturini, O.J. & Almazán del Olmo, O., Issues to consider, existing

tools and constraints in biofuels sustainability assessments. *Energy*, in press, 2010.
[3] Sukkasi, S., Chollacoop, N., Ellis, W., Grimley, S. & Jai-In, S., Challenges and considerations for planning toward sustainable biodiesel development in developing countries: Lessons from the Greater Mekong Subregion. Renewable and Sustainable Energy Reviews, **14**, pp. 3100-3107, 2010.
[4] Musango, J.K. & Brent, A.C., Assessing the sustainability of energy technological systems in Southern Africa: A review and way forward. *IAMOT Proceedings*, Cairo, 2010.
[5] Musango, J.K. & Brent, A.C., A conceptual framework for energy technology sustainability assessment. *Energy for Sustainable Development*, in press, 2010.
[6] Brent, A.C. & Pretorius, M.W., Sustainable development and technology management. In: Sherif, M.H. & Khalil, T.M. (eds), *Management of Technology Innovation and Value Creation*. Management of Technology **2**, World Scientific, New Jersey, 2008.
[7] Palm, E.T. & Hansson, S.O., The case for ethical technology assessment (eTA). *Technological Forecasting and Social Change*, **73**, pp. 543-558, 2006.
[8] Afgan, N.H. & Carvalho, M.G., Multi-criteria assessment of new and renewable energy power plants. *Energy*, **27**, pp. 739-755, 2002.
[9] Jones, C.A., *The renewable energy industry in Massachusetts as a complex system: Developing a shared understanding for policy making*. PhD Dissertation, University of Massachusetts, Boston, 2008.
[10] Snyder, N. & Antkowiak, M., Applying systems engineering in a renewable energy research and development environment. National Renewable Energy Laboratory, NREL/CP-6A1-48159, *INCOSE International Symposium*, Chicago, 2010, available from: http://www.nrel.gov/docs/fy10osti/48159.pdf.
[11] De Piante Henriksen, A., A technology assessment primer for management of technology. *International Journal of Technology Management*, **13**, pp. 615-638, 1997.
[12] Tran, T.A. & Daim, T., A taxonomic review of methods and tools applied in technology assessment. *Technological Forecasting and Social Change*, 75, pp. 1396-1405, 2008.
[13] Sterman, J.D., *Business dynamics: systems thinking and modelling for a complex world*. McGraw-Hill/Irwin, New York, 2000.
[14] Forrester, J.W., *Industrial dynamics*. Productivity Press, Cambridge, MA, 1961.
[15] Wolstenholme, E.F., The use of system dynamics as a tool for intermediate level technology evaluation: three case studies. *Journal of Engineering and Technology Management*, **20**, pp. 193-204, 2003.
[16] Fiddaman, T., Dynamics of climate policy. *System Dynamics Review*, **23**, pp. 21-34, 2007.
[17] Tesch, T., Descamps, P. & Weiler, R., The COSMOPAD modelling framework: Conceptual system dynamics model of plenary agricultural and

biomass development. *Digital Earth Conference*, BRNO, Czech Republic, 2003.
[18] Flynn, H., & Ford, D., A system dynamics study of carbon cycling and electricity generation from energy crops. *23rd International Conference of the System Dynamics Society*, Boston, 2005.
[19] Dyner, I., Alvarez, C. & Cherni, J., Energy contribution to sustainable rural livelihoods in developing countries: A system dynamics approach. *23rd International Conference of the System Dynamics Society*, Boston, 2005.
[20] Heun, M.K., van Niekerk, J.L., Swilling, M., Meyer, A.J., Brent, A.C. & Fluri, T.P., Learnable lessons on sustainability from the provision of electricity in South Africa. *Proceedings of the ASME 2010 4th International Conference on Energy Sustainability*, Phoenix, Arizona, 2010.
[21] Brent, A.C., Pretorius, M.W., An analysis of the industrial and commercial opportunities to utilise concentrated solar thermal systems in South Africa. *Industrial and Commercial Use of Energy*, Cape Town, 2010.
[22] Department of Economic Development and Tourism, *Five year strategic plan – 2010/15 – Western Cape. Cape Town*, 2010, available from: http://www.capegateway.gov.za/Text/2010/3/fiveyearstrategic_sml.pdf.
[23] Fluri, T.P., The potential of concentrating solar power in South Africa. *Energy Policy*, 37, pp. 5075-5080, 2009.
[24] Radzicki, M.J., Taylor, R.A., Introduction to system dynamics: A systems approach to understanding complex policy issues. US Department of Energy, 1997, available from: http://www.systemdynamics.org/DL-IntroSysDyn/.