Sustainability Assessment of Energy Systems

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This research project set out to develop and apply a framework for assessing how energy systems may be structured to help society progress towards sustainability. The general intent was to outline a way to decide upon the things that matter in order to make better decisions that will lead to positive near- and long-term outcomes. There are various ways of reaching the goal described above, and the path chosen in this dissertation centred on Gibson's (2006) sustainability assessment framework, an approach to integrated sustainability-based decision-making. In order to contribute to extending and specifying Gibson's approach to sustainability assessment for energy undertakings, this project developed a theoretical framework grounded in various forms of complexity and energy.

The journey described in the dissertation begins with an exploration of the complexity of science, the subject of Chapter 2. We live in a world characterized by inherent uncertainty, multiple worldviews, conflicting values, power dynamics and a whole host of other challenges to science and decision-making. Many of the environmental and human challenges we currently face have arisen in part because we do not sufficiently respect the limits to knowledge and the personal biases we all bring to the table. Chapter 2 develops a framework for knowledge generation and decision-making situated within its social context, and operationalizes this framework through the process of criteria specification. Drawing from multiple sources of data – particularly documentary analysis, semi-structured interviews and observation – the criteria specification cycle provided the means of and determining and deciding upon the things that matter in a given case and context.

The complexity of science is only half the story emerging from the complex systems literature. From a different perspective, it is evident that we live in a world of complex dynamics and interconnections, and it is important to ensure that whatever energy paths we set out on recognize these dynamics. Fortunately, there is a wide range of literature relating to the characteristics of complex systems in general, as well as their energy and material flows in societies. These literatures are explored in Chapter 3 to develop an understanding of and guidelines for managing complex systems to the extent possible and appropriate.

Building on the theory developed in Chapters 2 and 3, the discussion in Chapter 4 began to develop an understanding of energy systems and energy decision-making and was structured around three general questions: (1) what is the energy problem? (2) what are the characteristics of an appropriate and constructive relationship with energy? and (3) how can the necessary and desired sociotechnical systems changes be achieved. These questions were largely addressed through an exploration of the soft energy path and transition management and led to two sets of guidelines designed to address energy systems structure and change.

The theoretical framework developed over Chapters 2-4 was consolidated into a proposed set of sustainability criteria for energy undertakings. The sustainability criteria set represents the principal theoretical contribution of the dissertation to the academy and the broader assessment community, and outlines a suite of generally desirable system attributes and actions for achieving *progress* towards sustainability, as opposed to an acceptability threshold. The proposed sustainability criteria are primarily intended for application regarding energy undertakings at a wide variety of scales, but are much more broadly relevant.

In a manner that is more iterative than can be described in this abstract, the sustainability assessment framework described in this dissertation was applied in, and enriched through, four distinct case studies that assessed

(1) the 2006 Ontario Integrated Power Systems Plan proposed by the Ontario Power Authority. The Integrated Power Systems Plan was originally framed as a coal versus nuclear problem, as opposed to a critical appraisal of power systems planning; and in doing so it underplayed potential for conservation, demand management, increased renewable energy, and social change;
(2) a small-scale biodiesel operation in Barbados. The plant owner collected used cooking oil from restaurants, roadside stands, and individual homes, and converted it into biodiesel using a first-generation processing technology known as transesterification.
(3) a sugarcane-ethanol plant in the Tietê-Jacaré Watershed of São Paulo, Brazil. The sugarcane ethanol mill harvests approximately 21,000 hectares of sugarcane crops from seven municipalities and produces hydrated ethanol for domestic markets, and sugar for domestic and international markets; and
(4) the agricultural and energy systems in Senegal. Senegal suffers from significant deforestation and soil fertility decline coupled with demographic change. The many interconnections between the energy and agricultural systems require an integrated assessment of both.

Each individual case study stands alone in providing novel insights emerging from application of the framework in the particular case and context. At the more general level, five important insights emerged from the case studies, including: (1) the benefits of, and need for, maintaining a flexible unit of analysis so as to improve problem structuring; (2) the importance of grounding an assessment within its context; (3) the benefits of seeking integration and positive indirect effects; (4), the need to plan for and develop energy bridges towards feasible and desirable energy futures; and (5), the need for caution in the face of thresholds and uncertainty.

The individual and general insights from the case studies were incorporated into the most recent version of the sustainability assessment framework described in this dissertation. The framework is suitable for application, with specification for particular case and context, to all types of energy systems at all scales.

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Dedication

I dedicate this thesis to the farmers and cyclists out there struggling to make the world a tastier and healthier place.

“The ultimate goal of farming is not the growing of crops, but the cultivation and perfection of human beings.” — Masanobu Fukuoka

“El socialismo puede llegar sólo en bicicleta.” - José Antonio Viera-Gallo

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Nomenclature

One of the problems with systems thinking (defined below) is that there are so many terms that may or may not mean the same thing to depending on the context. To help disambiguate some of the language, the following terminology is employed:

<u>*The complexity of science*</u> refers to approaches to learning and decision-making that characterize important challenges and opportunities emerging from the complexity of our world. These characteristics are elaborated upon in Chapter 2, and include issues of uncertainty, ethics, problem formulation, and scientific neutrality. Well-known approaches that fall within this rubric include post-normal science (Funtowicz and Ravetz 1993), transdisciplinarity (Hirsch Hadorn et al. 2006), critical systems thinking (Midgley 2000), soft systems methodology (Checkland and Scholes 1990), science and technology studies (Winner 1986), and ideas from more popular writers of many stripes (Ellul 1967; Illich 1973; Schumacher 1973).

<u>*The science of complexity*</u> refers to approaches that attempt to characterize the structure and dynamics of complex systems. This is a very broad field, and some well-known approaches in this area include systems dynamics (Meadows and Wright 2008), general systems theory (von Bertalanffy 1969), resilience thinking (Gunderson and Holling 2002), bioeconomics (Giampietro and Mayumi 2000) and the ecosystem approach (Kay et al. 1999). Giddens' structuration theory is also included in this category, although that may upset sociologists. For the purpose of this dissertation, the emphasis is on big picture ideas rather than formal dynamic models.

<u>*Systems thinking*</u> refers to both the complexity of science and the science of complexity It is a catch-all term that acknowledges that many approaches cover both the characteristics of complex systems as well as the process of learning and decision-making in the face of complexity.

There is no single best way to define <u>*a system*</u>. Meadows and Wright provide the following definition:

> *A system is an interconnected set of elements that is coherently organized in a way that achieves something. Some interconnections in a system are physical flows, while other interconnections are flows of information. Systems generally replace their individual elements while still maintaining the integrity of the whole. - Meadows and Wright (2008, ch. 1)*

List of Abbreviations

AT – Appropriate technology
COS – Complexity of science
EROI – Energy return on investment
Gibson's SA framework – Gibson's (2006) framework for sustainability assessment
ISO – International Organization for Standards
SEP – Soft energy path
TM – Transition management

Preface – On the presentation of a hybrid dissertation

Before reading the actual dissertation, the reader may benefit from two points of explanation.

First, this dissertation represents an experimental approach to dissertation presentation, one that represents a hybrid of the conventional monograph and the newer paper-based approach. The empirical component of this dissertation (Chapters 5-8) comprises four case studies, three of which have been published (one where this author is primary author, one where the author is secondary author, and one where this author is fourth author), and one that will be shortly submitted to a journal. In this regards this dissertation shows similarities to the paper-based approach. In contrast to the casework, the theoretical development of this dissertation is built upon the monograph style, and unfolds over the first four chapters. The theoretical framework draws from a wide range of disciplines that cannot be easily summarized in a paper, or added as a bookend, and rather represents a substantial contribution in and of itself. The most obvious feature of this hybrid approach is that redundant information appears in the case study chapters, particularly in Chapters 6-8, where the methods and Gibson's framework for sustainability assessment are repeated.

Second, the research reported on in this dissertation iterated between theory and empirical casework. While the basic theoretical framework was in place before the casework began, the insights from the casework influenced the final presentation of the theoretical framework, ideally producing a stronger framework that has been tested and updated several times. For example, the insights from bioeconomics were included after it became clear they are not fully appreciated in energy decision-making. The disadvantage of the iterative approach is that it complicates the process of writing a dissertation in a linear form that begins from a set of first principles, builds a conceptual framework, applies the framework in an empirical setting, and then reports on the results. Despite this difficulty, all attempts have been made to structure the dissertation within the linear format, while recognizing that this was not entirely how the research unfolded.

Chapter 1 - Introduction

1.1 Objective

The objective of this dissertation is to develop and apply a framework for assessing how energy systems can be designed to help society progress towards sustainability. In order to do so, this research adopts Gibson's (2006b) sustainability assessment framework, an approach to integrated assessment that covers the full suite of requirements for sustainability. To apply Gibson's framework to energy systems, this dissertation develops a theoretical framework that centres on four sub-objectives: (1) the description of an assessment approach for a world characterized by uncertainty, incomplete knowledge and value conflicts; (2) the proposal of two sets of guidelines for managing complex social-ecological systems relating to their general and, more specifically, metabolic characteristics; (3) the proposal of two sets of guidelines for defining the characteristics of an appropriate and constructive relationship with energy, and the necessary steps to foster sociotechnical systems change; and (4) a synthesis of the previous sub-objectives into a unique, normative, and comprehensive set of sustainability criteria for energy undertakings.

The theoretical framework is applied in four case studies that took place between 2008 and 2012. The case studies represent a substantive contribution on their own, but also served as a means to continually improve upon the theory, particularly the sustainability criteria set for energy undertakings. The sub-objectives are elaborated upon in section 1.3.

Meeting these objectives is to be the outcome of the research process outlined in this chapter and undertaken in the following chapters. The question remains, why is such a process is being undertaken in the first place?

1.2 Rationale - key challenges facing the world today

Societies today are facing an escalating and interrelated series of challenges and crises at an unprecedented scale. For example, Diamond (2005) describes twelve interdependent biophysical problems facing our world, relating to climate change, biodiversity, water availability and quality, the spread of invasive species, land-use change and diminishing forest cover, declining soil fertility, overreliance on fossil fuels, and the increasing amount of primary productivity being captured for human purposes. Many of these challenges are directly or indirectly related to humanity's relationship with energy, particularly the use of high quality energy sources (Fargione et al. 2008; Homer-Dixon 2006; Nikiforuk 2012; Tainter 1988). Any one of these challenges on its own is worrisome, and their synergy even more so.

The challenges societies face are not simply biophysical, but also social, metaphysical and ethical (Schumacher 1973). There are profound inequalities both within and between countries in terms of resource consumption, material prosperity, power relations, livelihood opportunities, ability to withstand and weather external shocks, and ability to develop equitably within the current world order (Giampietro and Mayumi 2009; Rip and Kemp 1998; Sagar 2005). Even in the more affluent countries – where technological innovations have brought almost unimaginable progress in many domains – doubt remains about whether material prosperity and technological progress have dawned a new renaissance or simply changed the nature of the challenges (e.g. Illich 1978; Lerner et al. 1999; Marcuse 2010; Nikiforuk 2012).

Energy represents a common thread weaving through the various biophysical, metaphysical and ethical challenges facing society. Energy is fundamental for survival and development (Kay et al. 1999). The implications of humanity's relationship with energy are becoming increasingly evident and relevant for challenges as varied as climate change, economic vulnerability, war, and human rights abuses (e.g. Lovins 1977; Nikiforuk 2012; Nuffield 2011). There is growing agreement that we must profoundly change our energy systems in the coming few decades if we are to avoid collapse in one form or another (Hall et al. 2008; Hall and Klitgaard 2006; Lovins 1977; Rotmans and Loorbach 2008).

Yet change in basic structures and behaviour is difficult to drive and direct for a wide variety of reasons. First, energy is deeply embedded within current societal structures and influences how we relate to one another and situate ourselves within society at large (Hall and Klitgaard 2006; Meadows 1972; Nikiforuk 2012; Schumacher 1973, ch. 8). For example, the benefits of modern culture – including modern health care, science and the arts – are all predicated on surplus energy produced with a minimum of human labour (Cottrell 1955). Furthermore, the role of energy in providing basic services that underpin society is often ignored in part because energy is often confused with the services it provides (e.g. light versus electricity) (e.g. Lovins 1976) and also because the full lifecycle costs of energy consumption are rarely evident to the consumer (e.g. Berl et al. 2010; Williams 2004). As well, there is little clear shared understanding of the power levels embodied in most technologies (Giampietro and Mayumi 2009; Nikiforuk 2012), nor full appreciation of how the use of these technologies shapes and conditions individuals and societies (Winner 1986).

Second, the energy-related challenges facing society span multiple levels and transcend societal domains, including agriculture, transport, geographical organization, politics, ethics and social relationships (Bellamy-Foster 2009; Loorbach 2010; Meadows and Wright 2008, ch. 1; Robinson 2004; Roling 2005). Energy systems change provides both challenges and opportunities for all facets of society, including outcomes as varied as rural development, public health, and the planning and makeup of cities (Bauchspies et al. 2006; Nikiforuk 2012). Furthermore, with dynamics occurring over multiple scales, rigid command and control become impossible for many situations that matter (De Marchi and Ravetz 1999; Kay et al. 1999; Midgley 2000, ch. 1; Munda and Russi 2008; Walker et al. 2002; Waltner-Toews 2008).

In many instances, especially with regards to energy system trends and effects, there is no clear understanding of even what the "problems" are (Robinson 2004; Robinson 1982), and the multiplicity of worldviews views lead to profoundly different conclusions regarding what solutions are feasible, desirable and probable (Bardwell 1991; Bott et al. 1983, ch. 1; Giampietro and Mayumi 2009; Schon and Rein 1994, ch. 1). Furthermore, decisions about, and changes to, societal energy patterns have ethical implications for individuals, societies, and the natural environment, including questions of inequality (both between individuals and nations), environmental racism and justice, energy poverty, and justice to the environment (Agyeman et al. 2003; Dobson 2004; Guruswamy 2011; Illich 1978; Rees and Westra 2003; Spaul 2009).

The challenges described above imply a complex situation of interconnected problems and opportunities, multiple indirect effects, conflicting worldviews and ethics, and deep uncertainty (Funtowicz and Ravetz 1993; Kay 2008a). The insights about and characteristics of complexity must be taken seriously in order to seek meaningful progress towards sustainability (e.g. Holling 2001; Kay 2008b).

This dissertation develops and explores one possible approach to knowledge generation and decision-making that is grounded within an understanding of systems thinking and that seeks progress towards sustainability with a specific focus on energy systems. The insights of complexity provides opportunities for seeking positive change through an approach that is problem-based, integrated and ethically grounded, and sensitive to local context (e.g. Waltner-Toews et al. 2008). This dissertation seeks to understand better the role of energy and energy systems in society and determining – both in general and for given cases and contexts – the key issues to be addressed to achieve meaningful progress towards sustainability. To this end, energy is an entry point into deeper social-ecological dynamics and characteristics of societies.

The emphasis of this dissertation is on *progress* towards sustainability, which for the purpose of this dissertation has been broadly defined as follows

> *a process of building towards futures that are desirable and viable on a single, limited planet where the possibilities for human wellbeing, social justice, and ecological stewardship are deeply entwined and where complexity and surprise are unavoidable. (Gibson 2012, pers. comm.)*

This definition is one of many that attempt to capture the nebulous nature of sustainability, sustainable development, and progress towards sustainability, and needs to be elaborated upon and explored both in general and in specific contexts (e.g. Robinson 2004). For our purposes, the intent is not to define whether a given undertaking is sustainable or not, but rather to outline how the undertaking may be structured to help society move in a positive direction, and then consider where we go from there. This task is undertaken in the theoretical and empirical research that follows.

1.3 Research Design - Gibson's Sustainability Assessment framework

This section describes the research design. It begins by describing Gibson's (2006b) framework for sustainability assessment (which I will refer to as "Gibson's SA framework" for short) and then further elaborates upon the four sub-objectives defined to meet the overall objective.

Sustainability assessment frameworks are generally similar to broadly conceived strategic environmental assessment though they may also be applied at the project level (Devuyst 1999; Gibson et al. 2005; Pope et al. 2004; Sheate et al. 2008). The purpose of Gibson's SA framework is to provide a comprehensive normative framework that integrates broad and universal requirements for sustainability while recognizing the case specific context (Gibson et al. 2005, ch. 1; Partidário et al. 2009; Pope and Grace 2006). As the framework may be modified in terms of scope and rigour, it is promoted for any situation where sustainability is an issue, and may be applied to both proposed and ongoing projects, plans and policies (Pope et al. 2004). The bases of Gibson's SA framework are eight categories of progress towards sustainability that are described in Table 1.

Table 1 - Gibson's (2006) eight categories for progress towards sustainability

Socio-ecological system integrity Build human-ecological relations to establish and maintain the long-term integrity of socio-biophysical systems and protect the irreplaceable life support functions upon which human as well as ecological wellbeing depends.
Livelihood sufficiency and opportunity Ensure that everyone and every community has enough for a decent life and that everyone has opportunities to seek improvements in ways that do not compromise future generations' possibilities for sufficiency and opportunity.
Intragenerational equity Ensure that sufficiency and effective choices for all are pursued in ways that reduce dangerous gaps in sufficiency and opportunity (and health, security, social recognition, political influence, etc.) between the rich and the poor.
Intergenerational equity Favour present options and actions that are most likely to preserve or enhance the opportunities and capabilities of future generations to live sustainably.
Resource maintenance and efficiency Provide a larger base for ensuring sustainable livelihoods for all while reducing threats to the long term integrity of socio-ecological systems by reducing extractive damage, avoiding waste and cutting overall material and energy use per unit of benefit.
Socio-ecological civility and democratic governance Build the capacity, motivation and habitual inclination of individuals, communities and other collective decision-making bodies to apply sustainability requirements through more open and better informed deliberations, greater attention to fostering reciprocal awareness and collective responsibility, and more integrated use of administrative, market, customary and personal decision making practices.
Precaution and adaptation Respect uncertainty, avoid even poorly understood risks of serious or irreversible damage to the foundations for sustainability, plan to learn, design for surprise, and manage for adaptation.
Immediate and long term integration Apply all principles of sustainability at once, seeking mutually supportive benefits and multiple gains.

Gibson's SA framework is one possible means by which to move beyond narrowly defined considerations to address, as much as possible, the full suite of requirements for sustainability, as well as the interconnections, feedbacks and uncertainties that typify complex socio-ecological systems at multiple scales that were partly described above (Gibson et al. 2005; Holling 2001). To do so, Gibson's eight categories must be elaborated into an evaluative framework grounded within the case and context of the application. This elaboration is achieved through the process of criteria specification, which is described in Chapter 2 and applied in the four case studies described in Chapters 5-8.

There are two general means by which Gibson's SA framework has been informed by the study of complex social-ecological systems and energy systems assessment. First, the research process itself may be designed to recognize the challenges of decision-making in the face of multiple worldviews, uncertainty and conflicting ethics. This more procedural approach is described in sub-objective 1 below. Second, the study of complex social-ecological systems and energy systems assessment can inform the substance of the evaluative framework for assessment. This second approach is developed through sub-objectives 2-4 below, and culminates in the proposed sustainability criteria for energy undertakings.

Sub-objective 1 – Integrate the insights from the complexity of science to describe a framework for analysis

As described in the rationale above, the challenges facing society require working within the constraints of the complexity of science, including issues of ethics, uncertainty, and multiple worldviews. In order to address these challenges in the research process, the first sub-objective of the dissertation is to integrate the insights from the complexity of science with Gibson's SA framework to describe a generic framework for knowledge generation and decision-making.

Sub-objective 1 is the topic of Chapter 2 and draws from various conceptions of the complexity of science, particularly post-normal science, transdisciplinarity, integrated assessment, and science and technology studies. Chapter 2 culminates in the description of the process of criteria specification that underlies the assessment process of the casework.

Sub-objective 2 – Develop a set of guidelines for managing complex systems

As described in the rationale above, the challenges facing the world must recognize the characteristics of complex systems to understand how these systems can be appropriately managed. In order to address this challenge, the second sub-objective is to synthesize relevant insights from the science of complexity to provide a set of basic guidelines relating to managing complex systems in general, and their metabolic characteristics in particular.

Sub-objective 2 is the primary topic of Chapter 3, and is accomplished in two parts. The first section develops a basic understanding of complex systems in general, and pays particular attention to the ecosystem approach, resilience thinking, and hierarchy theory. The second part of Chapter 3 moves the discussion towards systems and society and draws primarily from Giddens' structuration theory and bioeconomics. Giddens' structuration theory is important to inform the discussions of sociotechnical systems change that are provided in Chapter 4, while bioeconomics reinterprets economic systems through a complexity lens with particular focus on metabolic characteristics (e.g. energy and resource flows).

Sub-objective 3 – Develop a set of guidelines for energy systems assessment

Drawing from the theory developed in the first two sub-objectives, the third sub-objective moves the discussion towards energy systems, which is the main focus of this dissertation. The purpose of sub-objective 3 is to develop two sets of guidelines relating to the general characteristics of a constructive relationship with energy, and the necessary steps for promoting sociotechnical systems change.

Sub-objective 3 is the topic of Chapter 4, and is structured around three general questions: (1) what is the energy problem? This question helps ground energy systems analysis and energy decision-making within the broader worldview outlined in this dissertation, and leads into the second question: (2) what are the characteristics of an appropriate and constructive societal relationship with energy? This second question is addressed through discussions of the soft energy path, an important theoretical cornerstone to this dissertation. Where the soft energy path encounters a rather hard barrier relates to how structural change can be achieved, and this leads to the third question: (3) how can sociotechnical systems change be achieved? The discussions in the third section are centered on transition management, an approach to sociotechnical systems change.

Sub-objective 4 - Consolidate the complex systems- and energy- informed guidelines into a generic set of sustainability criteria for energy undertakings.

In the fourth and final sub-objective of this research, the previous theory is consolidated into a proposed set of sustainability criteria for energy undertakings. The sustainability criteria set is provided in Table 14, at the end of Chapter 4, and represents a substantive evaluative framework for assessment.

The sustainability criteria set provides a useful starting point for assessing the potential for energy systems to help society progress towards sustainability, although its relevance is certainly not limited only to energy systems. The criteria set was developed iteratively between the theory development and the case study applications.

These four sub-objectives described above outline the basic path taken for the theory development. The process of criteria specification and the sustainability criteria set were both applied in a case study approach that is described next.

1.4 Case study approach

The theoretical framework developed in this dissertation was applied in and revised through four empirical case studies. This section outlines the case study approach and introduces the individual case studies.

Case studies are an appropriate approach for applying Gibson's SA framework for various reasons. First, Yin (2009, p. 18) describes case studies as "an empirical enquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident." The importance of case and context is paramount when assessing energy systems for their potential to promote progress towards sustainability. Second, case studies are relevant when the researcher has little control over events, and when the events are contemporary (Yin 2009, ch. 1), both of which characterize the case studies presented in this dissertation.

Third, case studies are relevant for exploratory research (e.g. Robson 2002) insofar as each case is an attempt to clarify and specify the criteria that matter with regards to progress towards sustainability. While the individual cases are guided by the preliminary energy sustainability criteria set provided in Chapter 4, each case is a unique exploration. Finally, Yin (2009, ch. 2) argues that case studies are relevant and useful for developing analytic generalization, whereby the investigator is trying to generalize a particular set of results to some broader theory. The most direct output of this research in terms of analytic generalization is the criteria set provided in Chapter 4.

In general, the case studies described in the following chapters apply multiple methods and synthesize information from a variety of sources, notably document analysis, key-informant semi-structured interviews, and observation (direct or participant). The use of multiple sources of data helps improve construct validity, allow for data triangulation (Eisenhardt 1989), and better informs criteria specification and the general development of the context.

The Barbados (Chapter 6), Brazil (Chapter 7) and Senegal (Chapter 8) case studies included key-stakeholder semi-structured interviews, as well as direct or participant observation. The interview participants represented a wide variety of expertise, including academia, local and international non-governmental organizations, private industry and other individuals involved in the relevant case and context. The interviews were semi-structured to address considerations within Gibson's eight categories, but were sufficiently open-ended to allow for the elucidation of unexpected insights. The interviews are further discussed in section 2.3.1 and a sample protocol is provided in Appendix 1.

Finally, observation (whether direct or participant) is important for the case study approach, because it allows the researcher to become grounded within the case and context. Observation helps contextualize the insights emerging from the document analysis and interviews, and provides a more experiential way of exploring some rather general systems criteria. The following sections briefly outline the four case studies that informed this dissertation.

Chapter 5 – Sustainability assessment of the Ontario Power Authority's 2006 Integrated Power Systems Plan

Chapter 5 briefly reports on a sustainability assessment of the Ontario Power Authority's (OPA) proposed 2006 Integrated Power Systems Plan (IPSP) for electricity supply, demand management and transmission. The research was undertaken in 2008 as a collaborative project involving faculty and students at York University (in Toronto) and the University of Waterloo. Using Gibson's SA, the IPSP was compared to an alternative power systems plan known as *Renewable is Doable* (Peters et al. 2007). The results of the research were published as a report submitted to the hearings regarding the IPSP (Gibson et al. 2008) as well as an article in *Energy Policy* (Winfield et al. 2010). My role was to evaluate the bioenergy options, including energy cropping, agricultural residues, forest residues, on-farm biogas, digestion of solids and municipal wastes, and landfill gas.

While the manuscript is not included in this dissertation, Chapter 5 discusses some of the important outcomes (both collective and individual to this author) of the research process that informs this dissertation. Furthermore, the case specific sustainability criteria set is provided in Appendix 2.

Chapter 6 – Sustainability assessment of a biodiesel operation in Barbados

Chapter 6 describes a sustainability assessment of a small-scale biodiesel operation in Barbados. The research was undertaken in Fall 2008 and the results were published in *Impact Assessment and Project Appraisal* (Gaudreau and Gibson 2010). The published version of the article is provided, respecting the formatting of the dissertation. The research was granted full ethics clearance by the University of Waterloo under ORE#14925.

Chapter 6 discusses the first explicit attempt to synthesize Gibson's SA framework with the Resilience Alliance's properties of a resilient world (Walker and Salt 2006, ch. 6). Furthermore, the case study illustrates the importance of seeking integration across sectors, and explores use of energy system initiatives for social learning and capacity building. Finally, it explores the potential for biodiesel to serve as an energy bridge and to foster a more broadly democratic energy transition.

Chapter 7 – Sustainability assessment of sugarcane ethanol in Brazil

Chapter 7 reports on a sustainability assessment of a sugarcane ethanol operation located in the Tietê-Jacaré Watershed of São Paulo, Brazil, as a group project involving the Universities of São Paulo and Waterloo. The research was published in the journal *Ecological Indicators* (Duarte et al. 2013). Carla Grigoletto Duarte, from the University of São Paulo, obtained ethics clearance for the interviews, and was the lead investigator for the project.

Chapter 7 highlights the importance of grounding the case study within its local context. Furthermore, the case study illustrates the difficulty of integrating and making sense of disparate data, as in many instances crucial data were simply not available or accessible, suffered from considerable fragmentation, or were withheld for private reasons. Despite data limitations, the analysis provided in Chapter 7 indicates in a preliminary manner that social-ecological thresholds are being approached in several areas of concern, including land-use change, fresh water availability, biodiversity, air quality, workers' rights and livelihood opportunities. Finally, the case study illustrates the importance of government oversight in energy decision-making.

Chapter 8 - Sustainability assessment of the agricultural and energy systems of Senegal

Chapter 8 reports on a sustainability assessment, undertaken in 2012, that originally focused on burning agricultural residues (primarily peanut shells) for cooking applications in Senegal, but ultimately was expanded to assess the agricultural and energy systems of Senegal. The research was granted full ethics clearance by the University of Waterloo under ORE#17118.

Chapter 8 highlights the need to be open to expanding the scope of assessment to address underlying and/or unexpected issues, in this case the interrelationships among the agricultural and energy systems of Senegal, as the overall desirability of burning peanut shells in cookstoves in Senegal is a question that cannot be addressed appropriately at the project scale. Furthermore, the case study illustrates how the assessment of an energy system may serve as an entry point into a deeper exploration of the context in which the energy system is embedded.

The Senegal case provides another example of the importance of energy bridges. In this case liquefied petroleum gas is proposed as a temporary energy source that may provide the soil and forests some reprieve, and provide Senegal time to develop alternative energy sources. Finally, Chapter 8 also provides a case in which there are no right answers, but rather different paths that may be followed, each with its own degree of uncertainty, path dependence, feasibility, degree of fairness, cultural sensitivity, trade-off acceptability and overall desirability.

1.5 Putting it all together

The research undertaken in this dissertation covers a broad suite of domains and disciplines. In the chapters that follow a path is charted through various concepts of complex systems thinking and different approaches to conceptualizing energy systems and their relationship with society in the pursuit of determining the things that matter for shaping energy systems to seek progress towards sustainability. A graphical representation of the research process is provided in Figure 1 below.

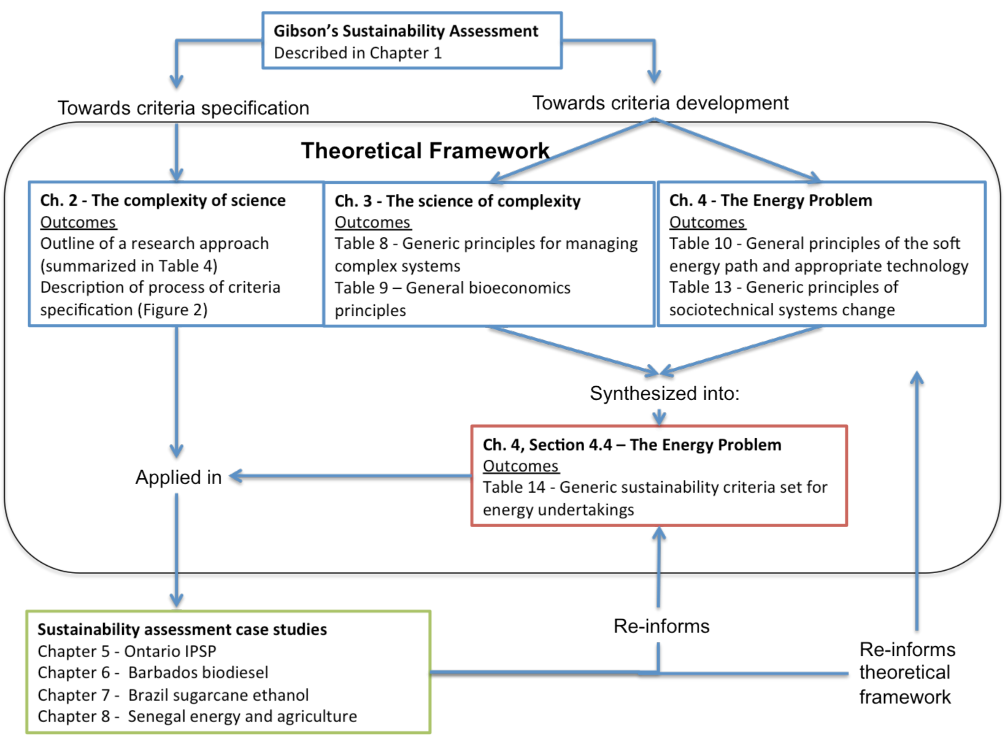

Figure 1 – The Conceptual Framework and Research Map

Chapter 9, the final chapter of this dissertation, provides a synthesis of the most important insights and contributions emerging from the research process. Because of the iterative and recursive nature of the research process, many of the important insights from the research have already been incorporated into the theoretical framework provided in Chapters 2-4. Finally, Chapter 9 describes avenues for future research resulting from this dissertation.

The narrative developed in this dissertation will never be complete. The work would benefit from attention to insights from additional fields and from other important theories of complexity and approaches to energy analysis. Nevertheless, the dissertation provides a significant and unique contribution to the energy and complex systems discourse, and the individual case studies are relevant within their individual contexts. Chapter 2 begins this journey by exploring what it means to undertake sustainability-based research in the face of complexity.

Chapter 2 – The complexity of science

This chapter draws from various conceptions of the complexity of science to characterize important challenges and opportunities of knowledge generation and decision-making in a real world context, and to outline how Gibson's SA framework is grounded within recognition of these challenges and opportunities. The chapter outlines a basic set of principles for undertaking knowledge generation and decision-making in the face of complexity and describes the process of criteria specification, which forms the basis of the case study research. For simplicity, the complexity of science will often be referred to as COS.

2.1 The complexity of science

The general premise of COS is that scientific work for public policy decision-making processes is generally characterized by uncertain facts, disputed values, high stakes, and an urgent need for decisions (Funtowicz and Ravetz 2008; Kay et al. 1999; Munda 2005). COS is generally less occupied with identifying some absolute, or even firm, truth, than with the quality of the knowledge generation process (Funtowicz and Ravetz 1993; 1994; Giampietro et al. 2006). This first part of Chapter 2 outlines the key challenges that arise due to the complexity of science and that are particularly relevant for this research.

2.1.1 The limits of knowledge

> *The study here under review employs a vast array of arbitrary assumptions, which are then, as it were, put into a calculating machine to produce a 'scientific' result. It would have been cheaper, and indeed more honest, simply to assume the result. - (Schumacher 1973, p. 122)-*

A basic tenet of COS is that reality is characterized by deep and irreducible uncertainty that is beyond complete comprehension (De Marchi and Ravetz 1999; Kay et al. 1999; Midgley 2000, ch. 1; Munda and Russi 2008; Walker et al. 2002; Waltner-Toews 2008). A normal science approach to managing uncertainty is to increase precision through a variety of means, including additional data collection, and more sophisticated modeling and simulation (Funtowicz and Ravetz 1994; Giampietro and Mayumi 2009, ch. 10). While precision certainly has value, it cannot entirely overcome the uncertainty inherent in many sustainability-related issues. For example, while the relative impacts and costs of a 2-4^{o} Celsius increase in the global mean temperature have been closely examined in several forums (e.g. Griffiths 2010, ch. 5), there are many potential dynamics – for example, technological advances, geopolitics, natural disasters, resource shortages, and economic volatility – that ensure the specific details of climate or human society in the year 2100 cannot be precisely described.

While not attempting to shake the pillars of science, this section outlines three implications of complexity and uncertainty that are particularly relevant for this research:

(1) multiple incomplete views of the world; (2) reductionism and commensurability; and (3) the presence of contradiction.

Multiple incomplete views on the world

Given that the world and/or the process of inquiry is considered complex, it is impossible to represent the world entirely from a single perspective, and COS researchers argue that everyone has a unique, imperfect, and non-reducible worldview (Allen 2008; Francis 1992; Giampietro 2004, ch. 2; Kay 2008a). Worldviews can and do change. For example, Kuhn (1963) described how worldviews change over time once sufficient counter-evidence accumulates to a point that the prevailing worldview is no longer considered useful and is abandoned for a new model.

Worldviews come into play in a particularly obvious manner in academic disciplines, which provide rules for parsing out the world into discrete and manageable components so as to make it intelligible. These structures may be many things, including culture, routines, rules, and propositions (Buanes and Jentoft 2009). Guba and Lincoln (1998) note that worldviews are premised on faith, not facts; more precisely, worldviews generally influence the selection of facts to consider (Robinson 1982; Schoenberger 2001). In many situations people hold similar enough worldviews that the tensions between worldviews, and even the contradictions within worldviews, are negligible. However, in contested situations, such as addressing Third World development or climate change, the differences in worldviews become more relevant for knowledge generation, fact interpretation, decision-making and action.

Incomparable and incommensurate factors

Normal science is often based upon the interrelated premises of reductionism and commensurability, which together assume that some particular dimension or characteristic – be it money, embodied energy, water, utility – represents a universal characteristic through which all things may be measured and ultimately compared (Martinez-Alier et al. 1998). There are varying degrees to which characteristics are considered commensurable or comparable, and Table 2 provides a basic description.

Table 2 - Different degrees of comparability

Strong commensurability Objects, outcomes, and actions may be compared using a common measure on a cardinal scale of measurement
Weak commensurability Objects, outcomes, and actions may be compared using a common measure based on an ordinal scale of measurement.
Incommensurability There is no common unit of measurement for comparison. Objects, outcomes, and actions may be compared, but only without recourse to a single type of value. Reductionism is rejected. This is the domain of ecological economics and multi-criteria evaluation.
Incomparability There is no common unit of measurement for comparison. Multi-criteria evaluation is not appropriate for comparison.

Source: adapted from (Martinez-Alier et al. 1998)

Reductionism allows complex dynamics to be reduced to a seemingly manageable set. While beneficial in moderation, extreme forms of reductionism are problematic. For example, claims by some conventional economists to be able to reduce everything of value down to the calculus of utility have been widely criticized (e.g. Hall and Klitgaard 2006; Martinez-Alier et al. 1998; Schumacher 1973).

Comparability and commensurability are of particular interest to sustainability assessment because they underlie the framing of alternatives and tradeoffs (e.g.Morrison-Saunders and Pope 2012). Some assessment practitioners argue that alternatives and their various tradeoffs may be compared through multi-criteria evaluation (e.g. through the analytical hierarchy process), in which each alternative is assigned a respective score, be it cardinal or ordinal. By contrast, other authors propose different rules – both procedural and substantive – for analyzing tradeoffs based on the premise that most tradeoffs are tradeoffs in kind[1], which are generally incomparable (e.g. Gibson et al. 2005, ch. 6).

Comparability and commensurability are also important when discussing issues of substitution. One important sustainability debate focuses on whether and to what extent the various types of capital (technical, social, economic, ecological, etc.) are substitutable for one another, as well as whether or not capital may be defined within any individual domain. This has led to the divide between strong sustainability (against substitution) and weak sustainability (based on substitution). It may be fair to say that while both sides tend to argue extreme positions, their respective proponents generally fall somewhere in the middle (c.f. Dobson 2004). Either way, adopting the premise that other forms of capital may substitute natural capital requires a means of characterizing and comparing the various forms of capital, implying commensurability.

The presence of contradictions

> *"Doublethink means the power of holding two contradictory beliefs in one's mind simultaneously, and accepting both of them." – George Orwell, 1984*

The third characteristic of knowledge discussed relates to the presence of contradiction in knowledge generation and decision-making due to the 'messiness' of the world (Bunch and Ramirez 2009; Funtowicz and Ravetz 2008; Waltner-Toews 2008). Contradiction may arise from many sources, but is often attributed to dynamics occurring over various scales (Ahl and Allen 1996, ch. 8; Cumming et al. 2006; Giampietro 1992; Giampietro 2004, ch. 5; Pritchard Jr. and Sanderson 2002). For example, the tragedy of the commons is an oft-cited example in which the desire by individuals to have a better quality of life comes into conflict with the goals of the collective interest in preserving common goods and trying to give everyone a better and more lasting quality of life (Giampietro 1992).

Contradictions are not inherently undesirable, although they may often pose difficulties. Schumacher (1973, ch. 6) notes that many tenets of life embody contradictions, such as the tension between individual freedom and the need for social structure, and these

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[1] A tradeoff in kind is one that is very difficult to judge in terms of comparison, such as trading off a lake of spiritual importance for the perceived economic benefits of a mine.

contradictions relate to family life, politics, economics, and education. Ultimately, the presence of contradictions implies that the pursuit of any unitary goal at the expense of all others is generally undesirable (e.g. Ulanowicz et al. 2008).

2.1.2 Disputed values

How much is a songbird worth? - (Funtowicz and Ravetz 1994)

A second topic area of COS to be discussed relates to values. As noted by Funtowicz and Ravetz (2008), the scientific process is often characterized by disputed values. This section briefly outlines issues of scientific neutrality, discourses and narratives, and power, all of which have become increasingly important in the scientific process.

The word "values" in the environmental and sustainability literature takes on many different meanings (e.g. Dobson 2004). Winner (1986, ch. 9) provides an interesting critique of current treatments of values in his book *The Whale and the Reactor.* Winner (1986, ch. 9) notes that historically, value was something that was intrinsic to an object: things had value. Over time, the approach to values changed to one where values are held by groups or societies (Winner 1986, ch. 9). Winner laments this approach to valuation as a merely subjective phenomenon and argues it has replaced much of what was formerly contained in moral and political philosophy, notably concepts such as virtue, good, worth, right and justice. Ultimately, Winner (1986, ch. 9) argues that the new language of values is often used by people who wish to avoid conflict: "you have your values and I have mine, and let's just leave it at that."

The interpretation of values has implications for both environmental impact assessment and energy assessment, especially with regards to multi-criteria analysis. Multi-criteria approaches generally rank alternatives based upon expressed preferences assumed to reflect the values of the decision-makers or the relevant stakeholders (e.g. Hobbs and Meier 2000). The elicitation of values is to a certain extent the main goal of many multi-criteria methods, such as the analytical hierarchy process. Winner argues that such instrumental approaches are inappropriate because "the kind of knowledge required for policy deliberations cannot be generated by surveys, inventories, and weightings, or provided through attitude research" (Winner 1986, p. 160).

Winner's concerns about the meaning of values are complemented by the related question of whether things, such as the songbird quoted above, should be valued in the first place. Funtowicz and Ravetz (1994) argue that in trying to determine the worth of a songbird, one ought not pretend that measurement is independent of methodology and ethics. In recent years, an important debate has been taking place in the ecological economics community (e.g. Costanza et al. 1997) regarding the economic valuation of natural capital. There appears to be no consensus as to whether, and how, natural capital should be valued in economic terms. For example, wetlands may be valued in terms of their ability to purify water, and a famous example of this relates to New York City, which bought up land around its upstream reservoirs to allow for natural filtration. The natural value of the wetlands in this case may be considered as $2.3 billion, which represents the difference between the $1.5 billion cost of the land and the estimated $3.8 billion cost of expanded treatment capacity that would have been otherwise required (WWF 2012).

There are many concerns related to ecological valuation. For example, promoting the valuation of natural capital makes it more difficult to fall back on other reasons for ecological preservation when the numbers do not work out (e.g. if it were cheaper for New York City to invest in the infrastructural upgrade) [2]. Second, the process of valuing natural capital promotes technocratic and managerial approaches to ecology. Third, such an approach to valuing natural capital adopts a utilitarian perspective, and Midgley (2000, ch. 1) argues environmentalists generally fare poorly when arguments are framed with regards to utility alone.

Scientific neutrality

Accepting that scientific and decision-making processes are value-laden leads into the topic of scientific neutrality. Positivist approaches tend to assume science is neutral and value-free, a possibility denied by COS (Berkes and Davidson-Hunt 2008; Giampietro and Mayumi 2008; Horlick-Jones and Sime 2004; Reason and Bradbury 2001; Robinson 2003).

In certain instances, it is argued and presupposed that scientific labours are neutral: whether they improve the state of the world and the human condition, or lead to world destruction is a question of how they are used, as a result of decisions that are out of the control of the scientists themselves. Schumacher (1973, ch. 6) critiqued this approach because it leads to science and engineering that produce know-how, simply a means with no ends. In *Jurassic Park*, Crichton (1991) labeled the situation as “thintelligence”, the ability to do something without the ability to ask whether and how it should be done.

This first interpretation of scientific neutrality parallels some concerns of technological autonomy. Notably, some researchers may argue their works are neutral because the knowledge is unavoidable; if they do not develop the knowledge, someone else will. For example, Norbert Wiener, an early developer of Cybernetics, justified his research as follows:

> *We have contributed to the initiation of a new science which, as I have said, embraces technical developments for good and evil. We can only hand it over into the world that exists about us, and this is the world of Belsen and Hiroshima. We do not even have the choice of suppressing these new technical developments. They belong to the age, and the most any of us can do by suppression is to put the development of the subject into the hands of the most irresponsible and most venal of our engineers. - (quoted in Winner 1977, p. 71)*

Wiener’s remarks are extreme, but they speak to a dynamic that is likely more general, and fosters the image of scientists dragged along by the prevailing currents, forced to keep uncovering knowledge no matter the consequences. Lowrance (2010) labels this situation a tragedy, and argues that scientists are part of a larger social narrative over

[2] This argument parallels a similar argument made by Winner with regards to prioritizing efficiency in decision-making, and will be revisited when the soft energy path is discussed in Chapter 4.

which they have little control, but ideally they may use their own autonomy and ethics to the fullest extent possible to promote a better world through their research and actions.

A second interpretation of scientific neutrality is less controversial, and relates to the understanding of the role of a scientist as someone tasked with getting the facts right, and letting decision-makers use those facts. This view is becoming less helpful in many of the contested and complex situations facing society, such as climate change. In many important situations are not amenable to simple facts, and even when a set of facts is more or less agreed upon, there are no guarantees they will be interpreted in the same manner. For example, it is not uncommon for different experts to reach antithetical conclusions while drawing from the same data set (Gibson 2006b, ch. 2; Schon and Rein 1994). Finally, the science itself may be co-opted or suppressed for purely political and ideological aims (e.g., McCarthy 2012).

It is important not to be overly critical of claims of scientific neutrality. While neutrality is impossible, striving for neutrality is often crucial. The intent here is not to claim that all science is biased, because such a claim is often espoused by those who would like to deny, among other things, that humans contribute to climate change or that asbestos is unhealthy. Instead, COS argues scientists should no longer consign themselves to simply producing sound science in the traditional sense, but rather be prepared to shepherd this knowledge into the real world and recognize uncertainty and its implications for choice among science-informed policy options (Fals Borda 2001; Funtowicz and Ravetz 1994; Lowe et al. 2009; Wynne 2005).

Shaped by narratives and frames

We inhabit a world replete with stories, narratives and meta-cultural images. For example, the discourses of neo-liberalism – including tenets of individuality, progress, growth, and efficiency – permeate society (Nader 2010; Sachs 2007; Wynne 2005). Many argue that the conditions in Third World countries are worsened by capitalism and its modernization discourse and practice (e.g. Fals Borda 2001; Hirsch Hadorn et al. 2006; Nikiforuk 2012, ch. 9).

Narratives and frames are important for how individuals and societies view themselves. Schon and Rein (1994, ch. 2) argue that societies draw heavily from meta-cultural images, which include images of health, naturalness, stability, and wholeness. Schon and Rein (1994, ch. 2) illustrate the use of meta-cultural images through the example of an urban renewal project, in which the proponents of renewal project focused on the urban area as being diseased that needed to be rebuilt, whereas opponents drew from the images of the natural and stable nature of the urban area, to argue that the area needed to be preserved. These images speak to emotions and seek to persuade.

Competing discourses and narratives are prevalent with regards to energy. Giampietro and Mayumi (2009, ch. 8) argue that the narrative we are told in every day life comes from a hegemonic group ruling society bent on fossil fuels. Criticism is often directed towards alternative energy paths (such as the soft energy path discussed in Chapter 4) because they provide a competing narrative about society's relationship with energy and the nature of prosperity (Nader 2004; Robinson 1982).

Power

The discussions of values, scientific neutrality and narratives all relate to power in its various manifestations (e.g. Foucault 1977; Freire 2000; Haugaard 2002; Reason and Bradbury 2001). Both knowledge generation and decision-making are undertaken in a world characterized by inequality and power imbalances, where certain ideologies dominate over others (Reason and Bradbury 2001; Schoenberger 2001; Shiva 1993). Power relations may influence the distribution of resources, the perceived legitimacy of knowledge and the nature and results of decision-making processes (Bauchspies et al. 2006, ch. 1; Giampietro and Mayumi 2008; Munda 2005; Russell et al. 2008).

One concern of presupposing scientific neutrality is that it risks perpetuating power imbalances and supporting the status quo, and in doing so may impair necessary societal change (Fals Borda 2001; Jackson 2000, ch 8). The research process itself is one mechanism of perpetuating dominant structures of society. For example, Gaventa and Cornwall (2001) note that positivist methods distort reality by separating those who study reality (the experts) from those who experience it, and traditional research methods (e.g. surveys) may promote the passivity of powerless groups. Even the academy is characterized by power imbalances, differential access to resources and conflicts over legitimacy (Caston Broto et al. 2009; Petts et al. 2008; Schoenberger 2001).

2.1.3 Difficulties with problem formulation

The limits of knowledge and the value-laden nature of inquiry are both manifest in problem formulation, which various authors note as being one of the most important, and often neglected, aspects of inquiry and decision-making (Giampietro 2004, ch. 5; Partidario 2007; Petkov et al. 2007; Rittel and Webber 1973). For example, in somewhat comical fashion, Interaction Associates claimed that ninety percent of problem solving is spent solving the wrong problem, stating the problem so it cannot be solved, solving a solution, stating problems too generally, or trying to get agreement on the solution before there is agreement on the problem (cited in Bardwell 1991).

To some extent, the very nature of the problems to be solved is responsible. For example, Bardwell (1991) defines the characteristics of environmental problems as being complex, uncertain, and extremely political. Schon and Rein (1994, ch. 1) argue many policy controversies are simply immune to resolution from any facts, in part because the facts are driven by the worldviews.

The nature of problems can be explored in terms of problem domains. For example, some problems are considered technical (e.g. the combustion characteristics of traditional cookstoves) while others are considered social or cultural (the cultural appropriateness of improved cookstoves). More often problems are societal and biophysical at the same time, span multiple domains and have causes and solutions that lie in different domains and at different scales (Partidario 2007; Roling 2005). For example, Bunch (2003) explored water pollution in Chennai, India and found that what appeared to be a technical-biophysical problem (the need for better water pollution control) was so deeply embedded in the broader socio-cultural context that any potential effective solutions lay there. Bunch's research is indicative of the advantages of soft systems methodology, which is open to the premise that technical problems often have social origins (Bunch 2008; Checkland 1999; de Ridder et al. 2007; Munda 2004),

Formulating problems is a normative exercise. Problems are constructed, and dependent on the boundaries of conception and investigation (Checkland 1999; Flood and Carson 1993, ch. 3; Foster et al. 2001; Kay and Boyle 2008; Midgley 2000 ch. 3). As Bardwell (1991) notes, problem definition embodies worldviews, assumptions and meta-cultural frames (e.g. the environment as an inheritance to be spent or something borrowed from one's children) and should take a conscious, critical approach to all three.

One important form of problem formulation worth mentioning is the risk frame[3]. For the purpose of the present discussion, what is most important is the underlying manner in which the risk framework influences thinking. Risk is a term often used to describe and characterize what is not known, although it is certainly not the only means of recognizing not knowing. Leach et al. (2010, ch. 3) provide a two dimensional heuristic for determining whether what is not known is best characterized by risk, uncertainty, ambiguity, or ignorance; this is provided in Table 3.

Table 3 - Four categories of not knowing (adapted from Leach et al. 2010, ch. 3)

		Knowledge about outcomes	
		Not problematic	*Problematic*
Knowledge about likelihoods	*Not problematic*	**Risk** confidence that the probabilities can be calculated over the relevant range of outcomes.	**Ambiguity** the problem is not the probabilities, but rather the characterization of the outcomes. Generally requires comparing incommensurate things (e.g. caribou versus oil revenue).
	Problematic	**Uncertainty** confidence in our characterization of the different possible outcomes but insufficient empirical information to assign probabilities.	**Ignorance** not knowing what we do not know. Sometimes called 'unknown unknowns'.

Leach et al. (2010, ch. 3) argue that there is often pressure to collapse uncertainty, ignorance, and ambiguity towards risk, so as to simplify analysis and allow for quantification.

According to Winner (1986, p. 148), "the risk debate is one that certain kinds of social interests can expect to lose simply by entering into it, in large part because of the conservative drift," which places the burden of proof on those trying to promote basic worldview change. Furthermore, traditional risk assessment may promote misleading quantification and dissociation of facts from ethics (Winner 1986, ch. 8), both of which are undesirable. While risk analysis remains highly useful for some purposes, for the

[3] Funtowicz and Ravetz were both involved in risk assessment, and this informed their description of post-normal science.

purposes of this research the risk frame overly limits the problem formulation process and frames the debate in a likely unconstructive manner. As will be evident in the case study chapters (Chapters 5-8), many of the important concerns are not easily addressed through a risk frame, even if risk as a guiding concept is both relevant and necessary.

This concludes the broad-brush discussion of knowledge generation in a complex world. The intent is not to redefine the scientific method, or to unduly criticize current practice, or to argue that researchers must always start from first principles. Rather, the basic implication emerging from the discussions above is that science (and more specifically knowledge generation and decision-making) must be situated within its social context and be presented with recognition of uncertainties and their implications. The following section outlines a basic suite of approaches for addressing this challenge.

2.2 Eight guidelines for research in a complex world

This section outlines a general framework for undertaking research and decision-making in the face of complexity grounded in the challenges described above. The discussion draws from various frameworks and proposals, including transdisciplinarity, sustainability science, and various systems approaches, most of which overlap.

How these individual guidelines are manifest within the research process is a decision that must be negotiated, and depends on various factors, including the types of problems being focused on, the context of the research, and the resources available for research. Some preliminary comments are provided regarding how these characteristics fit into Gibson's SA framework. Following that, the process of criteria specification is described in some detail.

Table 4 - A summary of eight guidelines for research in a complex world

Be integrated and problem focused Addresses difficulties with problem formulation, the presence of contradictions, multiple and incomplete views on the world, and incomparable and incommensurate factors.
Maintain a flexible approach to problem formulation Addresses difficulties with problem formulation, the presence of contradictions, multiple and incomplete views on the world, and incomparable and incommensurate factors.
Emphasize the process of assessment over the substantive outcome Proposed in response to disputed values, the presence of contradictions, multiple and incomplete views of the world, and incomparable and incommensurate factors.
Promote informed participation Addresses disputed values, multiple and incomplete views of the world, power imbalances, and narratives and frames.
Foster social learning Addresses disputed values, multiple and incomplete views of the world, power imbalances, and narratives and frames.
Be explicitly normative Proposed in response to disputed values, power imbalances and scientific neutrality.
Be grounded in context Addresses multiple and incomplete views of the world, disputed values, and difficulties with problem formulation.
Move from research to action and emancipation Addresses power imbalances, narratives and frames, and scientific neutrality.

Be integrated and problem focused

One means of improving science for governance is to break out of institutional and academic boundaries and seek integration (Robinson 2004). This argument has been framed in the calls for, among other things, holism, integration, systems thinking, and inter- and trans-disciplinarity. Regardless of terminology, all accept the basic premise that the narrowly focused worldview of a single discipline is incapable of addressing the problems facing the world today (Kay 2008b). For simplicity, integration will be used in what follows.

An integrated approach to knowledge generation often begins with the premise that human and natural systems are best understood as linked social-ecological systems (Buanes and Jentoft 2009; Kay et al. 1999) that often display a set of generalized properties that will be described in Chapter 3. Integrated approaches are often problem focused rather than discipline driven (Hirsch Hadorn et al. 2006), and must therefore be sufficiently flexible and critical in problem structuring.

Gibson's SA framework is integrated, and was structured to highlight the interrelationships among the eight categories of progress towards sustainability provided in Table 1. The eight categories were developed to avoid the usual reductionist triple bottom line pillars of sustainability, which Gibson et al. (2005) argue promotes balancing and conflict, and reduces the potential for positive synergy. Furthermore, the categories and ultimately the sustainability criteria are not premised upon notions of commensurability.

While several proponents of sustainability assessment promote integration (Gibson 2006a; Kemp et al. 2005; Pope and Grace 2006; Sheate et al. 2008), others, including Morrison-Saunders and Therivel (2006) express concern that integration may undermine environmental considerations. Drawing from the experience and insights of the case study work, it is difficult to perceive how sustainability assessment can be undertaken in a non-integrated manner. Furthermore, the most important gains are often those embedded within or lying beyond multiple domains (e.g. Kay et al. 1999; Waltner-Toews et al. 2008).

Maintain a flexible approach to problem formulation

Gibson's SA framework offers a novel approach to problem structuring. As will be discussed in Chapter 4, there are multiple perspectives on what the energy problem is, and these perspectives are embedded within differing worldviews. The multiplicity of worldviews coupled with the uniqueness of every local context and the integrated nature of most problems implies that appropriate problem structuring is an important first step.

There are two means by which the assessment process proves valuable for problem structuring. First, the process of criteria specification outlined in section 2.3 below is essentially an iterative approach to problem structuring. The process of specifying the important criteria for the case and context helps to determine what important challenges are to be addressed and opportunities to be pursued. Furthermore, proper problem structuring often points to initial recommendations for resolving the problems.

The second means by which the assessment process proves valuable for problem structuring is that it allows for flexible unit of analysis. For the initial assessment to begin, a problem or question must be defined, and this is generally defined as a specific type at a specific scale. As criteria specification takes place, and knowledge of case and context increases, the opportunity may arise to restructure the unit of analysis to address a more appropriate type and scale of problem and opportunity. For example, Chapter 8 describes an assessment that originally focused on burning peanut shells for cooking applications in Senegal; but over time it became clear a more appropriate unit of analysis was the intersection of the energy and agricultural systems of Senegal.

Different applications of Gibson's SA framework will necessarily offer varying degrees of flexibility. In more formal assessments, the terms of reference may be more constrained, in part because changing the terms can prolong the assessment, which is increasingly being considered unacceptable for reasons related to economic development (Gibson 2011a). That said, judicious application of Gibson's SA framework might benefit from a restructured problem, as this helps avoid developing an informed decision for a misdiagnosed problem. Furthermore, Pope et al. (2004) describe sustainability assessment as something that can be undertaken on pre-existing projects, as well as new and proposed projects, so the assessment process itself should not be limited to narrowly defined undertakings.

Emphasize the process of assessment over the substantive outcome

The third means by which the constraints imposed by complexity can be addressed is through focusing on the process of inquiry as opposed to the substantive outcomes (Giampietro 2004, ch. 8; Giampietro and Mayumi 2008; Midgley 2000 ch. 4; Pohl 2005; Reason and Bradbury 2001). At a general level, the substance-process divide can be understood as where insight is sought. For example, certain energy approaches are predicated upon the generation of final numbers, which are used to characterize systems. Emergy analysis is one such substance-based approach, where the efficiency and thermodynamic values of different systems are compared in terms of their perceived embodied energy contents (Odum 1996). By contrast, Munda (2004) proposes social multi-criteria evaluation, which emphasises the process of decision making in which the final numbers are considered useful insofar as they help develop a narrative and provide participants an opportunity to learn.

There is an important interplay between substance and process. At some point decisions will need to be made, and ideally these decisions will be informed by the best available information. However, the process of inquiry is necessary to determine which information is most important and why. Gibson's SA framework fosters iterative learning and deliberation, which couples substance to process. This is accomplished primarily in terms of criteria specification described in section 2.3.

Promote informed participation

The characteristic of science for governance that receives the most attention is public participation (Funtowicz and Ravetz 2008; Gasparatos et al. 2008; Hirsch Hadorn et al.

2006; Martinez-Alier et al. 1998; Munda 2004; Waltner-Toews and Kay 2008). Funtowicz and Ravetz (1993) provide a cogent argument for participation:

> *When problems lack neat solutions, when environmental and ethical aspects of the issues are prominent, when the phenomena themselves are ambiguous, and when all research techniques are open to methodological criticism, then the debates on quality are not enhanced by the exclusion of all but the specialist researchers and official experts. The extension of the peer community is then not merely an ethical or political act; it can positively enrich the processes of scientific investigation. - (Funtowicz and Ravetz 1993)*

The perceived benefits of participation are numerous. Participation fosters public engagement and local ownership (Giampietro and Mayumi 2009, ch. 10; Reason and Bradbury 2001; Waltner-Toews and Kay 2008), improves accountability (Kidd and Fischer 2007), helps manage uncertainty and unpredictability, and fosters learning (Lister 2008, p. 99) and increases legitimacy (Franklin 1990; Lovins 1977). Furthermore, participation in the specification of desirable futures promotes social learning (e.g. Robinson 2003).

Participation overlaps with governance[4], and there are many different frameworks for approaching and conceptualizing governance promoted in COS, including adaptive governance, spearheaded by the Resilience Alliance and ecosystem approach practitioners (Cumming et al. 2006; Gunderson and Holling 2002; Peterson 2002; Waltner-Toews et al. 2008), and reflexive governance, promoted by the Dutch transition researchers (Loorbach 2007). In most forms of governance promoted by COS, the knowledge and values of stakeholders are expected to evolve over time, and the governance institutions are ideally designed to respond accordingly (Ahl and Allen 1996, ch. 2; Kay et al. 1999).

Some sustainability assessments practitioners express concern that an overreliance on participation may neglect environmental and governance issues, and lack the necessary breadth for sustainability (Bond et al. 2010; Hermans and Knippenberg 2006; Hirsch Hadorn et al. 2006). Kidd and Fischer (2007) caution that participation may favour qualitative approaches to decision-making that fall short of the sound evidence required for sustainability decision-making, assuming that such evidence is available. Furthermore, participation must also address power imbalances and instrumental approaches to decision-making, as both may further legitimize the dominant power structures (Kemp et al. 2005; Kidd and Fischer 2007; Martinez-Alier et al. 1998; Munda 2004; Pope and Grace 2006). Decisions must be made about how boundaries are drawn and representation is arranged (Banville et al. 1998; Kay 2008a; Waltner-Toews and Kay 2008).

[4] Governance is a rather loose word at times. For the purpose of this dissertation, governance is defined in the manner proposed by the Institute on Governance (IoG 2011) as determining "who has power, who makes decisions, how other players make their voice heard and how account is rendered."

Governance, in the sense of some sets of decision makers deliberating and making authoritative choices, is unavoidable, and mobilization of as many different voices, interests and capacities as possible in the exercise of governance for sustainability is probably crucial. The key issues are what kinds of governance may be most useful and how these forms of governance can be fostered.

Gibson's SA framework was designed to be participatory while recognizing the concerns noted above (Gibson 2006a; Gibson et al. 2005, ch. 7). Despite acknowledging the need for greater participation, the case studies described in Chapters 5-8 are not sufficiently participatory, as they were not formal assessments and were limited by resource constraints. However, through the case study approach, both the interviewing and participant observations provided a means by which stakeholders could be involved.

Foster social learning

In a suitably informed, participative and iterative process, knowledge generation and decision-making can contribute to a cycle of continuous social learning and personal growth (Francis 1989; Midgley 2000 ch. 7; Pohl 2005). Social learning is sometimes called double loop learning, which is learning that questions the assumptions of the problem itself, and includes changing the structures of institutions in response to learning (Bunch and Ramirez 2009; Hirsch Hadorn et al. 2006; Loorbach 2007, ch. 3). Many hope that social learning will help transform individuals and societies and foster innovative behaviour (Keen et al. 2005; McCarthy et al. 2010).

Gibson's SA framework, as described in this dissertation, promotes social learning. The criteria specification process provides an opportunity to reflect upon personal and shared assumptions (e.g. what the energy problem is), and the sustainability criteria provide a vocabulary to help decide upon the things that matter. To the extent possible, sustainability assessment should encourage all those involved (both formally and informally) to reassess and where appropriate change their own actions so as to better address the shared problems facing society.

Be explicitly normative

> *Exceedingly traumatic choices will have to be confronted – not just made (we do that already, often by defaulting), but confronted. Weighed. Debated. Faced. (Lowrance 2010, p. 46)*

Ethical issues are deeply embedded with issues of sustainability, and are now becoming more apparent in energy domains as well (e.g. Guruswamy 2011; Kimmins 2001; Nuffield 2011). For our purpose, there is no single ethical framework that suffices for all relevant situations (Dobson 2004). It is clear that some important considerations relate to outcomes (e.g. maintenance of life support systems), while others are procedural, and many are intertwined, insofar as cultivating proper actions helps to foster appropriate intents. Some considerations may be measured and counted, while others may not. This does not imply that different ethical frameworks do not inform sustainability assessment. For example, various researchers have proposed Rawls' veil of ignorance as a starting ground for both energy ethics (Guruswamy 2011) and even assessment practice (Hermans and Knippenberg 2006). However, it is important that the normative and universal criteria used to begin the assessment must be specified for the context, all the while avoiding the trap of ethical relativism.

Gibson's SA framework provides an opportunity for exploring the ethics of energy. Gibson's eight categories presented in Table 1 provide a normative basis to decision-making founded in various principles of justice and ethics. Furthermore, the process of criteria specification helps make worldviews more explicit by providing practitioners an opportunity to define what constitutes progress towards sustainability, and this is made more robust through the comparison of different case studies. The specific ethical considerations of power systems planning in Ontario are considerably different from the ethical considerations relating to the combustion of peanut shells for cooking applications in Senegal. The differences result from the particular context, including historical, cultural, biophysical (including important thresholds), and spiritual considerations. However, even accounting for different contexts, a cursory examination of the different assessments reveals different conceptions of rights and obligations, worth and values, and highlights the stark inequality between different countries despite proclamations of universal human rights and noble development goals.

Specifying sustainability criteria encourages the analysts to address concerns related to the limits of personal consumption and lifestyle choices, and unequal livelihood opportunities. Criteria specification should not be an abstract undertaking, but rather propose what all members of that society should adhere to within reasonable limits. It is a small but important step for the analysts to use the opportunity provided to explore their own choices (e.g. consumption habits) and how these choices serve to perpetuate or challenge dominant societal structures.

Be grounded in context

When emphasis is placed on the process of knowledge generation and informed participation, context becomes increasingly relevant because it helps define what is important. Local stakeholders often have a richer understanding of the relevant issues and the important history of the local context, and this knowledge is necessary to interpret the insights and information from the research process, as well as to ensure the problem is appropriately structured.

While Gibson's eight categories and the sustainability criteria for energy undertakings (that are proposed in Table 14) are designed to ensure attention to all of the major requirements for progress towards sustainability, they must be elaborated and specified for the context at hand. Criteria specification is a fundamental component of this dissertation, and includes factors such as trends, resources, capacities and other assets, opportunities and barriers, concerns and aspirations, stresses and vulnerabilities. The factors span multiple scales, from the global (e.g., climate change and world market prices for peanut oil) to the local (e.g., nearby supply of used cooking oil for biodiesel production).

Move from research to action and emancipation

The final topic of discussion of science for governance relates to power, which must be addressed if meaningful change is to be achieved. There are many approaches to addressing power imbalances, and only a few that are particularly linked to sustainability and complexity are presented here.

Some proponents of science for governance call for Habermas' (1984) discursive rationality. Habermas argued people should engage in ideal speech situations, which are situations free from unequal power relations and allowing for open debates (Midgley 2000, ch. 2). In such ideal speech situations, emancipation would occur because the better argument prevails, as opposed to the ideology of the powerful (Jackson 2000, ch 8). Habermasian discursive rationality has been critiqued, in part because it presupposes the very thing it attempts to bring out, that being a society founded upon discursive rationality (Jackson 2000, ch 8). However, this seeming circular logic is found in many other power frameworks, such as Avelino's (2009) reconceptualization of power dynamics in transition management.

The systems literature also addresses power equalization, such as through emancipatory frameworks. Jackson (2000, ch 8) describes emancipatory frameworks as being suspicious of the current world order and seeking radical reform that would free both the oppressed and the oppressors (escape from psychic prisons and overthrow instruments of domination). These approaches focus on contradictions in society, such as the contradictions of capitalism, as a means of promoting social change (Jackson 2000, ch 8). Other systems practitioners prefer to seek emancipation through the oblique use of systems (e.g. Flood and Romm 1995). Flood and Romm (1995) argue that any method or framework can be used in an emancipatory manner, such as to promote discursive rationality, or liberation.

A popular approach to addressing power dynamics is action research, which is a "participatory, democratic process concerned with developing practical knowing in the pursuit of worthwhile human purposes" (Reason and Bradbury 2001). In general, action research adopts a social learning approach to promoting emancipation and social change, with focus on learning cycles of planning, acting, observing and reflecting (Loorbach 2007, ch. 2). Action research has become adopted by several organizations worldwide, including governments, NGOs and even the World Bank.

The approaches presented above broadly cover the general suite of means by which power imbalances may be addressed within the confines of research, namely: communication, learning, and directed (action) research. While all the approaches have their respective benefits, it is doubtful that all power imbalances can be overcome through better methodology or research design, if only because neither research design nor methodology can overcome the various forms of power structures and dynamics. Ultimately, Funtowicz and Ravetz (1994) call for "an honest recognition of conflicting interests and power relationships" to protect negotiations from co-optation, as opposed to any one specific methodology. Such efforts plus increased transparency at least represent an important step in a positive direction.

There are various means by which Gibson's SA framework can promote action and emancipation. First and foremost, sustainability assessment helps promote more informed and broadly participatory decision-making that ideally leads to better outcomes. Second, the process of specifying and elaborating sustainability criteria provide an interesting and unique means of not necessarily defining, but perhaps outlining the characteristics of the good life in a given case and context, and this provides an opportunity for social learning and personal growth. Third, sustainability assessment provides a vocabulary and framework for people to explore important issues. The sustainability assessment approach outlined in this dissertation can be performed by anyone, regardless of whether they are empowered or not, or whether there is a formal proposal.

When taken together, these eight proposals described above provide a broad and robust approach to knowledge generation in the face of complexity. However, to fully embed these proposals into Gibson's SA framework, it is necessary to describe the process of criteria specification, which helps operationalize many of the proposals.

2.3 Criteria specification for research and assessment in the face of complexity

An underlying premise of this dissertation is determining and deciding upon the things that matter is an important first step in decision-making (e.g. Checkland 1999). Furthermore, the process of specifying criteria requires integrating, organizing, and interpreting the collected information, and this provides an opportunity for exploring initial responses to the perceived problems; problem formulation and initial resolution are undertaken in a simultaneous manner (e.g. Rittel and Webber 1973). The sustainability criteria are specified for the case application, with the ultimate goal of assessing the options and alternatives available. This section outlines the means by which the sustainability criteria are specified for case and context, with the general steps depicted in Figure 2 below.

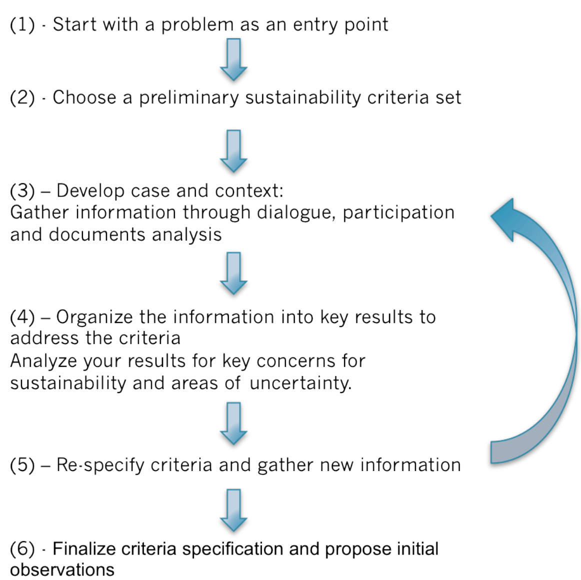

Figure 2 – Criteria specification for sustainability assessment

Step 1 – Begin with a problem and (potentially) a set of alternatives

The first step in criteria specification is to begin with a problem or purpose, which is an entry point into the assessment, and depending upon the terms of reference the problem may remain fixed (e.g. a formal assessment process) or may change during the assessment process as relevant insights emerge. The problem or purpose may take many forms, such as:

- an existing entity at the small scale – e.g. a biodiesel operation;
- a strategic large-scale question – e.g. a proposed provincial electrical power systems plan;
- a proposed project – e.g. a new natural gas pipeline; or
- a system in crisis – e.g. Senegal's energy and agricultural system

In most situations it is desirable to have a set of alternatives available for comparison, based upon the final sustainability criteria set. However, if the case and context under assessment does not yet include a suite of alternatives, the process of criteria specification may serve to outline broad alternative pathways. In the case studies reported upon in Chapters 6-8, the process of criteria specification served to outline alternative pathways.

Step 2 – Choose a preliminary set of sustainability criteria

Beginning with the initial problem, a generic set of sustainability criteria can be adopted to inform the criteria specification process. Table 14 at the end of Chapter 4 proposes a generic set of sustainability criteria for energy undertakings, which provides initial themes and areas of concern to guide the assessment process, and indicate important concerns that the alternatives (when they are defined) must address. The preliminary criteria set also offers a means of organizing what is learned about the relevant case and context.

For the purposes of this dissertation, the important aspects of case and context are organized in a table with two sets of headings: (1) Gibson's eight categories as the major headings; and (2) relevant themes within each category as a minor heading. Sample headings and a sample criterion, adapted from Chapter 7, are provided in Table 5.

Table 5 - Sample sustainability criteria and headings (adapted from Chapter 7)

Socio-ecological system integrity – Category *GHG emissions and air pollution – Theme* • mitigate GHG emissions, particularly upfront GHG emissions (e.g. soil carbon debt) (criteria)

The preliminary criteria set is generic and must be updated with the relevant information emerging from case and context (i.e. particular areas of challenge or opportunity, relevant cultural history, etc.).

Step 3 – Begin developing the case and context

Once the problem and preliminary set of criteria have been chosen, the case and context must be developed by drawing on a variety of methods, described in Chapter 1, notably interviews and dialogue, observation and participation, and document analysis. The information collected is generally both quantitative (which helps substantiate claims) and qualitative (which provides the context and narrative in which the numbers are interpreted). The exploration of case and context is guided by the sustainability criteria, which indicate important considerations regarding energy undertakings. The interview protocol is described in section 2.3.1.

Step 4 – Organize the information into key results to address the criteria

As the case and context are explored, it is possible to begin organizing and interpreting the information so as to re-specify the sustainability criteria, propose potential alternatives (if they have not already been defined), and construct an initial assessment of how the alternatives fare with regards to the criteria. At this point, however, alternatives are not formally assessed. As mentioned above, the information gathered through the exploration of case and context is organized in a table that mirrors the criteria set, so that when alternatives are compared, the relevant information is mapped to the criteria. A sample results table, adapted from Chapter 7, is provided in Table 6.

Table 6 - Sample key results table (adapted from Chapter 7)

Socio-ecological system integrity *Biodiversity and land-use change*	Impact	Scale
• Due to fierce competition, sugarcane mills do not reveal where they intend to expand sugarcane plantations. Such secrecy limits the environmental licensing process, and hampers land-use change assessment.	-	W

The middle column could adopt a simple three-point scale, identifying potential positive impact (+), potential negative impact (−), and potential impacts that may be mixed, or positive or negative depending on their characteristics and how they are situated within the broader context (=). The purpose of ranking is not to sum up all the positive and negative aspects in a quantitative test, but rather to gain broad insights into areas of strengths and weakness, and associated opportunities for improving contributions to sustainability. The assessment from which this result is taken emphasized the importance of multi-scalar interactions, and thus the rightmost column indicates the scale at which interactions are taking place (in this instance 'W' indicates the watershed scale).

The tabular approach to organizing data is not perfect, as many important pieces of information span multiple categories within the table, which leads to a tension between favouring repetitious entries or placing the information only under one specific category and theme. Experience with the four case studies indicates that in early stages it is preferable to maintain redundancy and repetition, as this helps illustrate both interactive effects and boundary crossing considerations. Interactive effects and boundary crossing considerations can be found by reading the results table in their entirety often enough and searching for key words if using controlled vocabulary.

Step 5 - Re-specify the criteria and gather new information

As the information is organized into the key results table, and interactive effects and boundary crossing considerations are explored, relevant themes will emerge. For example, in Chapter 6 (Biodiesel in Barbados) one important theme is the potential for energy planning and projects to promote social learning and capacity building. When such themes emerge, they should be added to the sustainability criteria set and further explored.

For the cases described in the following chapters, the relevant themes are organized within Gibson's eight categories (Table 1), which use terminology generally familiar to assessment professionals. For practical application in policy and project deliberations, it may be preferable to reorganize the criteria and results into categories and themes that facilitate understanding and informed discussion among the relevant stakeholders, so long as the criteria set maintains the full suite of requirements for progress towards sustainability (Gibson 2006c).

The process of organizing and analyzing the key results will also indicate what knowledge of case and context are missing and should be further developed. The new information will ultimately be analyzed and organized into the key results table.

Step 6 - Finalize criteria specification and propose initial observations

By constantly iterating between knowledge gathering, organizing the knowledge around key themes and re-specifying the criteria with regards to the themes, the sustainability criteria will become increasingly grounded in the particular case and context. Likewise, a set of alternatives (or, more broadly, potential pathways) will emerge and take coherence as they are considered in light of the criteria.

When criteria specification is complete, the analysis of alternatives may begin. For three of the case studies described in this dissertation, a formal analysis of alternatives did not take place, in large part because the assessments were not formal undertakings. Rather the emphasis was placed on criteria specification and the development of an initial set of observations – that emerge through the criteria specification cycle – reflecting important themes of concern and opportunity that demand further discussion and research, or for which there is sufficient analysis to provide preliminary conclusions. In many regards such themes form the basis for the development of alternatives, if they have not yet been proposed. A more in-depth treatment of comparison of alternatives and tradeoffs is provided in Gibson et al. (2005, ch. 6 and 7).

2.3.1 Undertaking the interviews

One subject that deserves greater attention relates to how the interviews were undertaken. For several reasons, it is very difficult to have one pre-defined set of interview questions in research such as this. First, as was previously noted, the interviews were semi-structured, and the interviewees represented a wide range of expertise (e.g. farmers, energy managers, government officials, extension officers, etc.). In many instances some interviewees were more able than others to address different topics. Second, the process of criteria specification often uncovered important issues that were not previously anticipated, and therefore could not be included in the original interview protocol. Third, in certain instances – such as the Senegal case study – the research problem had to be reformulated in response to new information. For all these reasons it was necessary to remain flexible with the interview protocol.

Table 33 of Appendix 1 provides a preliminary set of interview questions that were developed prior to the Senegal case study. Initially, the assessment centred on the use of agricultural residues for cooking applications in Senegal, while still addressing broader scale challenges and opportunities. As the assessment progressed and the scope of analysis changed to the broader energy and agricultural systems, the initial set of interview topics no longer addressed the primary concerns. Fortunately, the process of criteria specification provides an ongoing set of relevant topics for interviews. In effect, the sustainability criteria represent the important issues to be addressed in the given assessment.

Developing a more formal interview protocol represents a possible avenue for further research in sustainability assessment. In the meantime, the sustainability criteria set for energy undertakings proposed in Table 14 provides a relevant starting point for the interview protocol. The criteria set attempts to cover the full suite of requirements for energy sustainability, and the themes and criteria found in the criteria set may help guide discussion topics. Depending on the context of the interview, different themes and topics may be discussed, while still allowing for the conversation to guide itself.

2.3.2 Testing the framework

The process of criteria specification opens up the question of how sustainability assessment may be validated in practice. Sustainability assessment and other forms of assessment generally involve individual and unique cases that are embedded in a dynamic environment, and this implies some difficulty in terms of direct validation. Fortunately, there are various means by which the validity of the framework can still be ensured.

First, the development of Gibson's SA framework was a long process that extracted and synthesized a large and diverse body of literature, and the principles themselves bear the weight of historical evidence (Gibson 2000; Gibson et al. 2005). Second, the sustainability assessment process itself promotes designing for error and surprise, such as through the category "Prudence, precaution and adaptation" described in Table 1. Finally, sustainability assessment embodies the principles of procedural rationality and informed choice. Effectively, decisions and outcomes are generally improved when they involve open and informed choice, such that stakeholders can recognize the implications of decisions; both the explicit choices made by decision-makers, as well as the every day choices individuals make that help reinforce the structures of society. How informed choice is best manifested is context dependent (e.g. political, cultural, gender), but the general argument remains the same (Bond et al. 2010; Kidd and Fischer 2007; Morrison-Saunders and Therivel 2006; Pope and Grace 2006).

2.3.3 The use of quantitative metrics in Gibson's sustainability assessment

The final topic of discussion relating to the process of criteria specification relates to how quantitative metrics are used within the analysis. For the purposes of this dissertation, the focus is less upon any specific metrics of choice, and more on embedding the metrics within the context of the analysis.

There is, of course, a need for developing and applying energy metrics. For example, given that different energy sources and carriers may be used to accomplish the same task (e.g. both biodiesel and ethanol can be used as liquid fuels for transportation), it would be beneficial to determine which option is more desirable, where desirability may refer to one focal consideration (such as lowest greenhouse gas emissions, least amount of energy required for production (e.g. Howell 2010)) or to a set of sustainability-based criteria.

Ideally, any such metric would be rooted within a robust biophysical framework (Hagens and Mulder 2008; Hall and Klitgaard 2006; Odum 1996). Despite the desirability of such metrics, there are several challenges any metric must face, three of which are briefly discussed below.

First, many energy conversion pathways tend to produce by-products and waste products alongside the desired energy carrier, such as dried-distillers grain which is a co-product of ethanol production. Co-products are relevant because their characteristics impact the desirability of energy carrier. For example, the perceived advantages of ethanol, biodiesel and other renewable energy sources are generally quite sensitive with regard to whether or not their co-products are considered positively or negatively (e.g. Farrell et al. 2006; Giampietro and Mayumi 2009; Pimentel et al. 2007). The difficulty of co-products is two-fold. First, the value of a co-product depends upon both supply and demand levels. For example, at certain levels of production there may be a market for dried distillers grain as cattle feed, but once supply outpaces demand, dried distillers grain may become a waste product (Giampietro and Mayumi 2009; Hagens and Mulder 2008). Second, if the co-product has no obvious use in terms of energy, then it is difficult to include it in the calculus.

A second related challenge to quantifying energy metrics relates to externalities. Hagens and Mulder (2008) propose either to treat the externalities as separate indicators in a multi-criteria framework, or to convert the externalities into energy equivalents, such as by considering the energy required to prevent or remediate an adverse environmental impact (e.g. Chen and Ji 2007; Creyts and Carey 1997; Rosen and Dincer 1997; 1999; Sciubba 1999). The first option removes the possibility of having one single metric by which to compare different alternatives, while the second inappropriately assigns intrinsic energy value to items or processes for the purpose of having a single metric (as was mentioned previously) (Gaudreau et al. 2009). Both are undesirable but still necessary insofar as decisions need to be made and ideally are informed by biophysical concerns.

A third challenge to determining energy metrics relates to how boundaries are drawn. Tight boundaries simplify analysis, but may reduce the general applicability of the final numbers, whereas extensive boundaries increase the likelihood of encountering uncertainty, ambiguity and ignorance. For example, Giampietro and Mayumi (2008) note that different assessments of the energy equivalent of one hour of human labour vary from 0.2 MJ to more than 20 GJ, implying that at times even orders of magnitude are difficult to ascertain.

The challenges related to energy metrics do not imply that they have no value, but rather that the emphasis should be placed on the analysis as a learning process with indicative results, rather than a precise technical exercise that can deliver fully accurate numbers. Likewise, the metrics are helpful insofar as they provide justification for the narrative; but the metrics themselves are not the single final product of the assessment process.

2.4 Final thoughts - Research in the face of complexity

This concludes the formal discussion of the complexity of science. The basic vision coming from the discussions above is about science (and more specifically knowledge generation and decision-making) being situated within its social context. The sum of proposals for science in the face of complexity described above – focusing on problems, seeking integration, emphasizing the process of learning and decision-making, including and legitimizing others within the process, using the research process as a means of personal learning and deciding upon the things that matter, grounding the research within its broader context, and using research as one tool in a toolkit aimed at improving the world – are all more or less well acknowledged at this point. The preceding sections outlined the proposed means by which these insights have been incorporated into the research process, with particular emphasis on criteria specification.

The complexity of science is only half the story of complex systems, and the discussion thus far has mostly ignored the science of complexity, which is the subject of the following chapter. Chapter 3 complements Chapter 2, but uses the literature to outline general characteristics and dynamics of complex systems particularly relevant for this research.

Chapter 3 - The science of complexity

This chapter provides a theoretical grounding in the science of complexity by synthesizing various approaches to complex systems thinking. As was argued in Chapter 1 (section 1.2), the challenges facing the world must recognize the characteristics of complex systems and provides insights into how such systems can be appropriately managed. This chapter is divided into two components. The first section develops a basic understanding of complex systems in general, and pays particular attention to the ecosystem approach, resilience thinking, hierarchy theory and general systems theory. The insights from this discussion are summarized into a set of guidelines for managing complex systems that is proposed in Table 8.

The second part of this chapter moves the discussion towards systems and society and draws primarily from Giddens' structuration theory and bioeconomics. Giddens' structuration theory is presented in this chapter to serve as a foundation for further discussions of sociotechnical systems change provided in Chapter 4. Bioeconomics reinterprets economic systems through a biophysical lens with particular focus on energy and resource flows, and the insights from bioeconomics are synthesized into a set of guidelines for developing desirable bioeconomic systems proposed in Table 9. Both sets of guidelines are ultimately translated into the sustainability criteria set proposed in Table 14 at the end of Chapter 4.

3.1 Towards a general understanding of systems

The science of complexity is a broad subject, and entire library shelves are dedicated to the dynamic properties of systems, often in a language of feedback, stocks and flows, steady states and dynamic equilibrium (e.g. Meadows and Wright 2008; Odum 1994; von Bertalanffy 1969). In this first part, the focus is on big picture ideas that emerge from the science of complexity. For present purposes, it is necessary to suspend judgment about whether and to what extent systems are real or socially constructed, and simply consider systems as being useful to convey important concepts.

The basic premise that underpins the science of complexity is that of isomorphies, which is the idea that:

> *There exist models, principles, and laws that apply to generalized systems or their subclasses, irrespective of their particular kind, the nature of their component elements, and the relations or 'forces' between them. It seems legitimate to ask for a theory, not of systems of a more or less special kind, but of universal principles applying to systems in general. - (von Bertalanffy 1969, p. 32)*

Isomorphism is a powerful and contentious idea, one that when taken to extreme ends leads to deeper philosophical debate about for human freedom; a debate that is out of the remit of this dissertation. Von Bertalanffy (1969, p. 14) argued the point is to provide "scientific interpretation and theory where previously there was none, and higher generality than that in the special sciences." This chapter begins from this premise, and notes that any discussion of the general properties or patterns of systems (e.g. Holling and Gunderson 2002; Meadows and Wright 2008) is premised either implicitly or explicitly on isomorphies.

In order to understand how to navigate the challenges of complexity, it is necessary to have a basic understanding of systems dynamics (Kay 2008b). This section describes five basic characteristics of self-organizing (S-O) systems and then two proposals for appropriately managing complex systems. The discussion provided here is kept general, because the concepts will be further contextualized in section 3.2, which discusses systems in society.

3.1.1 Five characteristics of self-organizing systems

This section explores S-O systems, which are effectively the building blocks of complex systems. The basic premise is that systems self-organize in a self-perpetuating process, and in doing so they capture resources, build structure, and enhance their own survivability (Jorgensen 2006 , ch. 4; Kay 1991; Kay et al. 1999; Lotka 1922; Odum 1996; Schneider and Kay 1994). In the process of self-organization, such systems tend to display some basic properties, five of which are briefly discussed in what follows. Following this general treatment, two proposals for managing S-O systems are discussed.

Displaying internal causality

S-O systems display internal causality in the sense that parts and the whole provide meaning to one another as well as create and recreate one another (Giampietro 2004, ch. 6; Giampietro and Mayumi 2009, ch. 3; Wicken 1987). Internal causality does not imply that S-O systems are closed to material and energy flows from outside their boundaries, but rather that how resources and wastes are defined depends upon the characteristics of the system under investigation (Mayumi and Giampietro 2006). For the most part, resources are generally characterized as being some combination of useful energy, material, and information (e.g. Kay and Boyle 2008).

Of the three types of resources, useful energy is the one that receives the most attention and is most relevant for this dissertation. Self-organization is often considered in terms of its relationship to energy gradients, and the capture of energy throughput (e.g. Giampietro and Mayumi 2000; Giampietro and Mayumi 2009; Kay 1991; Kay et al. 1999; Lotka 1922; Odum 1996). For example, Hall and Klitgaard (2006) describe the importance of energy for ecosystems in the following manner:

> *In the absence of a continual input of energy, the highly ordered molecules within an ecosystem will, over time, degrade into completely random assemblages. It is only the continual input of energy from the sun, the capture of this energy by green plants, and the effective transfer of energy to other components of the system that allows ecosystems and their components to fight the general tendency of all things towards randomness. - (Hall and Klitgaard 2006)*

Self-organization around energy gradients will be discussed in terms of bioeconomics in section 3.2.2.

Maintaining resilience within a window of vitality

Second, S-O systems maintain coherence through positive and negative feedbacks that are internally structured and develop over time (Kay et al. 1999; Ulanowicz 1980). The domains of coherence for S-O systems are known variously as windows of vitality or basins of attraction (Gunderson and Holling 2002; Ulanowicz 2002).

An S-O system's ability to remain within its window of vitality is often conceived of in terms of resilience, which is understood to be the amount of change or shock a system can undergo and still retain its structure and function (Folke 2006; Holling 2001; Walker and Salt 2006). If pushed out of its windows of vitality, an S-O system may collapse and/or reorganize within a new domain, generally in a discontinuous and sudden manner (recognizing that "sudden" is a relative term) (Ahl and Allen 1996; Kay 1991; Kay and Schneider 1992).

Windows of vitality are generally discrete from one another in terms of their basic characteristics, such as intensity of energy throughput. For example, the Bénard cell displays qualitatively different structures of energy dissipation at different energy throughputs (Kay 1991). Similarly, societies may be considered to operate in discrete basins of energy intensity, as there are threshold levels that both developed and developing countries must maintain to remain stable (Giampietro 1992). Such an assertion has implications for whether developed societies are able to dematerialize through drastic increases in efficiency (e.g. factor 10 (Hawken 1999)), because it implies that the overall energy throughput of a society is an emergent property. However, given concerns about climate change and other global scale stresses, such stability may be short lived.

Co-evolutionary

A third characteristic of S-O systems is that they display properties of co-evolution, a concept that draws inspiration from autopoiesis (developed by Maturana and Varela (1992)). The premise of co-evolution is that systems and their environments evolve with, and in response to, one another (Rammel et al. 2007). The interactions evolve over time as the relationship develops, and is characterized by ongoing change, learning, adaptation, and mutualism (Roling 2005). Co-evolution provides a frame for exploring how an individual affects, and is affected by, its context. For example, Maturana and Varela (1992, ch. 5) note that while the environment is often seen as the selector of living beings, the reverse is equally relevant: living beings are selectors of the environment.

As a concept, co-evolution is becoming increasingly common in a variety of fields, including ecology, technology studies, innovation studies, and transition management, speaking to the isomorphic nature of the concept (e.g. Arthur 2009; Loorbach 2007, ch. 2; Rammel et al. 2007; van den Bergh and Kemp 2008). In Chapter 8 (assessing the energy and agricultural systems of Senegal) important questions of co-evolution emerge with regards to energy and economic development.

Hierarchical

S-O systems tend to become hierarchical (otherwise called holonarchical, holarchic, panarchical, etc.), in that they are composed of interrelated subsystems, each of which are in turn hierarchic in structure until some lowest level of elementary subsystems (Ahl and Allen 1996; Allen 2008; Blauberg et al. 1977; Holling et al. 2002a; Kay et al. 1999; Odum 1996; Van Gigch 1978; von Bertalanffy 1969).

In a hierarchical system the relationships (or strength of connection) within subsystems are stronger than between subsystems (Bland and Bell 2008; Meadows and Wright 2008, ch. 4). Furthermore, the higher levels of a hierarchy tend to operate on longer time-scales, and in this regard they set the conditions within which smaller faster ones operate, although they generally do not control the smaller levels (Ahl and Allen 1996, ch. 5; Holling and Gunderson 2002).

While all hierarchical levels must adhere to basic physical laws, different levels tend to have different laws and processes that are most relevant (Giampietro 2004; Ulanowicz 2007). For example, the lungs operate in a very different context and with a different goal function than their host human. Likewise, some of the goals of individuals (e.g. freedom) must be tempered by needs of society (e.g. structure and stability), even though society is made up of individuals.

Without implying teleology, systems tend to become hierarchical because, within the reasonable limits of environmental context, hierarchies provide systems with greater stability and resilience, and reduce the amount of information required to maintain coherence (Meadows and Wright 2008, ch. 4). Different authors suggest hierarchies provide a measure of robustness, as upper levels may collapse without necessarily collapsing the lower level entities, and vice versa (Ahl and Allen 1996; Holling et al. 2002b; Peterson 2002).

Cyclical

The final general characteristic of S-O systems is that they tend to operate in cycles (Gunderson and Holling 2002; Walker and Salt 2006). According to resilience practitioners, the essential characteristics of the cyclical behaviour are consistent enough to be described using the adaptive cycle metaphor consisting of four general phases: (1) a period of rapid growth and exploitation; (2) a long phase of accumulation and conservation of structure; (3) a rapid breakdown; and (4), a short phase of renewal and reorganization) (Carpenter et al. 2001; Holling and Gunderson 2002; Walker et al. 2002).

The adaptive cycle is inspired by the work of Schumpeter (2012). A graphical representation of the adaptive cycle is shown in Figure 3.

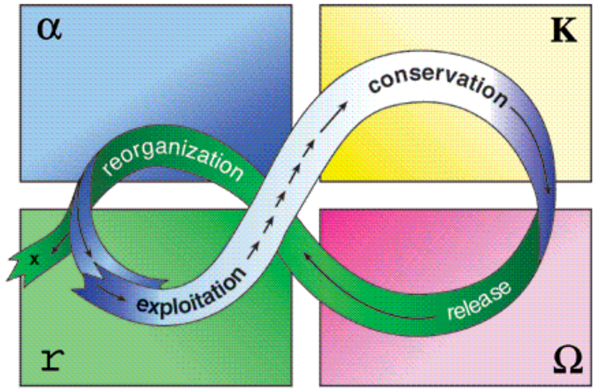

Figure 3 - The 4 box adaptive cycle (source: Holling 2007)

There are many different graphical representations of the adaptive cycle (e.g. ResAlliance 2002), and they all more or less tell the same story. This one was chosen because it does not display any axes, but rather simply shows the four phases and the general nature of the cyclical behaviour.

The adaptive cycle is also inherently focused on cross scale dynamics. For example, Peterson (2002) describes four ways through which change can propagate in a system: (1) larger systems trigger top-down change in sub-systems – such as carbon dioxide affecting photosynthesis; (2) reorganization at a higher level triggers reorganization at a lower level – such as pine-beetles reorganizing the trees allows for more light to hit the ground; (3) small-scale disturbance triggers large-scale – lightning strike on a single tree causes forest fire; and (4) following collapse of a system, surrounding systems (both meta-, sub-, and same scale) provide information.

In its most general interpretation, the adaptive cycle implies that nothing lasts forever and change is the only certainty. If resilience and windows of vitality reflect the ability of a system to maintain its structure, the adaptive cycle shows that things are born, grow, mature, die and are reborn in a different manner. For the adaptive cycle to take place, the resilience of a system at one point in time must be overcome, even if the system endures over the longer period (e.g. a forest may go through cycles of fire and regrowth). This idea is not new; cycles of birth, death and rebirth are present in mythology and religion. However, when moving from the generalities of life to describing specific systems (such as ecosystems), the adaptive cycle becomes more difficult to apply. The Resilience Alliance has argued that the adaptive cycle is best understood as a metaphor, in other words as a heuristic for exploring dynamic change, but one that is ultimately unverifiable.

3.1.2 Managing self-organizing systems

While the five characteristics of S-O systems described above imply systems display basic properties, they do not ensure the ability to control systems. For example, Walker et al. (2002) describes social-ecological systems as being highly uncertain, containing thresholds, exhibiting hysteretic (lag) effects and irreversible changes, and generally open to only imperfect management by human agency. When coupled with cross-scale dynamics, the danger of managing social-ecological systems becomes apparent (Peterson 2002). At the same time, systems are managed in some form or other. For the purpose of this dissertation, two approaches to management are relevant, and they are parametric management and adaptive management.

The concept of parametric management emerged from the study of hierarchies. The basic premise of parametric management is that managing complex systems requires managing for context. According to Allen et al. (1999) S-O systems generally maintain internal coherence as long as the context in which they are embedded is appropriate. For example, agriculture may be considered as a type of management where the farmer does not grow crops so much as he or she provides the proper context in which crops can grow. Proponents of parametric management argue that current management paradigms for ecosystems generally ignore the importance of context, such as by removing the large fish from ocean ecosystems (Allen et al. 1999; Waltner-Toews et al. 2008). Managing for context requires working across various physical and temporal scales (Kay et al. 1999).

The second approach to managing for complexity is adaptive management, which is promoted by the Resilience Alliance and is premised upon developing adaptive and anticipatory capacity to change (Peterson 2002; Rammel et al. 2007; Walker and Salt 2006). Adaptive management is in some regards a no regrets approach (Loorbach 2007, ch. 4), because it often starts with securing to the extent possible the necessary building blocks for social-ecological system integrity, and builds incrementally from there. Due to their respect for system complexity and uncertainty, advocates of resilience thinking and associated analyses are hesitant to embrace prescriptive approaches that might encourage overconfidence in prediction and management. With this caveat, however, Walker and Salt (2006) identify the nine properties of a resilient world that are presented in the form of criteria in Table 7.

These nine properties do not identify desirable qualities of socio-ecological systems beyond the capacity to adapt and persist. The resilience criteria do, however, clarify the qualities needed for socio-ecological integrity and suggest means of acting on requirements for precaution and adaptation. Moreover, they point to the need for sufficient system redundancy and for safety cushions between exploitation levels and potential system thresholds (Walker et al. 2002).

The resilience criteria can be integrated with the generic sustainability assessment criteria (Gibson 2011b), most effectively by direct insertion as clarifications and adjustments of the sustainability assessment criteria and by giving particular attention to the resilience qualities in the elaboration of case- and context-specific criteria (see Gaudreau and Gibson 2010, or Chapter 6). In the following section, the resilience criteria are folded into a broader set of guidelines for managing complex systems, which in turn inform the systems- and energy-informed criteria set proposed at the end of Chapter 4.

Table 7 - Criteria for resilient societies

Diversity Promote and sustain diversity in all forms (biological, landscape, cultural, social and economic) as a major source of future options and system capacity to response to change and disturbance
Ecological variability Embrace and work with ecological variability rather than attempting to control it (e.g. to maximize returns)
Modularity Favour largely self-reliant systems (modules) to avoid over-connectedness and associated relations of dependence, which become vulnerable to shocks
Acknowledge slow variables Focus on slow controlling variables that configure social/ecological systems and are associated with thresholds
Tight feedbacks Maintain or strengthen feedbacks that are tight and strong enough to allow detection of thresholds before they are crossed (versus slow or delayed feedbacks with weak signals)
Social capital Promote trust, well-developed social networks, and responsive leadership, all of which serve adaptability
Innovation Emphasize learning, experimentation, locally developed rules, and capacity and willingness to shift away from thresholds to undesirable futures or over thresholds to more desirable futures
Overlap in governance Foster redundancy of institutions, and a mix of governance players and relations and tools (e.g. common and private properties with overlapping access rights) to increase response diversity and flexibility
Ecosystem services Recognize all ecosystems services, including those currently unpriced (e.g. pollination, water regime maintenance, climate reliability, and nutrient cycling)

Source: adapted from (Walker and Salt 2006, chapter 6)

3.1.3 A proposed set of guidelines for managing complex systems

The science of complexity provides a useful way of understanding the world. Systems approaches highlight the importance of limits, the peril and opportunity of thresholds, and the possibilities that arise from collapse and reorganization, even if the actual quantification of limits in relevant situations is impossible. This dissertation favours the use of systems concepts as big picture heuristics that must be contextualized to address issues such as level of development, history, and culture.

The insights from the science of complexity may inform Gibson's SA framework in various ways. In terms of the research approach, the science of complexity complements the discussions in Chapter 2, and points to the importance of searching for interconnections and patterns, and managing uncertainty through precaution and adaptation (Devuyst 1999; Gibson et al. 2005; Partidario 2007; Pope and Grace 2006). However, given this dissertation focuses on criteria specification, it is possible and desirable to go one step further and codify some of the insights into a set of guidelines that will then inform the sustainability criteria for energy undertakings proposed in Chapter 4. In order to do so, Table 8 below proposes a set of guidelines for managing complex systems particularly relevant for sustainability assessment. In the table, the letter-number combination before the principle (e.g. C9) is provided so as to allow crossreferencing between these principles and the sustainability criteria set provided in Table 14

Table 8 - Generic guidelines for managing complex systems

C1 - Manage at the whole system and avoid sub-optimization
Manage at the whole system level, and seek to understand the focal system's characteristics and dynamics to identify valued qualities as well as continuing and impending stresses and disturbances from internal and external sources. Promote full systems accounting and resource cascading – derived from (Allen et al. 1999; Kay 2002; Kay et al. 1999)

C2 – Manage at multiple levels while embracing contradiction
System control occurs through reciprocal interactions at multiple scales and is often manifested in different ways. Manage hierarchies to promote redundancy and robustness, and optimize response diversity, while acknowledging that different hierarchies exhibit different goals and values, which often lead to contradiction. Promote top-down and bottom-up control– derived from (Ahl and Allen 1996; Allen et al. 1999)

C3 - Allow systems to move in cycles that involve unexpected behaviour, death and renewal
Work within the tendency of systems to grow, develop, collapse and reorganize. Anticipate and avoid catastrophic and chaotic behaviour when possible and desirable, while recognizing that human ability to predict and forecast is limited – derived from (Holling et al. 2002b; Meadows and Wright 2008; Walker and Salt 2006)

C4 - Manage feedback to maintain desired system structures within their windows of vitality
Aim to manage positive and negative feedback mechanisms so system structures remain within desired windows of vitality. Maintain or strengthen feedbacks that allow detection of thresholds before they are crossed (versus slow or delayed feedbacks with weak signals), while avoiding cascading collapse – derived from (Kay 2008b; Meadows and Wright 2008; Ulanowicz 1980)

C5 – Provide appropriate contexts for positive co-evolution of systems and their environments
Influence systems by providing the appropriate context for their development and prosperity. Allow the system and its environment to co-evolve with one another, thereby changing the nature of both, all the while avoiding creating an overdependence of the system on its context. Anticipate and manage for changing contexts (e.g. climate induced species migration) – derived from (Allen et al. 1999; Maturana and Varela 1992; Meadows and Wright 2008)

C6 - Avoid undesirable feedback mechanisms
Reduce the gain of positive feedback loops so as to prevent undesirable dynamics, such as promoting gains to these who are already advantaged. Avoid the ratcheting effect where intensification from one side leads to intensification from the other side (e.g. the pesticide treadmill). Promote diversification, regulation, and other policies that level the playing field, and let go when necessary – derived from (Franklin 1990; Meadows and Wright 2008)

C7 - Promote diversity, variability, redundancy and modularity
Promote and sustain diversity in all forms (biological, landscape, cultural, social and economic) as a major source of future options and system capacity to response to change and disturbance. Embrace and work with ecological variability rather than attempting to control it. Favour largely self-reliant systems to avoid over-connectedness and overdependence – derived from (Holling et al. 2002b; Meadows and Wright 2008; Walker and Salt 2006)

C8 - Follow systems over the long-term
Seek to understand systems by following their long-term dynamics as opposed to understanding systems as a series of events. Look for emergent patterns at all scales. Develop the capacity to monitor changes (e.g. by providing baseline data, finding a balance between rigid and loose control) – derived from (Kay et al. 1999; Meadows and Wright 2008; Weinberg 1975)

C9 - Maintain the structures and services that underlie and support desirable systems
Maintain and promote the functioning of critical systems structures (e.g. soil fertility, pollination) that underlie systems dynamics and support greater complexity – derived from (Holling et al. 2002b; Kay et al. 1999; Walker and Salt 2006)

The guidelines outlined above have merit for criteria development, but may also be explored with regards to society. To do so it is necessary to turn to approaches such as Giddens' structuration theory and bioeconomics.

3.2 Systems in Society

This section discusses two approaches to understanding society, those being Giddens' structuration theory, and bioeconomics. Giddens' structuration theory serves as a foundation for further discussions of sociotechnical systems change provided in Chapter 4. Bioeconomics provides a necessary interpretation of economic systems through a complexity lens that emphasises energy and resource flows and parallels other energy-based systems approaches (such as industrial ecology and societal metabolism). Giddens' structuration theory and bioeconomics do not represent an exhaustive list of systems theories applied to society. They do, however, represent approaches to systems thinking that emerged as being particularly relevant for this dissertation, particularly upon reflection of the case studies

3.2.1 Structuration

Giddens' structuration theory is a grand sociological theory that made an important contribution to sociology (Bryman and Teevan 2005, ch. 1), and more in depth treatments may be found elsewhere (e.g. Giddens 1984). Structuration complements co-evolution, which was discussed above. In structuration theory, as Giddens (1984, ch. 1) presents it, social activities are structured across space and time, and exhibit an important "duality of structure": the structural properties of social systems provide the context for individuals in terms of rules, regulations, and structures (of legitimation, domination and signification), while at the same time these structural properties are reproduced and created through the actions and social conduct of the totality of individuals (Giddens 1984, preface). As Giddens (1984, ch. 1) notes, "In and through their activities, agents reproduce the conditions that make these activities possible." For example, Giddens argues the act of writing proper English is constrained by the rules of the English language, and every act of writing reproduces and reinforces these rules.

Various schools of complexity have applied structuration, including social innovation generation (Westley 2008) and transition management (e.g. Loorbach 2007, ch. 3), which will be discussed in Chapter 4. Structuration provides a framework for those seeking systems change due to three general reasons. First, the duality of structure mentioned above highlights the relevance of social learning for promoting change. In effect, how people perceive the world influences the presence and importance of power structures, thereby changing the world. Second, Giddens' regimes (i.e. structures of domination) are understood as both enabling and constraining, which represents the context that change-seekers must act in (Giddens 1984, ch. 4; Loorbach 2007, ch. 3).

Third, structuration opens up the potential for what Giddens (1984, ch. 6) called the double hermeneutic, which is a nuanced form of co-evolution. The double hermeneutic is best described through an example, and Giddens chose Machiavelli's *The Prince*. According to Giddens (1984, ch. 6), *The Prince* was so influential because it spelled out the rules of the game for rulers, but in a manner available to everyone. In doing so, Machiavelli changed the nature of ruling because the motives of rulers could now be questioned in a way that could not be done as easily before the publication. The double hermeneutic provides, at least in theory, an opportunity for those seeking change to write their theories and approaches into the "rules of the game" and create a self-fulfilling prophecy, whereby if everyone follows the rules then the desired change will occur. Whether approaching change through the double hermeneutic represents good strategy, or a recipe for having a regime co-opt dissent, or both, is left as an open question for the purpose of this dissertation. At the very least, the double hermeneutic provides a fascinating approach for addressing power imbalances and underlies theories of sociotechnical systems change, which are discussed in Chapter 4.

3.2.2 Bioeconomics

The second approach to understanding society through a complexity lens is broadly known as bioeconomics. Bioeconomics characterizes economic systems and sectors largely in terms of biophysical characteristics such as energy flows (not necessarily using any one specific metric), labour (measured in hours of human activity) and levels of complexity. Drawing from the discussion of S-O around energy gradients, several authors argue that complexity in society tends to increase concomitant with the consumption of high power and high energy-return-on-investment energy sources and associated minerals (Allen et al. 1999; Georgescu-Roegen 1975; Giampietro and Mayumi 2008; Hagens and Mulder 2008; Hall and Klitgaard 2006). This discussion will first focus on energy flows and labour, and then afterwards address energy and complexity in a complementary manner.

One of the most important insights of bioeconomics is the concept of bioeconomic pressure, defined as the intensity of the throughput of matter and energy per unit of labour in the productive sub-sectors of the economy (Giampietro and Mayumi 2009, ch. 4). Generally speaking, as societies develop bioeconomic pressure increases, for a variety of reasons, including longer life spans, increased levels of education, increased consumption patterns, and increasingly large service and government sectors (Giampietro and Mayumi 2009, ch. 4). In response to this increased bioeconomic pressure, the productive sectors of the economy are required to supply more energy and material products to meet the growing demand of the rest of society, all the while employing a progressively smaller percentage of labour (Giampietro and Mayumi 2009, ch. 4; Nikiforuk 2012). For example, Giampietro and Mayumi (2009, ch. 3) show that in 1999 the Italian energy sector accounted for less than 0.1 percent of total hours of human labour activity, a ratio characteristic of developed societies. The most general means of addressing increasing bioeconomic pressure is through technological capitalization, which allows individuals and societies to channel ever-greater amounts of energy and materials per hour of labour. For example, in Brazilian sugarcane ethanol production, the average cane cutter can harvest less than ten tonnes of sugarcane in a day, whereas that same worker can harvest 300 tonnes per day with appropriate machinery (MME and Epelly 2011, p. 279).

Over time, however, it becomes increasingly difficult for societies to maintain the required bioeconomic pressure. They tend to overdraw from natural resources and become increasingly reliant upon energy and material resources (e.g. marginal lands, off-shore oil) with more negative impacts, and larger internal resource and labour requirements (Hagens and Mulder 2008; Tainter 2000). In this situation, societies are presented with a dilemma: it is clear that reliance on non-renewable resources is not a long-term solution, but the proposed renewable energy systems do not seem capable of matching the required bioeconomic pressure of modern society.

The dilemma presented above may be explored in terms of the "heart transplant metaphor", in which the old "heart" of society is replaced with a new one, and it is important to ensure that the new energy systems match the relevant metabolic characteristics of society and can meet the same bioeconomic pressure (should that bioeconomic pressure be considered desirable) (Giampietro and Mayumi 2008; Giampietro and Ulgiati 2005). Among a suite of related issues, one question particularly relevant is:

> *Can the proposed energy system procure sufficient energy to maintain its own operations as well as have sufficient and durable surplus power to meet current and future societal needs?*

One metric often proposed to address this question is that of Energy Return On Investment (EROI). EROI helps inform feasibility by comparing the total amount of energy available to society compared to how much energy was used up by the energy sector itself - in the energy-for-energy cycle - in terms of procuring the surplus. As EROI decreases, an increasingly large proportion of total energy throughput is required simply to maintain the energy sector itself, the consequence of which is decreasing energy surplus (both in terms of quantity and rate) available to society.

EROI is not simply academic; renewable energy systems must ultimately be able to reproduce themselves in the long-term the while providing surplus energy at a sufficient rate to meet the metabolic patterns of societies (Bott et al. 1983; Georgescu-Roegen 1978). Presently, modern renewable energy technologies are generally underwritten by fossil fuels (Farrell et al. 2006; Gupta and Hall 2011; Pimentel et al. 2007). For example, corn-ethanol is considered to have an EROI of approximately 1.3, which is both extremely low and would be even lower if dried distillers grain (the co-product of corn ethanol production, discussed in Chapter 2) were not included positively in the calculations (Giampietro and Mayumi 2009). Furthermore, in order to produce corn-ethanol at a sufficient rate, a large degree of technological capitalization is required, which tends to lower EROI further (Giampietro and Mayumi 2009).

The consequences of low EROI extend beyond energy to affect, *inter alia*, labour, land, water and mineral requirements, all of which are inputs to most energy production systems, and are generally resources of concern due to overconsumption and undesirable side effects. To provide an idea of the consequences of corn ethanol production for land and labour in the United States, Giampietro and Mayumi (2009, ch. 7) argue that simply replacing three percent of total US energy demand with corn-ethanol would require about half of the labour supply in the US workforce (including the unemployed) and more than 30 times the current land under production in the United States. Such a shift in employment patterns and land use would have important implications for the economy as a whole.

While the accuracy of EROI numbers can and should be debated, the underlying reasoning appears sound. In this regard, EROI may be understood as a limit check. It is unlikely an energy pathway of low EROI has long-term potential, although it may yet have value as a bridging energy source.

Tainter (1988) and Allen et al. (1999) provide a complementary interpretation of bioeconomics that emphasizes societal complexity. Tainter (2000) notes that problems emerge at all scales, and must be addressed or mitigated if society is to continue existing. While each individual response to an individual problem may be rational, the summation of responses often displays emergent properties (Allen et al. 1999; Saul 1995). Over time, in response to problems, societies tend to become more complex through various means, including more technology, increased institutional oversight (e.g. bureaucracy), deeper organization and regulation, and gathering and processing more information (Allen et al. 1999; Nikiforuk 2012, ch. 9; Tainter 2000). Tainter (1988) argues that since problems always emerge, complexity appears to keep increasing. There are energy and resource costs to increased complexity.

According to Tainter (1988), in early phases increasing complexity in response to problems generally provides increasingly positive returns and reinforcing feedbacks. For example, in the industrial revolution, coal was used to pump water out of the mines, which led to more coal production (Allen et al. 1999). Over time, however, the return on increasing complexity begins to diminish for various reasons: transaction costs increase; information becomes more abundant and less coherent and processing costs (in time and resources) increase; and the highest return solutions are generally used first. As returns on complexity diminish Tainter (2000) argues there are generally three options for a society to redefine its relationship with complexity.

First, there is sustainability through simplification, which requires eliminating much of the complex structure that requires such high overhead, including, for example, the management regime and the army. This approach to complexity prioritizes austerity, and Tainter (2000) describes the Catholic Church as having adopted this approach during the dark ages. The potential for simplification at this point is unknown. Governments now may want to simplify, but if the global economy continues to deliver ever-greater needs for government action (e.g. to address both financial and ecological debts), mere simplification may not work.

The second option is to develop new resources and technologies that allow for a return to increasing returns on complexity, a sort of ecological modernization. The long term potential for this approach is in doubt because of social-ecological limits and mal-distribution of the gains. The third option is what many refer to as collapse (Tainter 1988), which can take many forms, including biophysical, economic, and metaphysical (Ahl and Allen 1996, ch. 8; Allen et al. 1999; Schuetz 2000).

Tainter's narrative may be critiqued on many grounds, including the accuracy of his history, as well as the relevance of previous collapses for present day and future societies.

Furthermore, the language of "collapse" is perhaps extreme at times because it often implies a large scale and rather sudden event, which may not be the case.

All critique aside, Tainter's narrative highlights the importance of addressing societal problems in an integrated and consolidated manner, and at a sufficiently strategic level (Saul 1995). What appears rational and desirable at the level of individual problems may be undesirable when considered at the aggregate level. Finally, all domains and sectors have implications for resource use, and this opens up the possibility of addressing resource related problems through indirect means.

The discussion of bioeconomics points to an interrelated set of guidelines for developing desirable bioeconomic systems that focuses on the relationships among energy, complexity and society. These guidelines are summarized in Table 9 below, and are drawn from the discussions above and intended for sustainability assessment of energy systems.

Table 9 – General guidelines for developing desirable bioeconomic systems

B1 – Favour energy sources with high energy return on investment and seek to close the energy-for-energy cycle Ensure anticipated energy systems have a sufficient energy return on investment to maximize net output from the energy-for-energy cycle. Over time seek to close the energy-for-energy cycle of renewable energy systems such that they may self-perpetuate – derived from (Georgescu-Roegen 1975; Giampietro and Mayumi 2009)
B2 - Optimize labour allocation in the economy Work within the current labour allocation requirements and return-on-investment of labour in complex societies (notably in the energy and agricultural sectors). Seek to reallocate labour back to the energy sector while minimizing disruption – derived from (Giampietro and Mayumi 2009)
B3 - Maintain non-energy resource consumption within renewable limits Ensure that land and other resource (e.g. water, minerals) requirements for energy production respect ecological and social limits, especially when attempting to close the energy-for-energy cycle – derived from (Giampietro and Mayumi 2009)
B4 – Encourage flexibility in societal metabolic patterns Favour energy systems that do not lock society into undesirable metabolic characteristics (in terms of resource consumption, labour allocation, and energy usage), but rather may respond to the changing nature of society's relationships with energy and resource consumption. Ensure that the proposed energy source matches both the metabolic characteristics (e.g., energy consumption, power density) and the constraints (e.g., land and labour availability) of society, both now and envisioned – derived from (Giampietro and Mayumi 2009; Kay 2002; Lovins 1976)
B5 – Manage the rate, and rate of change, of energy supply and demand Ensure the rate at which society is supplied with energy avoids the collapse of current societal and economic systems. Likewise, maintain the rate of change of energy supply and demand within the adaptive capacity of society – derived from (Giampietro and Mayumi 2009; Tainter 2000)
B6 – Reduce societal complexity and its energy and resource cost Recognize that managerial complexity has a resource cost, and that individually rational and innovative responses to societal problems often increase societal complexity. Seek to manage complexity at emergent levels, and reduce complexity where feasible – derived from (Allen et al. 1999; Schumacher 1973; Tainter 2000)

When combined with the more general description of S-O systems provided in section 3.1 above, the guidelines provide a strong basis for informing sustainability assessment. Furthermore, these insights will be further reinterpreted in terms of energy in Chapter 4.

3.3 Final thoughts

This chapter provided a theoretical grounding in the science of complexity by synthesizing various approaches to complex systems thinking. As was argued in Chapter 1, the challenges facing the world must recognize the characteristics of complex systems to understand how they may be appropriately managed. This chapter proposed two sets of guidelines relating to complex systems in general (Table 8) and bioeconomics (Table 9). Both the complex systems and bioeconomics guidelines are ultimately translated into the sustainability criteria set proposed in Table 14 at the end of Chapter 4, while the insights from Giddens' structuration theory informs the discussion of transition management in Chapter 4.

This concludes the discussion of both the complexity of science (Chapter 2) and the science of complexity (Chapter 3), two interrelated bodies of knowledge. It is now possible to apply the insights from both Chapters 2 and 3 to the more specific area of energy and society, and this is the topic of the following chapter. Chapter 4 covers a lot of theoretical ground, including what the energy problem is, what a constructive relationship with energy entails, and how change may be fostered to move towards desirable energy future.

Chapter 4 – The energy problem

This chapter builds from the theory presented in Chapters 2 and 3 and explores the relationships between energy, society, technology, and the environment. The purpose is to develop a framework for understanding what a constructive and appropriate relationship with energy entails and what steps are required to achieve the necessary sociotechnical systems change.

Similar to Chapter 3, this chapter focuses on criteria development, and in doing so, proposes two sets of energy-informed guidelines relating to the soft energy path and sociotechnical systems change. These principle sets are then incorporated into the systems- and energy-informed sustainability criteria set proposed at the end of the chapter. The criteria set provides a generic normative framework for assessing energy system options for the potential to promote progress towards sustainability.

This chapter is structured around three general questions. First, what is the energy problem? This question helps ground energy systems analysis and energy decision-making within the broader worldview presented in this dissertation. Second, what are the characteristics of an appropriate and constructive societal relationship with energy? This second question builds upon the first question by exploring the soft energy path (SEP) and appropriate technology (AT). The SEP is an important theoretical cornerstone to this dissertation, and provides a means of energy decision-making grounded in the context of the complexity of science. Where the SEP is less helpful relates to how structural change can be achieved, and this leads to the third question; how can sociotechnical systems change be achieved? The discussions in the third section are centered on transition management, a descriptive approach to sociotechnical systems change.

Following the exploration of those three questions, the last section completes sub-objective 4 by synthesizing the complex systems- and energy- informed guidelines into a generic set of sustainability criteria for energy undertakings. In doing so, this chapter completes the updating of Gibson's SA framework for the purpose of this dissertation.

4.1 Framing the energy problem

The first task in chapter is to outline various frames through which the energy problem may be conceptualized. Problem framing does not necessarily need to be considered negatively (Bardwell 1991), as an energy problem is also an opportunity. This section draws inspiration from Robinson (1982), who reviewed the energy literature and noted three broad conceptions of the energy problem that are commonly discussed:

(1) The energy problem is essentially a problem of developing new supplies and enhanced conservation measures to meet the energy demands of society
(2) The energy problem is a matter of the increasingly intolerable social-ecological impacts related to energy use.

(3) The energy problem is one manifestation of a far more fundamental crisis relating to the modern society.

It is helpful to elaborate briefly on these three different framings, because all three of them are relevant for this dissertation, as well as for broader debate.

1 - The energy problem as a question of supply and conservation

The first framing noted by Robinson is largely supply oriented. Drawing from discussions of self-organization around energy provided in Chapter 3, we note that as societies develop and become more complex, bioeconomic pressure increases (Georgescu-Roegen 1975; Hall and Klitgaard 2006; Meadows 1972; Rosa and Machlis 1983; Schumacher 1973, ch. 8). In this first problem framing, the concern is largely energy security; i.e. ensuring the uninterrupted physical availability of energy products on the market at an affordable price for all consumers (Chester 2010; Nuffield 2011). Energy security is threatened in part by the declining EROI of energy sources, particularly as the search for new energy sources extends in increasingly hostile environments (e.g. deep water, the arctic, shale) (Hall et al. 2009).

Focusing on supply management promotes both conservation and efficiency, and "negawatts," as they are sometimes called, may be developed to defer the expansion of energy production. The Ford Foundation (EIR 1977), for example, has considered conservation to be a source of energy.

In the long-term, the concern over energy supply relates to the overall availability of energy supplies, and the issue of fossil fuel supplies being finite. By contrast, short-term considerations may prioritize attention to the rate of energy supply versus consumption. Both short-term and long-term viewpoints must address the challenge of transitioning away from fossil fuels that are becoming increasingly difficult and costly to obtain (Hall et al. 2008).

2 - The energy problem as a question of social-ecological impacts

With its focus on supply, the first problem framing ignores many critical issues facing the world, several of which were outlined in Chapter 1, and explored in terms of systems terminology in Chapter 3. Addressing the broader sustainability concerns generally leads to a second problem framing, which Robinson (1982) describes as the increasing social-ecological impacts of energy production and consumption. Many of these energy-related problems are well documented, including, but certainly not limited to, climate change (e.g. Fargione et al. 2008), land use change (e.g. related to biofuel production, or wind farms) and deforestation (Nikiforuk 2012, ch. 11; Nuffield 2011), and the storage of long-term nuclear wastes (Schneider et al. 2012).

This second problem framing described by Robinson is one many environmental and social justice groups are likely to adopt, although how the problems are defined may vary enormously. This second framing is not new, and became increasingly prevalent during the rise of industrial society (Kovarik 2005; Polanyi 1944). The concerns recognized in this second framing have been addressed in a range of policy and legal initiatives, including assessments of energy-related undertakings. The basic objective associated with the framing is to ensure that any expansions in energy production and consumption – if they are to occur at all – are managed in a way that promotes positive social-ecological outcomes, or at the least minimizes further damage.

Because the second framing draws from a wider range of concerns than the first (supply-oriented) framing, there are many instances where these framings conflict. Notably, within the second problem framing it is recognized that the rate of expansion of energy production frequently overwhelms capacity to manage, and this contributes to human rights violations (such as through the formation of petrostates) (Illich 1978; Karl 1999; Nikiforuk 2012; Nuffield 2011). Likewise, the very question of focusing on meeting and increasing supply may in many instances be considered undesirable.

3 - The energy problem as a deeper critique of modern society

The second problem framing is more comprehensive than the first. However, at some point, if all the challenges and contradictions related to humanity's relationship with energy are taken together, along with their mutual interactions, and considered alongside the myriad other challenges facing society (e.g. unemployment, inequality, war, disappearance of cultures), it becomes reasonable to question whether the problems associated with energy indicate more fundamental concerns (Ellul 1967; Franklin 1990, ch. 3; Hanks 2010; Illich 1973; Lerner et al. 1999, ch. 1; Schumacher 1973, ch. 4; von Bertalanffy 1969; Winner 1977). This leads to a third problem framing, which Robinson describes as being centred on the survival of modern society. The roots of this problem framing run deep, and are often focused on arguments that the very structure of society and the way in which individuals and societies envision the world are faulty, and no amount of ecological modernization will suffice (Ellul 1967; Marcuse 2010; Whyte 1967; Winner 1977). With regards to the discussion of power in Chapter 2, this third problem framing could be interpreted as emancipation from psychic prisons, and the overthrow of instruments of domination; often through the unveiling of contradictions (Jackson 2000; Marcuse 2010).

In this third problem framing, it is argued that the social contracts amongst humans and between humans and nature must be renegotiated. Some of those who adopt this problem framing may perhaps be best described as favouring local sovereignty and decentralization. Others may have more radical tendencies, calling for an abolition of capitalism in favour of other economic and political systems (Bellamy-Foster 2009; Roman-Alcala 2010). There may be a feeling that another "great transformation" (Haberl et al. 2011) is necessary, even if there are competing visions of what that transformation will be (an agrarian revolution? a technological utopia? a deep respiritualization?). In this framing, energy, and humanity's relationship to it, are no longer the principal unit of analysis, but rather form one thread of a deeper critique of modernity (Holt-Gimenez 2009; Illich 1973; La Via Campesina 2010; Schumacher 1973; van der Ploeg 2008).

For present purposes, the third problem framing requires critical thinking about technology, which is broadly defined as: (1) the design and choice of individual technologies; (2) the structure of broader sociotechnical systems (e.g. electricity systems); and (3) technique[5], described by Ellul (1967, p. xxv) as the “totality of all methods rationally arrived at and having absolute efficiency,” and expressed similarly by others (Borgmann 1987; Heidegger 2010; Hickman 2010; Marcuse 2010). Technology is often what mediates an individual’s relationship to the world, and the use of technology conditions humans and orders societies (Ellul 1967; Jonas 2010; Marcuse 2010; Ortega y Gasset 2010; Winner 1977). Likewise, technology is rooted in discussions of many facets of the human condition, including the relevance of labour, political involvement, the search for the good life (e.g. Borgmann 1987; Ellul 1967; Higgs et al. 2000; Winner 1986, ch. 1). Both the discussions of the SEP and transition management approach energy through a lens of technology, and issues relating to technology will be revisited as necessary.

It is notable that the three different problem framings described above generally recognize or anticipate different types of feedback and actions. Changes in the cost of gasoline or electricity (largely first problem framing) have relatively direct and visible implications, which lead to quick responses. By contrast, the loss of biodiversity due to land fragmentation (which fits better within the second problem framing) is more difficult to measure because it deals with cumulative impacts, time lags, and greater uncertainties; is less visible to consumers and policy-makers; and is less likely to spur timely response. The problems associated with overall social and ecological effects of energy production and use generally involve even weaker feedback links due to the difficulty connecting big cumulative effects with specific actions and response options. In general, acknowledging and addressing problems from the viewpoint of the second and third framings becomes consistently more difficult because they are more indirect, abstract, metaphysical, uncertain, complex, and ethical; and their solutions rarely relate to any one particular problem, but rather to the totality of problems as conceived by the individual or group.

Even if one were to deny the need to overthrow modern society, it is becoming increasingly evident that the energy problem touches upon many issues that extend well beyond the boundaries of thermodynamics and into broader societal concerns. Gibson’s SA framework attempts to provide the necessary breadth, and the eight categories of progress towards sustainability described in Chapter 1 are evidence of this. However, in order to develop energy-related sustainability criteria, it is necessary to have more guidance specific to energy systems regarding what a constructive and appropriate relationship entails. To help further this exploration, the following section describes the soft energy path, an approach to energy systems planning that attempts to outline the basic characteristics of a constructive relationship with energy.

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[5] Ellul describes technique as encompassing both individual technologies as well as sociotechnical systems. The reason I have partitioned technology into three categories is that sustainability assessment must deal with individual technologies, sociotechnical systems and worldviews, and so it is helpful to distinguish them as such. When technology is mentioned it refers to all three aspects, unless the context clearly indicates otherwise (e.g. “individual technologies”).

4.2 Developing an appropriate and constructive relationship with energy

> *The most important, difficult, and neglected questions of energy strategy are not mainly technical or economic but rather social and ethical (Lovins 1976, p. 15).*

According to Lovins (1977), the true energy problem is how to meet social goals elegantly with a minimum of energy, while maintaining social fabric and biophysical integrity. The soft energy path (SEP), popularized by Lovins is a proposal for doing just that. The SEP is explored in this section, which reports important insights of the SEP, as well as draws in a deeper critique rooted in the appropriate technology (AT) movement. This section attempts to provide a basic conception of what an appropriate and constructive relationship between society and its energy sources entails, and consider implications for recognizing key complexities in energy assessments.

There is no one single rationale for the SEP and AT. Both emerged from a wide variety of intersecting areas of challenge and opportunity, which reflected the prevailing societal context. Both draw from the second and third problem framings discussed above. As a term, AT became popular in the 1960s to address problems facing development in Third World countries (Winner 1986, ch. 4). For example, Schumacher (1973) argued development projects must account for local context, including the available skill levels and resources, and the actual local needs. The premise was to promote development and technologies that were appropriate for the local context – matched in size, power and complexity – and met basic human needs (e.g. cooking, heating, lighting, pumping) (Lovins 1978).

Over time, AT thinking began to infiltrate developed countries, often as a response to unease related to sociotechnical systems and modern society, and frustration resulting from political activism of the 1960s (Illich 1973; Marcuse 2010; Winner 1979; Winner 1986, ch. 4). Consistent with what was described in the second and third problem framings, people were questioning the belief that economic growth with increased energy consumption were the best way to improve societal welfare (Franklin 1990; Robinson 1982; Science Council of Canada 1977). More generally, it was becoming clear there needed to be deeper reflection upon the means and ends of technology, and not simply in an instrumental sense but at the societal level as well (Borgmann 2010; Drengson 2010; Ellul 1967).

The SEP is a broad approach to energy systems planning that focuses on energy paths, as opposed to specific technologies. Morrison and Lodwick (1981) define an energy path as "a complex, interacting set of mutually reinforcing, internally consistent features that together constitute an energy system that is, in effect, a sociotechnical system." According to Morrison and Lodwick (1981), three important features of an energy path are: (1) a social context consisting of cultural values (e.g. preferences, policies) and associated institutions and organizations (e.g. economic, political, legal) that generate and support; (2) a set of technological features (e.g. materials, fuels, processes, flows, skills), which produce; (3) a set of impacts related to social welfare.

There are various reasons why calls for an alternative energy strategy were being raised. Several problems of the then current energy pathway (called the hard energy path, or

HEP) were emerging, and mirrored the problems arising from industrial society. The HEP was perceived as relying on a small suite of highly powerful and complex technologies of a profoundly geopolitical nature (Lovins 1977, ch. 2). For example, nuclear power brought with it the threat of nuclear weapon proliferation; the search for oil had led to military uprisings, war, coups, and human rights abuses; and nations and states were becoming increasingly economically dependent upon various energy sources (e.g. coal mining) as a source of employment (Lovins 1977, ch. 2; Meadowcroft 2009; Nikiforuk 2012).

Proponents of AT and the SEP argued that modern societies fared rather poorly in terms of achieving goals in an efficient, effective, and elegant manner (Schumacher 1973, ch. 8). For example, much useful energy is lost in conversion and transmission, well before it reaches the consumer; and the energy that does reach the consumer is then often mismatched to the purpose of the intended task (Lovins 1977). The capital intensity of large-scale energy systems implies they are unable to benefit from economies of mass production, because there simply aren't enough of them being built (e.g. nuclear plants) (Lovins 1977). And when they are built, large-scale energy systems tend to have high external costs, such as the costs of air pollution from coal-fired electricity or insurance liabilities for the nuclear industry are often borne by society at large.

There are other concerns relating to the HEP, but for present purposes it was clear that energy strategy needed to be rethought, and the SEP remains arguably the most convincing and coherent proposal of an alternative pathway. The SEP is much more than simply a response to supply and demand realities, but rather opens the door to deeper exploration regarding society and material prosperity. The following section articulates the vision.

4.2.1 Characteristics of the soft path and appropriate technology

The many facets of AT and the SEP have been theorized, developed and applied – successfully and not – all over the world. Because of the resulting diversity of contexts and approaches, developing a coherent suite of criteria of the SEP and AT is difficult, although some have tried (e.g. Clarke and Clarke 1972). What are provided below are six basic tenets of the SEP and appropriate technology relevant for this dissertation.

See energy as a service and promote end-use matching

The first tenet of the SEP is that energy must be understood a means to a social end (Bott et al. 1983, ch. 4; Brooks et al. 2009b; Lovins 1977, ch. 1). As Lovins notes, people do not want oil or electricity, but rather real things like comfortable rooms, light, and food (Lovins 1976). While energy is necessary to meet these ends, the energy itself is not the end goal. Conceiving of energy as a means to a set of ends is obvious, but easily forgotten with the focus on barrels of oil being refined and shipped worldwide, and megawatts of offshore wind power. Furthermore, at the aggregate level there is – perhaps justifiably – less interest in how people want comfortable homes and proximity to loved ones, than in how much electricity and liquid fuel the aggregate lifestyles require.

Focusing on energy as a means to an end is an instrumental approach that promotes the examining of tasks, and the posing of two basic questions (Lovins 1978): (1) is this task worth doing? and (2) what is the most elegant and effective way to match the quality of energy supply with the quality of the end-use? For the time being, it is helpful to focus on the second question, which Lovins explored through end-use matching (Brooks and Casey 1979; Lovins 1977, ch. 2). Proponents of end-use matching argue the approach is a far more efficient and effective means of achieving goals than supply management. Given that a great deal of energy is lost during conversion from one form to another, end-use matching promises to reduce the number of energy conversions wherever possible (Lovins 1977, ch. 2). For example, electricity is improperly matched when it is used for tasks – such as heating and lighting – that can be provided through lower quality sources (Holtz and Brooks 2009). Holtz and Brooks (2009) note that for reasons of analysis, end-uses can effectively be grouped into four basic categories: (1) lower-temperature heat – e.g. for household heating; (2) higher-temperature heat – e.g. for industrial applications; (3) electricity – e.g. lights, electronics and electric motors; and (4) transportation.

Beginning with the end-use and working backwards also opens up a wider range of possibilities for meeting needs, and tends to increase the diversity of energy related technologies. It is noteworthy that end-use matching is being applied in water studies as well (e.g. Brooks et al. 2009b).

Apply technology at the appropriate scale and degree of centralization

Two important and interrelated themes for the SEP and appropriate technology relate to scale and centralization, both of which are important considerations in the study of technology. The SEP is often misinterpreted as only promoting *small*-scale technologies and systems, when it actually seeks the *appropriate* scale (Schumacher 1973, ch. 5). For example, Lovins (1976) wrote favourably of community sized energy systems and their many benefits (e.g. combined heat and power). However, within the SEP worldview, a large centralized nuclear power plant or an equally large hydro dam is likely too big under any circumstances.

There is no easy formula for determining the correct scale of energy or any other sociotechnical systems. Generally, beginning at the end-use and working backwards likely favours a diversity of smaller scale sources and promoting system resilience, whereas starting from supply and moving forwards perhaps favours larger scale and seemingly brittle supply (Lovins 1978).

SEP proponents argue that smaller scale technologies increase reciprocity, embody a more humanizing approach to work (i.e. non-mechanized or automated), offer the potential to mobilize the minds and hands of people, allow for democratic control, and provide higher quality employment opportunities where people live and need jobs (Franklin 1990; Schumacher 1973, ch. 5 and 10). These technologies are generally considered flexible and simple, and can be better understood, used and maintained by individuals (Lovins 1977, ch. 2). In other words, small-scale technologies, or a least a certain manifestation of them, serve the potential to foster and better the human condition through the promotion of character-building work and the development of greater autonomy (Schumacher 1973, ch. 2). On the other hand, some terrible human rights abuses take place in sweatshops that operate with small-scale technologies as well, and there is the risk of becoming nostalgic (Bauchspies et al. 2006; Winner 1986, ch. 4).

Closely coupled to scale is centrality, and the SEP promotes a more decentralized energy system than current practice (Brooks et al. 2009b). For example, Lovins (1977, ch. 2) calls for energy systems that are matched in scale and in geographic distribution to their ultimate uses. Decentralization is seen as a means of promoting smaller scales of social organization, and reducing the rural exodus plaguing society at the time, and still now (Lovins 1978; Morrison and Lodwick 1981; Schumacher 1973, ch. 2). Decentralized production could be localized and promote local self-sufficiency, with better use of local resources and more equitable distribution of benefits and risks (Franklin 1990; Lovins 1978, p. 140; Morrison and Lodwick 1981). Likewise, decentralization could reduce alienation by increasing individual control and reciprocity, and reducing dependence upon large complex systems that are effectively out of an individual's sphere of influence (Cordell 1980, p. 6; Franklin 1990; Winner 1986, ch. 5). Promoting decentralized energy systems is as much an argument for improved efficiency – for example, sourcing energy systems near their end-use reduces transmission losses and infrastructure costs (Lovins 1977, ch. 2) – as it is a plea for a greater degree of individual autonomy and self-actualization (Winner 1986, ch. 5).

Decentralization is not inherently desirable. For example, some questions posed by Winner (1986, ch. 5) include: Which centres? What activity is problematic? How many are there, and are there too many or too few? Winner (1986, ch. 4) argues that a perfectly plausible scenario of decentralized energy could be going to a big box store and purchasing a solar water heater designed by General Electric and installed by the local plumber. It is unclear whether this is what proponents of decentralization have in mind. What this means for the purposes of this dissertation is that centralization must be elaborated upon within its context. Furthermore, Holtz and Brooks (2009, p. 46) admit that "the emphasis placed on finding low-tech and easy-to-understand technologies, as well as the aversion to *any* technologies involving large-scale, centralized facilities, was overstated" (emphasis in original). However, the argument remains that current practice is overly centralized and there are benefits associated with moving towards greater decentralization.

Focus on the economics of permanence

A third characteristic of the SEP is that it takes a long-term view by focusing upon permanence and sustainability (Brooks et al. 2009b; Cordell 1980). As Schumacher (1973, ch. 2) argues, nothing makes economic sense unless its continuance can0 be projected many years into the future without becoming absurd. In part to achieve permanence, the SEP is premised on renewable energy flows and drawing from income rather than natural capital (Holtz and Brooks 2009; Lovins 1977, ch. 2). The primary flows of interest to the SEP are those that flow continuously regardless of whether they are used or not, and have the characteristics of being passively managed insofar as the energy density of supply is beyond control, namely: sunlight, wind, water, and deep earth heat. While the SEP does not preclude other forms of renewable energy, such as biomass, there is a risk of taking too much too fast because the biomass itself represents a physical stock, as well as a flow.

The focus on permanence requires that the energy-for-energy loop be closed, something Morrison and Lodwick (1981) and Bott et al. (1983, ch. 6) recognize is not sufficiently addressed in the SEP, although Bott et al. (1983, ch. 6) argue that in the long run the HEP is even worse off in this regards.

Reduce vulnerability and the cost of failure

A fourth characteristic of the SEP is that it emphasizes system resilience by reducing vulnerability to and the cost of failure (Lovins 1978; Morrison and Lodwick 1981). SEP practitioners promote safe-fail technologies, which can stop working without causing undue hardship to people, the environment or the economy (Lovins 1978). By contrast, many large-scale technologies must be designed to be fail-safe so as to avoid catastrophic failure (Winfield et al. 2010): a nuclear plant explosion could release radiation to its surrounding environment, and a centralized electricity grid could fail and take down the economy with it, as well as impact those depending on electricity for needed services (e.g. heating and cooling).

SEP proponents argue that while hard technologies must be fail-safe, their scale and complexity make them prone to failure in a way that is not applicable for soft technologies. For example, the HEP is vulnerable to shocks, disruptions, malfunctions and malice (Homer-Dixon 2006; Lovins 1978; Lovins and Lovins 1982). By contrast, Lovins argues that the technological diversity of SEP technologies, and the fact that there are so many of them, increases resilience, and even demands a lower reserve margin, because they are unlikely all to fail at the same time (Lovins 1978).

The discussions above touch upon reliability, and with its focus on meeting all needs with electricity and liquid fuels, the HEP forces the same level of reliability on all forms of energy usage (Lovins 1978). It is a diseconomy that within the HEP, those using coffee grinders must pay for the same reliability as subways and hospitals (Lovins 1978).

A final type of vulnerability worth noting is that of path dependency. One of the enduring critiques of the hard path is that the focus on large power plants with long lead times entails high path dependency and lock-in (Lovins 1978; Peters et al. 2007; Winfield et al. 2010). By contrast, SEP technologies generally have much shorter lead times that allow them to respond quickly to changing conditions (Lovins 1978).

Embed energy strategy in a new ethic

The fifth characteristic of the SEP is that it extends well beyond supply management, and instead embodies a new ethic (Holtz and Brooks 2009). Some values linked with the SEP include thrift, simplicity, diversity, neighbourliness, humility and craftsmanship, and the notion that requiring large amounts of energy to accomplish social goals should be taken as an indicator of failure as opposed to success (Franklin 1990, ch. 6; Lovins 1977, ch. 1 and 2; Lovins 1978). While Lovins does not claim the SEP will solve all social problems, he contends that it will help address them and certainly won't make them worse (Morrison and Lodwick 1981).

The SEP also promises greater equity and environmental justice (Franklin 1990, ch. 6). In terms of employment, the SEP is conceived as providing more readily available and easily learned jobs in the energy system (Lovins 1977, p. 9; Lovins 1978). From an international perspective, the SEP seeks to foster international stability, order and peace by reducing geopolitical conflicts and resource problems (including climate change and resource depletion) (Lovins 1977; Morrison and Lodwick 1981).

An important aspect of the soft path ethic is that it is self-reflective (or reflexive), in that soft technologies and soft social impacts both create the necessary social conditions for the soft path itself to flourish (Morrison and Lodwick 1981). For example, the SEP both promotes and depends upon greater public participation (Lovins 1977, p. 14; Morrison and Lodwick 1981).

Whether the SEP, properly designed and implemented, is in fact capable of moving societies significantly closer to these lofty goals is an open question. However, it is important not to take credit away from the SEP as an energy strategy that, unlike the HEP alternatives, explicitly promotes the pursuit of these goals.

Develop energy bridges for the needed transitions

The final characteristic of the SEP that will be discussed here is the notion of energy bridges and transitions. A transition to an SEP is not something that can be achieved overnight; infrastructure must turn over, attitudes must change, and the natural world must heal. Proponents of the SEP recognized the need to develop energy bridges to ease the transition from a fossil fuel system to renewable energy system (Brooks and Casey 1979; Morrison and Lodwick 1981).

For Lovins, the general time scale is on the order of 50 years, and in that time period both soft and hard technologies would co-exist (Lovins 1978). Keeping in line with the SEP ethic, the transition must be broadly democratic and with a concern for equity (Morrison and Lodwick 1981). At some point the expectation was that critical mass would be reached and a threshold would be crossed (Morrison and Lodwick 1981). The concept of an energy bridge requires that the gains realized from using non-renewable flows be devoted to the purpose of leading society towards renewability (Schumacher 1973, ch. 1).

At the time of writing, Lovins (1976) proposed coal as an ideal bridging energy source for the United States due to its availability, scalability, and the promising short-term horizon of new clean technologies (e.g. coal-bed gasification). Lovins expressed concern that failure to act soon enough with regards to coal as a bridging energy source might close the window of opportunity (Lovins 1977, ch. 2). Given the concerns of climate change today, and the still distant promises of "clean coal," it is not clear whether coal remains viable.

The focus on energy transition brings into question of the extent to which the SEP is compatible, at last over the short term, with the HEP. According to Lovins, the distinction between the SEP and HEP is not how much energy is used but "on the technical and socio-political structure of the energy system" (Lovins 1976; 1979). The dominant characteristics of the HEP – notably centrism, autocracy, vulnerability and technocracy – are considered antithetical to those of the SEP, which emphasize decentralization, and mature exercise of pluralistic choice. To this end, the two paths are also considered culturally incompatible, in that each promotes a worldview that makes the other path harder to imagine and understand, require policy actions that inhibit one another, and must compete for the same limited resources (Ellul 1967; Lovins 1977; Winner 1986, ch. 3).

The potential incompatibility of the SEP and the HEP raises two questions: can soft technologies be hard? And how does one move from the HEP to the SEP? With regards to the first question, Lovins argues it is possible for soft technologies to display hard characteristics, such as wind farms installed using coercive means. Likewise, the increasingly large renewable energy systems (such as large hydro dams and 10MW wind turbines) do not necessarily fit into the soft path worldview. These approaches do little to change the socio-political structure of the energy system, and nor do they promote better end-use matching.

With regards to the second question of moving from the HEP to the SEP, it appears that Lovins' promotion of a 50-year energy bridge indicates that it is possible for soft and hard technologies to co-exist. However, the very nature of a transition implies instability, and it appears doubtful that a co-existence could last for very long if not undertaken for the purposes of transition. As Lovins (1979, p. 9) notes:

> *in a soft path you would start with a bunch of hard technologies and you would end up with a bunch of soft ones, and for fifty years they would be co-existing side by side as their mix gradually shifted.*

What this means in actual practice is debatable, and while Lovins' assertion implies a smooth transition (e.g. through the use of the word 'gradual'), there is no reason to believe this is the case.

The six characteristics noted above – seeing energy as a means to an end; applying technology at the appropriate scale and degree of centralization; focusing on the economics of permanence; reducing vulnerability and the cost of failure; developing a new energy ethic; and promoting the development of energy bridges – describe the principal thrust of the SEP. What they don't address is an important controversy of the SEP relating to efficiency versus social change.

4.2.2 Soft paths, hard controversies – Efficiency versus social change

As an approach to energy planning and improving social welfare, the SEP is controversial (c.f. Lovins and Nash 1979), and one controversy particularly relevant for this dissertation is the conflict between efficiency and social change. Many critics have accused Lovins of trying to promote radical social change, whereas Lovins has claimed his focus was largely technical (Morrison and Lodwick 1981; Robinson 1982). As Lovins (1976) notes in his seminal *Foreign Affairs* article, there are two ways to approach conservation: " (1) purely technical – plug leaks and use thriftier technology, substituting resources; (2) making changes to our lifestyles such as smaller cars, mass transit." At the time of writing, Lovins (1976) argued studies were showing that in the long term, using purely technical fixes, energy efficiency can be increased by a factor of four.

Winner (1986, ch. 2) argues that people generally feel compelled to make moral arguments based upon efficiency, material wellbeing, and the fear of death, as opposed to deeper virtues such as liberty, justice and equality. While it is possible to use efficiency as a means of entering into the debate, this risks perpetuating the very technological worldview that many proponents of AT and the SEP were concerned with in the first place (Ellul 1967; Heidegger 2010; Winner 1986, ch. 4). For this reason Lovins was criticized by proponents of the SEP for claiming that social change was not necessary, because such claims tend to confuse the energy debate (Winner 1986, ch. 3). What in the minds of many should be a social question now becomes one of technical improvements and efficiency, both of which imply no heroic effort and allow for ecological modernization and an instrumental approach to technology (Robinson 1982; Winner 1986). As Winner (1986, ch. 4) asks, what if it turned out that the soft path were in fact less efficient or more costly than the hard path? By shifting away from the moral high ground, the SEP stands to win or lose on purely technical matters, and in doing so loses much of what many originally valued in it (e.g. Franklin 1990, ch. 6).

A different concern with the efficiency argument is that it may lead to what is known as the efficiency paradox (also called Jevons' paradox, or the rebound effect). The basis of the efficiency paradox is that increases in efficiency may ultimately lead to increased consumption, because as per-unit costs of an activity decrease due to efficiency increases, the aggregate activity increases, thereby negating and potentially reversing efficiency gains. With regards to the soft energy path, the concern would be that money saved from not using energy would then be spent on energy consumptive activities (e.g. airline travel), rather than less impactful alternatives (such as music or language lessons). To address the efficiency paradox in a soft path framework, one notes that Lovins' promotion of a new ethic grounded in qualities such as thrift would generally prevent such a rebound from occurring. Likewise, from the perspective of sustainability assessment, the intent of the framework and criteria is to ensure that decisions and savings will increasingly be protected from the rebound effect, and further that the benefits of any gains in growth go to those who most need it.

Despite the potential for improving efficiency, it is clear the SEP depends upon, and promotes social change at all scales (Robinson 1982), which the discussion of a new energy ethic described above alludes to. Then, the questions that must be addressed are whether such changes are necessary and desirable, and how they compare with changes required by other energy paths. Morrison and Lodwick (1981) argue the basic advantage claimed for the SEP is that the social impacts are more desirable than those of the HEP. Lovins (1977, p. 23) also weighs in on the question:

> *Critics who say a soft energy path is unacceptable because it must change lifestyles are implying that they themselves favo[u]r no change in lifestyles, even over fifty years. This implies a static, zero growth economy with no technical or social progress – presumably not what they have in mind. What they probably mean is that they desire no change in*

certain highly selective patterns and rates of change in lifestyle that they consider agreeable for themselves and appropriate for other people.

There is no final resolution to the debate between efficiency – and, more broadly technical change – and social change. Both are clearly necessary, and are interrelated. Within Gibson's SA framework and this dissertation, both efficiency and social change are sought, although similar to what Lovins called for, the emphasis is on developing soft societal systems in which soft technologies may flourish. That being said, one notes that ultimately quantitative calculations must be undertaken (e.g. for supply and demand options) (e.g. Bott et al. 1983), and by their very nature those calculations emphasise technical thinking and instrumentalism because they often focus on the things that can be counted, as opposed to the things that count (as discussed briefly in section 2.3.3).

4.2.3 Guidelines for a soft energy path

The soft energy path is an integral part of the conceptual framework underlying this research. It provides a means of conceptualizing energy systems and incorporates an ethic. The principles described above focus on energy but are more widely relevant, such as for water planning and governance (Brooks et al. 2009a). Likewise, the focus on moving from supply to end uses, to services, and ultimately to human needs promotes a critical reassessment of what it is we desire and what is the most efficient, effective, ethical and elegant way to achieve the goals, if they are to be achieved at all.

There are many important insights that can be drawn from the discussion of the SEP and AT. The SEP illustrates the importance of how energy system change is implemented. Likewise, the focus on end-use matching and the deeper questions it engenders about needs and ends provides an important critical perspective, both for energy systems at all levels, and even more broadly (e.g. Brooks et al. 2009a; Morrison and Lodwick 1981).

To complement the systems and bioeconomics guidelines proposed in Chapter 3, Table 10 below summarizes the insights of the SEP and AT into a basic set of guidelines for achieving a soft energy path.

Table 10 – General guidelines for achieving a soft energy path

S1 - Promote end-use matching Match the scale and quality of the energy supply to the scale and quality of its final use. Seek opportunities for multiple uses of energy inputs (e.g. cogeneration) – derived from (Lovins 1976; 1977; Robinson 1982; Science Council of Canada 1977)
S2 - Prioritize energy services in the pursuit of worthwhile ends Use energy a means for social ends that is valued for the services that it provides (e.g. comfortable rooms, light). Use energy policy as a vehicle for meeting end-use demands for those services in the most efficient, effective, ethical and elegant manner possible. Promote constructive discussions about means and ends in society, both with regards to energy policy and beyond – derived from (Lovins 1976; 1977; Science Council of Canada 1977)
S3 - Design energy bridges that aim to close the energy-for-energy loop Design systems as bridges to more sustainable social structures, recognizing there is no ultimate energy or social end state. Bridging mechanisms should be minimally disruptive but will require societal and technical change and require seeking and developing means of production and consumption that do not (or minimally) rely on fossil fuels. Non-renewable goods must only be used if they are indispensable, and then only with the greatest care – derived from (Lovins 1976; 1977; Schumacher 1973; Science Council of Canada 1977)

S4 - Use energy policy to catalyze broader change in social values Recognize that energy strategy has implications far beyond energy supply and demand, and rather affects a wide variety of sectors (e.g. public health, food sovereignty). Design energy systems as a democratic means of constructively re-patterning society (e.g. promoting urban agriculture, fostering social learning). Ground quantitative calculations within qualitative narratives of desired future states – derived from (Franklin 1990; Lovins 1976; 1977; Morrison and Lodwick 1981; Robinson 1982)
S5 - Maintain rate and scale of production and consumption within local limits Control the pace and rate of change of energy production and consumption to ensure that they remain within local capacity for system management and for change. Recognize that having too much energy too fast is as harmful as too little energy too late, and rapid expansion is harmful both to producing nations (e.g. resource curse and petrostates) as well as to consuming nations (fuel security) – derived from (Schumacher 1973; Science Council of Canada 1977)
S6 - Promote soft societal and political systems Seek structures and dynamics in society that reinforce and are reinforced by the feasibility and desirability of the soft energy path, including appropriately decentralized decision-making and energy production, and local self-reliance. Favour energy systems that promote sovereignty and minimize geopolitical risk – derived from (Lovins 1976; 1977; Morrison and Lodwick 1981)
S7 - Promote reciprocity, responsibility and fairness in production and consumption Design energy systems that promote intrinsic responsibility, and foster greater reciprocity so as to allow people to become more involved in and aware of the production, consumption and operation of their energy technologies. Encourage the fair sharing of benefits and risks – derived from (Franklin 1990; Lovins 1976; 1977; Morrison and Lodwick 1981)
S8 - Prioritize democratic participation to benefit both individual and public interest Favour energy technologies, employment opportunities and decision-making processes that promote informed and participatory decision-making and citizen engagement. Prioritize basic virtues, rights and the public good (e.g. liberty, justice, equality, fairness, self-realization) – derived from (Schumacher 1973)
S9 – Plan for the cumulative and emergent consequences of mass adoption Recognize that many of the important benefits and drawbacks of energy technologies emerge during mass adoption. To the extent possible, anticipate such cumulative and emergent effects and plan accordingly. Seek positive cumulative and synergistic impacts in energy systems – derived from (Franklin 1990)
S10 – Foster an economics of permanence and non-violence Prioritize sociotechnical and energy systems that may be considered permanent, while recognizing the need for bridging technologies and practices. Favour energy technologies that are non-violent with respect to people and the environment. Favour technologies and technological systems that can fail safely and do not unduly depend on human infallibility – derived from (Franklin 1990; Schumacher 1973; Science Council of Canada 1977)
S11 - Design diverse, redundant and modular energy pathways Favour sociotechnical systems that ensure the ability of future generations to determine their own desirable futures. Promote energy technologies that are modular, incremental, diverse, redundant and with short lead times, so as to improve resilience and responsiveness. Favour precaution (e.g. safe fail vs. fail safe) – derived from (Lovins 1976; 1977)

It is important to note that the guidelines proposed in Table 10 above do not lead to a single unique result; there is no “softest” path. Rather, it is up to the relevant stakeholders to decide upon a range of soft paths to achieve the energy goals, and the intent of this dissertation is to provide one means of doing so, in this case by comparing various energy paths in light of the sustainability criteria set that is proposed at the end of this chapter.

Both the SEP and AT were successful and influential in many regards. As Winner (1986, ch. 4) notes, AT offers a fundamental re-evaluation of the place and meaning of technology and attempts to link technology in a constructive manner with notions of the good life. The movement also fostered a greater awareness and reinterpretation of some terms applied to characterize technologies and technological pathways – efficiency, rationality, productivity, etc. – and introduced the world to terms such as second law efficiency (Winner 1986, ch. 5).

Where the soft path hits a rather hard barrier relates to how to achieve the necessary sociotechnical change so as to move towards a better future. This still open question is explored in the following section in terms of transition management.

4.3 Promoting sociotechnical systems change

One generally held premise of those who promote progress towards sustainability is that current practice is not readily leading towards desirable futures, and some form of system change is evidently needed to address the persistent social-ecological problems (Kemp et al. 2005; Loorbach 2010; Rotmans and Loorbach 2008; Westley et al. 2011). This section discuses some relevant descriptions of sociotechnical systems through the framework of transition management (TM), one popular approach to describing structural change in society. TM shares similarities with other approaches to describing change in social-ecological and sociotechnical systems (e.g. Biggs et al. 2010; Westley et al. 2011). In this section, TM is briefly introduced, and this is followed by a discussion of relevant theory of TM with regards to sociotechnical change.

4.3.1 Transition Management – sociotechnical change grounded in systems thinking

The basic premise of TM is that sociotechnical systems changes result from the co-evolution of economic, technological, ecological and institutional systems (Geels and Schot 2007; Loorbach 2010; Rotmans and Loorbach 2008; van den Bergh and Kemp 2008). To better understand how these transitions can be conceived of and managed, TM practitioners draw insights from both the science of complexity (Chapter 3) and the complexity of science (Chapter 2).

TM is a multi-scale and multi-phase approach that focuses on cross-scale dynamics between three levels: the landscape, the regime, and the niche (Geels 2002; Grin 2008; Rotmans and Loorbach 2008). The landscape level represents the environment of the particular socio-technical system of interest, and includes dynamics out of the control of the regime (Avelino and Rotmans 2009; Kern and Smith 2008). Important landscape factors include climate change, world market energy prices, social values, the built environment and economic trends, all of which tend to be slower changing and seemingly autonomous relative to smaller scales (Avelino and Rotmans 2009; Loorbach 2007, ch. 1).

Inside the landscape is the regime, and this is the focal system of note for TM. The regime is the dominant configuration of actors, policies, institutions, technologies, scientific knowledge, structures, rules, routines and habits, and in general the regime seeks self-perpetuation (Avelino and Rotmans 2009; Kern and Smith 2008; Rotmans and Loorbach 2008). Similar to Giddens' duality of structure, the regime provides the context for lower levels in terms of rules, regulations, and structures, while at the same time the regime is in part reproduced and created through repeated behaviour of the lower levels. The third and smallest scale in TM is the niche, which is an area where new and potentially subversive practices, innovations, configurations and rules are allowed to evolve and develop in a manner that deviates from the logic of the regime (Avelino and Rotmans 2009; Grin 2008; Loorbach 2007, ch. 1; Rotmans and Loorbach 2008). The niche activities are protected from the regime by what are known as transition arenas, which are safe places for subversive activity.

The basic description proposed by TM is that sociotechnical change occurs when the spreading effects of activities in a niche overthrow a regime (Rotmans and Loorbach 2008). For this to occur, niche activities are provided time and space to develop inside the protected area where innovation is fostered. As the niche activities become more powerful and organized, they slowly push the regime out of its equilibrium point, and this may be aided or hindered by landscape level dynamics (such as changing world market prices for oil), which may offer a window of opportunity for the niche activities to exert leverage (Geels and Schot 2007; Loorbach 2007, ch. 2). At some point, when the regime is so far out of equilibrium that it loses coherence, a new regime emerges from the niches (Loorbach 2007, ch. 1). At this point a transition is considered to have occurred, and the cycle may begin anew. The narrative for change described above is often described as four phases of a cycle, which are noted in Table 11.

By adopting a multi-phase approach to sociotechnical systems change, it is possible to see the potential advantages as well as the complexity of managing for transitions. If the regime were pushed out of equilibrium and over a threshold, the ensuing reorganization may foster a more desirable power structure.

Table 11 - The four phases of a transition

1 - Pre-development Changes occur in the 'background' at landscape and niche level, which are resisted by the regime. A lot of experimentation takes place.
2 - Take-off Structural change picks up momentum and the system begins to change state.
3 - Acceleration Structural changes become visible as old regime structures are being replaced by new structures. Changes may be socio-cultural, economic, ecological, institutional, etc.
4 - Stabilization A new dynamic state of equilibrium is achieved with a new regime

Sources: (Avelino and Rotmans 2009; Loorbach 2007, ch. 1; van den Bergh and Bruinsma 2008; van den Bergh and Kemp 2008)

4.3.2 Four general barriers to change

The description of change provided above provides a broad idea of how sociotechnical systems change may occur, but does not address how barriers to change are overcome. The following section attempts to elaborate on more specific barriers to change, as well as describe how TM, and other approaches to innovation and change seek to overcome them. The discussion begins with general types of lock-in, and then moves on to address chicken-egg problems, long-term dynamics, and finally power imbalances.

General lock-in

A general barrier to change is exemplified by the concept of lock-in, which results from a wide variety of dynamics (Kemp et al. 2005; Unruh 2000). As technologies and societies co-evolve, certain technologies become embedded in, and necessary for, the functioning of society (Arthur 2009; Ellul 1967; Winner 1986, ch. 1). Embedded technologies include infrastructure (e.g. pumps, sewers, power lines), general-purpose technologies (e.g. combustion engines) and even ways of thinking (e.g. the constant search for efficiency) (Arthur 2009; Ellul 1967; Rip and Kemp 1998). The more technologies become embedded, the more that structures of support and dependence build up around them, and a dynamic of lock-in is created (Arthur 2009). Table 12 provides a non-exhaustive list of ways in which lock-in may be manifest.

Table 12 - Some manifestations of lock-in

Financial reasons
• Economies of scale
• Sunk investments in machines, infrastructure and skills
• Ease in obtaining financing and insurance
• Vertical integration within sectors
• Improper pricing signals
Psychological reasons
• Cognitive routines that ignore relevant outside developments
• Organizational commitments, vested interests, and political influence
• Adaptation of lifestyles to technical systems that increase social dependence on new technologies
• Familiarity by customers
Co-evolutionary reasons
• Success breeds imitation
• Tight fight with existing regulatory approaches developed around original technology
• Technologies create their own needs (e.g., the ability to diagnose diabetes creates a need to treat it; the impacts of one technology are addressed by another technology).
• Dependence of social and institutional structures (e.g. design of cities, infrastructure)

Source: adapted from (Arthur 2009; Idenburg and Faber 2008; Jordaan et al. 2009; Meadowcroft 2009; Verbong and Geels 2008)

One example of financial lock-in particularly relevant to energy relates to energy utilities (e.g. electricity, or gas) that earn revenue from the sale of energy. For these utilities, promoting conservation is counterproductive because they require the revenue to retire infrastructure debts and may end up becoming over-capitalized. This form of lock-in is also an important barrier to adoption of the water soft path (Jordaan et al. 2009).

Lock-in isn't always undesirable; the stability provided by lock-in helps reduce complexity and uncertainty (Berkhout 2008; Rip and Kemp 1998; van den Bergh and Kemp 2008). Likewise, lock-in can provide increasing-returns to scale through such things as learning by using, imitation, and the bandwagon effect. Lock-in becomes problematic, however, when the technological regimes that societies become dependent upon are considered undesirable. TM describes three general means to overcome lock-in.

The first means proposed to overcome lock-in is by increasing technological plasticity, the degree to which technology can be shaped to prevailing and evolving economic and social conditions (Berkhout 2008). Technological plasticity draws from the premise that technologies have inherent properties and tendencies, but are also socially constructed. TM practitioners promote the use of hybrid technologies, which are sufficiently malleable to straddle both sides of a transition divide (Meadowcroft 2009). Solar PV provides an example of technological plasticity. Winner (1986, ch. 3) argues that solar PV can be designed in a wide variety of ways (centralized, dispersed, public, private). It is noteworthy that the characteristics of soft technologies (e.g. they are modular and scalable (Lovins 1978)) favour technological plasticity.

There are limits to technological plasticity. Bauchspies et al. (2006, ch. 4) argue most technologies are flexible to the extent that they can be used for purposes other than their original intention, but at their core technologies are designed to serve an initial purpose in an associated context, and are likely to be less suitable for other purposes and contexts.

A second means of over-coming lock-in is to promote a wide variety of options and avoid selecting winners too early. TM is designed to provide a safe space for innovations to develop, and assure a level playing field that provides competing innovations a fair chance of succeeding (Kern and Smith 2008; Loorbach 2010; Rotmans and Loorbach 2008; van den Bergh and Oosterhuis 2008). The consequence of keeping options open is that it may reduce efficiency and stability, both of which may be desirable in the long term (Berkhout 2008).

A third means of avoiding lock-in is to promote experimentation. TM encourages experimentation based upon a generalized model of technological evolution (e.g. Arthur 2009; Drengson 2010; Ellul 1967; Loorbach 2010). Starting from the premise that all technologies are combinations and descendants of previous technologies (and here technology is used in the broadest sense) one can adopt a combinatorial approach and note that the more technologies there are, the more possible permutations there are for future technologies. To this end, technology appears to create itself out of itself (Arthur 2009; Ellul 1967).

There are a wide variety of costs associated with both successful and unsuccessful experimentation. Many experiments have a high risk of failure, which in the real world may impact livelihood opportunities, especially in contexts of limited social safety networks. Even successful experiments – such as a shift away from coal – may be disruptive, and entail winners and losers (Kern and Smith 2008; Meadowcroft 2009; Turner 2012). Finally, experimentation has a resource cost that must be considered (Nikiforuk 2012, ch. 9), and faster cycles of innovation reduce the time available to amortize the resource costs (c.f. Science Council of Canada 1977, ch. 3).

The TM approach to experimentation and innovation has been critiqued for emphasizing innovation largely in terms of physical technologies and infrastructure and ignoring social innovations (e.g. energy service companies, demand side management) (Berkhout 2008; Grin 2008; Kern and Smith 2008; Meadowcroft 2009; Westley et al. 2011). The social innovation literature (e.g. Biggs et al. 2010) helps expand the perspective.

The upshot is that at some point in the multi-phase transition cycle, lock-in must occur; and ostensibly this will occur when the niche activities have replaced the regime. Within TM, however, the concern is not to avoid lock-in forever, but rather to ensure that lock-in and path dependence do not occur too quickly in the process, and that the resulting regime be designed to be relatively flexible.

The chicken-egg problem

The second barrier to systems change is co-evolutionary dynamics known as chicken-egg problems (Giampietro 2004), which are problems where all actors seeking change must work in concert. For example, chicken-egg problems occur in situations where the private sector requires market stimulation to justify investment, but markets cannot be stimulated without private sector initiative (van den Bergh and Oosterhuis 2008). One chicken-egg problem described in Chapter 8 (Senegal) relates to the expansion and improvement of Senegal's electricity system. In this instance, unreliable electricity supply hinders private investment in productive technologies (e.g. welding equipment) because the investment will not be repaid if the technologies are not put to productive use. Instead, electricity is often used for discretionary purposes (e.g. listening to radio). From the perspective of the government, however, electricity production is already a major driver of Senegal's debt load, and further investment in reliability and supply risks worsening the debt if the electricity is not used for productive purposes.

The TM framework provides a co-evolutionary lens for interpreting and describing chicken-egg problems. TM proponents argue their multi-scale framework of systems change overcomes such chicken-egg problems by promoting concerted effort at all relevant levels (Loorbach 2010; Loorbach 2007, ch. 2; Rotmans and Loorbach 2008).

The difficulty of managing long-term technological dynamics

The third barrier to constructive change relates to the long-term planning of sociotechnical systems in society. Many societal problems must be addressed over several generations so as to account for infrastructure turnover time and other forms of lock-in (Kemp et al. 2005; Loorbach 2010; van den Bergh and Bruinsma 2008). Planning for change over the long-term, however, must contend with the Collingridge dilemma. According to Collingridge, the management of technology encounters two linked problems (cited in Rip and Kemp 1998; Rip et al. 1995): (1) an information problem – the impacts of the adoption of a technology cannot easily be predicted and important effects may not be revealed until the technology is extensively developed and widely used; and, (2) a power problem – control over or change to a technology and its associated technological structure is difficult when the technology has become entrenched. This leaves decision makers to choose between making early choices about whether and how to develop and apply new technologies, when information about potential effects (especially unanticipated adverse effects) is poor but flexibility is great, or leave the key decisions until later, when the actual effects of application are evident but the technology is entrenched and a change of direction is at best difficult (Collingridge 1980). An example of the dilemma in practice is the development and regulation of genetically modified organisms.

Rip and Kemp argue that Collingridge incorrectly assumes that technological pathways are decided upon with discrete yes or no decisions, and that instead path dependency and technological embedding are inevitable, and what matters most is choosing the preferable technological pathways (Rip and Kemp 1998; Rip et al. 1995). For the purpose of this dissertation, the Collingridge dilemma provides another example of the need for prudence and precaution in the face of great uncertainty and the potential for great harm. The key factors on the side of precaution appear to be the potential for significant adverse effects (the plausibility of potential adverse effects times the significance of what could be damaged), the reversibility of the path (considering the extent and nature of likely dependencies), the political and economic strength of interested parties, and the plasticity of the technology. Ideally, attention to the nature and distribution of the anticipated benefits, and their feedbacks, is also needed. Careful examination of all these factors – preferably informed by attention to generic and case-specific sustainability considerations – should assist judgements about the appropriate weight of precaution to apply in early decision making.

A second challenge of long-term thinking is the mismatch between long-term sociotechnical dynamics and short-term political cycles (Loorbach 2007, ch. 3). TM offers some suggestions. First, develop positive visions of the future (e.g. envisioning, backcasting and forecasting) that situate short-term results in the broader story (Kern and Smith 2008; Loorbach 2007, ch. 4). Second, establish short-term goals that can be showcased, as long as this does not lead to an overly short-term and risk adverse strategy (Kern and Smith 2008).

Addressing power imbalances

The fourth, and perhaps most difficult barrier to change relates to power dynamics. While the language of TM describes structural change and regime collapse, TM practice is non-confrontational (Rotmans et al. 2001). Rotmans and Loorbach (2008) note that TM tries to subtly pressure the regime into changing as opposed to mounting an all out attack on the current structures of society. This nuanced approach to systems change is reasonable insofar as TM needs to maintain sufficient credibility to be implemented and supported by the very regimes it is attempting to change (Grin 2008), something Rotmans and Loorbach (2008) label as the regime paradox.

In a recent assessment of TM practice, Kern and Smith (2008) critique the Dutch transition experiment towards sustainable energy, which was oriented around six themes: chain efficiency, green resources, new gas, sustainable mobility, sustainable electricity, and the built environment (Meadowcroft 2009). The taskforce appointed for the experiment – including high-level members of industry and the public sector, and chaired by the CEO of Shell Netherlands – represented a powerful group of regime actors intent on maintaining status quo and able to co-opt the experiment for their own gains (Kern and Smith 2008; Meadowcroft 2009). The experiment prioritized conventional economic activities and supply side management, and largely ignored conservation and broader social and institutional changes (Kern and Smith 2008).

Meadowcroft (2009) argues that the social actors who become involved in transition activities will inevitably be concerned with the impact of change on themselves, and this promotes political struggle. Likewise, the TM approach emphasizes opinion leaders as opposed to aiming for broad consensus (Loorbach 2007, ch. 4), which renders the process vulnerable to elitism and in service to vested interests (Grin 2008; Kern and Smith 2008; Meadowcroft 2009).

In response to the critique, TM practitioners have redeveloped their narrative so as to account for power imbalances (Avelino 2009; Avelino and Rotmans 2009; 2010). However, the conclusion here is identical to what was described in Chapter 2 (section 2.2): it is doubtful that all power imbalances can be overcome through better methodology or research design, and there is more promise in "an honest recognition of conflicting interests and power relationships" (Funtowicz and Ravetz 1994), increased transparency, greater participation, and a willingness to stand up for one's beliefs.

As may be evident from the discussions provided above, there are still challenges for TM to address in terms of overcoming barriers to change in a peaceful manner. However, this is less a weakness on the part of TM, and more a reflection of the state of the art in the academy. As TM and other theories of change continue to develop, time will tell how successful they will be in terms of both short-term (e.g. enacting change) and long-term (ensuring the changes are positive) outcomes.

4.3.3 Guidelines for fostering sociotechnical systems change

At this point the important insights relating to sociotechnical systems change may be summarized – as in the systems, bioeconomics and soft energy path discussions – as a set of guidelines for fostering sociotechnical systems change. The principles are provided in Table 13, and are adapted from Gibson's (2011b) principles of innovation for transition.

Table 13 – Generic guidelines for fostering sociotechnical systems change

T1 - Design for the long term Adopt a time scale for transition of at least 25 years for developing and evaluating options for immediate action while recognizing the need for short-term successes to maintain momentum. Allow for continued learning and adjustment, and work within economic cycles – derived from (Gibson 2011b; Johansson et al. 2005; Kemp et al. 2005; Loorbach 2010)
T2 – Foster positive innovation and synergy in the broader economy Promote synergy among the various intersecting domains (e.g. health, energy, agriculture, waste) at all levels, and with attention to the current and potential participants. Foster co-evolution that leads to a more constructive relationship between technology and society. Where appropriate, build upon existing capital – derived from (Grin 2008; Loorbach 2010; Loorbach 2007, ch. 4; van den Bergh and Kemp 2008)
T3 - Apply leverage when windows of opportunity are open Identify and prepare for windows of opportunity due to impending stresses and disturbances. Develop the capacity to apply leverage points so as to manage during disequilibria – derived from (Loorbach 2007, ch. 2; Rotmans and Loorbach 2008; Westley 2008)
T4 - Build supportive networks that promote participation Foster development of collaborative networks of interaction among current and potential participants, with emphasis on building an enabling environment, exploring many options, and ensuring experiential learning and responsive flexibility. Promote participation so as to build common ground among actors – derived from (Gibson 2011b)

T5 – Develop positive visions of the future Develop, test and compare alternative future scenarios to clarify long term objectives and their interrelations, identify apparently viable options for sustainability and resilience, and map pathways to reaching them. Combine visioning with analysis of current trends to identify key transition challenges, vulnerabilities and possibilities – derived from (Gibson 2011b; Kern and Smith 2008; Loorbach 2007, ch. 4)
T6 - Balance consistency and stability with adaptiveness during a transition Build transition strategy and policies on a foundation of well-defined and transparent objectives; ensure the supportive regime (legal, financial, etc.) is responsive to learning but also stable enough to provide a reliable base for investment of significant resources in longer-term initiatives – derived from (Gibson 2011b; van den Bergh and Oosterhuis 2008)
T7 - Create space for positive innovations to develop and mature Provide a safe and level playing for innovations (both technical and social) to experiment and grow. Avoid picking winners so as to keep multiple options open. Experiment with alternative system options with different structures, linkages, participants and roles, motivations, resources, knowledge bases and practices, while recognizing the cost of experimentation and failure. Promote successful innovations (e.g. publicizing results) – derived from (Berkhout 2008; Rotmans and Loorbach 2008; van den Bergh and Kemp 2008)
T8 – Favour adaptiveness and flexibility Favour safe-fail, reversible and adaptable initiatives while recognizing innovation, adaptiveness and diversity may impact efficiency, stability, and increase uncertainty. Temper co-evolution to avoid lock-in – derived from (Berkhout 2008; van den Bergh and Kemp 2008)
T9 - Strengthen democratic legitimacy and fairness Favour policy and decision making processes that are inclusive, transparent, accountable, and democratically representative. Ensure attention to distributional impacts, power imbalances and trade-offs. Prioritize those vulnerable to loss of essential wellbeing, and seek to enhance intra- and inter-generational equity in transitions – derived from (Kemp et al. 2005; Kern and Smith 2008; Meadowcroft 2009)
T10 - Foster transformative learning Focus on learning for innovation, with constant experimentation, monitoring, re-assessment and adaptation; integrate conventional scientific, local and traditional knowledge; focus on the process of learning – derived from (Grin 2008; Loorbach 2010; van den Bergh and Kemp 2008)
T11 - Challenge power structures through constructive conflict Recognize that conflict with vested interests is an expected step towards positive change. Prioritize peaceful and constructive conflict that can overcome barriers to transition – derived from (Avelino and Rotmans 2009; Grin 2008; Loorbach 2010)

Source: adapted from (Gibson 2011b)

The guidelines from TM and sociotechnical systems studies are clearly not a recipe for implementing change. Rather the guidelines describe the general conditions that the literature recognizes as encouraging innovation for change. Over time, as practitioners gain more experience with TM and other approaches, perhaps the guidelines may become more prescriptive, while still recognizing that important aspects of systems change are likely inherently uncontrollable. For present purposes, however, the guidelines suffice to inform both Gibson's SA framework approach and criteria specification for energy applications.

The guidelines for fostering sociotechnical systems change provided above are the final set of guidelines related to the complexity of science, the science of complexity, and energy systems analysis. The following section will describes how these principles are converted in the systems- and energy-informed sustainability criteria set that represents one important output of this dissertation.

4.4 Moving forward with sustainability assessment

This chapter built upon the theory presented in Chapters 2 and 3 to explore the relationships among energy, society, technology, and the environment. In order to do so, this chapter explored three general and related questions: what is the energy problem? what are the characteristics of an appropriate and constructive societal relationship with energy? and how can the necessary sociotechnical systems change be achieved?

Similar to Chapter 3, this chapter proposed two tables of guidelines – relating to the SEP and sociotechnical systems change – to inform Gibson's SA framework, and particularly criteria specification. These two tables of proposed principles complement the principles proposed in Chapter 3 relating to navigating complex systems (Table 8) and bioeconomics (Table 9). The guidelines contained in these four tables have merit on their own, but also serve to inform the criteria set proposed below.

At this point it is possible to outline the sustainability criteria for energy undertakings, and in doing so complete the conceptual framework. The sustainability criteria set is provided in Table 14 below. The criteria are integrated within Gibson's eight categories, while recognizing that in many instances a single criterion may be relevant to multiple categories. The second column of the table cross-references the criterion to the relevant guideline from the tables (Table 8, Table 9, Table 10 and Table 13) based upon the following legend: C refers to the science of complexity (Table 8); B refers to bioeconomics (Table 9), S refers to the soft energy path (Table 10) and T refers to sociotechnical systems change (Table 13). The number in the second column refers to the number listed in the guideline. For example, B4 would refer to the 4th guideline from the bioeconomics set.

The transposition of the guidelines into sustainability criteria is not a simple linear process. In certain instances the guidelines are more directly and easily transposed into sustainability criteria, while oftentimes principles must be interpreted. The interpretations here have been informed by the casework presented in the following chapters. Furthermore, a single guideline may inform several criteria, and likewise a single criterion may be informed by multiple guidelines. The overlap between guidelines and criteria reflects both the complexity of the task being undertaken as well as the overlaps among the various theories that informed the conceptual framework of this dissertation.

Table 14 – Sustainability criteria for energy undertakings

Criteria	Source
Socio-ecological system integrity	
Promoting social-ecological integrity	
• manage ecological integrity at the whole system level, including direct, indirect and induced effects (e.g. ecological connectivity, biodiversity)	C1, C5
• maintain critical ecological services, keystone species and culturally important species and ecotypes that provide necessary context (e.g. forest cover)	C5, C9
• anticipate and prepare for social-ecological systems change (e.g. climate induced species migration)	C5
• maintain sufficient land available for ecological and societal uses (e.g. grazing, gathering medicine)	S10, C9
Anticipating and adapting to systems effects and thresholds	
• allow ecosystems to move through necessary cycles, including growth, development, collapse and renewal, while avoiding undesirable dynamics (e.g. desertification)	C3
• maintain and promote ecological life support systems (e.g. pollination, nutrient cycling)	C5, C9
• manage for cumulative impacts and thresholds while respecting uncertainty and vulnerable social-ecological components	C4
• avoid escalation and other unwanted reinforcing cycles (e.g. energy poverty, desertification)	C6
• manage rate of growth of energy and resource demand such that it stays with local and global ecological carrying capacity	B5, S5
Avoiding and addressing waste production	
• where feasible and desirable, seek productive uses for wastes (e.g. anaerobic digestion of organic wastes)	C1, S1
• manage wastes in a way to avoid adverse social-ecological impacts (e.g. discharge of agricultural effluents)	S10
Livelihood sufficiency and opportunity	
Promoting meaningful employment opportunities and self-actualization	
• promote respectful and fulfilling employment that respect workers' rights (e.g. fair wages, respecting migrant workers) and fosters their ability to self-actualize	S8
• provide fair opportunities to all those seeking gainful employment (esp. poor, marginalized, youth)	S8, T9
• promote worker and user health and safety along the full energy supply chains and in the broader population (e.g., reduce indoor air pollution, promote biking as opposed to driving)	S7, S4, S6
Fostering local economic development and capacity building	
• support economic systems able to accommodate changing labour allocation due to the increase in renewable energy production and generally ecologically friendly practices	B2
• support the provisioning of public services necessary for lasting economic and social development (e.g. schools, health facilities)	C9
• control the pace and scale of energy production and consumption such that it remains within local capacity for management and avoids boom and bust effects	S5, B5
• provide opportunities for retraining in the transition towards sustainable energy practices	T9, S7
• create space for positive social and technical innovations to develop and mature	T7
Promoting appropriate degrees of centralization	
• promote local employment and capacity building (e.g. economic spinoffs) of both urban and rural regions in an appropriately decentralized economy	S6, S8

• promote economic self-sufficiency and energy sovereignty at all scales (e.g. facilitate domestic and decentralized ownership of production)	S6, C7
• promote small-scale and local energy production to improve resilience and counter current dynamics of centralization	S11
Intragenerational equity	
Fostering equality	
• promote gender equality broadly in society (e.g. access to education, livelihoods, and decision-making powers) as well as employment within the energy system	S8
• promote equitable energy pricing , while respecting that some groups have lower capacity to pay the true cost of goods and services	S7
Promoting fair distribution of benefits and risks	
• contribute to the maintenance of and access basic infrastructure and services (e.g. roads, schools, hospitals)	S4, S6
• promote fair distribution of wealth, income generating opportunities, and influence (incl. age, gender, ethnicity) both within and between societies and nations	C6, S7
• promote fair distribution of risks within local communities and by age, gender, ethnicity, respecting that some groups have less capacity than others to accommodate increased risks	T9
• promote equitable distribution of resources and opportunities among and within urban and rural regions, while addressing different urban and rural needs	C6, S8, S7
• promote internalized accounting of social and ecological costs of production and consumption	S7
Promoting international equity	
• promote responsible and equitable practices by the international community (e.g. fair trade)	S7
• promote policies and consumption patterns that do not harm other nations, or prevent them from exercising their sovereignty	S6
Intergenerational equity	
Maintaining long-term social-ecological integrity	
• maintain long-term resource availability (e.g. mineral resources) and ecological integrity (e.g. land productivity, water and other livelihood essentials)	B3
• avoid economic boom and bust cycles and their associated social-ecological impacts	S5, C4
• promote long-term equitable distribution of wealth (incl. age, gender, ethnicity)	S7, C6
• maintain and enhance long-term social capital (e.g. traditions of mutual assistance, active engagement in addressing collective concerns)	S6, S8
Avoiding lock-in and perverse effects	
• avoid energy undertakings with long-term legacy costs (e.g. nuclear wastes)	S11, T8
• maintain sufficient options for future generations to avoid lock-in	S11, T8
• avoid rebound effects that may cause long-term social-ecological harm	C6, C4
• avoid trading off long-term needs for short-term gains	S7
Fairly distributing costs and benefits	
• promote equitable long-term distribution of wealth, income generating opportunities, and influence (incl. age, gender, ethnicity) both within the energy systems and in society at large	S7, S8
• promote equitable long-term distribution of risks within local communities (esp. urban-rural) and by age, gender, ethnicity, respecting that some groups have less capacity than others to accommodate increased risks (e.g. elderly)	S7, S8

Resource maintenance and efficiency	
Managing at the whole system level	
• favour projects, plans and policies that reduce societal complexity and its consequent resource costs (e.g. governance burdens and regulatory costs)	B6
• minimize whole system costs (e.g. GHG emissions, resource extraction) of energy systems by optimizing conservation resources and demand-management opportunities	C1, B3
• prioritize conservation, thrift, and demand management	S2, S7
• promote resilient energy supply systems with sufficient diversity, modularity and redundancy of energy pathways	C7, S11
Prioritizing system efficiencies	
• match the quality of the energy and other resources (e.g. water) to the quality of the end-use	S1, S2
• focus on consuming energy only as necessary to provide services in the pursuit of constructive social ends	S1, S2
• seek opportunities for multiple uses of energy inputs (e.g. cogeneration) and for energy cascading	C1, C7, S1
Fostering resource stewardship	
• promote socially and ecologically beneficial energy system operations (e.g., energy crops that rebuild soil fertility)	S10
• manage for total resource supply as well as rate of resource consumption	B5
• promote the usage of locally available resources and avoid resource conflicts	S5, S6, B3
• minimize the use of non-renewable resources along the entire lifecycle, and avoid extractive uses of renewable resources (e.g. water mining)	C1, S3, B3
Matching current and future metabolic patterns	
• promote renewable energy systems with a sufficiently positive Energy Return On Investment	B1
• develop and plan for self-sufficient renewable energy systems that minimize and/or eliminate non-renewable inputs and close the energy for energy loop	B1, S3, S10
• account for the resources and services that underlie the industrial and post-industrial societies (e.g. cloud computing)	B4, S10
• prioritize the use of non-renewable resources for the purpose of developing energy bridges to renewable and equitable energy systems	S3
Socio-ecological civility and democratic governance	
Providing a positive social-ecological regulatory environment	
• promote an integrated regulatory environment that provides the necessary social-ecological and economic context for sustainability-based decision-making and actions while fostering creativity and individual choice (e.g. more stringent building codes)	C5, S7
• promote respect for social and environmental laws and regulations both domestically and internationally (e.g. corporate social responsibility	S6,
• ensure the supportive regime (legal, financial, etc.) is responsive to learning but also stable enough to provide a reliable base for investment of significant resources in longer-term initiatives.	T6, T9
Promoting good governance	
• promote local decision-making and more broadly participative and decentralized local multi-stakeholder governance	T4, S6
• enhance collaborative and transparent governance, system legitimacy, accountability, and trustworthiness.	S6, T6
• favour policy and decision making processes that are inclusive, transparent, accountable and reflexive, linked closely to bodies of representative democracy.	T9
Fostering responsible and virtuous individuals and societies	
• promote responsible consumption understood as an ecologically and socially shared	S7

privilege as opposed to an intrinsic right	
• promote respect for marginal members of society	S7, S8
• promote respect for, and maintenance of, desirable spiritual values, and traditional ways of knowing	S7, S8
• promote basic rights (liberty rights, security rights, gender equity)	S6, S8
Developing an awareness of means and ends	
• increase awareness of the social ends being met by energy consumption and promote constructive dialogue of how best to meet those ends in the most effective, elegant and ethical manner	S2
• promote open deliberation on means and ends (e.g. through forecasting and backcasting)	S2, T5
• promote a culture of conservation and resilience, and seek to delink welfare from energy and resource consumption	S2, S6
• promote energy systems that foster reciprocity such that people become more involved with and aware of the operation of their energy systems and the impacts of their lifestyles	S7
Fostering individual and collective learning and understanding	
• promote creative, virtuous and integrated thinking in the broader society	T10, S8
• promote learning to build individual and collective understanding of, and commitment to addressing, important societal challenges	S4, T5
• use energy policy as a means of catalyzing broader constructive social change (e.g. public transport and urban agriculture)	S4, T2
• promote active, informed and self-reflective participation in environmental management and other environmental initiatives (e.g. public transit)	S4, T10
• use energy related conflicts (e.g. wind turbine siting) to explore broader ethical concerns in society	C2, S4, T11
Promoting ecological literacy and responsibility	
• contribute to improved public understanding of socio-ecological systems and their interdependencies, and to the protection and conservation of natural resources	S4, S6
• promote energy pricing that internalizes social and environmental costs, while ensuring fairness for the disadvantaged (e.g. poor, marginalized)	S7, T9, C1
• promote appropriate means of valuing ecological services	C9, S6
Prudence, precaution and adaptation	
Fostering resilience, reliability and adaptive capacity	
• promote sufficient adaptive capacity in the broader social-ecological system, and at multiple scales, to maintain desired system structures in the face of changing conditions (e.g. drought, global economic recession)	C4, C9
• favour technological systems that are relatively insensitive to human error, and with low cost of technological failure and accidents	S10
• promote diversity, flexibility, modularity, reversibility, fallback options, and safe-fail characteristics at all levels in the energy systems and in society at large	C7, T14, S11
• seek mutual gains in resilience and efficiency	C7, S11, T6
Avoiding lock-in	
• avoid lock-in (e.g. one type of energy system) by favouring energy investments that are flexible, incremental, and with comparatively short lead times and appropriate lifetimes.	B4, S11, T8
• promote economic diversification and reduce vulnerability to world market volatility	S11,
• favour energy options that minimize geopolitical risk (e.g. nuclear proliferation)	S5, S6
Developing anticipatory planning and managing for uncertainty and complexity	
• manage for key social-ecological system thresholds, vulnerabilities and windows of vitality	C4, T3
• acknowledge and address key areas of uncertainty and recognize the presence of irreducible uncertainty	C3

• promote anticipatory planning for risk management to avoid or reduce the risks of significant damage (e.g. high risk of minor damage, low or ill-understood risks of significant problems) as compared to alternative practices	T5
• provide the capacity for monitoring changes in complex situations (e.g. by providing baseline data, finding a balance between rigid and loose control)	C8
Mitigating perverse and other undesirable systems effects	
• anticipate and prepare for cumulative impacts of mass adoption of energy and other technologies	S9
• avoid rebound effects (efficiency gains facilitating more consumption in ways that add to sustainability problems, increasing supply and consequently requiring increased demand)	C1, C6, S9
• avoid trading off long-term needs for short-term gains (e.g. cutting down mangroves for fuelwood)	T1
• avoid and mitigate negative cumulative and escalating effects	C6
Immediate and long-term integration	
Promoting constructive co-evolution	
• seek positive integration with other industries and stakeholders	C5, T2
• seek the appropriate combination of self-reliance and cooperative networks of support	S6
• promote cultural-technological co-evolution favouring sustainability objectives	C5
• promote positive indirect effects within the social-ecological system (e.g. public health, education)	T2, S4
Creating opportunity for multi-level change	
• provide a level playing field so as to ensure fair competition between and amongst alternatives (e.g. organic farming, renewable energy)	T7
• provide space to test, adapt and improve alternatives	T7
• promote bottom up and top-down change at all levels	C2, T2
• favour peaceful and constructive means to achieve meaningful change	T11
Harnessing key windows and players for change	
• take advantage of avenues for rapid change and seek leverage points to obtain maximum net gains	T3
• empower key stakeholders at all scales to promote positive change	T7
• provide space for alternative structures of organization (shadow tracks) to develop	T7
Developing energy bridges	
• develop energy systems as a constant bridge to more sustainable societal structures and dynamics, and that match both current and desirable future societal metabolic patterns and that minimize consumption of non-renewable resources	S3, B4
• plan for the transition to more sustainable energy within longer cycles of change (e.g. economic cycles) and within the timeframe of capital stock turnover	C8, B4, T1
• meet short-term and long-term needs, recognizing they may be different	T1

4.4.1 Characteristics of the sustainability criteria set for energy undertakings

Five general characteristics of the criteria set proposed above are discussed in the sections below.

The criteria set is designed as a full suite

The criteria set proposed above provides an initial framework for assessing energy system options for the potential to promote progress towards sustainability. There are 107 criteria, which may seem an ungainly amount, but they are necessary if the assessment is to remain sufficiently general to accommodate all types of energy systems, and to ensure multiple benefits and interactive effects.

While the criteria set must be understood as a full suite, the criteria certainly can be – and indeed must be – organized and consolidated into packages and themes that relate to the local context such that decision-makers and stakeholders can make sense of the information. The case studies described in Chapters 5-8 represent attempts to specify the relevant sustainability criteria for different cases and contexts. That said, it is important to stress that attempts to minimize the number of criteria must be undertaken in a way that does not undermine the intent of the assessment.

As they are currently presented, the criteria in Table 14 cannot be taken as individual, non-overlapping, and equivalently weighted. Important themes are double counted, and in specific contexts some criteria will be more important than others. This does not preclude the possibility of organizing the criteria to make them minimally overlapping or of applying weights or other means to recognize that some criteria are more or less important.

The criteria set combines principles and goals into requirements for progress towards sustainability

A cursory analysis of the sustainability criteria set reveals a mix of principles and goals. In some instances there are benefits to proposing a criteria set that is either uniquely a set of principles or a set of goals, but not both. However, in practical application it is difficult if not impossible to isolate the criteria set as only principles or only goals; both goals and principles are clearly needed. Furthermore, insofar as the principles are as of yet unmet – e.g. the principle of proper end-use matching is rarely applied – they remain goals as well.

In order to avoid the principles versus goals debate, the criteria set may be best understood as describing *requirements* for progress towards sustainability. The requirements include characteristics to be favoured (e.g. favour low risk approaches), and goals to be achieved based on predictions of what is to come (e.g., given anticipated future climate fluctuations, it is necessary to build adaptive capacity). The generic requirements are about moving in a desirable direction.

Oftentimes, focusing on requirements as opposed to goals and principles is largely a matter of appropriate phrasing, and to the extent possible, all of the criteria in Table 14 are phrased in the same manner as things that are necessary to move towards sustainability.

The criteria set seeks progress towards sustainability rather than defining an acceptability threshold

Building from the previous discussion, the criteria outline a set of generally desirable system attributes and actions for achieving *progress* towards sustainability, rather than defining an acceptability threshold. Conventional assessment practice generally prefers an acceptability threshold, whereby if a project meets the minimum requirement than it may to proceed. Many of the concerns with environmental assessment – including ignoring cumulative and synergistic effects, and prioritizing minimizing harm as opposed to promoting positive steps – are due in part to the acceptability threshold approach. While there are obvious cases where a proposed project is unacceptable, there is no clear delineation of acceptability at any point.

In order to avoid the threshold of acceptability, the sustainability assessment criteria should be applied primarily for the comparison amongst alternatives. The premise is that as societies move along choosing the best alternatives then they will move in the direction of sustainability.

In the case studies that follow, there was generally no predetermined set of alternatives to compare. In these instances, the principal role of the sustainability assessment is to map out a basic set of alternative pathways, which ultimately allows for more formal alternatives to be defined.

The criteria set is informed by the casework

The criteria set proposed above was significantly informed by the casework, even though the basic structure was present before the casework began. The criteria set has evolved as each subsequent case study has incorporated the insights from the previous cases. This is not to imply that earlier cases have less value to the dissertation, but rather serves to illustrate the iterative nature of the research process.

The benefit of such an iterative approach is that it allows for insights and ideas explored through the theory and previous cases to be further explored and refined. To this end, the sustainability criteria set for energy undertakings proposed in Table 14 may continue to evolve with further theoretical and empirical casework beyond what is undertaken in this dissertation.

A second benefit of the iterative approach is that the casework provides a means of contextualizing the individual criteria. Even though the criteria are designed to be generally applicable to all energy undertakings, it is helpful at times to provide more concrete examples within the criteria. For example, one criterion above calls for the avoidance trading off long-term needs for short-term gains and provides the example of cutting down mangroves for fuelwood. This example is drawn from experience of the Senegal fieldwork, and ideally helps provide a more solid example of what the criterion means.

Focused on energy undertakings but more broadly relevant

The sustainability criteria proposed above is primarily intended for application regarding energy undertakings. These undertakings may be at a wide variety of scales. Indeed, the case studies include the assessment of individual operations (e.g. a small-scale biodiesel plant in Barbados; a sugarcane-ethanol mill in Brazil), all the up to a provincial wide electricity system (the Ontario power system) and even a national energy and agricultural system (of Senegal). Clearly at different scales, and with regards to different undertakings, the most relevant themes and criteria will differ, although all four cases address broader strategic level implications regardless of the principal focus of analysis.

Although the criteria set is centred upon energy undertakings, it is much more broadly relevant. The energy undertaking is used as a means of exploring the broader social-ecological context in which the undertaking is situated. Many of the important considerations addressed in the criteria set are by no means confined to energy systems. For this reason it is hoped that the criteria set may be applied to all manner of undertakings, requiring only a minimum of editorial restructuring.

4.4.2 A complete package for specifying and extending Gibson's SA framework for application to transition in energy systems

At this point the basic theoretical framework for this dissertation is complete and may be applied to the assessment of energy systems, a task undertaken in Chapters 5-8. Before that, however, it is helpful to summarize what has been accomplished over the preceding four chapters.

Chapters 1 and 2 described the basic framework of Gibson's SA framework. They began by outlining Gibson's eight categories of progress towards sustainability, which were provided in Table 1. Following that, the basic research design for the case studies was described, which are implemented in the following chapters. Chapter 2 situated Gibson's SA framework within the challenges and opportunities of the complexity of science, by drawing from approaches such as post-normal science, transdisciplinarity, integrated assessment and science and technology studies. The second part of Chapter 2 further operationalized Gibson's SA framework approach by describing the iterative process of criteria specification, which represents the primary analytical approach applied in this dissertation.

Building from the framework and approach outlined in Chapters 1 and 2, Chapter 3 focused on the science of complexity to develop a set of guidelines for managing complex systems. The first half of Chapter 3 described complex systems in general, while the second half approached focused more specifically on systems in society, and drew primarily from Giddens' structuration theory and bioeconomics.

Finally, Chapter 4 contextualized the previous discussions into the subject of energy. To do so, Chapter 4 posed three general questions: what is the energy problem? what are the characteristics of an appropriate and constructive societal relationship with energy? and how can the necessary sociotechnical systems change be achieved? To answer these questions, Chapter 4 drew from various theoretical frameworks, namely the soft energy path, appropriate technology, transition management, and science and technology studies.

The theoretical development presented in the first four chapters culminated in the set of sustainability criteria for energy undertakings proposed in Table 14. This criteria set provides a unique starting point for assessing the potential for energy systems to help society progress towards sustainability, although its relevance is certainly not limited to energy systems.

Sustainability assessment as both evolutionary and revolutionary

It is worth discussing whether the sustainability assessment framework presented over the past four chapters represents a revolutionary or evolutionary approach to systems change. In short, it is both.

The theory presented above draws from theoretical frameworks – such as transition management and the soft energy path – that promote and describe fundamental changes to the structure and function of society. Likewise, when understood as a full suite, the sustainability criteria proposed in Table 14 provide the foundations for a comprehensive critique of prevailing institutional assumptions and behaviour, and promotes consideration of broad alternatives. The intent is to recognize the important challenges facing society, and provide a unique and integrated means of addressing the challenges.

Despite the more revolutionary undertone of the theory, it will be evident in the casework that the results of sustainability assessment generally tend towards incremental change. To a certain extent this is a common occurrence when theory meets practice, especially so when the types of decisions related to sustainability assessment – were they to be implemented by those in power – would have far reaching consequences on livelihood opportunities, biophysical integrity, etc., both now and in the future.

The incremental nature of the case study insights does not detract from the revolutionary intent of sustainability assessment. Rather, the hope is that as societies move along incrementally the end result will be more radical. In other words, sustainability assessment must be demanding and practical, incremental and revolutionary.

Towards the case studies

By drawing from the basic approach, the criteria specification process, and the sustainability criteria for energy undertakings, we many now move to the case studies, which are reported upon in Chapters 5-8.

In each case, a short initial preface describes relevant information about the case study, and a final section on outcomes summarizes insights emerging from the case that are relevant for this dissertation. Aside from Chapter 5, which represents simply a summary of the case study, each case study is written up as a manuscript, implying overlap between the case studies and the theory described in the preceding chapters. Such is the challenge of describing an iterative research process in a linear format, as well as hybridizing the monograph and manuscript approaches to dissertation.

Chapter 5 – Sustainability assessment of Ontario IPSP

This chapter briefly reports on a sustainability assessment of the Ontario Power Authority's (OPA) proposed 2006 Integrated electrical Power Systems Plan (IPSP). The research was undertaken in 2008 as a collaborative project between professors and students at York University (in Toronto) and the University of Waterloo. The results of the research were published as a report submitted to the hearings regarding the IPSP (Gibson et al. 2008) as well as an article in *Energy Policy* (Winfield et al. 2010).

In relative contribution, I contributed equally to the collective exercise of specifying the case specific sustainability criteria and undertook the application of the sustainability criteria to bioenergy systems. I also helped consolidate and analyze the various other assessments (e.g. relating to solar PV, wind, gas), but did not contribute substantively to the writing of the report or the article.

5.1 Description of the research

The IPSP was not considered to be a serious attempt for seeking progress towards sustainability. Overall, the IPSP appeared to promote business-as-usual and prioritize nuclear power in Ontario. The OPA framed its IPSP largely as a coal versus nuclear problem, as opposed to a critical appraisal of power systems planning; and in doing so it underplayed potential for conservation, demand management, increased renewable energy, and social change (Winfield et al. 2010). While one of the discussion papers released by the OPA (2006) in support of the IPSP addressed sustainability concerns through an application of Gibson's SA framework, the attempt appeared to be largely post hoc and self-justifying. In response, the Waterloo-York research team reapplied Gibson's SA framework to both the IPSP as well as *Renewable is Doable*, an alternative power systems plan proposed by the Pembina Institute and WWF Canada (Peters et al. 2007).

The research project began with a collective process of criteria specification, similar to what was described in Chapter 2 (section 2.3), but relying solely upon documentary analysis and literature review. The general criteria set is provided in Table 34 in Appendix 2, and has been included in this dissertation because it informed the systems- and energy-informed criteria set proposed in Chapter 4. Development of the criteria set was a group undertaking. The criteria set proposed in Table 34 provides a preliminary synthesis of resilience criteria with Gibson's SA framework. In this manner, the research highlighted the importance of concepts such as system reliability, modularity, path dependence, lead-time and lock-in, all of which are also considered within the soft energy path. These concepts have been incorporated into the generic criteria set provided in Chapter 4.

5.2 Key recommendations for sustainability assessment of energy systems emerging from the IPSP case study

Once the criteria set was finalized, each student participant applied it to evaluate of one or several key components of the IPSP (e.g. wind, transmission, solar PV). I focused upon bioenergy – notably energy cropping, agricultural residues, forest residues, on-farm biogas, digestion of solids and municipal wastes, and landfill gas (see Table 35 - Table 39 in Appendix 2) – and this would become the common theme in all four case studies. This section describes three relevant insights drawn from the general results of the bioenergy assessment.

First, the bioenergy assessment highlighted the importance of flexibility in energy supply systems. Bioenergy is particularly flexible through a variety of means. Notably, there are multiple energy pathways available for bioenergy production, including thermochemical, electrochemical, anaerobic digestion (biogas), and fermentation (Gaudreau 2009). Biogas showed particular promise because it separates the energy (methane) and material (digestate) pathways from one another, and the digestate has value as fertilizer. Likewise, most bioenergy systems are also flexible in terms of dispatching. For example, most forms of solid bioenergy (e.g. residues) can be stored for significant lengths of time and can be brought online relatively quickly. While biogas is not as easily stored for long-term applications, it is still possible to store it for dispatch throughout the day. The ability to dispatch bioenergy throughout the day and year implies it may help support other renewable energy technologies, notably wind and solar.

Second, the bioenergy assessment of the IPSP highlighted importance of recognizing ecological limits to bioenergy production, particularly due to water and soil requirements, the overharvesting of wood and the increased capture of primary productivity. If undertaken improperly (e.g. in large monocultures, on ecologically sensitive lands), bioenergy may be harvested in a non-renewable manner. The limits to bioenergy production must also account for other uses of the bio-products, such as pharmaceuticals, liquid fuels, food and fibre.

Third, the assessment indicated how energy policy provides opportunities for pursuing broader societal goals. How bioenergy is developed in Ontario may have important implications for rural viability in Ontario, including providing rural employment opportunities, and improving the feasibility and desirability of agriculture. This presents an opportunity to pursue constructive rural development goals along with energy policy development, but one that must be properly undertaken in a broadly democratic manner. For example, for bioenergy to provide employment opportunities in rural areas in part depends on local ownership and the size of the energy systems (e.g. Morris 2007), both of which are themes noted in the discussion of the soft energy path.

The three insights noted above – the benefits of bioenergy flexibility, the importance of ecological limits, and the potential for using energy policy to pursue broader societal goals – have all been incorporated in a generalized manner into the systems- and energy-informed criteria set proposed in Chapter 4. Furthermore, these insights will be revisited in the concluding chapter (Chapter 9) in consideration with the insights emerging from the other case studies.

While the assessment described in this chapter contributed to energy discourse in Ontario and developed insights relevant to this dissertation, the assessment had a supply-oriented perspective highlighted by the focus on individual supply options. However, these constraints are more a result of the context in which the assessment was undertaken, given that its purpose was to compare the IPSP against *Renewable is Doable.* The less formal and constrained nature of the case studies presented in Chapters 6-8 allow for deeper exploration of the energy-society nexus.

Chapter 6 – Sustainability assessment of biodiesel in Barbados

This chapter reports on a sustainability assessment of a small-scale biodiesel operation in Barbados that was undertaken in Fall 2008. The biodiesel plant, located in the interior of Barbados, was designed and built in 2006 by a group of McGill students that included this author as part of a field study semester through McGill University. In 2008, this author returned to Barbados to assess the biodiesel operation as part of a grant from the Association of Universities and Colleges of Canada. Part of the 2008 assessment was undertaken collaboratively with Handel Callender, the former owner and managing director of the biodiesel operation, and Athena-Sofia Delimanolis and Lesley Winterhalt, both of whom were being mentored by this author for their respective McGill field study internships. The results were published in *Impact Assessment and Project Appraisal,* the journal of the International Association for Impact Assessment (Gaudreau and Gibson 2010). The final published version of the article, respecting the formatting of the dissertation is provided in what follows. The final section summarizes key insights for the purpose of this dissertation.

In relative contribution, I was the principal investigator for the case study, and undertook all of the field research, with help from Athena-Sofia Delimanolis and Lesley Winterhalt. Prof. Gibson provided supervisory oversight and contributed to the analysis.

An illustration of integrated sustainability and resilience based assessment: application to a small-scale biodiesel project in Barbados

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Overview

Assessments today need to help reverse trends towards deeper unsustainability and address the unavoidable interconnections, feedbacks and uncertainties that typify complex socio-ecological systems at all scales. To illustrate one promising approach, this paper describes a modest effort to integrate understandings from Gibson et al.'s approach to sustainability assessment with the Resilience Alliance's applications of complex systems thinking into a suite of systems and sustainability based criteria. The integrated sustainability–resilience criteria were used to assess an existing small-scale biodiesel operation on Barbados that involves waste management, public health, transportation, energy security and community involvement considerations. The assessment revealed that the main benefit of this biodiesel project is in social learning rather than enhancing energy security and waste management, and the best ways of enhancing the project lie in larger scale policy initiatives. The findings suggest that the use of a sustainability-resilience approach can contribute insights unlikely to emerge from more narrowly focused assessments.

6.1 Introduction

Two of the most significant challenges facing impact assessment in the twenty-first century are the needs to reverse trends towards deeper unsustainability and to address the unavoidable interconnections, feedbacks and uncertainties that typify complex socio-ecological systems at all scales (Holling et al. 2002b). These challenges are closely connected. Many of our failures to behave in a sustainable manner are a product of fragmented, narrow thinking and hubris.

An evident implication for assessment work is that the selection, design and implementation of important undertakings – policies, plans and programmes as well as projects, large and small – ought to be guided by integrated attention to sustainability requirements and complex systems realities. Conceptual work in both the sustainability and complex systems literature has recognized the desirability of such integration (Bunch and Ramirez 2009; Francis 2006; Kay 2008b), and many practical strategic and project level undertakings have at least implicitly explored means of integrating systems and sustainability considerations (Buchholz et al. 2007; Partidário et al. 2009; Rotmans et al. 2000a; Rotmans et al. 2000b). So far, however, these efforts still represent the initial explorations of a wide range of rich possibilities.

This paper attempts to illustrate what can emerge from a modest effort to integrate and apply understandings from the two fields in the assessment of a particular undertaking. The work centres on the development and application of a comprehensive set of evaluation criteria that combine generic systems and sustainability considerations with recognition to the particular concerns arising from the case and context of a small existing biodiesel operation on the island of Barbados.

The case application here has two core foundations. The first is a sustainability assessment approach built by Gibson et al. (2005), which synthesizes insights from the literature on requirements for progress towards sustainability and is essentially defined by its focus on how the interrelations of these requirements can be addressed in ways that deliver multiple, mutually reinforcing and lasting gains. The second is the application of insights from the study of complex socio-ecological systems, relying chiefly on the systems understanding that underpins the ecosystem approach (Kay et al. 1999; Waltner-Toews et al. 2008) and on the Resilience Alliance's identification of the properties of a resilient world (ResAlliance 2007a; b; Walker and Salt 2006). Both point to desired system traits (e.g. resilience, flexibility, modularity, and reversibility) that can be maintained and enhanced. These two foundations overlap and each has been applied in some forms of assessment (Gibson 2006c; Gibson et al. 2008; Walker and Salt 2006; Waltner-Toews et al. 2008), but the two have not previously been integrated and applied in any published work so far as we know.

Because the resulting approach to assessment is centred on sustainability and resilience objectives, it is considerably more ambitious than assessment work that aims only to reduce biophysical damage. The integrated sustainability-resilience approach is, however, not a long stretch from comprehensive and ambitious forms of environmental impact assessment in which "environment" is defined to include social, economic, cultural and biophysical components and their interactions; the objective is durable betterment rather than mere mitigation of significant adverse effects; and the assessment agenda covers implementation as well as selection, design and approval of the relevant undertakings.

To illustrate the application of an integrated sustainability-resilience approach we have used it to assess a small, apparently "green" initiative that involves collecting used cooking oil from restaurants and other food related businesses and converting the oil into biodiesel, which may be used as a transport fuel. In addition to reducing dependency on imported conventional diesel, the initiative promises to serve waste management, public health, transportation, and community involvement objectives. Whether the biodiesel operation does deliver benefits in these and other areas, and whether it has other strengths and limitations as a potential contributor to sustainability and resilience, are the main immediate questions underlying the application here. For our purposes, the Barbadian biodiesel case has the advantages of being potentially attractive from a sustainability and resilience perspective, broadly similar to countless other initiatives, and small enough to illustrate how a quite modest sustainability and resilience based review can serve common project evaluation purposes.

Post-hoc application to an ongoing undertaking rather than an anticipated one departs from the usual emphasis on assessment of proposed undertakings, but benefits from more evidence about actual effects. The lessons from the case discussed here should be nonetheless relevant for potential application to the development and review of new proposals.

6.2 Methodology

The basic methodology illustrated here centres on combining established sets of generic sustainability and resilience analysis criteria in the specification of an evaluation framework for the particular case and context of our illustrative small biodiesel operation in Barbados. The specified criteria were used to identify the key strengths and limitations of the biodiesel project, to assist consideration of their implications as a package, and to help identify ways by which the operation could make more consistently positive contributions to sustainability and resilience.

6.2.1 Sustainability assessment criteria

The generic sustainability assessment criteria set out in Table 15 from Gibson et al. (2005) were developed for a broad range of applications in broadly defined environmental assessments and planning. They are meant to cover the full set of key requirements for progress towards sustainability, with emphasis on the interrelations among these requirements and attention to the potential for an upward spiral of positive feedbacks for mutually reinforcing gains. To encourage integrated thinking, the generic categories have been defined to avoid the usual reductionist triple bottom line pillars of sustainability (Gibson et al. 2005).

These generic sustainability assessment criteria provide a common base for assessment anywhere and on any undertaking, and apply to examination of options and results at all stages of an assessment process from the initial delineation of purposes, through comparative evaluation of alternatives and potential approval options, to implementation and eventual closure or renewal. In all applications, however, specification for case and context is needed. Approaches to such specification have been documented, particularly for a major project review (Gibson 2006c) and for evaluation of a proposed provincial scale, electricity sector systems plan (Gibson 2006c; Gibson et al. 2008), but have not explicitly incorporated attention to resilience criteria.

Table 15 – Gibson's (2006) generic sustainability assessment criteria

Socio-ecological system integrity Build human-ecological relations to establish and maintain the long-term integrity of socio-biophysical systems and protect the irreplaceable life support functions upon which human as well as ecological wellbeing depends.
Livelihood sufficiency and opportunity Ensure that everyone and every community has enough for a decent life and that everyone has opportunities to seek improvements in ways that do not compromise future generations' possibilities for sufficiency and opportunity.
Intragenerational equity Ensure that sufficiency and effective choices for all are pursued in ways that reduce dangerous gaps in sufficiency and opportunity (and health, security, social recognition, political influence, etc.) between the rich and the poor.
Intergenerational equity Favour present options and actions that are most likely to preserve or enhance the opportunities and capabilities of future generations to live sustainably.
Resource maintenance and efficiency Provide a larger base for ensuring sustainable livelihoods for all while reducing threats to the long term integrity of socio-ecological systems by reducing extractive damage, avoiding waste and cutting overall material and energy use per unit of benefit.
Socio-ecological civility and democratic governance Build the capacity, motivation and habitual inclination of individuals, communities and other collective decision-making bodies to apply sustainability requirements through more open and better-informed deliberations, greater attention to fostering reciprocal awareness and collective responsibility, and more integrated use of administrative, market, customary and personal decision-making practices.
Precaution and adaptation Respect uncertainty, avoid even poorly understood risks of serious or irreversible damage to the foundations for sustainability, plan to learn, design for surprise, and manage for adaptation.
Immediate and long term integration Apply all principles of sustainability at once, seeking mutually supportive benefits and multiple gains.

6.2.2 Resilience criteria

Resilience approaches to social-ecological systems issues commonly faced in environmental assessment emerged largely from the domains of ecological modeling and resource management. While not as comprehensive as the sustainability assessment agenda represented by the criteria above, resilience thinking is useful in elucidating system dynamics within and among various scales (Walker et al. 2004; Walker and Salt 2006). Resilience analysis is still being developed as a methodology, with preliminary forms described in several works including the Resilience Alliance workbooks (ResAlliance 2007a; b). Because of their respect for system complexity and uncertainty, advocates of resilience thinking and associated analyses are hesitant to embrace prescriptive approaches that might encourage overconfidence in prediction and management. With this caveat, Walker and Salt (Walker and Salt 2006) identify the nine properties of a resilient world that are presented in the form of criteria in Table 16.

Table 16 - Criteria for resilient societies

Diversity - Promote and sustain diversity in all forms (biological, landscape, cultural, social and economic) as a major source of future options and system capacity to response to change and disturbance
Ecological variability - Embrace and work with ecological variability rather than attempting to control it (e.g. to maximize returns)
Modularity - Favour largely self-reliant systems (modules) to avoid over-connectedness and associated relations of dependence, which become vulnerable to shocks
Acknowledge slow variables - Focus on slow controlling variables that configure social/ecological systems and are associated with thresholds
Tight feedbacks - Maintain or strengthen feedbacks that are tight and strong enough to allow detection of thresholds before they are crossed (versus slow or delayed feedbacks with weak signals)
Social capital - Promote trust, well-developed social networks, and responsive leadership, all of which serve adaptability
Innovation - Emphasize learning, experimentation, locally developed rules, and capacity and willingness to shift away from thresholds to undesirable futures or over thresholds to more desirable futures
Overlap in governance - Foster redundancy of institutions, and a mix of governance players and relations and tools (e.g. common and private properties with overlapping access rights) to increase response diversity and flexibility
Ecosystem services - Recognize all ecosystems services, including those currently unpriced (e.g. pollination, water regime maintenance, climate reliability, and nutrient cycling)

– adapted from (Walker and Salt 2006, ch. 6)

These nine criteria are narrower in scope than the sustainability criteria, in part because they do not attempt to identify the desirable qualities of socio-ecological systems beyond the capacity to adapt and persist. The resilience criteria do, however, complement the sustainability-based assessment criteria in several important ways. They clarify the qualities needed for socio-ecological integrity and suggest means of acting on requirements for precaution and adaptation. Moreover, they temper the sustainability criterion for enhanced resource and energy efficiencies by pointing to the need for sufficient system redundancy and for safety cushions between exploitation levels and potential system thresholds. At least for the purposes of the present case study, the resilience criteria can be integrated with the generic sustainability assessment criteria most effectively by direct insertion as clarifications and adjustments of the sustainability assessment criteria and by giving particular attention to the resilience qualities in the elaboration of case- and context-specific criteria.

6.2.3 Integrating and specifying sustainability and resilience criteria

Both the sustainability and resilience criteria have been conceived for broad application to evaluations of situations, options and undertakings of various kinds, scales and locations. In every application, however, the particulars of case and context are crucial. Different contexts feature different trajectories, capacities, vulnerabilities, possibilities and preferences; different cases raise different options and face different influences, barriers and openings. Neglect of these is likely to be fatal to prospects for success. Development of evaluation criteria for an individual case and context therefore requires integration of the generic criteria with attention to the key case and context factors – especially those that define aspirations and limitations.

Identifying all the potentially relevant case and context specific factors, and their interrelations, for any case is probably impossible. While there can be no end of debate on what is needed for an adequate understanding, it is evident that highly ambitious research and analysis is not always necessary. For cases of limited potential impact and controversy, where time and resources are more constrained, and where the key factors are already quite clearly evident due to earlier expert studies and public deliberations, reliable conclusions can be drawn from a more modest combination of research methods including review of existing literature, key informant interviews, and participant observation. In all situations, however, it is important to spend sufficient time immersed in the case and context to gain an adequate understanding of the realities behind the standard accounts and common assumptions.

6.3 Sample application – Small-scale biodiesel in Barbados

To illustrate application of a sustainability-resilience framework, we assessed an existing small-scale biodiesel plant in Barbados. As noted above, the first step involved constructing a framework for assessment by integrating and specifying the generic sustainability and resilience criteria for the particular case and context (presented in Table 18, below). For the purposes of this exercise, the research into the particulars of the biodiesel operation and the relevant aspects of the Barbadian context drew on three different sources of evidence: documentary evidence on the biodiesel systems and related aspects of the Barbadian socio-economic and ecological systems, participant observation working with the biodiesel operation over a three-month period in 2008, and informal interviews with stakeholders directly involved in the biodiesel system. To build a better understanding of the small-scale biodiesel operation and options, a system description was also undertaken.[6]

Even for an illustrative review of a small and uncontroversial undertaking, details are important, especially where they involve the range of potentially feasible alternatives to current project design and operation, and the interactions among contextual factors that influence project viability and effects. A full reporting of those details is not possible here; however, the following summary should provide an indication of the key considerations.

[6] The systems description provides a means of conceptualizing interrelationships amongst actors at various scales in a system whose boundaries are defined by the analyst. Systems descriptions promote the understanding of a situation through multiple perspectives (e.g., social, thermodynamic, economic). Whereas in certain applications (e.g. Waltner-Toews et al. 2008) the systems description is formally undertaken, within the present work the systems description served as a means of stimulating transdisciplinary thinking.

6.3.1 The context

Barbados is a relatively prosperous Caribbean island. Nonetheless, like many other small island nations, it faces significant sustainability and resilience challenges. Some of these are rooted in its reliance on and vulnerability to outside forces (from global economic shifts and oil price changes, to changes in tourist behaviour and international steps to discourage tax dodging) over which it has little influence. Also like many other jurisdictions, Barbados suffers from disparities in opportunity and participates in productive and consumptive activities that cannot be maintained in the long run. These considerations suggest needs for further economic diversification, enhancement of self-reliance, conversion to renewable energy sources, and development of more broadly distributed livelihood opportunities (SIDS 2003; UN 1994; 2007).

Means of acting on these needs are constrained by the island's limited resources. A large percentage of food is imported (WRI 2006), especially to meet tourist demands. Barbados is also one of the fifteen most water scarce countries in the world (Sealy 2006), is only five percent forested (Mongabay 2007), and is quickly running out of landfill capacity (Barbados 2004). Finally, Barbados imports approximately ninety percent of its oil, and almost all of its other fossil fuels (EIA 2009), in part to serve electricity production, all of which is fossil fuel based, with the primary fuels being diesel, fuel oil and natural gas (BL&P 2009). Recent Barbados energy policy aims to reduce dependence on imported fossil fuels by replacing the imports with indigenous renewable energy production (Sealy 2006), such as the recently proposed ethanol fuel cane project (Lutter 2007).

6.3.2 The case

The case study biodiesel system is a small-scale biodiesel plant in the centre of the island. At the time of the research, the plant employed three workers (two men and one woman). The used cooking oil necessary for biodiesel production was collected by pickup truck from a wide range of suppliers (a restaurant chain, individual restaurants, road-side stands, and a local high school), with support from a United Nations Development Programme grant. As well, many individuals voluntarily donated their stored used cooking oil after hearing about the biodiesel operation through the news or by word of mouth.

Biodiesel production was based on first generation thermo-chemical technology that produces biodiesel and glycerine from methanol, vegetable oil and sodium hydroxide using a process known as transesterification. This first generation system is common for small-scale projects (Kemp 2006; Phalakornkule et al. 2009).

Small-scale biodiesel production is characterized by many different possible variations in input and processing. The available variations add to system resilience by providing a diversity of input and organizational alternatives that can be adopted if problems emerge in the use of the current components, although conversion from one configuration to another is not necessarily easy. Some possible variations are provided in Table 17.

While the main output is biodiesel, the process also produces glycerine (0.2 L glycerine / L biodiesel) and washwater (3 L washwater / L biodiesel) (Callender 2008, personal communication). Both the glycerine and the washwater are toxic – contaminated with sodium hydroxide, methanol and raw biodiesel (Kemp 2006).

Table 17 - Production alternatives

Location	Barbados Case	Variations
Input	Methanol	Ethanol and other alcohols
	Waste cooking oil	Other vegetable oils, as well as fats, oils, and greases.
	Sodium hydroxide	Potassium hydroxide, sulphuric acid.
	Water for washing	Waterless washing, e.g. using Magnesol (Sims 2007)
	Electrical heat	Passive solar or natural gas heating.
	Electrical mixing	Pedal powered mixing (Vaidyanathan and Sankaranarayanan 2007)
Operation	Batch processing	Continuous processing
	Single operator	Multiple operators, each capable of performing all or a subset of the tasks

One disadvantage of the small-scale production system is the relative difficulty of maintaining quality control, as formal quality control (e.g., ASME standards) is often prohibitively expensive for small-scale operations (Kemp 2006, ch. 8). Many small-scale producers rely instead on experience and simple non-standardized tests of fuel quality (Kemp 2006, Callender 2008 personal communication). This can be insufficient and in the extreme case of poor quality biodiesel, engine damage may result.

A second diseconomy of scale involves input costs. For example, methanol purchased in small units can account for a large percentage of the production cost (Callender 2009, personal communication). The resulting high input costs result in a low profit margin which, when coupled with the small volumes of production, undermines financial feasibility.

6.3.3 The case-specific sustainability and resilience criteria

The specification of the combined generic sustainability and resilience criteria for the particular case and context was initiated as a group exercise that included the researchers, interns working at the biodiesel plant, and key stakeholders involved in the biodiesel operation. The work relied on data from the documentary evidence, participant observation and informal interviews, and was informed by development of a systems description depicting linkages within the operation and between the operation and the larger environment. Moreover an iterative process was used, so that development of case-specific criteria (presented in Table 18) both guided and was influenced by the preparation and initial test uses of the sustainability-resilience assessment table (presented in Table 19).

Table 18 - Case-specific sustainability criteria for the Barbados biodiesel operation

Socio-ecological system integrity and resilience How does the operation affect: • the capacity of the local ecosystem to deliver valued ecosystem services reliably into the future (e.g., effects on water and air quality, and wildlife habitat)? • the capacity of national and global ecosystems and socio-ecosystems to deliver valued services reliably into the future (e.g., effects on regional pollution levels, energy sources, and transport systems)? • the resilience of local and national socio-ecosystems (including economic options, transportation, food and health systems, water and waste management)? • longer term availability of non-renewable and renewable resources?
Livelihood sufficiency and opportunity How does the operation affect: • opportunities for lasting employment? • human health (including exposure to toxic substances and sanitation issues)? • the availability of resources for others? • learning and associated capacity building, including the indirect effects on education and training by other bodies? • potential for further investment and scale enlargement?
Intragenerational equity How does the operation affect: • the unequal distribution of wealth, access to resources, and influence on the island? • the equality of access to health, valued employment, respected knowledge and community security? • gender equality on the island? • the distribution of wealth, influence and access to resources between advantaged and disadvantaged nations (including effects on revenue flows, dependency effects, etc.)? • the material and energy intensity of consumer and other satisfactions for the wealthy? • the wellbeing of non-human species (including effects on habitat, quality of ecosystem services, and vulnerability to stresses)?
Intergenerational equity How does the operation affect: • potential costs and benefits for future generations? • transition towards a future energy supply? • legacy costs (e.g., storage of long term wastes)?
Resource maintenance and efficiency How does the operation affect: • the severity of damage from resource extraction (over full life cycle, including induced and cumulative effects) as compared to existing practices and to alternatives? • the net use of energy, energy quality matching, and the nature of energy sources (including any bridging to renewable and low impact sources)? • the net use of water (including effects on availability of water for ecosystem functions as well as human needs)? • the net use of other materials and resources, and the potential hazardousness of direct and embodied pollution and other wastes? • the transition from non-renewable high impact energy and material sources to renewable and low impact sources? • the potential for rebound effects (e.g. savings from biodiesel efficiencies facilitating expansion of demands and adverse effects elsewhere)? • the potential for efficiencies that reduce desirable diversity, local suitability and redundancy?

Social-ecological civility and democratic governance How does the operation affect: • the social awareness of citizens (including through involvement in framing problems and solutions, opportunities to create or strengthen social ties of mutual learning and assistance, and sensitivity to disadvantaged groups)? • the ecological awareness of citizens (e.g. about ecosystem functions and capacities and associated values)? • the social responsibility of market participants? • the capacity of participants to be actively involved in deliberations and decision making on public issues?
Precaution and adaptation for resilience How does the operation affect: • risks of significant damage (e.g. high risk of minor damage, low or ill-understood risks of potentially significant problems) as compared to existing practices and to alternatives? • capacity for monitoring changes (e.g. by providing good baseline information on initial conditions)? • the adaptive and precautionary qualities of the island's waste and energy systems (including incorporation of qualities facilitating adaptation in the face of surprise: flexibility, reversibility, diversity, fallback options, and safe-fail characteristics)? • development of a context and culture of precaution and adaptation? Does the operation itself have sufficiently robust resilience characteristics (including diverse source and process options, modular components, market alternatives, administrative flexibility and learning capacity) for viability in the face of change and surprise?
Immediate and long-term integration How do the interrelations among the operation's effects influence: • the delivery or potential for positive feedbacks and mutual reinforcement of desirable effects from the project itself and from other current and reasonably anticipated activities and undertakings? • the capacity to enhance these positive effects? • the delivery or risk of negative feedbacks and mutually reinforcing adverse effects? • the capacity to interrupt and reverse these negative effects?

6.3.4 Application of the criteria

An initial version of the case specific criteria in Table 18 was adopted as the basis for a first draft of the sustainability–resilience assessment that centred on developing and filling out a sustainability–resilience assessment table. The final version of that table is reproduced as Table 19, which sets out the most significant particular considerations related to the final Table 18 criteria. While the result appears as a linear development from the criteria table to the assessment table, in practice the two tables were prepared jointly, through several iterations of adjustments of each table, involving decisions on what to include where, and with what emphasis and specificity.

Throughout the iterations, care was taken to ensure all the generic criteria in Table 15 and Table 16 were addressed in the case specific criteria in Table 18 and all of these specific criteria were addressed in the Table 19 assessment, though not necessarily in directly parallel terms and categories. Initial iterations of the criteria specification and the sustainability-resilience assessment table were completed over a period of several weeks as a joint exercise involving the research team, the interns and the biodiesel workers. Each iteration allowed the research team to understand more clearly the key aspects of and insights from the case at hand. The differences between Table 18 and Table 19 reflect the learning process in the iterative elaborations of the criteria development and application in the assessment. The research team prepared the final versions of the two tables.

For each consideration, the project's contributions to sustainability are ranked on a simple 3-point scale, identifying positive impact (+), negative impact (-), and impact that may be mixed, or positive or negative depending on how it is undertaken (=). For a more advanced analysis, a 5-point scale could be used and care taken to avoid overlapping criteria. However, for the case at hand, the purpose was not to sum up all the positive and negative aspects in a quantitative test, but rather to gain broad insights into areas of strengths and weakness, and associated openings for improving contributions to sustainability and resilience.

Table 19 - Key results from the sustainability-resilience assessment

Social-ecological system integrity and resilience	
• Dumping or indefinite storage of toxic wastes materials (methanol, glycerine and washwater) present occupational hazards and local endanger flora, fauna and groundwater.	-
• Process has large on-site water requirements (3:1 ratio water to biodiesel) in a water scarce country; partial mitigation through rainwater harvesting during the wet season is possible.	-
• Operation takes waste oil out of the waste stream, reducing pressure on very limited landfill capacity.	+
• Combustion emissions are not significantly less problematic than those from conventional diesel and unlikely to improve air quality.	=
• Product displaces non-renewable diesel fuel, but requires imported methanol at a ratio of 1L methanol for each 5L biodiesel.	+
• Main input for biodiesel production is a product of an unhealthy fast and fried food lifestyle.	-
• Little infrastructure is in place to handle serious disruptions such as failed batches.	-
• Small-scale production is modular, leading to greater system resilience.	+
• Local production innovation, with largely local feedstock and local consumption, establishes visible system links for better understanding and management.	+
• Production could be scaled up for greater impact on long term resource availability	+
• Initiative adds economic diversity to a tourist oriented economy.	+
Livelihood sufficiency and opportunity	
• Diseconomies of small scale limit financial viability. Long-term success requires subsidization, lower input costs, or a willingness by consumers to pay higher prices.	-
• Employment of three people represents far more jobs per litre of production than in larger scale operations, although current low selling price for biodiesel reduces potential for workers to make a decent income.	=
• Government subsidy of conventional diesel limits selling price of biodiesel, currently rendering small-scale biodiesel economically uncompetitive.	-
• Improper handling of toxic materials is dangerous to worker health.	-
• Further employment along the production chain (e.g. refining glycerine into a value added product) is possible, especially if aggregate production increases.	+
• There are competing uses for the most desirable waste oil (high quality and/or readily available) including pet food manufacturing and heat generation.	-
• Multiple small-scale operations could cooperate to gain some economies of scale.	+
• Small scale and ability for multiple configurations provide potential to produce biodiesel in different contexts and niches.	+
• The island may be suitable for 5-10 small-scale operations, with many more operations possible if the used oil from cruise ships were made available, or if proper financial incentives were present.	+

Intragenerational equity	
• Higher selling price for biodiesel than for regular diesel favours customers who can afford higher product price.	-
• Desire to encourage biodiesel could help win support for higher fuel prices that would adversely affect lower income residents in the absence of compensatory measures.	-
• Biodiesel demand is greater than present supply, suggesting potential for expansion and more jobs if more input oil could be found, and if this input use did not supplant more desirable re-uses.	+
• Both men and women have equal opportunity to produce biodiesel.	+
• Scale of operation has low impact on Barbados' fossil fuel dependence.	=
• Project has little impact on non-human species other than local flora (where glycerine and wash water may be dumped at times).	=
Intergenerational equity	
• Biodiesel contributions should help foster a more self-reliant, diverse and lasting energy supply system.	+
• Desire to encourage biodiesel could help win support for higher fuel prices that would discourage energy consumption and bring longer term environmental benefits.	+
• Biodiesel is a good transition fuel to facilitate a move from the current fossil based energy system to a variety of potential future renewable energy systems.	+
• Social learning involved in small-scale biodiesel amounts to knowledge development for the next generation.	+
• Biodiesel reliance on waste cooking oil could delay action to discourage heavy consumption of fried foods to improve long-term population health.	-
• System has low legacy costs because components can be easily disassembled and used for other purposes and wastes are not persistent hazards.	+
Resource maintenance and efficiency	
• Energy return on investment and the lifecycle energy costs remain uncertain (in part due to limits of assessment data).	=
• Use of waste vegetable oil as the primary input reduces current resource extraction, and lowers landfill pressure.	+
• Product partially displaces non-renewable diesel, although it still requires methanol and uses diesel-based electricity.	+
• Process water demands add to pressures on limited resource.	-
• Used cooking oil supply vastly exceeds production capacity, although some is low quality (due to over-use), too small a volume to collect, or legally inaccessible (cruise-ship oil).	+
• Small-scale operation suffers from diseconomies of scale, (e.g., methanol input costs and quality control testing).	-
• Importing methanol to produce biodiesel is not efficient in the long run, but Barbados' fuel cane project could allow switch from methanol-based to ethanol-based biodiesel.	=
• Small-scale operation has potential to use more energy efficient technologies, such as passive solar heating.	+
• Biodiesel has multiple uses, including transport fuel, heating, and electricity generation.	+
• Small scale and multiple possible configurations improve modularity and flexibility.	+
• Physical operation components are quite generic and can often be sourced second hand (e.g. an old water heater as a reactor tank), although some specialized components (e.g., pumps) must be imported. This leads to low upfront resource cost.	+
• Perceived green benefits of biodiesel may rationalize fuel over-consumption, thereby inducing an undesirable feedback (i.e. efficiency paradox).	-
• Resilience could be improved by a co-operative of small-scale producers (production could halt at one operation without major effects on fuel supply).	+

Social-ecological civility, networks and governance	
• Operation promotes capacity building through community groups (e.g. it was part of the 2008 Parish Ambassador programs to promote energy independence).	+
• Process is simple enough that it can be learned relatively quickly.	+
• Process is an excellent education tool to raise understanding of waste reduction, fuel consumption, CO_2 emissions, and water use issues.	+
• Biodiesel production training could be developed and marketed as a green tourism strategy.	+
• On a small close-knit island, a successful small-scale operation can affect government policy positively (e.g. building support for decentralized renewable energy production).	+
• Biodiesel encourages broad involvement of diverse participants (e.g. government agencies, organic farmers, local high school, parish representatives, High Commissions/embassies, restaurants).	+
Precaution and adaptation for resilience	
• Project presents low risk of significant damage.	+
• Conventional diesel remains as a back-up fuel source.	+
• Lack of accurate data for lifecycle assessments adds some uncertainty to the analysis, requiring ongoing research and adaptive management on the part of all stakeholders.	=
• Biodiesel production system is flexible enough for physical and operational reorganization, thereby improving resilience.	+
• Small-scale encourages interpersonal communication and tight feedbacks.	+
• Multiple small-scale biodiesel operations would provide modularity (one could shut down without seriously affecting biodiesel supply) as well as joint savings.	+
• Social learning aspects of production may encourage culture of conservation.	+
Interactive effects delivering multiple, mutually reinforcing and lasting benefits	
• Operation has mostly positive effects on several linked sectors, including waste management, energy security, local employment and economic diversification.	+
• Biodiesel demonstration may promote a transition from imported non-renewable to domestic renewable energy sources, improving resilience and energy security	+
• Knowledge could be exported to other small island developing states in the Caribbean and beyond.	+
• Example could lead to further attention placed on waste management and water issues and encourage a comprehensive response to both.	+
• Operation's effects promote social learning in a variety of social-ecological contexts (waste management, energy security, human and ecological health).	+
• Without proper government support, there is risk of biodiesel operations ceasing on the island (or operating well below potential).	-

6.4 Analysis of the findings: Critical themes

The sustainability-resilience assessment outlined above points to three critical themes – socio-ecological issues, scale issues, and social learning issues – that are not likely to have been revealed so clearly by less broadly framed assessments. The assessment also facilitates identification of a set of promising larger scale options for response to the current limitations of, and opportunities presented by, small-scale biodiesel in Barbados.

Socio-ecological issues

While renewable energy and waste reduction reasons are often given for promoting biodiesel and biofuels, the analysis above does not indicate that the Barbados biodiesel operation has strongly positive overall socio-ecological system effects. While the biodiesel operation reduces waste oil volumes sent for landfilling (presuming it would not otherwise go to other competing re-users), and conventional fossil diesel imports to the island, these advantages are compromised by substantial process water requirements in a water scarce country, production of a waste product that is rarely handled properly, and use of electricity from a grid powered by diesel generators.

Scale issues

Small-scale biodiesel generally has the capacity to be more dynamic and adaptable, and to engage more stakeholders. Other advantages of small scale include increased resilience due to modularity of design; simplicity of operation; the possibility of physical, operational and institutional reorganization; tighter feedbacks among different stakeholders because more stakeholders are operating in the same level; and increased employment per unit biodiesel produced. Unfortunately, there are also diseconomies of small scale. Small-scale producers, each producing independently, cannot afford to produce biodiesel in Barbados at a competitive price in part because of the subsidization of conventional diesel and the current lack of subsidies for biodiesel, but also because of the high unit cost of small volume purchases of methanol. Small producers also often lack proper quality control and manage hazardous materials and wastes poorly, in part because of the high unit costs of quality control, material handling, and training.

Social learning issues:

Biodiesel is not often promoted or examined for its potential to create networks linking different stakeholder groups and to foster social learning. These benefits are visible in a sustainability and resilience analysis in part because the social learning effects of small-scale biodiesel are not related to the biodiesel end product so much as to the larger biodiesel production system. Furthermore, both scale and socio-ecological systems factors are important to the social learning: the systems provide the context for social learning, while the small scale allows for greater networking with tighter feedbacks. For social learning, biodiesel has several advantages. Biodiesel production involves and can link a great diversity of stakeholders (government, public health, organic farming, schools, and restaurants) in a system that raises important national issues, including diet (and health), waste and water management, energy security, and economic diversification. As a hub for discussion, biodiesel initiatives can build social awareness of important issues, and also encourage further research into more environmental friendly production techniques. Because the operations are small, multiple initiatives can be distributed across the island. Moreover, the process is simple enough for use as a learning activity (e.g. by high schools). Finally, with gradual scaling up, biodiesel could be a transition fuel, facilitating a shift from the current transportation and energy infrastructure to more sustainable future options.

6.5 Response options

The findings of the sustainability-resilience assessment, especially as consolidated in the theme discussion above, point to limitations and opportunities that could be addressed in initiatives beyond the scale of the individual biodiesel operation. Three possibilities are outlined below.

A co-operative of small-scale biodiesel producers

Barbados could support several small-scale biodiesel producers working together. The co-operative participants could purchase inputs (especially methanol) in bulk to enjoy economies of scale, but still operate their own facilities individually, thereby preserving the tight feedbacks between producers and consumers. Overall biodiesel production would be more resilient because it is unlikely that all the small-scale operations would be shut down simultaneously. Furthermore, larger aggregate glycerine production could supply a viable small-scale operation processing it into biogas (Phalakornkule et al. 2009), soap or ethanol. The disadvantage of having multiple producers is they may be competing for the same used cooking oil inputs.

Government assistance and education expansion:

The government of Barbados might take a more active role in biodiesel production by adjusting regulatory control to allow access to used cooking oil from cruise ships, and by subsidizing methanol costs, at least to match its subsidy of conventional diesel. In return, small-scale biodiesel producers might have to extend their education outreach, such as by teaming up with local high schools and community groups to educate citizens of the issues surrounding biodiesel (waste management, energy security, diet, etc.). There is the potential to develop a joint research program with the University of the West Indies to address the disadvantages of small-scale production (e.g., inadequate quality control). While increased government involvement could reduce the independence of the individual producers, Barbados is a small island, there are few levels of government and bureaucracy to steer through, and government-producers interactions could be positive.

Biodiesel as a green tourism project:

The simplicity, accessibility, and socio-ecological benefits of small-scale biodiesel could be marketed for green tourism on the island. Tourists could pay to learn how to produce their own biodiesel, and even donate the final product to disadvantaged local citizens. The added revenue stream from green tourism could offset the high input costs and obviate the diseconomies of small scale. Furthermore, marketing biodiesel as a green tourist attraction would encourage small-scale producers to find innovative solutions for the waste products of biodiesel production. This initiative would tie the fate of biodiesel production to the uncertain future of the tourism industry, but this might be acceptable as a short-term means of strengthening small-scale production infrastructure.

6.6 Conclusion

In principle, an assessment framework that incorporates sustainability purposes and appreciation of complex system realities is well suited to our times. In practice, its scope is daunting. The illustrative case here demonstrates, however, that a comprehensive but minimally demanding sustainability- and resilience-based assessment of a modest existing undertaking can be feasible and illuminating.

The assessment indicated that for the specific context at hand, the main benefit of biodiesel production is in promoting social learning rather than enhancing energy security and waste management. It also found that the most promising means of improving the operation lay in larger scale policy and programme initiatives rather than at the project level. Both results were unlikely to emerge from more narrowly scoped, conventional assessments focusing only on energetic, economic or biophysical concerns.

The broader agenda entails some care in developing a comprehensive set of criteria, specified to recognize the particular issues and system characteristics of the case and context. However, the generic criteria can be drawn from easily accessible sources and the specification can be accomplished without much difficulty using stakeholder knowledge and available published data. Use of these criteria directs attention to interrelated issues – especially ones that cross social, economic and ecological boundaries – and identification of broader response options.

The approach described in this paper has some important limitations. Ideally, the kind of sustainability-resilience assessment explored here would be applied iteratively throughout the selection, planning, implementation and closure/renewal of undertakings large and small. In this case, it would have been better if an initial sustainability-resilience assessment had been performed at the beginning of the project, and reviewed several times throughout the life of the project. Furthermore, while the assessment involved key stakeholders in research process, broader consultation would have added to the legitimacy of the assessment and the plurality of perspectives. Often, however, full-scale application of sustainability-resilience assessment may be prohibitively demanding and unnecessary. What we have illustrated here is an application with ambitious scope that can be completed in a short time with reasonable means and illuminating results.

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This is the end of the manuscript.

6.7 Key recommendations for sustainability assessment of energy systems emerging from the Barbados case study

This section describes the outcomes from the biodiesel case study that have broader importance for the dissertation, focusing on four points. First, the research highlights the importance of seeking integration across sectors. As is noted in the manuscript, biodiesel production from used cooking oil in Barbados involves and links a diversity of stakeholders including government, energy planners, public health officials, organic farmers, high schools and restaurants. Likewise, the impacts of biodiesel production in Barbados relate to several issues of national concern, including diet (the high consumption of fried foods), waste and water management, energy security, economic diversification and livelihood opportunities. Integrating across sectors provides an opportunity for seeking positive synergy, and in this case, it was proposed that the government might be best situated to seek such positive synergy.

Second, the research highlights the potential for energy undertakings to promote social learning and capacity building. As a nexus for discussion, biodiesel initiatives can build social awareness of important issues, such as those mentioned in the paragraph above, and also encourage further research into more environmentally friendly production techniques. The social learning benefits of small-scale biodiesel are not related to the actual biodiesel produced, but rather to the characteristics of the biodiesel operation, notably the size of the operation, the relative simplicity and scalability of production, and the people involved. For example, small-scale operations allow for multiple initiatives to be distributed across the island. Likewise, the very same chemical transformation process used to produce biodiesel can be applied in many different niches, such as a mobile operation on a bus, inside a school science laboratory, or using pedal-powered production (Kemp 2006; Vaidyanathan and Sankaranarayanan 2007).

Third, with appropriate implementation, biodiesel offers benefits as a transition fuel, facilitating a shift from the current transportation and energy infrastructure to more sustainable future options. Notably, biodiesel allows the characteristics of the supply infrastructure to change without unduly impacting current demand infrastructure (e.g. diesel engines, gas stations). Likewise, the potential to produce biodiesel at a small-scale provides the opportunity to foster a more broadly democratic energy transition, as promoted by the soft energy path.

Finally, it is necessary to discuss the energy return on investment (EROI) of biodiesel, which was not fully treated in the manuscript. While no certain numbers are available, Giampietro and Ulgiati (2005) argue the EROI of large-scale biodiesel with current technology is below 2, which implies biodiesel will continue to rely on fossil fuel subsidies for its production, and will be unable to meet the energy demands of modern society. As such, biodiesel should not be seen as the end goal of an energy transition, but rather as an energy bridge in a dynamic process of change. While the low EROI of biodiesel does not detract from the benefits discussed above, it indicates that the indirect benefits alone are insufficient as an end goal. At some point, alternative sources of energy will need to be produced with a sufficiently high EROI. Likewise, the metabolic characteristics of societies will need to change so as to match the new biophysical constraints (Hall and Klitgaard 2012; Hall et al. 2008). This topic is still a rather undeveloped area of research (e.g. Haberl et al. 2011).

The themes discussed above – the importance of integration, the potential for social learning and capacity building, the potential for a broadly democratic transition fuel, and EROI – have all be incorporated in a generalized manner into the systems- and energy-informed criteria set proposed in Chapter 4. Furthermore, these topics will be revisited in the concluding chapter (Chapter 9) in consideration with the insights emerging from the other case studies.

Chapter 7 – Sustainability assessment of sugarcane ethanol in Brazil

This chapter reports on a sustainability assessment of a sugarcane ethanol operation located in the Tietê-Jacaré Watershed of São Paulo, Brazil. The assessment was undertaken as a team project between University of São Paulo and University of Waterloo. The research began in early Winter 2011, and the analysis was completed in 2012. The manuscript was published in the journal *Ecological Indicators* (Duarte et al. 2013).

The outcomes of the assessment are generally described in attached manuscript. The collaborative nature of the research implied that not all relevant topics of discussion for this dissertation are included in the manuscript, but rather are presented following the manuscript.

In relative contribution, Carla Grigoletto Duarte was the principal investigator, and she undertook the fieldwork. I contributed significantly to the criteria specification process as well as the analysis of the sugarcane-ethanol operation in light of the sustainability criteria. Furthermore, throughout the fieldwork stage (primarily summer 2011) I provided guidance to Carla to ensure the data collection would properly inform the assessment. To supplement our work, Prof. Gibson from Waterloo and Prof. Malheiros from São Paulo acted as supervisors.

Sustainability assessment of sugarcane-ethanol production in Brazil: a case study of a sugarcane mill in São Paulo state

By Carla Grigoletto Duarte, Kyrke Gaudreau, Robert B. Gibson, and Tadeu Malheiros

Overview

To improve decision-making, sustainability-based approaches to impact assessment demand that we move beyond narrowly defined considerations to address the full suite of requirements for sustainability, as well as the interconnections, feedbacks and uncertainties that typify complex socio-ecological systems at all scales. This paper applies a sustainability assessment framework to assess a sugarcane-ethanol mill in São Paulo state, Brazil, seeking to identify opportunities for improvements towards sustainability. The analysis highlights the importance of broader strategic planning for providing an appropriate context for more sustainable sugarcane-ethanol production at the watershed, municipal, and mill level. Five particularly important multi-scalar issues that were identified are (1) the maintenance of long-term water availability and quality; (2) the enhancement of biodiversity and reversal of ecological fragmentation; (3) the planned elimination of sugarcane straw burning and subsequence increase in mechanized

harvesting; (4) the impacts of indirect and direct land-use change; and (5) the quality, availability and durability of livelihood opportunities. To address these issues requires long term integrated planning and monitoring, better understanding of cumulative impacts and thresholds, recognition of important tradeoffs, and a credible and collaborative decision-making process that involves and empowers stakeholders to set the agendas and seek common goals.

Keywords: sustainability assessment, sugarcane ethanol, multi-criteria assessment, systems analysis.

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7.1 Introduction

In order for humanity to address the interrelated challenges facing us we must improve our decision-making processes such that they move beyond narrowly defined considerations to address as much as possible the full suite of requirements for sustainability, as well as the interconnections, feedbacks and uncertainties that typify complex socio-ecological systems at multiple scales (Gibson et al. 2005). One potential tool for such decision-making is "Sustainability Assessment", a framework for integrated assessment that attempts to identify, predict, and evaluate the potential impacts of undertakings and their best alternatives for progress towards sustainability. These undertakings can be at both project and strategic (programme, plan, and policy) levels, and for proposals as well as on-going initiatives (Devuyst 1999; Gibson et al. 2005; Pope et al. 2004).

This article describes an application of Gibson's sustainability assessment framework to assess a sugarcane ethanol production mill in São Paulo, Brazil, seeking to identify opportunities for improvements towards sustainability (Gibson 2006b). Gibson provides eight generic requirements for progress towards sustainability that must be specified for the particular context to supply a comprehensive set of evaluation and decision criteria (Gibson 2006b; Gibson et al. 2005) and the framework has been applied for energy systems both at the strategic level, assessing the proposed Ontario Electrical Systems Plan (Winfield et al. 2010), as well at the on-going project level, assessing a small-scale biodiesel operation (Gaudreau and Gibson 2010).

The assessment highlights the importance of both strategic and project level implications that must be understood within the local context of the mill and its watershed, and this research provides a unique attempt to integrate important findings across these scales, from the local to the international and vice-versa. The analysis provides key recommendations for decision-making that should help ensure the expected growth in Brazilian sugarcane ethanol production is undertaken in a manner that improves the long-term welfare of Brazil and São Paulo.

7.2 Rationale - The broader context of Brazilian sugarcane ethanol

Brazil is currently the world's largest producer and exporter of sugar, the largest exporter of ethanol, and second largest producer of ethanol (MDIC 2010), and growth is expected to continue in coming years due to rising domestic and international demand. While sugarcane ethanol promises advantages in the form of fuel substitution, climate change mitigation, employment opportunities and economic growth (Martinelli et al. 2011), the sector is facing criticism on many fronts. Sugarcane production is associated with various adverse environmental and health impacts including land degradation and deforestation in the Savannah (Schlesinger et al. 2008; Sparovek et al. 2009); direct and indirect land-use change (Gallardo and Bond 2011; Lapola et al. 2010); soil and water pollution (Smeets et al. 2008); loss of biodiversity due to monocultures and straw burning (Schlesinger et al. 2008); and carcinogenic air emissions from sugarcane straw burning (Avolio 2002; Ometto et al. 2009; Schaffel and La Rovere 2010). Furthermore, the expansion of sugarcane crops has worsened inequality in the countryside and promoted poor working conditions through overworking, low wages, the use of temporary and seasonal labour, and even child and slave labour (Nuffield 2011; Repórter Brasil 2010; Schlesinger et al. 2008).

In order to mitigate the adverse impacts of sugarcane ethanol, the federal and state governments have developed regulatory and voluntary measures that include new zoning laws, environmental regulations (e.g. to eliminate sugarcane waste burning by 2014 São Paulo state), and workers' rights commitments (e.g. the voluntary National Commitment for the Improvement of Labour Conditions in Sugarcane Production) (Martinelli et al. 2011; SGPR 2009; SMA 2008). Such efforts are a notable first step to improve decision-making, regulation and practice at all scales (local, state and federal), but more is needed to ensure sufficient attention to, and integration of, sustainability concerns at higher levels of decision-making. For example, Brazilian Environmental Impact Assessments examine the biophysical and social aspects of particular projects, but many important concerns and opportunities lie at the regional level (Gallardo and Bond 2011), and Brazil still lacks a legislated strategic environmental assessment protocol (de Oliveira et al. 2009). This research provides a unique attempt to bridge the project-strategic level divide to help ensure that the manner in which sugarcane-ethanol unfolds in Brazil provides the best opportunity to obtain mutually reinforcing positive gains and avoid worsening the environmental and social challenges facing the industry.

7.3 The case specific context

This section provides a brief introduction to the case context, while further elaboration is provided in sections 7.7 (initial observations) and 7.8 (discussion of important findings). The sugarcane ethanol mill under investigation is located in the central region of São Paulo state, and harvests approximately 21,000 ha of sugarcane crops from seven municipalities in three different watersheds. The mill produces hydrated ethanol for domestic markets, and sugar for domestic and international markets. The most important watershed where the mill is located is the Tietê-Jacaré Watershed, an important producer of sugar and ethanol; its twenty-two mills account for thirteen percent of sugarcane and ethanol production in São Paulo state, and eleven percent of national production (CBH-TJ 2010; CPLA/SMA 2011). In the municipality where the industrial plant of the mill is located, land under sugarcane cultivation increased by ninety percent between 2003 and

2010 (INPE 2011), and sugarcane now covers one quarter of the total area (approximately 300,000 ha) and supplies several mills. The mill under investigation has plans for additional increases in land under cultivation in the following years.

The 2008 GDP per capita of the Tietê-Jacaré Watershed was US$9,840[7], which is slightly higher than the national average (US$9,310), but trails the average of São Paulo state (US$11,950) (CBH-TJ 2010). The economy of the Tietê-Jacaré Watershed is dominated by ethanol and sugar both from sugarcane, as well as the production and processing of citrus, primarily oranges. While still primarily agricultural, the regions of the watershed are diversifying into pulp and paper, beverages, footwear, metalworking, mining, leather tanning and ecotourism (CBH-TJ 2010).

The Tietê-Jacaré Watershed is already experiencing environmental constraints. In 2008, the watershed was in a state of alert over water because 48.5 percent of supply had already been appropriated for human uses (up from 32 percent in 2007), and this is close to the 50 percent ratio that is considered a critical threshold (CBH-TJ 2010; CPLA/SMA 2011). The sub-basin of the industrial plant is polluted due to improper sewage treatment (from lack of urban water treatment capacity), and non-point source pollution from agricultural and urban areas. Likewise agriculture, cattle raising and improper tourist practices are worsening soil erosion and causing gully formation. Several municipalities in the basin are approaching ozone (a precursor to smog) saturation, which may limit further expansion of electricity production from bagasse[8].

Regarding land use, the watershed lost 20,000 ha of natural vegetation between 2005 and 2009; currently 91,400 ha remain (CPLA/SMA 2011). The vegetation index of the watershed was eight percent in 2009, less than half of the twenty percent index of vegetation cover São Paulo state has targeted by 2020 (CPLA/SMA 2011). The remaining natural vegetation is highly fragmented; more than 95 percent of vegetation fragments are smaller than 100 ha, thereby increasing isolation of populations of plants and animals and threatening genetic diversity (von Glehn 2008).

Future development in Tietê-Jacaré Watershed, whether for agricultural, industrial, commercial or residential purposes, will be increasingly subject to biophysical constraints, notably for land, water, air quality, and biodiversity. These concerns have social and cultural implications as well, including livelihood opportunities, the maintenance of natural capital, and quality of life. The sugarcane ethanol industry must become far more proactive in the face of rising sustainability concerns, as even maintaining the economy in its current state may not be possible.

7.4 Methodology

This section provides a general description of Gibson's framework for sustainability assessment; more in-depth descriptions are treated elsewhere (Gibson 2006c; Gibson et al. 2005). It is noted that Gibson's framework for sustainability assessment is

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[7] US$1.00 = R$ 1.635 (September 2,16h59, 2011)

[8] Bagasse is "the dry pulpy residue left after the extraction of juice from sugarcane, used as fuel for electricity generators, etc." (Oxford English Dictionary)

complementary to other strategic level frameworks (Partidário et al. 2009; Svarstad et al. 2008; Teigão dos Santos and Partidário 2011). The basic approach centres on combining established sets of generic sustainability and resilience criteria in the specification of an evaluation framework for the particular case and context. Gibson proposes a basic set of categories and criteria that are applicable to a wide range of evaluations. This set is shown in Table 20 (Gibson 2006c).

Table 20 – Initial sustainability assessment decision criteria

Socio-ecological system integrity Build human-ecological relations to establish and maintain the long-term integrity of socio-biophysical systems and protect the irreplaceable life support functions upon which human as well as ecological wellbeing depends.
Livelihood sufficiency and opportunity Ensure that everyone and every community has enough for a decent life and that everyone has opportunities to seek improvements in ways that do not compromise future generations' possibilities for sufficiency and opportunity.
Intragenerational equity Ensure that sufficiency and effective choices for all are pursued in ways that reduce dangerous gaps in sufficiency and opportunity (and health, security, social recognition, political influence, etc.) between the rich and the poor.
Intergenerational equity Favour present options and actions that are most likely to preserve or enhance the opportunities and capabilities of future generations to live sustainably.
Resource maintenance and efficiency Provide a larger base for ensuring sustainable livelihoods for all while reducing threats to the long term integrity of socio-ecological systems by reducing extractive damage, avoiding waste and cutting overall material and energy use per unit of benefit.
Socio-ecological civility and democratic governance Build the capacity, motivation and habitual inclination of individuals, communities and other collective decision-making bodies to apply sustainability requirements through more open and better informed deliberations, greater attention to fostering reciprocal awareness and collective responsibility, and more integrated use of administrative, market, customary and personal decision making practices.
Precaution and adaptation Respect uncertainty, avoid even poorly understood risks of serious or irreversible damage to the foundations for sustainability, plan to learn, design for surprise, and manage for adaptation.
Immediate and long term integration Apply all principles of sustainability at once, seeking mutually supportive benefits and multiple gains.

Source: Gibson et al. (2005, p.116)

7.5 Data collection

The research adopted a case study approach to data collection (Yin 2009). A variety of methods were applied, including key stakeholder interviews, document analysis, and direct observation. By using multiple methods it is possible to obtain triangulation of results and improve construct validity (Yin 2009).

In total, fourteen stakeholders were interviewed. They represented a broad set of backgrounds, expertise and experience, including the municipal level secretary of the environment, two technical analysts from the Municipal Department of the Environment, two technical analysts from the State Department of the Environment, two members of the regional tourism association, the environmental manager of the mill, the assistant for training and corporate responsibility of the mill, the work safety manager of the mill, three local residents, and a former sugarcane cutter. Due to the broad and comprehensive nature of the analysis, the interviews were open-ended, but still guided by the full suite of requirements for progress towards sustainability. The interviews were analyzed for relevant themes – both general and specific – relating to sugarcane and sugarcane-ethanol production. The interviews were not audio recorded.

Beyond the formal interviews, members of the research team attended five multi-party meetings that included stakeholders from environmental and civil society non-governmental organizations, government representatives from agriculture and planning, and environmental enforcement. All attempts were made to cover all relevant perspectives, and ensure that all stakeholders were provided a positive environment for contributing insights.

To supplement the interviews, the research team also drew from a wide variety of documents relating to sugarcane and sugarcane-ethanol production in Brazil, São Paulo state, and the watershed. The documents were identified through various means, including the city hall website, the watershed committee, as well as from the interviewees. The documents were also supplemented by the broader academic literature relating to sugarcane-ethanol production in Brazil.

The final approach to data collection was direct observation, including multiple site visits to the sugarcane fields and the ethanol process plant. The direct observations helped situate the broader concerns and insights into the more immediate context of the mill under assessment, and allowed the research team to develop a richer understanding of the realities behind the standard accounts and common assumptions.

7.6 Sustainability assessment criteria

Over the course of one year of data collection and analysis, the research team developed a set of sustainability criteria relevant to the particular case and context. The sustainability criteria, presented in Table 21 below, were developed with guidance from the interviews, document analysis and site visits, and were approved by the various stakeholders, including representatives from the mill and the municipal government. The criteria were structured and organized within Gibson's sustainability assessment decision criteria presented in Table 20. The criteria were phrased as a series of questions that reflect important concerns of the case and context, as well as general (and often universal) requirements of progress towards sustainability. For practical application in policy and project deliberations in Brazil, the categories would need to be re-organized and expressed in terms that facilitate understanding and informed discussion among the relevant stakeholders (Gibson 2006c), as long as the full suite of requirements for progress towards sustainability is respected.

The case specific sustainability criteria provided in Table 21 were initially addressed in a set of observations (i.e. qualitative and quantitative indicators) relating to the case and context presented in Table 22. The observations served to justify the proposed criteria set, as well as provide an initial analysis of the sugarcane-ethanol mill. While the observations are presented here after the sustainability criteria, in reality the criteria and the observations were developed simultaneously, and in an iterative manner. The initial sustainability criteria and literature and document review informed the data collection and site visits, which in turn informed further iterations of criteria specification and assessment. Finally, both the criteria set proposed in Table 21, and the observations outlined in Table 22 were revised in accordance with comments from key stakeholders, including the mill and the municipality.

The context-specified criteria provided in Table 21, and initial indicators provided in Table 22 provide a package to help identify the key strengths and limitations of ethanol production at multiple scales, and elaborate means by which ethanol could make more consistently positive contributions to sustainability of Brazil, São Paulo state, and the sugarcane production region. The criteria are contestable, both in terms of whether or not they in fact represent the full set of important desirable characteristics, as well as how these characteristics may be actualized for the given context. We believe one benefit of undertaking a sustainability assessment is that it serves to promote more open and constructive dialogue about what is considered important and desirable.

Table 21 – Sustainability Assessment criteria for sugarcane-ethanol undertakings in São Paulo state, Brazil

Socio-ecological system integrity *Water and wastewater management* • Does the mill practice proper water management and work within the regulatory and ecological limits of the watershed? • Does the mill treat its wastewater to an acceptable quality? *Residue and waste management* • Is the waste generated in the activities of the mill minimized and are unavoidable residues treated or disposed of properly? *Biodiversity and ecological integrity* • Are appropriate steps taken to evaluate and protect the biodiversity and ecological integrity of the watershed (e.g. improving the connectivity of natural ecosystems and protecting wildlife), including lands outside of protected areas in the watershed? • Are the adverse cumulative impacts of monoculture on biodiversity appropriately managed? • Are economically viable alternatives for more ecologically appropriate sugarcane production fostered? *Sugarcane straw burning for harvesting* • Is the mill burning the sugarcane straw in the fields? Has the practice of sugarcane straw burning in the watershed been controlled, especially to minimize adverse impacts in the vicinity of protected areas and urban areas? • Does São Paulo have a feasible plan for eliminating sugarcane straw burning? *Air pollution* • Are air emissions from the mill properly evaluated, mitigated, controlled and treated? *Land use change* • Does sugarcane production maintain sufficient land for forests and other agricultural and food crops? *Socio-economic resilience* • Is sufficient socio-economic resilience being maintained for future generations (e.g. diversity of economic activities, maintenance of the local resource base, protection of local sources for food, water and other livelihood essentials, and encouragement of innovation and experimentation)? *Effects on soil quality and maintenance* • Is long-term soil fertility being evaluated and maintained?
Livelihood sufficiency and opportunity *Employment opportunities* • Does the company prioritize local labour?

- Are training opportunities for alternative employment available for all company workers (esp. cane cutters affected by mechanization)?
- Are company workers paid in a fair and transparent manner?

Quality of employment and safety

- Do company employees enjoy safe and healthy working and living conditions?
- Does the company respect worker rights and build positive worker-management relationships?

Community and regional development

- Does the company contribute to the surrounding community for education, culture and capacity building?
- Do the municipality and region have sufficient capacity to accommodate migrant sugarcane cutters (e.g. housing and other facilities) during harvest?
- Does the company enhance local economic opportunities and economic diversity (e.g. economic spinoffs)?
- Do the company's activities respect (eco)tourism activities of the region (visual impact, water quality, air pollution)?

National sovereignty

- Does sugarcane ethanol production serve to benefit all citizens (e.g. reducing import dependence)?

Intragenerational equity

Distribution of benefits and risks

- Are the benefits and risks generated by the presence of the company distributed equitably within local municipalities?

Interference in food production

- Will current and future sugarcane production respect other agricultural activities and avoid the replacement of food crops for energy production?

Intergenerational equity

Long-term ecological integrity

- Is sufficient biophysical and ecological integrity being maintained for future generations at all scales (esp. soil fertility, crop diversity, forest cover)?
- Does sugarcane production maintain soil quality well enough to allow sugarcane to be replaced by other crops in the future?

Economic resilience

- Is sufficient economic resilience being maintained for future generations (e.g. economic diversity, maintenance of the local resource base, protection of local sources for food, water and other livelihood essentials, encouragement of innovation and experimentation)?

Maintenance of culture and local knowledge

- Are traditional cultures and ways of knowing and local knowledge systems protected nationally (e.g. farming skills, local ecological knowledge, unique products)?

Resource maintenance and efficiency

Ecological efficiency of production

- Does the company seek cleaner production technologies?
- Has the company adopted more sustainable agricultural practices (soil conservation, biological pest control, green cane harvesting, non-chemical control of weeds)?
- Does the company maximize use of its resources and capacities through co- and by-production (e.g. multiple uses of residues for heat, power, liquid fuel, and soil amendment)?

Soil fertility

- Is soil fertility maintained and enhanced on the company's land (both owned and administered)?

GHG impacts

- Are GHG emissions and direct and indirect fossil energy use evaluated and minimized along the company's entire ethanol production chain, within an appropriate degree of certainty?

Perverse effects (efficiency paradox)

- Does ethanol production encourage automotive usage at any scale?
- Does increased ethanol production increase overall energy usage at any scale?

Social-ecological civility and democratic governance

Local governance

- Does the company contribute to and foster local good governance (e.g. participation in decision making, partnerships in initiatives)?
- Does the company contribute fairly to the costs of infrastructure and resources consumed that are shared with the community (e.g. schools, roads)?

Federal and state governance

- Do national regulations for the sugar-energy sector consider sustainability aspects, including transparency, participation of civil society and long term planning?

Corporate management

- Does decision-making within the company include all relevant stakeholders?
- Does the company sufficiently consider sustainability in its decisions?

Distribution of risks

- Are the risks presented by the company equitably distributed (e.g. among communities, genders and social groups), recognizing that some people have less capacity than others to accommodate increased risk?

Enhancement of learning

- Does the company help to build deeper and more widely shared understanding of local sustainability issues?
- Does the company provide opportunities for discussions and experience in collective decision making?
- International awareness
- Does international attention and scrutiny promote positive dialogue and practice in the sugar-energy sector and for this company in particular?

Prudence, precaution and adaptation

Uncertainty and adaptation

- Is the company sufficiently resilient in the face of change and surprise (e.g. multiple products, modular components, market alternatives, administrative flexibility and learning capacity)?
- Does the company promote the adaptive capacities of the region and reduce local vulnerability to external dynamics (e.g., extreme weather events, economic disturbances)

Data limitations

- Are key areas of uncertainty in environmental management being addressed at all levels (e.g. water resources, sugarcane straw burning, GHG emissions)?
- Is sufficient and timely information being shared between the various stakeholders (governments, mills, NGOs, citizen groups, international organizations) to promote informed decision-making?

Immediate and long-term integration

Promoting collective visioning and action

- Are appropriate and collaborative steps being taken by stakeholders at all levels to ensure the challenges and opportunities of sugarcane ethanol are addressed in an integrated manner (including the specification of desired short- and long-term goals)?
- Are tradeoffs amongst alternative options discussed and assessed in a sufficiently inclusive and informed manner, and designed in a way that does not displace significant adverse effects to future generations?

Promoting positive synergy

- Can the expansion of sugarcane positively influence other agricultural sectors at all scales (e.g. increased international attention)?
- Can positive actions undertaken by the company serve as a means of improving social-ecological outcomes, and promote better practices by other companies (both sugarcane-ethanol based, and otherwise)?

7.7 Observations regarding the sustainability criteria

As noted above, the case specific sustainability criteria provided in Table 21 were initially addressed in a set of observations of the case and context presented in Table 22 below. The observations draw from a wide variety of quantitative and qualitative indicators, and provide an initial analysis of the most significant considerations relating to the sugarcane-ethanol mill in its broader context. Throughout the iterations between criteria and observations, care was taken to ensure all the generic sustainability assessment criteria were addressed in the case specific context.

As previously noted, the observations were revised in accordance with comments by the mill and representatives from the municipal government. Both the sustainability criteria and the observations were well received. It is notable that the representatives from municipal government favoured quantitative indicators, and all attempts were made to provide such indicators in the observations. However, in order to protect the confidentiality of the mill – which was an initial requirement for participation – some indicators may only be presented in a qualitative manner. Ideally, future assessments may proceed with greater disclosure, while ensuring the mills are not harmed in the process, but rather benefit from the opportunity to improve their operations.

For each consideration in Table 22, the contributions to sustainability are ranked on a simple three-point scale, identifying potential positive impact (+), potential negative impact (−), and potential impacts that may be mixed, or positive or negative depending on how the project is undertaken (=). The purpose of ranking is not to sum up all the positive and negative indicators in a quantitative test, but rather to gain broad insights into areas of strengths and weakness, and associated openings for improving contributions to sustainability. Furthermore, to illustrate the importance of cross-scale interactions more explicitly, Table 22 provides a column detailing at what scales the interactions occur, recognizing that this process is imperfect, in that it attempts to simplify complex dynamics. The legend is as follows: M – Mill; C – Community; W – Watershed, region; S - São Paulo; B - Brazil; I - International; All- All scales (i.e. no particular scale).

Table 22 – Initial observations and indicators from sustainability assessment of the sugarcane-ethanol mill in São Paulo state, Brazil

Socio-ecological system integrity		
Water and wastewater management		
• The mill collects surface and ground water, and water usage is monitored. Regional licence data are not easily accessible, and there are reports of several small producers that collect water illegally. None of the interviewed actors had been audited in recent years regarding water consumption.	M	=
• Water consumption and the effects (including cumulative) of diffuse water pollution (e.g. fertilizer and soil runoff) at the regional level are insufficiently monitored, and the resulting uncertainty hinders proper long-term planning.	W	=
• Net water consumption at the mill is between 0.7 and 0.8 m^3 per ton sugarcane processed, which compares favourably to other mills. Further conservation is possible through improved irrigation, increased reuse of process water, and novel techniques (e.g. mechanical harvest permits washless sugarcane processing). Most water is returned to the watershed as treated wastewater or during ferti-irrigation with some evaporation losses during ferti-irrigation and in the cooling towers.	MW	+
• The mill's sewage is treated in a combination of a septic tank/filter and a compact sewage treatment plant with high percentage treatment efficiency, meeting government requirements.	M	+
• The mill's industrial wastewater is treated in treatment ponds. When pond capacity is exceeded, excess water is released into nearby freshwater in accordance with legislation. The mill is planning to construct a more efficient sewage treatment plant to better handle industrial wastewater.	M	=

• Where improper handling of stillage in ferti-irrigation occurs, it damages soil and contaminates rivers and groundwater, and is already occurring in some sugarcane operations.	MW	-
Residue and waste management		
• Brazilian sugarcane operations generally have effective organic material handling. In the studied mill, stillage, filter cake, and waste from septic tank are used to ferti-irrigate sugarcane plantation and riparian forests; bagasse is used for steam generation or stored for anticipated future power generation; and straw (when not burned) is left in fields for soil protection.	MB	+
• Improper handling of organic and inorganic substances (e.g. fertilizer, lime, pesticides, filter cake, stillage and ash from bagasse burning) can harm soil and water (e.g. eutrophication of waterways).	All	=
• Hazardous wastes (e.g. oils, greases, agrochemical packaging) are treated and disposed according to legislation.	M	+
• The recyclables are donated to an educational institution, which then sells them to fund programs.	ML	+
Biodiversity and ecological integrity		
• Since 2009 the company has recovered 65 ha of Permanent Preservation Areas[9], with a further 60 ha committed for recovery and currently under mapping. Part of this recovery was required by government, but also represents a proactive stance by the company. Some of the recovered area is on land administered by the company, which is notable because most sugarcane companies only recover their own land (despite approximately 80 percent of sugarcane coming from administered land).	ML	+
• As part of its environmental system, the company is developing a Legal Reserve (protected area) in neighbouring areas indicated by the environmental agency. In this case, the Legal Reserve area is equal to twenty percent of the total area of the mill.	ML	=
• The mill managers are studying areas to create a private protected area to be managed by regional stakeholders.	ML	+
• The lack of historical data on species richness in the region makes it difficult to assess the impact on biodiversity caused by the expansion of crops in the region in recent years. The mill is in the final stages of preparation of an Environmental Impact Statement that will include a broad survey of flora and fauna throughout the region, and then they will start a program for monitoring fauna.	W	-
• Land fragmentation is a serious threat to biodiversity conservation. Priority Areas for Biodiversity Conservation are considered during environmental licensing in São Paulo (Joly et al. 2010). The mill's land is located primarily in high priority areas that require ecological corridors to link native vegetation.	S	=
• Due to competition pressures, sugarcane mills do not reveal where they intend to expand sugarcane plantations, and this secrecy limits the environmental licensing process and land-use change assessment.	W	-
• Brazilian research indicates smaller units of ethanol production based on agroforestry and organic practices can contribute to greater biological diversity and reduce environmental impacts (Lombardi et al. 2009). However, such alternative forms of production have no competitive economic advantage and require government support for their implementation.	All	=
Burning of straw		
• Sugarcane straw is burned on forty percent of harvested area, although the practice has been controlled to minimize impacts to the vicinity of protected areas (Avolio 2002; Ometto et al.	M	-

[9] Under Brazilian law, the Permanent Preservation Areas (APP) are composed of belts of forest that are found on the edges of rivers, lakes and lagoons, hill-tops and slopes, and other environmentally sensitive areas which are essential to the preservation of water resources, scenery, health of animals and plants, biodiversity, soil, and the health of human populations in the area; they are mandatory on public and private lands.

2009; Ribeiro 2008). Straw burning harms humans, flora, fauna and water resources.		
• The mill has signed the Agro-Environmental Protocol, a state government initiative that aims to eliminate straw burning in areas with slopes less than 12 percent (suitable for mechanization) by 2014, and all land by 2017. To do so, leased areas with slopes greater than 12 percent will be returned to their owners, and the mill will expand into areas suitable for mechanized cutting. Elimination of straw burning will reduce both the ecological and health problems, and water usage in the processing step. The mill plans to achieve 85 percent mechanical harvesting by 2017, and 15 percent of manual harvesting without burning, carried out with new sugarcane cultivars with lower and softer straw content to facilitate manual cutting. It is not certain what land the mill will expand onto.	MWS	=
• Forty percent of the mill's sugarcane is grown in a loosely protected area (similar to IUCN Category V), where sugarcane plantations are allowed but straw burning is forbidden. The mill is still burning sugarcane straw there. The protected area committee is attempting to prevent the burning, while the mill is challenging the legitimacy of the protected area. The conflict is under negotiation.	M	-
• There is currently disagreement regarding burning regulation. Burning is banned within 1 km from urban centres, and local stakeholders and government want to enlarge the radius to 3 km, which the sugarcane industry challenges. In the past four years, there have been two occurrences of burning less than 1 km from urban areas.	ML	-
Air pollution		
• Air emissions at the industrial plant of the mill conform to regulations.	M	+
• The region in which the mill is located is becoming ozone saturated (a precursor to smog). The emissions of NOx from the mill lead to tropospheric ozone (an atmospheric pollutant). This current saturation may limit future regional expansion in ethanol production. The environmental agency is attempting to restrict electricity production from straw due to smog concerns, which reduces profitability of sugarcane.	W	-
• While emissions due to straw burning are not treated, the timing of burning is planned to avoid plume formation over urban centres, and conforms to regulation.	LW	=
Land use change		
• Sugarcane is replacing diseased orange crops as an approach to disease control, with a subsequent decrease in pesticide application.	L	=
• Regional direct and indirect land use changes due to sugarcane ethanol are both uncertain and contested.	B	=
• At the behest of the environment agency, the mill recently removed sugarcane crops under cultivation in a Permanent Protected Area (where agriculture is forbidden), and the land is becoming re-naturalized. It is notable that the sugarcane had been in the protected area for 30 years, implying a long history of inappropriate monitoring and enforcement by government now being corrected.	M	=
Livelihood sufficiency and opportunity		
Employment opportunities		
• The increase in mechanized harvest eliminates cane-cutting jobs while providing employment to more qualified workers (e.g. machinery operation). Recent plant expansion has maintained overall level of employment but changed employment demographics. The company offers retraining programs for all employees, to enable mobility towards more qualified positions. The company established intensive training in the off-season and also extensive training during the harvest, releasing staff to attend day classes and taking exams. Cane cutters who are illiterate or lack driver's licences (i.e. the more vulnerable) are less likely to be retrained.	M	=
• The total loss of jobs due to the elimination of manual cane harvesting represents a pool of unemployed workers that is too large to be absorbed by the sugarcane sector. Other economic sectors such as construction have absorbed part of the workforce (Mello 2011).	B	+
• The company prioritizes local labour, but has difficulty in finding candidates for many positions, because local residents lack qualification or prefer work in other areas (e.g. tourism).	ML	-

• The private sector of Brazil bears the cost for much staff training due to a lack of trained professionals and deficiencies in the Brazilian educational system.	B	-
Quality of employment and safety		
• In 2009 the mill implemented a Health and Safety Action Plan to reduce accidents in the field and industry. The Plan includes better equipment and improved monitoring, and reduced accidents by 54 percent during the last harvest, even accounting for expanded production.	M	+
• The cane cutters perform gymnastics every day before the start of the workday.	M	+
• Migrant workers receive routine inspections of their housing quality (e.g. treated water and sewage collection), daily transportation to the field, and return transportation back home after the harvest.	M	=
• According to the mill, harvesters are paid a fixed income plus a bonus for cane cut, in a manner that is considered transparent. This reduce problems of exhaustion, as the additional cane cut is not as high as in payment systems based only on production (Alves 2008).	M	+
• In the last six years the mill received one fine for breaking an agreement on the limitation of working hours. The fine was paid as a donation to the community. The company is supervised monthly, and currently is meeting all the requirements.	M	=
Community development		
• Of the 900 cutters 500 are migrants and are installed in non-permanent settlements, thereby creating the potential for social tensions due to seasonal population movement.	MLS B	-
• The mill provides kindergarten for children of employees with remaining vacancies filled by the municipal population. The company also has a program to encourage sports for teenagers.	L	+
• The mill has a project to collect used oil in the city, and also a partnership for proper disposal of fluorescent lamps generated by the municipal government.	L	+
• The mill organizes environmental education activities and provides learning material for primary schools in the neighbouring counties, as well as general environmental information available to residents.	LW	+
• There is a partnership between the mill and municipal government to maintain a seedling nursery, which provides seedlings to the public and for reforestation projects.	LW	+
Impact on other economic activities		
• Trucks transporting cane use the same highways as vehicles used by ecotourism lodges, potentially creating a nuisance during the tourist season. The smoke and ash from straw burning and the odour of stillage[10] applications are considered a nuisance to tourists.	L	-
• Tourism entrepreneurs and mill managers maintain a dialogue to find ways for mutual benefit. The mill avoids application of stillage and burning during high tourist season and informs the local inn prior to application.	L	+
Regional and local economy		
• The mill generates economic spinoffs (e.g., the company that handles the hazardous wastes and the provisioning of local services for neighbouring cities) (Martinelli et al. 2011).	L	+
• The company contributes to the development of local economy, and its tax contribution represents nearly half of total revenues received by City Hall.	L	+
Intragenerational equity		
Distribution of benefits and risks		
• The mill prioritizes hiring local labour, which can promote local employment and improve regional development.	L	+
• The mill directs its social and environmental programs to the surrounding municipalities benefiting the local population.	LW	+
• The large influx of migrant workers helps spread economic benefits farther, but creates	B	=

[10] Stillage (or vinasse) is "the residue grain from the manufacture of alcohol from grain." (McGraw-Hill Science and Technology Dictionary)

social problems in the sending and receiving communities. • The most direct health impacts on communities result from the smoke and ash released during sugarcane straw burning, which cause respiratory ailments in children, asthmatics, and elderly people, and increase the burden of health care on public services and families (Ribeiro, 2008).	LW	-
Interference in food production		
• The impacts of sugarcane ethanol on food production (and land use change more broadly) remain contested.	I	=
Intergenerational equity		
Long-term environmental impacts		
• Due to regulations that trade off ecological for economic considerations, compliance with environmental legislation does not ensure long-term ecological integrity. Furthermore, the quality of ecological monitoring and evaluation is insufficient to determine long-term trends.	B	-
• The impact of ethanol on GHG emissions depends greatly on land use change, which remains contested and uncertain (Lapola et al. 2010; Pacca and Moreira 2009; Sparovek et al. 2009). The mill lacks a Greenhouse Gas Inventory.	M	=
• Soil testing is performed in the fields associated with the plant with the objective of maintaining soil quality, and ensuring long-term productivity.	M	+
Economic resilience		
• There is ongoing research into transforming old sugar and ethanol mills into biorefineries capable of producing a wide range of products so as to increase economic resilience (assuming climatic conditions remain favourable). The mill is investing in product diversification.	MI	+
• The economy of São Paulo is diversified, and it is not expected to become overly dependent on ethanol and sugarcane (IBGE 2009).	S	+
Maintenance of culture and local knowledge		
• The impact (if any) of the mill and ethanol production on local traditional cultures and ways of knowing was not identified.	ML	=
Resource maintenance and efficiency		
Ecological efficiency of production		
• The mill is investing in cleaner production technologies (esp. reduce emissions, improve wastewater treatment, and reduce water consumption).	M	+
• Farming practices include precision agriculture for application of gypsum to correct soil acidity; organic and chemical fertilizers; herbicides, pesticides and maturing within the limits defined in national legislation. There is limited organic sugarcane production, and the product is limited to sugar.	M	=
• The region in which the mill is located is considered saturated with ozone (a precursor to smog). The emissions of NOx from the mill lead to further ozone production and ultimately smog and poor air quality. This current saturation may limit future regional expansion in ethanol production, as well as electricity production from bagasse.	MW	-
• The mill is diversifying their sugarcane products (including sugar and hydrated ethanol).	M	+
Soil fertility		
• The mill has measures to promote soil conservation (e.g. straw to protect soil from wind and water erosion, terracing to reduce volume and velocity of runoff, and rotation with peanuts).	M	+
• Soil loss is not measured and some of the agrochemicals used have not been tested for local conditions and their ecotoxicity remains uncertain.	MLW	-
GHG impacts		
• The plant lacks a GHG inventory to determine the carbon balance of its production process.	M	-
• Sugarcane ethanol production is still highly dependent on fossil fuels for the acquisition and transportation of inputs, operating machines, and chemical fertilizers. While it is possible to produce diesel from sugarcane, current costs are prohibitive.	B	-

Perverse effects (efficiency paradox)		
• The low cost of ethanol encourages car usage, and when coupled with government policies that support the automotive industry, both emissions (including GHGs) and traffic have increased.	S	-
• Combustion technology in cars has not improved in recent years.	All	-
Social-ecological civility and democratic governance		
Local governance		
• The mill is the largest company in municipality in employment and tax revenue, and may influence municipal decisions.	L	=
• Municipal public authorities are empowered only to supervise and enforce environmental standards defined by state government and environmental agencies. The municipality exercised its power by extending the required riparian buffer zone from 30 to 50 metres along the main river of the city. This buffer expansion was both to help maintain water quality and to make the river more enjoyable for tourists (who raft on the river), and has been considered as one successful means of managing sugarcane production.	L	+
• The mill is represented on municipal advisory councils on environmental, tourism and rural development, which promotes regional dialogue to address sugarcane-related problems, and tries to foster collective action and partnerships.	L	+
Federal and state governance		
• The environmental licensing process in São Paulo state tailors licensing rules based on the size and the location of the mill (e.g., an agri-environmental zoning being considered at the state level will be context sensitive).	S	+
• In order to improve good practice in the industry, the state government has developed the Agri-Environmental Protocol, a voluntary partnership between the departments of environment and agriculture and industry representatives. The agreement has high adherence of the mills, has increased mechanized harvest from 34 percent in 2007 to 55 percent in 2011, and aims to recover 265,000 ha of riparian vegetation by 2014 (SMA 2011).	S	+
• There is no government regulation of the maximum area of sugarcane crops in São Paulo, and crop area is largely dependent on market dynamics.	S	=
• The Federal Government has developed an inter-ministerial agreement that includes dialogue with industry and rural worker representatives. The agreement is generally regarded positively by the agrarian and land reform movements, although monitoring has not yet begun, and some of the signatory mills have been recently fined for using slave labour (CONTAG 2009; Scolese and Iglesias 2009). The mill related to this research is not yet a signatory.	BM	=
Corporate management		
• The mill was originally family run until the 2008 global financial crisis, at which point the owners sold a part of the company and hired professionals to the company's senior management. The change in the board brought attention to environmental management, work safety, and improved community relations.	M	+
• The current mill board has created a Sustainability Committee, with monthly meetings among senior and technical managers to discuss sustainability issues (e.g. environmentally friendly technologies, and social and environmental programmes).	M	+
International awareness		
• The interest of other countries in buying sugarcane ethanol may promote better practices in Brazil (both social and ecological) through non-tariff barriers such as certification; although excessive growth of demand may overwhelm capacity for monitoring.	All	+
• The company has customers who make broad and rigorous audits in order to follow international standards, thereby pushing the mill to raise its quality standards above the legal requirements.	All	+

Prudence, precaution and adaptation		
Adaptation		
• To promote adaptation, the industry has diversified its production and has invested in technology for the development of new products derived from sugarcane: bio-electricity, green plastics, biodiesel, diesel and hydrocarbons of low carbon.	M	+
• The mill can quickly respond to changing market prices for sugar and ethanol by changing the final product.	M	+
• Sugarcane production is climate sensitive. Drought (e.g. 2010) and excess rainfall (e.g. 2009) reduce productivity and cause shortages in the domestic market.	All	-
Uncertainty and data limitations		
• Indirect land use change is still a critical uncertainty. Conflicting scientific research is inadequate to support policy making, and regulation is lacking (e.g. the mill's anticipated expansion of sugarcane crops will not require any study of indirect land-use change).	M, All	-
• Cumulative impacts of sugarcane monocrops, especially effects on biodiversity, have not been studied enough.	B	-
• Notable data limitations include the impact of diffuse pollution (from agricultural inputs and eroded soil) on water bodies, the maintenance of biodiversity, GHG emissions, and long-term groundwater availability in the watershed. The São Paulo environmental agency is expected to increase data collection, although care is needed to ensure data are representative and the proper indicators are chosen. Furthermore, it is important for the municipality to invest in local monitoring to aid decision-making and outcomes.	S	-
• There is no available information about the energy return on investment (EROI) of sugarcane by region, although the general EROI for sugarcane ethanol is considered favourable compared to most biofuels (Giampietro and Mayumi 2009). How the EROI will change with mechanization was not found.	S	=
• The rapid expansion of sugarcane plantation in the Tiete-Jacaré Watershed has not been monitored and the impacts are difficult to measure.	W	-
• Lack of accurate data for lifecycle assessments limits certainty in any overall analysis of the production chain, requiring on-going research and adaptive management on the part of all stakeholders.	M	-
• The company is conducting an Environmental Impact Statement as part of the requirements for acquiring environmental licensing to expand its production. The company is also planning to develop a Sustainability Report using GRI guidelines, and apply the Ethos Indicators of Corporate Social Responsibility, which can improve planning and increase transparency.	MLW	+
Immediate and long-term integration		
Promoting collective visioning and action		
• The regulation of activities of all the mills needs better knowledge of carrying capacity and cumulative effects (esp. on water and biodiversity) to ensure long-term benefits for the region. To this end it will be necessary to expand and integrate the existing environmental and social information, in order to overcome data limitations and be prepared to deal with uncertainties. This issue demands collaboration (esp. involving government, industries, agriculture, university and civil society organizations).	ALL	=
• Many important decisions (e.g. watershed management, policies that increase energy usage through low-cost ethanol, regulating agricultural practices, and biodiversity management) are made at the state and federal government levels and may neglect local and regional factors (e.g. the importance of ensuring desirable local ways of knowing and living are not harmed).	B	=

Promoting positive synergy		
• The sugarcane industry may be a good means of seeking improvements in other Brazilian agriculture sectors in a manner that respects natural limits, promotes good governance, and improves both quality of life and employment at the local level. Newly advanced benchmarks and good agriculture practices can result in mutually reinforcing and lasting benefit.	BI	+
• The municipality may benefit by developing qualified professionals in a way that the local population receives the benefits and the company avoids hiring employees from distant cities.	ML	=
• If properly undertaken, Brazil could be a model for other nations on how to develop sustainable fuels.	MB	+
• The actions of corporate social responsibility can contribute to regional development and improved quality of life. To this end, the company needs to continually improve social programs and employee training, evaluate the quality of its initiatives and dialogue with the local population. Likewise, the municipality must be proactive and willing to invest in the future.	ML	=
• The mill can enhance its framework for action from the generation of more environmental information and links with other regional players to increase protection of animal species and protected areas, share information about water and soil quality and invest more in monitoring, cooperate in designing training for alternative employment, demonstrate how best to integrate stakeholders in decision making, etc.	MLW	+

7.8 Discussion

The observations provided in Table 22 above reveal that this sugarcane ethanol operation and its broader context have a wide range of positive and negative effects, many areas of potential improvement, serious pitfalls to avoid and uncertainties to address. While not every important theme can be discussed in the limited space, we will elaborate on some key issues that emerged during the assessment: (1) long-term water availability and water quality maintenance; (2) biodiversity enhancement and reversal of ecological fragmentation; (3) the elimination of sugarcane straw burning and increasing mechanization; (4) indirect and direct land-use change; and (5) the quality and availability of livelihood opportunities. These five issues were proposed by the research team and approved by various stakeholders, including mill management and government environmental officers. Furthermore, we propose these issues as priority issues for broader national strategy relating to sugarcane-ethanol production.

The five issues are first discussed at the strategic level, as they all have strategic level implications and cumulative impacts. Following that, the issues will be grounded in the local context of the mill as part of a brief discussion on the potential benefits of collaborative partnerships at the municipal level. Finally, it is worth noting that the more direct impacts of the mill, both positive and negative, discussed in the observations and indicators shown in Table 22, provide the mill's sustainability committee with a comprehensive framework for exploring opportunities for improvement. To this end, the assessment process provides both strategic and practical insights for progress towards sustainability.

7.8.1 Key strategic issues in sugarcane ethanol assessment

This section will briefly elaborate on the five issues noted above. These issues are all embedded in the social-ecological context of Brazil and influence one another as well. These issues must be addressed through better integration across sectors and scales.

None of these areas of concern discussed below can be adequately addressed at the mill level.

Water, biodiversity and land use change

At local to national levels, sugarcane ethanol is engendering important ecological problems. Water is an important concern for agriculture in Brazil, in terms of freshwater availability and quality. The continued availability of water for sugarcane processing is subject to future freshwater supply, and the changing consumption patterns of municipalities and industry. As was previously noted, the watershed of the mill under investigation is approaching regulatory thresholds. At some point water rationing may become necessary, and the ethanol mills may be required to increase water efficiency simply to maintain current levels of production. One means of addressing water usage related to sugarcane production is through agri-environmental zoning, which can set targets and limits to consumption, but requires much more stringent monitoring and enforcement.

Concerning water quality, there is relatively poor knowledge of non-point-source pollution (e.g., agricultural inputs and soil runoff) and its impacts on waterways and human health. The state environmental agency is expanding monitoring points for surface and ground water (as well as air and soil), and the indicators are periodically evaluated so as to provide a general understanding of the current situation. Monitoring is to be more concentrated in areas that experience higher levels of pollution. While the state monitoring system provides general baseline data, the data must be enriched through separate monitoring programs at the municipal and watershed levels. Local monitoring programs can provide finer detail on specific concerns not addressed by the state agencies, and may also supplement areas that are poorly monitored by the state (because they are less polluted). The water quality data for our case specific watershed are considered insufficient to support decision-making, in part because the watershed is not in a state priority area given that pollution levels are below thresholds, and local monitoring has not addressed the data limitations.

Biodiversity is another area of concern that requires a regional and strategic approach. While the mill complies with the legal requirements, successful enhancement of biodiversity is an issue of regional connectivity and cumulative effects, which result from the mosaic of monocultures and protected areas. The characteristics of sugarcane plantations themselves also undermine biodiversity due to a number of factors: monoculture leads to low diversity of organisms; sugarcane plants have a low physiognomic and floristic similarity with the natural habitat of forest or savannah; pesticides and burning harm flora and fauna; and isolated trees are suppressed to facilitate mechanization (von Glehn 2008). Durigan (2010) argues a paradigm shift is needed to better recognize that while conservation has individual costs, it is of collective interest and therefore should be supported fairly on private land. The economic incentives for protection of remnant vegetation and restoration of areas relevant to biodiversity conservation on private lands are urgent, and need to be implemented in Brazil.

Biodiversity depends strongly upon land use, and the watershed in which the mill is located is experiencing tremendous land fragmentation, as more than 95 percent of vegetation fragments are smaller than 100 ha, which worsens the isolation of populations of plants and animals and threatens genetic diversity. As noted in Table 22, there is general uncertainty regarding the land-use impacts of sugarcane ethanol, in part because Brazilian environmental impact statements do not monitor several aspects of land-use change, including crop substitution and land fragmentation (da Costa 2008), and are limited by the culture of secrecy among ethanol mills surrounding future land developments, because such knowledge is of strategic economic value. Finally, as will be discussed below, the expansion of mechanical harvesting will result in sugarcane crop displacement, as mechanized harvesting cannot take place on highly sloped land.

Straw burning, mechanization and employment rights and opportunities

The elimination of straw burning in the fields, which should be nearly complete by 2017, is expected to have several impacts worth considering. There are obvious benefits to eliminating burning, particularly in terms of air quality and health, as straw burning is a major source of local air pollution and releases carcinogens. Furthermore, straw burning is a nuisance to tourists and undermines the ecotourism sector in the region of our mill. Eliminating straw burning may allow for more residues to remain on the field, which benefit soil fertility. Alternatively, the straw may be used for electricity production and even second-generation (cellulosic) ethanol production.

Despite noted benefits, the elimination of straw burning will entail other consequences. The impacts of mechanical harvesting on the energy return on investment (EROI) of ethanol production is uncertain, although experience with corn ethanol indicates that mechanization may lower EROI (Giampietro and Mayumi 2009, ch 7). Switching to mechanical harvesting would entail land-use change because mechanization requires abandoning steep-sloped land (greater than 12 percent grade). Land-use change is a central concern in sugarcane ethanol assessment in Brazil (Lapola et al. 2010). If properly undertaken, the transfer between steep- and shallow-sloped lands may promote greater crop diversity and enhance ecological connectivity, although this requires analysis beyond what is provided herein. The mill under investigation has considered maintaining some portion of the steep land and harvesting it with manual labour beyond the 2017 deadline. It is also important to note that decisions are highly influenced by economic and financial considerations, which are quite dynamic and dependent upon world market signals.

The mechanization of sugarcane ethanol will also impact employment patterns and the sugarcane agroindustry sector will continue to change its worker profiles in coming years. While mechanical harvesting requires more specialized work, it removes a source of employment that is relied upon by many workers (including migrants), especially those who lack the minimum requirements to participate in the retraining programs. While other sectors of Brazil have been able to absorb some of the labour, notably the construction sector, there are seemingly insufficient alternative livelihood opportunities for these displaced workers. Furthermore, the most vulnerable workers are likely those who lack basic skills, such as literacy, that are necessary to secure other employment. At the same time, mechanized harvesting will eliminate many of the jobs for which the ethanol sector has been criticized internationally, notably with regard to labour conditions and the impacts of and on migrant labour (Martinelli and Filoso 2008; Nuffield 2011).

In sum, mechanization will not be without benefits and drawbacks, and despite being fundamental to environmental protection, it is inevitable that mechanization will create different winners and losers. Ideally, whatever changes to agricultural practices that occur should take place with some idea of what the desirable end goals are, and how best they may be achieved.

7.8.2 The local context – the need for collaborative partnership

The five issues discussed above all relate to the context of the mill under investigation, and in certain instances the mill has responded in a progressive manner. First, the mill is investing in technology to decrease water consumption and improve treatment, and is restoring sensitive ecological areas and will soon implement fauna monitoring and establish ecological corridors of riparian vegetation. As for eliminating straw burning, the mill will follow the planned phase-out of straw burning by 2017, and this can be considered positive for environment, public health and ecotourism reasons noted above. In terms of land use change, the mill has prioritized expanding into land that previously grew diseased oranges. To address worker rights and safety, recent mill programs have resulted in reduced accidents, and improved work safety. The mill also offers retraining programs for displaced workers although it is uncertain how successful the retraining programs are at reaching the most vulnerable (for this particular mill and in general). Finally, the mill is also in the process of improving its environmental and social monitoring through initiatives that include Global Reporting Initiative Sustainability Reporting, Ethos Indicators of Corporate Social Responsibility, Bonsucro Certification and ISO 22000.

Despite the efforts by the mill regarding the issues described above among others, achieving significant positive gains requires collaborative partnership at the community and regional levels and strict limits on the negative impacts. For example, to ensure positive water benefits, the local government must identify the priority concerns, such as soil runoff into the rivers used for ecotourism. Similarly, without a regional plan for improving ecological connectivity, the benefits of the mill's individual efforts will be diminished. Likewise, the government must also be involved in providing new employment and training opportunities for displaced workers. Responsibility for better practice and outcomes must be widely shared.

There appears to be tremendous potential for the mill and local government to develop joint strategic water, biodiversity, and capacity building initiatives, and dialogue is already taking place. To participate more effectively in regional governance, the mill sends representatives to municipal councils, and has initiated dialogue with the regional tourism association to help resolve conflicts between sugarcane production and tourism. Furthermore, as was noted in Table 22, the mill and the community collaborate on social programs in education and sports, although there is recognition that procedures are necessary to evaluate effectiveness of the initiatives.

To ensure positive outcomes from collaborative partnership, it will be necessary to navigate both power dynamics and politics. The mill is a powerful stakeholder – as it is the largest employer and is responsible for approximately half of municipal tax revenue – and its favoured position implies that it may shape dialogue for its own interests and be a source of both positive and negative change, depending on how it interacts with local stakeholders and the environment. In these political actions, all stakeholders must ensure that any partnerships are sufficiently nonpartisan such that long-term plans survive changes to the municipal government.

7.9 Towards more sustainable ethanol production

This paper applies a sustainability assessment framework to assess a sugarcane ethanol mill in São Paulo state, Brazil, seeking to identify opportunities for improvements towards sustainability. A sustainability-based strategic level assessment, such as the one described above, may serve well in guiding and informing an anticipatory and participatory planning program by helping to identify the broad objectives to be met, and providing a comprehensive framework with explicit criteria for comparative evaluation of the main options for fiscal, regulatory, planning and other means of managing the growth. The case described above demonstrates that important insights can be drawn by applying an assessment framework that covers the full range of sustainability issues and seeks integration across disciplines and scales. The research presented above ideally demonstrates both the importance of such kind of assessment and the unavoidable complexity inherent in the integration of things that matter. Sugarcane ethanol production is not good or bad in and of itself, but rather as a result of how it is undertaken.

The results of the assessment indicated that for the specific context at hand, important opportunities for improvement fall under five categories: (1) long-term water availability and water quality maintenance; (2) biodiversity enhancement and reversal of ecological fragmentation; (3) the elimination of sugarcane straw burning in the fields and increasing mechanization; (4) indirect and direct land-use change; and (5) the quality, availability and durability of livelihood opportunities. The five issues all require broader strategic planning, but must also be understood within the local context of the mill and its watershed. To address these issues requires long term integrated planning and monitoring, better understanding of cumulative impacts and thresholds, recognition of important tradeoffs, an enforcement of limits, and a credible and collaborative decision-making process that involves and empowers stakeholders to set the agendas and seek common goals. Furthermore, we propose these issues as priority issues for broader national strategy relating to sugarcane-ethanol production. Ultimately, important and difficult decisions must be made, decisions that will be simultaneously technical, economic, social and ethical. This work contributes to that broader conversation.

This is the end of the manuscript.

7.10 Key recommendations for sustainability assessment of energy systems emerging from the case Brazil study

This section describes some of the outcomes from the sugarcane-ethanol case study more generally relevant for the dissertation, and focuses on four points of note.

First, this chapter highlighted the importance of grounding the assessment within its broader context. Many of the impacts related to the mill can only be understood within the broader social-ecological system. For example, water supply and water quality depend upon, among other things, development in the watershed leading to other uses of water, rainfall variability, and point and non-point source pollution. These issues cannot be addressed adequately at the level of the individual mill, but rather require planning, regulation and monitoring at multiple scales (local, regional, watershed, state, etc.). In order to make some of the cross-scale interactions more explicit, the key results table included a column detailing at what scale(s) the noted result is taking place. Much deeper "connecting the dots" is evidently needed and currently unavailable.

Second, the case study illustrated the difficulty of interpreting quantitative data, which arose in this case for several reasons. Notably, in many instances necessary data are unavailable, such as detailed and credible analyses of land-use change, measurements of greenhouse gas emissions, and ecological connectivity. To complicate matters, the data sets are often fragmented, as different departments at various governmental levels collect different types of data with no apparent means of integrating them across areas of (e.g. to determine the impact of water pollution on health). In certain instances, data are withheld for private reasons, such as proposed expansions of sugarcane production, which have financial implications. This is not to argue that informed decisions cannot be made, but they are hindered by data limitations at all scales.

Third, despite its limitations, the data presented in the key results indicate in a preliminary manner that social-ecological thresholds are being approached, especially concerning land-use change, fresh water availability, biodiversity, air quality, workers' rights and livelihood opportunities. Uncertainty remains regarding which thresholds are most important, how they interrelate, the time frame available to address them, and what the outcomes will be. The thresholds must be explored in relation to upcoming trends in the Brazilian sugarcane ethanol sector, particularly efforts to expand sugarcane production and increase mechanization. A more rigorous analysis of these concerns was outside the scope of the present case study.

Finally, this research illustrates the importance of government oversight in the energy industry. As noted by the Nuffield (2011), unfettered expansion of sugarcane ethanol, in large part due to rising international demand, risks both overwhelming capacity for management at all levels, and crossing important social-ecological thresholds. Governments, both Brazilian and beyond, must take responsibility for ensuring that sugarcane ethanol is produced in a manner that contributes to sustainability, and this requires regulating both the amount of sugarcane ethanol produced, as well as the manner in which it is produced. Some extreme consequences of unfettered market expansion include the use of slave labour and death due to over-exhaustion (Nuffield 2011).

Likewise, the key results note the mill under investigation has been fined for issues that include exceeding labour hours and illegally burning straw in protected areas. While the mill has also shown many progressive tendencies, current market forces encourage inappropriate activity, and local communities appear overwhelmed by the power of the sugarcane ethanol industry.

The themes discussed above – the importance of the broader social-ecological context, the difficulty in interpreting data, the presence of thresholds, and the importance of government oversight – have all been incorporated in a generalized manner into the systems- and energy-informed criteria set proposed in Chapter 4. Furthermore, these topics will be revisited in the concluding chapter (Chapter 9) along with the insights emerging from the other case studies. Before that, however, it is necessary to travel to Senegal for the fourth and final case study underpinning this dissertation.

Chapter 8 – Sustainability assessment of the agricultural and energy systems of Senegal

This chapter reports on the final case study undertaken for this dissertation: a sustainability assessment that originally centred on the burning of agricultural residues (primarily peanut shells) for cooking applications in Senegal, and ultimately focused on the broader agricultural and energy systems of Senegal. The field research began in April 2011 and continued until August 2011. The manuscript is in the process of being submitted to a journal. The outcomes of the assessment are generally described in the following manuscript. However, for the purpose of this dissertation, there are some interrelated insights worth highlighting, and these insights will be presented following the manuscript.

In relative contribution, I was the principal investigator for the case study, and undertook all of the field research. Prof. Gibson provided supervisory oversight and contributed to the analysis.

Sustainability assessment of the agricultural and energy systems of Senegal
By Kyrke Gaudreau and Robert B. Gibson

Overview

To improve decision-making, sustainability-based approaches to assessment of options and undertakings demand that we move beyond narrowly defined considerations to address the full suite of requirements for progress towards sustainability, as well as the interconnections, feedbacks and uncertainties that typify complex socio-ecological systems at all scales. This paper reports on a sustainability assessment exercise that originally focused on burning agricultural residues, primarily peanut shells, for cooking applications in Senegal. The scope of assessment had to be expanded to address the agricultural and energy systems of Senegal when closer examination revealed a complex set of energy and agricultural system interactions that could undermine the anticipated positive effects of initiatives centred primarily on peanut residue cookstoves. The case highlights the need to be open to expanding the scope of assessment to address underlying and/or unexpected issues that cannot be addressed appropriately at the project scale. In particular the case illustrates how the assessment of an energy system may serve as an entry point into a deeper exploration of the context in which the energy system is embedded. The analysis also illustrates a situation in which there are no evident right answers, but rather different paths that may be followed, each with its own degree of uncertainty, path dependence, feasibility, degree of fairness, cultural sensitivity, trade-off acceptability and possibilities for public judgement of overall desirability. To address these issues requires long term integrated planning and monitoring, better understanding of cumulative impacts and thresholds, recognition of important trade-offs, and a credible

and collaborative decision-making process that involves and empowers stakeholders to set the agendas and seek common goals.

Keywords: sustainability assessment, agricultural residues, peanut production, international development, bioenergy, sustainability criteria.

8.1 Introduction

How sustainable is it to burn peanut shells as a cooking fuel in Senegal? In Senegal and elsewhere, using agricultural residues as a cooking fuel appears to offer an attractive means of reversing deforestation, eliminating the hazards related to collecting fuelwood, and – with properly designed cookstoves – reducing the adverse health impacts related to cooking with traditional stoves[11] (GIZ 2011; Hrubesch 2011; REAP-Canada 2011; Rehfuess 2006). Since peanut shells in Senegal tend to collect next to processing facilities, or are burned in the fields, the potential to use residues for a seemingly more productive task is enticing. Given that Senegal has lost almost half of its forest cover since the 1960s (Mbow et al. 2008; Tappan et al. 2004), the need to provide the forests some respite is all too apparent.

We set out to explore the potential for burning peanut shells in Senegal, with a particular focus on the country's Peanut Basin, an area that accounts for approximately 30 percent of Senegal's surface area and 75 percent of Senegal's grain and peanut production (ASPAB 2009). The objective was to determine whether, and under what conditions, cookstoves burning peanut-shell residues could promote progress towards sustainability. As is typically the case, however, there are other factors involved, and the initial assessment process revealed that two important and interrelated constraints would hamper the assessment objective as it was originally defined for Senegal, and might similarly affect assessments elsewhere.

First, the general question of burning peanut shells in cookstoves in Senegal cannot be addressed appropriately at the project scale. There are too many strategic level considerations, such as the historical importance and perils of reliance on peanuts as an export crop, and the complex interrelationship between deforestation and soil fertility,. These represent key challenges and opportunities that must be addressed simultaneously, in an integrated manner, and at a sufficiently broad scale. Second, Senegal and its various governance institutions do not have established criteria for evaluating initiatives such as peanut residue cookstove programs, to ensure they are conceived and designed to promote progress towards sustainability within the energy and agricultural systems of Senegal, and broader Senegalese society. While both government and non-governmental organizations at all scales have outlined important strategic issues regarding the energy and agricultural systems of Senegal (CSRE 2008; e.g. MDE 2007; UNDP 2010b), the issues have not been integrated and elaborated into an articulated understanding of what is needed to determine and strive towards a more desirable future for Senegal. This

[11] Many people are familiar with the German development agency GTZ, which is now known as GIZ, due to a consolidation with other agencies in January 2011. All references to this agency will use the current acronym GIZ as opposed to the previous GTZ.

situation is not unique to Senegal; few jurisdictions anywhere have clearly established, sustainability-based criteria to guide decision making. But without such criteria, it is difficult to determine whether, and under what circumstances, burning peanut shells in cookstoves would be a positive step forward.

This paper reports on a research project that explored these complex interactions at both the project and strategic scale and considered the broader implications for how best to approach the evaluation of apparently desirable options for improving ecological stewardship and human wellbeing. In doing so, we developed a comprehensive set of sustainability criteria for energy and agricultural undertakings in Senegal, and provide initial observations for how these criteria are being met in Senegal.

The outline of this paper is as follows. First we explain why assessing the potential for burning agricultural residues requires us to expand the scope of assessment to the strategic level to address the complexity and interrelationships among the agricultural and energy systems of Senegal. Following that, we apply Gibson's (2006b) sustainability assessment framework as a means of crossing the project-strategic divide and specifying criteria for evaluations and decisions. The methodology, described in section 8.4, involved a case study approach combing documentary analysis, key stakeholder interviews and participant observation. Third, we propose a preliminary set of criteria for guiding decision making on energy and agricultural initiatives in Senegal to promote progress towards sustainability, and provide an initial set of observations about factors (conditions and trends) that represent key energy and agricultural considerations with implications for deliberations on use of peanut residues in cookstoves in Senegal as a whole. Finally, we provide an initial response to the original question by arguing that burning agricultural residues for cooking applications appears to be generally unadvisable, and instead we suggest two alternatives that merit further research.

8.2 The larger context for peanut shell fuelled cookstoves

Using peanut shells instead of charcoal and wood as cookstove fuel seems on the surface to be an attractive way of reducing deforestation pressures while finding a valuable use for a waste product. But like other seemingly simple solutions, the peanut shell cookstoves idea needs to be evaluated with careful attention to the complex interactions of factors in the larger context. In this case, the larger context includes the linkages between the energy and agricultural sectors of Senegal.

With a population that is already about 13 million and is growing by 2.5 percent per year (UNDP 2010b), Senegal faces increasing challenges in providing adequate livelihoods for all while maintaining its non-renewable resource base and ecological systems. The country ranks low on the human development index (144th place out of 169 countries), although its GINI index has improved, and currently stands at 39 (UNDP 2010a). Over half the population lives below the poverty line, with many in extreme poverty (Diaz-Chavez et al. 2010; UNDP 2010b). Literacy rates and education levels are both low and, coupled with poverty, prevent many Senegalese from becoming active citizens (UNDP 2010b). Gender inequality is pervasive; girls are often pulled out of school early to perform household duties, and women cannot own land and are effectively barred from certain forms of employment (IYF 2009; OECD 2008; Perry 2005).

Senegal's economy is characterized by a structural deficit and high unemployment (IYF 2009; UNDP 2010b). The country is rapidly urbanizing, in part due to the shortage of livelihood opportunities in the rural villages (Fall et al. 2008; UNDP 2010b). Facing high rural poverty rates, many youth migrate to the cities, where they become part of approximately 100,000 youth who enter the job market each year and wait on average four years to find employment (IYF 2009; OECD 2008; UNDP 2010b). Most employment opportunities are informal and maintained in a context of uncertainty characterized by personal networks of credit and exchange, a lack of basic services (e.g. running water), vulnerability to external shocks, improper land tenure, underage labour and low wages (IYF 2009; Osborn 2009; UNDP 2010b).

Senegalese agriculture is primarily rainfed, and based on small farms growing peanuts, millet, and sorghum (OECD 2008), although peanuts have been the primary cash crop for decades. Despite its extensive agricultural base, Senegal suffers from serious food insecurity, which is expected to worsen in coming years due to the increased cost of imported staple foods (notably rice and dairy products), declining yields due to reduced soil fertility as a result of intensive and improper peanut farming practices, and the reduced export earnings from peanuts on the world market (Brown 2008; Diaz-Chavez et al. 2010; Elberling et al. 2003; UNDP 2010b).

Senegalese agriculture is perhaps best understood by recognizing the diminishing centrality of peanuts (e.g. Caswell 1985), which were once the economic engine of Senegal due to years of government and colonial promotion. The percentage of export earnings related to peanuts has dropped approximately sevenfold, from 80 to 12 percent, since the 1960s (Hathie and Lopez 2002; UNDP 2010b), in part due to competition from other oils, reduced yields and increased foreign trade barriers (e.g. regulations on Aflatoxin contamination). Peanut farming still employs up to a million people and occupies 40 percent of cultivated land. Although the government has been promoting agricultural diversification in order to improve food security (Diaz-Chavez et al. 2010; OECD 2008), no viable alternatives have yet taken root.

The decline of peanuts is involved in, and affected by, Senegal's evolving urban-rural dynamic. The low prices paid to agricultural producers for their peanuts has been seen as an indirect taxation of rural areas for urban benefits, and has encouraged an unlicensed peanut trade through Mali.[12] Furthermore, the reduction of farm income is an important driver of Senegal's rapid urbanization (Tappan et al. 2004), which has been associated with, among other things overtaxed infrastructure in urban and peri-urban areas, high levels of youth unemployment, and growing social discontent (Fall et al. 2008; IYF 2009; OECD 2008; UNDP 2010b).

[12] The unlicensed trade of peanuts was noted by several interviewees. At the time of writing, there had been a military coup and ongoing violence in Mali, and it is unclear how this will impact the peanut trade (both licensed and unlicensed).

Similar to the agricultural system, Senegal's energy system (both modern and traditional) is facing various challenges. The electricity system is composed of largely inefficient fossil-fueled infrastructure that is unable to meet demand and suffers from increasingly frequent power outages, which discourage economic growth and fuels public discontent (African Bulletin 2010; Callimachi 2011; CSRE 2008; Diop 2009). The cost of importing oil for electricity production increased from approximately US$400 million in 2000 to US$800 million in 2006, an increase 24 percent due to rising consumption and 78 percent due to increases in oil cost. It is consumed almost half of export earnings by 2007 (MDE 2007). Due to inadequate refining capacity, a significant fraction of imported oil is externally refined at a higher cost (CSRE 2008; Youm et al. 2000). While Senegal has petroleum deposits off its southern coast, exploitation is currently not feasible due to inadequate infrastructure and low refining capacity (CSRE 2008; Youm et al. 2000).

One consequence of the weakness of Senegal's energy system is that the country remains heavily reliant upon traditional bioenergy, primarily fuelwood and charcoal for cooking, and is overexploiting its forest resource base (MDE 2007). The overuse of wood and charcoal for cooking has worsened deforestation and desertification, and when coupled with overgrazing and agricultural expansion, has led to an almost 50 percent reduction in forest cover since 1965 (Mbow et al. 2008; Tappan et al. 2004).

Deforestation is also intimately connected to problems in Senegal's agricultural system. The decrease in soil fertility and productivity, and associated loss of livelihood opportunities, have encouraged farmers to abandon their fields and clear forests in the southeast in order to renew farming (Tappan et al. 2004). Initiatives to maintain or recover soil fertility would therefore also help to protect the remaining forests and using peanut shells and other agricultural residues for soil enhancement is one possibility. What this means is that burning agricultural residues as a fuel source removes their potential use as a soil amendment, and may ultimately lead to deforestation, the very outcome their use was designed to prevent.

The context described above has significant implications for decision making on possible initiatives that affect among other things soil fertility, deforestation, and urban-rural dynamics in Senegal. It is clear there are important interconnections between the energy and agricultural systems of Senegal. Unfortunately, the current energy system is clearly not now in a position to supply electric alternatives to cookstoves. Likewise, the current agricultural system is now currently able to provide an alternative to growing peanuts. Finally, the anticipated requirements for livelihoods as well as the trends in deforestation are sufficiently desperate to impose serious imperatives for action.

The discussion above establishes that the larger context of soil depletion, and charcoal and fuelwood burning, entails reformulating the initial scope of inquiry to address the interrelationships between the energy and agricultural systems. The broader inquiry, including attention to a framework for identifying and evaluating options, will be outlined in the following section.

8.3 Sustainability assessment

Because of the larger contextual factors discussed above, it is not reasonable to assume that burning peanut shells in cookstoves is a good idea and that the key question is how best to design the cookstoves and facilitate their adoption. Instead, the question is broader and more strategic: what to do with peanut shells in the context of improving the alignment of energy and agricultural policies and associated systems in Senegal to enhance rural livelihood opportunities, reverse deforestation and strengthen the national and local economies. In that assessment, peanut shell fuelled cookstoves are only one option, probably at best an imperfect one.

For this larger agenda, the assessment framework to guide the identification and evaluation of options needs to integrate attention to the interacting set of influencing energy and agricultural system factors, and recognize the full suite of objectives for enhancement of prospects for lasting wellbeing in Senegal, especially the rural, peanut growing areas. To illustrative how such a framework may be constructed and elaborated, this section outlines how a generic sustainability assessment framework can be adopted and specified for the particular

Sustainability assessment refers to the use of integrated frameworks to identify and evaluate the potential effects of alternative undertakings and find the best options for progress towards sustainability (Devuyst 1999; Gibson et al. 2005; Pope et al. 2004). The frameworks require assessment agendas defined broadly enough to capture all significant social-ecological system interconnections, feedbacks and uncertainties and to address the full suite of requirements for sustainability (Gibson et al. 2005; Walker and Salt 2006). The objective is to identify options most likely to deliver multiple, mutually reinforcing fairly distributed and lasting gains while avoiding significant adverse effects. An important step in undertaking sustainability assessment is combining established sets of generic sustainability criteria with attention to the key considerations for the particular case and context.

For the current research we began with Gibson's (2006b) sustainability assessment framework, versions of which have been applied in several energy systems cases at both the strategic and project levels (Duarte et al. 2013; Gaudreau and Gibson 2010; JRP 2009; Winfield et al. 2010). The starting point is generic criteria based on eight categories of requirements for progress towards sustainability. These are shown in Table 23.

The criteria presented in Table 23 serve as a broad template that must be elaborated and specified for the particular case and context. It is through the elaboration and specification of these criteria for a specific case that the researchers and practitioners develop an understanding of the scope and priority foci for the assessment.

Table 23 – Sustainability assessment decision criteria

Socio-ecological system integrity Build human-ecological relations to establish and maintain the long-term integrity of socio-biophysical systems and protect the irreplaceable life support functions upon which human as well as ecological well-being depends.
Livelihood sufficiency and opportunity Ensure that everyone and every community has enough for a decent life and that everyone has opportunities to seek improvements in ways that do not compromise future generations' possibilities for sufficiency and opportunity.
Intragenerational equity Ensure that sufficiency and effective choices for all are pursued in ways that reduce dangerous gaps in sufficiency and opportunity (and health, security, social recognition, political influence, etc.) between the rich and the poor.
Intergenerational equity Favour present options and actions that are most likely to preserve or enhance the opportunities and capabilities of future generations to live sustainably.
Resource maintenance and efficiency Provide a larger base for ensuring sustainable livelihoods for all while reducing threats to the long term integrity of socio-ecological systems by reducing extractive damage, avoiding waste and cutting overall material and energy use per unit of benefit.
Socio-ecological civility and democratic governance Build the capacity, motivation and habitual inclination of individuals, communities and other collective decision-making bodies to apply sustainability requirements through more open and better informed deliberations, greater attention to fostering reciprocal awareness and collective responsibility, and more integrated use of administrative, market, customary and personal decision making practices.
Precaution and adaptation Respect uncertainty, avoid even poorly understood risks of serious or irreversible damage to the foundations for sustainability, plan to learn, design for surprise, and manage for adaptation.
Immediate and long term integration Apply all principles of sustainability at once, seeking mutually supportive benefits and multiple gains.

Source: Gibson et al. (2005, p. 116)

8.4 Data collection

The research adopted a case study approach to data collection (Yin 2009). A variety of methods were applied, including document analysis, literature reviews, key stakeholder interviews, and participant observation. By using multiple methods it is possible to obtain triangulation of results and improve construct validity (Yin 2009).

In total, eleven formal interviews were conducted, with representatives from local agricultural extension officers (2), international NGOs with a long-term presence in Senegal (3), peanut producers and their representatives (2) private enterprises (3), and biochar developers (1). Due to the broad and comprehensive nature of the analysis, the interviews were open-ended, but still guided by the full suite of requirements for progress towards sustainability. The interviews were analyzed for relevant themes – both general and specific – relating to peanut production, and agriculture and energy production and consumption more broadly. Beyond the formal interviews, a member of the research team attended many multi-party meetings that included stakeholders from environmental and civil society, industry, and agricultural extension.

To supplement the interviews, the research team also drew from a wide variety of documents relating to the energy and agricultural systems of Senegal, as well as broader social, ecological, cultural and economic concerns. The documents were identified through various means, including NGO websites, broader academic literature, as well as from the interviewees.

The final approach to data collection was participant observation. One member of the research team was directly involved in both improved cookstove production and ecological farming practices in Senegal over a five-month period. The participant observations helped situate the broader concerns and insights into the more immediate context of burning agricultural residues in cookstoves, and allowed the research team to develop a richer understanding of the realities behind the standard accounts and common assumptions.

8.5 Specification of sustainability criteria

Over the course of five months of data collection and one year of analysis, the research team developed a set of sustainability criteria relevant to the particular case and context. The sustainability criteria, presented in Table 24 below, are presented as a set of positive objectives to which potential undertakings should contribute, preferably in ways that generate feedbacks with mutually reinforcing results. The criteria were developed with guidance from the interviews and meetings, document analysis and participant observation. Several of the respondents were available for further interviewing and were thus able to help ensure that the key issues developed through the research process were captured and remained relevant to the case.

For the current Senegal case, the key themes in the criteria and initial observations are grouped under the eight categories of the initial generic criteria set, which use terminology generally familiar to assessment professionals. For practical application in policy and project deliberations, it is typically preferable to reorganize the criteria and results into categories and terms that facilitate understanding and informed discussion among the relevant stakeholders (Gibson 2006b). Such reorganization would also allow a deeper deliberation regarding trade-offs among the various possible avenues for cookstoves and peanut residues, and present an avenue for further deliberation.

The context-specified criteria provided in Table 24 and initial observations provided in Table 25 provide a package to help identify the key strengths and limitations of the energy and agricultural systems of Senegal. The criteria are contestable, and further discussion of whether or not they in fact represent the full set of relevant characteristics would help clarify what should be recognized as important and desirable.

The criteria themes and particular points overlap to some extent, as is to be expected in a world of intertwined components. As well, the points are unlikely to be equally important or to have the same relative importance in each particular application. Consequently, this is not a framework of criteria that can be used in a simple matrix for adding up the positives and subtracting the negatives. Our intent here is merely to establish a reasonably comprehensive base of considerations that ought to be addressed in the design, evaluation and implementation of undertakings involving energy and agricultural systems in Senegal.

Table 24 – Proposed sustainability criteria for energy-agriculture applications in Senegal

Socio-ecological system integrity
GHG emissions and air pollution
• reduce GHG emissions; particularly upfront GHG emissions (e.g. from land clearing)
• avoid or mitigate air pollution that threatens human and ecological health (e.g. field burning)
Water supply and quality
• promote responsible water management that allows for the maintenance and/or recovery of aquatic and terrestrial ecological integrity and reduces invasive species pressure (e.g. Typha in riverine systems)
Land use change and soil resources
• reverse the spread of desertification and promote the revitalization of marginal land
• promote practices that rebuild soil fertility and maintain long-term agricultural livelihoods
• maintain long-term forest resources and avoid the conversion of forest into agricultural land
Biodiversity and ecological integrity
• improve biodiversity and ecological integrity (e.g. eliminate field burning, minimize pesticides)
• manage for species migration due to climate change
Livelihood sufficiency and opportunity
Quality of employment and business opportunities
• promote fulfilling and healthy employment and respect workers' rights (e.g. fair wages, worker safety)
• where feasible, avoid child labour and improve conditions for rural migrant workers
• provide more opportunities for youth and others seeking meaningful employment
Promotion of local economic development and capacity building
• expand desirable local employment and resilient local economic development
• promote small-business diversity and capacity
National self-reliance
• increase economic self-sufficiency (e.g. improve national balance of payments)
• strengthen energy and food security and sovereignty (e.g. through agricultural and energy diversification)
Health and safety
• improve basic health (esp. indoor air quality, adequate nutrition and sanitation, clean water)
Intragenerational equity
Gender equality
• promote gender equality in broader society
Reduction of poverty
• avoid environmental poverty cycles
• promote equitable sharing of limited resources and avoid resource conflicts
Rural-urban equality
• maintain livelihood opportunities in rural as well as urban regions (esp. those facing rural exodus)
• address different rural and urban needs without furthering urban-rural inequality
Land tenure
• promote appropriate and equitable land tenure rights and avoid forced migration and land pressure
Distribution of benefits and risks
• enhance fairness in the distribution of wealth and income generating opportunities (incl. age, gender)
• promote retraining for those harmed by a transition to sustainable energy and agricultural practices
Promotion of international equity
• promote responsible and equitable practices by the international community (e.g. removing trade barriers to products from poorer countries)

Intergenerational equity *Long-term social-ecological integrity* • reverse negative trends in long term resource availability, ecological integrity and land fertility • promote long-term equitable distribution of wealth • maintain and enhance long-term social capital (e.g. traditions of mutual assistance) *Perverse effects* • avoid trading off long-term needs for short-term gains (e.g. cutting down mangroves for fuelwood)
Resource maintenance and efficiency *Ecological efficiency and effectiveness of agricultural systems* • promote ecologically beneficial farming practices that build soil fertility (e.g. residue management, fallowing) • enhance food system efficiency (e.g. avoiding food wastage) and effectiveness (e.g. improved nutrition through a varied diet) *Ecological efficiency and effectiveness of energy systems* • promote ecological means of energy production with a feasible energy return on investment • enhance energy system efficiency and effectiveness (e.g. matching energy quality to end-use) • promote passive uses of energy (e.g. solar bottle lights, passive ventilation) *Resources for a resilient energy and agricultural system* • prioritize reliance on locally available resources while maintaining them within their ecological limits • promote appropriate scales and degree of centralization of energy generation and food processing *Resource stewardship* • promote stewardship, resilience and effective use of both renewable and non-renewable resources (e.g. forests, water, mines) • prioritize uses of non-renewable resources to facilitate transition to renewable resource systems (e.g. LPG as a transition fuel)
Socio-ecological civility and democratic governance *Good governance* • foster local decision-making and more broadly participative multi-stakeholder governance • enhance collaborative and transparent governance, accountability, and trustworthiness (e.g. resource allocation rights) *Ecological civility* • contribute to public understanding of ecological systems and to the protection of natural resources • promote active and informed participation in environmental management • provide appropriate means of valuing ecological services and avoid market distortion (e.g. through NGO subsidization) *Social civility* • promote respect for marginal members of society and the maintenance of desirable spiritual values and traditional knowledge • respect basic rights (liberty, security, equity, health, education) • promote corporate social responsibility and respect for laws and regulations • maintain and promote current culture of mutual assistance *Promotion of a positive social-ecological regulatory environment* • provide an integrated regulatory environment that promotes equity and stewardship (e.g. fair land tenure)
Prudence, precaution and adaptation *Promoting resilience and adaptive capacity and avoiding lock-in* • ensure sufficient resilience and adaptive capacity in food and energy production as well as broader society to accommodate changing conditions (e.g. drought, increased fossil fuel prices) • seek mutual gains in resilience and efficiency (e.g. ecological farming practices) *Developing anticipatory planning and managing for uncertainty* • promote anticipatory planning for risk management with attention to indirect effects • reduce vulnerability in key areas of uncertainty (e.g. resource availability, world market demands, soil fertility)

Immediate and long-term integration
Seeking mutually reinforcing impacts and synergy • seek positive integration linking energy, agriculture and other industries and stakeholders at all scales • promote the co-evolution of energy and agricultural systems with one another and with broader society, at an appropriate pace and in a manner that favours sustainability objectives *Creating opportunity for multi-level change* • provide innovation space for promising alternative approaches to energy and agriculture (esp. organic farming, renewable energy, and local processing) that fit well with sustainability objectives • promote grassroots and top-down change *Harnessing key windows and players for change* • plan for long cycles of change (e.g. transition away from foreign aid), while using avenues for rapid change • seek out leverage points and windows of opportunity (e.g. decline of peanuts, electricity crisis) to foster changes that can deliver maximum net gains • empower key stakeholders for positive change at all levels

8.6 Consideration of Senegal's current energy and agriculture systems in light of the sustainability criteria

The case specific sustainability criteria provided in Table 24 were initially addressed in a set of observations of the case and context presented in Table 25 below. The observations draw from a wide variety of quantitative and qualitative indicators, and provide an initial analysis of the most significant considerations relating to Senegal's energy and agricultural systems. The observations provide a baseline against which potential contributions of new policies, programme, and projects may be judged. The criteria presented above and the observations presented below were developed iteratively, with the initial sustainability criteria informing the data collection, which in turn informed further iterations of criteria specification.

Throughout the iterations between criteria and observations, care was taken to ensure all the generic sustainability assessment criteria were addressed in the case specific context.

Table 25 – Initial observations of the energy and agricultural systems of Senegal

Socio-ecological system integrity
GHG emissions and air pollution • Inefficient energy infrastructure (e.g. diesel power stations, charcoal production, cookstove usage) and transportation infrastructure are a source of air pollution and GHG emissions. • Field burning and land clearing have contributed significantly to air pollution and GHG emissions (Elberling et al. 2003). *Water supply and quality* • Agriculture, which is predominantly rainfed, already suffers from drought and rainfall variability, which has been increasing in recent decades and is predicted to worsen, with adverse effects on food production (Mbow et al. 2008; UNDP 2010b). *Land use change and soil resources* • Soil fertility in much of Senegal is dropping rapidly (approximately 418 kg/ha/yr.) due to inappropriate farming practices, field burning, and erosion, and will be worsened by climate change (Tappan et al. 2004; Woomer et al. 2004). • In some areas soil fertility is increasing due to land abandonment (Mbow et al. 2008). • Fuelwood and charcoal production, agricultural expansion (esp. for peanuts), and illegal herding and overgrazing are causing deforestation and harming other forest products (Hrubesch 2011; Tappan et al. 2004; UNDP 2010b). • Desertification is worsened by deforestation, drought and soil erosion. The government is promoting a

Great Green Wall of vegetation to reverse encroachment of the Sahara (UNDP 2010b). *Biodiversity and ecological integrity* • Drought is expanding the presence of Sahelian plants from the north, and promoting shrubland and savannah (Diop 2009; Woomer et al. 2004). • Large areas of monoculture, improper pesticide use, and deforestation are threatening biodiversity and ecological integrity (Thiam 2010). • Field burning harms wildlife and changes soil cover (Diop 2009; Mbow et al. 2008).
Livelihood sufficiency and opportunity *Quality of agricultural and energy business opportunities* • Agriculture provides the livelihood foundations for a majority of population but accounts for 1/5th of GDP, and generally provides seasonal employment, leading to urban migration. Farm incomes have not increased despite agricultural expansion, due to external shocks including droughts, energy crises, and structural adjustment (IYF 2009; Mbow et al. 2008; Thiam 2010). • Low prices paid to producers reduce capacity and incentive to invest in better techniques and resource stewardship. Farmers lack credit to purchase inputs, resulting in lower yields and incomes (Brown 2008; Freeman et al. 1999; Perry 2005). *Promotion of local economic development and capacity building* • Poor infrastructure (esp. unreliable electricity) hampers economic development and provisioning of essential needs (e.g. education), and discourages investment in productive activities that justify infrastructural investment (Boccanfuso et al. 2009; Diop 2009; FIDA 2011). • Small businesses are hampered by low technical knowledge (e.g. for food processing), lack of capital, poor access to markets, and improper commodity chains. Low diversity of small enterprises in agri-business leads to oversupply and waste (Freeman et al. 1999; Mbow et al. 2008). New ideas may require cultural change and proactive market creation to flourish. • Agricultural processing (e.g. peanut oil) has been historically dominated by large para-statal industries. Small-scale processors are proving capable of achieving quality standards with sufficient support. *National self-reliance* • Government suffers from a balance of payment crisis due to reduced agricultural export earnings, increased cost of importing staple foods, and increased fossil fuels prices for transportation and electricity (MDE 2007; OECD 2008). • Senegal is food insecure and imports staple foods (rice, milk), with the food deficit increasing, staple food prices increasing, and agricultural export revenues dropping (Diaz-Chavez et al. 2010; UNDP 2010b). • Peanuts are no longer considered a reliable crop but still employ up to 1 million people, and use 40 percent of cultivated land. Government is promoting diversification of food production, although success has been limited by inadequate supply chains (Diaz-Chavez et al. 2010; OECD 2008). *Health and safety* • Food insecurity causes a high prevalence of malnutrition notably in women and children (WFP 2011). • Indoor air pollution from traditional cookstoves impacts health, reduces productivity, and reinforces environmental poverty. WHO estimates 5400 annual cooking-related deaths in Senegal (Hrubesch 2011). • Deforestation is increasing burdens of, and risks to, rural women (e.g. collecting fuelwood) (Youm et al. 2000).
Intragenerational equity *Gender equality* • In return for food and access to farm plots, rural women and children perform household tasks (e.g. cooking, caring for children, fetching water, collecting fuelwood) (Perry 2005; Rehfuess 2006). Women cannot own land, and are thus discouraged from investing in stewardship. • Previous government promotion of peanuts prioritized men, who expanded peanut production at the expense of their dependents. Women were unable to access farm equipment, causing late seeding and weeding, and lowering yields. Market liberalization indirectly addressed the inequality, but has heightened social tensions (Perry 2005). *Reduction of poverty* • Due to lack of upfront capital, the poor must generally purchase items in single usage units (e.g., charcoal), and obtain illegal electrical connections, generally at higher per unit costs (Fall et al. 2008). • Urban poor spend a significant portion of their income on charcoal, while in rural areas LPG and charcoal

are unavailable, and fuelwood is generally gathered for cooking (Fall et al. 2008; Youm et al. 2000).

- Poverty and gender have strong influence on levels of education. Girls are often removed from school to perform household duties (UNDP 2010b).
- Structural adjustment programs have dismantled supply chains and deepened poverty and unemployment. Despite this, the government is still planning to privatize SENELEC in accordance with structural adjustment (African Bulletin 2010; Boccanfuso et al. 2009; OECD 2008).

Reduction of urban-rural disparity

- Urban areas generally have better access to health, education, electricity and other necessary services and opportunities (OECD 2008).
- Large urban migration (esp. men and youth) is causing rural labour shortage and urban unemployment.
- Low government regulated price for peanuts is considered an indirect taxation of rural areas to support cities. Similarly, the sale of grains to cities exacerbates rural grain shortages during hungry season and drives up prices in rural areas (Freeman et al. 1999; Perry 2005).

Land tenure

- Migrants often settle in peri-urban areas that lack basic services and harm peri-urban agriculture (Cotula et al. 2004; Fall et al. 2008; Mbow et al. 2008).
- Pressures on marginal and fragile land are rising due to drought, population growth, withdrawal of state support, and poverty), all without adequate understanding of the adverse effects or enough effort to identify livelihood alternatives (Brown 2008; Woomer et al. 2004).

Distribution of benefits and risks

- The recently cancelled government subsidy of LPG often benefited the rich and Gambians (who crossed the border), at the expense of poor Senegalese who were the intended beneficiaries.
- Government targeting richer households for solar PV (esp. where transmission and distribution infrastructure are lacking) (MDE 2007).
- Government control of charcoal quota system allows urban companies to profit from charcoal production at the expense of rural gains. International agencies are seeking to change this (Poteete and Ribot 2011).
- Agricultural and bioenergy initiatives (e.g. projects to rebuild soil carbon) may worsen land tenure problems, and reduce livelihood opportunities of people using the land (Diaz-Chavez et al. 2010; Woomer et al. 2004).

Promotion of international equity

- International pressure maintains Senegal in an export mode of agriculture that is sensitive to world dynamics and threatens the long-term resource base (UNDP 2010b).
- Consolidation of foreign direct investment in agri-food leads to unequal bargaining power and exploitation by multi-national companies (e.g. export of tomatoes) (Maertens et al. 2011).
- International food quality standards and agricultural subsidies present a trade barrier to Senegal (e.g. U.S. domestic peanut subsidies and threshold levels for Aflatoxin contamination) (Fairfood 2011; Maertens et al. 2011).

Intergenerational equity

Long term socio-ecological integrity

- Overuse of natural resources is reducing the productive base and worsening poverty. Population growth and climate change are expected to accelerate resource degradation and exacerbate social problems (e.g. youth unemployment) (UNDP 2010b).
- Climate change is expected to have negative health impacts (e.g. increased waterborne diseases) that will affect vulnerable populations most (Brown 2008; UNDP 2010b).

Perverse effects

- Population growth coupled with resource degradation (deforestation, desertification, soil erosion) is leading to negatively reinforcing long-term trends (e.g. loss of livelihood, reduced yields) (Hrubesch 2011; UNDP 2010b).
- Urbanization places pressure on peri-urban farmland and promotes ‘hit and run’ farming (farmers crop intensively but apply few amendments to regenerate the soils) that prioritizes short term gains (McClintock and Diop 2006).
- Structural balance of payments problem may create economic lock-in (e.g. continued focus on export crops) and spiral of debt.

Resource maintenance and efficiency

Ecological efficiency and effectiveness of agricultural systems

- Soil fertility is declining due to mono-cropping, inadequate fallow and inputs, and drought and rainfall variability. Compost and increased fallow have not compensated for lack of fertilizers (Brown 2008). Most fallow periods result from unavailable seeds and land abandonment (Diop 1999; Mbow et al. 2008).
- Peanuts, the primary cash crop, cause soil depletion (with yields dropping over 50 percent over several decades) because they are harvested by pulling entire crop up (Brown 2008; Elberling et al. 2003).
- Residues are often used as livestock feed or as a construction material, or are burned in the fields, rather than directly used for soil fertility improvements (Diop 1999; McClintock and Diop 2006).
- Inability to store food products causes a glut in the market during harvest, reduces income, and produces waste (e.g. milk is spoiled during the rainy season) (Freeman et al. 1999).

Ecological efficiency and effectiveness of energy systems

- Charcoal is currently produced by inefficient means by workers with generally low vested interest in resource stewardship, although improved methods exist (Hrubesch 2011).
- Electricity is largely fossil based with inefficient and poorly maintained generation facilities (estimated 21 percent losses). Power outages have increased due to under-capacity and high fuel costs (CSRE 2008; MDE 2007; OECD 2008).
- About 40 percent of electricity is used for low quality applications (e.g. cooling) (Hrubesch 2011).
- Increasing energy supply may promote increased usage (meeting suppressed demand), not necessarily for productive purposes, potentially increasing household expenditures while not increasing income.

Resources for a resilient energy and agricultural system

- High solar potential (3,000 hours annual sunshine) provides opportunities for PV and thermal electricity, thermal drying, and water distillation with a comparatively low system cost (Thiam 2010; Youm et al. 2000).
- Government is promoting Jatropha, a rainfed oil crop that may grow for 50 years with minimal upkeep although yield is based on soil fertility. If properly implemented, Jatropha oil can be used for community purposes (e.g. pumping water), and the residues for energy or compost.
- Diversity of secondary sources includes wind, anaerobic digestion, and energy tree plantations, all at varying degrees of technological sophistication (Hrubesch 2011).
- Residues are processed at multiple scales and have multiple uses (e.g. electricity, biochar, direct combustion), opening possibilities for coordinated multi-scale approaches to residue management.
- LPG could serve as a bridge between current over-exploitation of soils and forests and a future renewable energy supply for cooking

Stewardship of forest resources

- Deforestation due to fuelwood and charcoal production, and land clearing has led to 40 percent drop in forest cover since 1960. Land pressure prevents the 4-12 years necessary for proper forest regrowth and will be worsened by population growth and poverty. Ecologically and economically important trees are not protected (Hrubesch 2011).
- Tree seedlings are often not protected and many do not reach maturity. Some villages are banning goats in lieu of chickens to better protect trees.
- Agroforestry is being slowly introduced with positive results (e.g. Moringa) (Mbow et al. 2008).

Stewardship of aquatic resources

- Degradation of mangroves has adverse effects on fishing and tourism (UNDP 2010b).
- Water quality is threatened (e.g. in sulphurous regions water is becoming acidified, causing soil destruction).
- Fish is an important part of Senegalese economy and food security, but marine resources are being depleted. Government is limiting international fishing and promoting aquaculture. Climate change is expected to lower catches and cause seawater intrusion (UNDP 2010b).

Social ecological civility and democratic governance

Good governance

- Government has abdicated many social service responsibilities to NGOs and municipalities. Lack of coordination between NGOs reduces their effectiveness, encourages duplication, and hampers sharing of knowledge and experiences (Mbow et al. 2008; OECD 2008; UNDP 2010b).
- Mix of traditional and rational-legal methods for determining property rights and other land use rules may

create conflict, but also provide diversity of available perspectives and mechanisms (Cotula et al. 2004).

- Low level of citizen involvement in decision making is partly due to lack of education and poverty (UNDP 2010b).

Ecological civility

- Better stewardship of natural capital is needed, but short term needs often outweigh long-term stewardship (e.g. cutting down mangroves provides fuel but removes an ecological service).
- Dependence on traditional and 'free' biomass may lead to undervaluing of renewable resources (Thiam 2010).
- International aid generally does not promote full cost accounting (e.g. indirect subsidization of cookstoves can distort markets and hamper local self-reliance).

Social civility

- Peanuts are deeply embedded in the culture and are important for cooking, soap-making, and livestock feed. Cultural habits can run counter to desired best practices (e.g. adopting improved cookstoves) (Hrubesch 2011).
- Community solidarity is an important asset (Diop 2011), which may facilitate or slow desired change.

Promotion of a positive social-ecological regulatory environment

- Senegal's regulatory system is plagued by overlapping and potentially conflicting policies concerning forests (protect forests), agriculture (promote peanut production, expand land under cultivation), livestock and rangelands management, land tenure, and water resources (Mbow et al. 2008; UNDP 2010b).
- Environmental enforcement is inadequate (e.g. too few park rangers) (Diop 2009; Hrubesch 2011).
- Land management decisions are often driven by religious, political, or financial motives, often for urban benefit (UNDP 2010b). Government has historically ignored relationships between property rights and poverty (Cotula et al. 2004).

Prudence, precaution and adaptation

Promoting general resilience and adaptive capacity and avoiding lock-in

- In many places locally available drivers for adaptive change are addressing many problems in an integrated manner (e.g. eco-villages, market gardening) (Gensen 2010).
- History of adaptation and income diversification in Senegal is positive, notably in agricultural areas that have suffered from drought (Brown 2008).
- Lack of education and poverty impede adaptive capacity (e.g. for climate change) (Brown 2008).

Promoting agricultural resilience and adaptive capacity and avoiding lock-in

- Agricultural dependence on erratic and declining rainfall coupled with inability to purchase inputs increases yearly variability, and complicates long term planning that must account for both poor years and seasonality (Brown 2008; McClintock and Diop 2006).
- Reliance on exports of cash crops (e.g. peanut oil) and imports of staple foods increases vulnerability to world market prices. If properly undertaken, increased domestic production of staple crops and development of internal markets may reduce food wastage, improve food security and promote local economic development (Mbow et al. 2008; UNDP 2010b).

Promoting energy resilience and adaptive capacity and avoiding lock-in

- Dependence on fossil fuel imports for electricity generation increases economic vulnerability due to fluctuating world market prices (Diop 2009).
- Both urban and rural populations have adapted to the fluctuating availability of electricity, although discontent is increasing and entrepreneurialism is discouraged (Callimachi 2011).
- Adaptive energy technologies (e.g. solar PV) exist at a number of scales and exhibit high technical potential, are minimally vulnerable to geopolitics and could save on transmission and distribution infrastructure and losses, but care must be taken to ensure cultural sensitivity.

Developing anticipatory planning and managing for uncertainty

- Challenges of keeping up with the pace of environmental change (e.g. deforestation rate) and the expected acceleration of change due to population growth are overwhelming capacities to consider long-term implications.
- Social-ecological effects of structural adjustment and other policy decisions are still undetermined.
- Data on some significant concerns are inadequate: only estimates available on the impact of government subsidy of LPG; total agricultural production is uncertain due to non-regulated supply chains; total charcoal consumption is unknown but is estimated to be growing (CSRE 2008; Hrubesch 2011)

Immediate and long-term integration

Seeking mutually reinforcing impacts and synergy and promoting virtuous circles

- Increases in food and energy security could improve health and access to education, which may reduce population growth and improve long-term food and energy security.
- Promotion of small-scale energy and agricultural systems could improve food and energy security while targeting youth and promoting steps towards greater gender equality.
- Farming productivity could be greatly improved by eliminating bad practices including those with logistical, institutional and cultural roots (Freeman et al. 1999). Efficiency and resilience of farming and energy practices can be increased simultaneously.
- More appropriate means of valuing alternative energy and agricultural practices (e.g. solar PV, organic farming) could reduce dependence on long-term financial support from the international community.
- Strengthening the capacities of community and regional level bodies to direct interventions (e.g. training, equipment, market access), could reduce unnecessary duplication, facilitate citizen engagement, and assist a transition away from foreign aid.
- Modern energy services (notably electricity) can bring livelihood opportunities, but they require productive uses to be justified, and this depends on effective design and use of market instruments as well as government policies and programmes, and emphasis on delivering benefits to the disadvantaged rather than only to the already successful.

Creating opportunity for multi-level change

- The potential for positive gains is spread across the full spectrum of technology levels: many types of bioenergy can be both low-tech and hi-tech (e.g. biogas, combustion of residues).
- Empowering small agricultural and energy entrepreneurs could mobilize new capacities, though mechanisms will be needed to ensure sufficient diversity in new products.

Harnessing key windows and players for change

- The declining strategic value of peanuts opens a window to exploring alternative cash crops that may promote food and energy security.
- The current crisis facing the electricity system (declining infrastructure and expensive imported fossil fuels), opens possibilities for more decentralized and endogenous electricity supply systems.
- Coordination with other West African countries (e.g. West African electricity power pool) could improve efficiencies, and encourage cooperation, and build on Dakar's reputation as a hub.

8.7 Discussion

The sustainability criteria in Table 24 and observations in Table 25 reveal the range and significance of the many factors and interdependent dynamics at play within and between the energy and agricultural sectors in Senegal. While the criteria and observations are necessarily tentative, they indicate what desirable characteristics and trends ought to be supported, protected and enhanced, and what undesirable characteristics and trends need to be corrected or reversed at several scales from local to national. The criteria need debate, elaboration, revision and reorganization by the relevant stakeholders and experts in Senegal. Nevertheless, they illustrate the rich complexity of the matters that merit attention in evaluations of potential large and small energy and agriculture initiatives in Senegal, including cookstoves for burning peanut shells.

The following two sections address two important themes that emerged during the assessment. First, we revisit the importance of addressing broader strategic scale issues that emerged during project level assessment. Second, we return to the original question of burning peanut residues in cookstoves and attempt to illustrate use of the criteria and context description in guiding decision making.

8.7.1 The importance of addressing the broader strategic scale

For the particular case of cookstoves burning agricultural residues, the sustainability-based exploration of key criteria and relevant considerations revealed how unwise it would have been simply to assume that such cookstoves would be beneficial. There are broader energy and agricultural system factors and interactions that must be addressed, and require expanding the scope of analysis to encompass these broader concerns, as well as their relations to other cultural, economic and urban-rural concerns. In this case, clearly, moving the assessment focus from the project to the strategic level is needed to recognize crucial issues, to encourage attention to a broader range of options, and to open richer opportunities for positive gains.

While some of the specifics of this case are more or less unique to Senegal, the basic narrative of declining soil fertility, deforestation, inadequate energy infrastructure, food insecurity and dependence on export-oriented cash crops is roughly comparable to the sets of linked challenges facing other developing countries. Furthermore, the general phenomenon of a project level assessment raising strategic level considerations not uncommon in assessment practice. Often the recognized strategic issues are tied to the significance of cumulative regional effects (Cooper and Sheate 2002; Duinker and Greig 2006; Harriman and Noble 2008). In the Senegal cookstoves case, moving to the strategic level did involve a need for attention to cumulative effects, but was also driven by the importance of interrelationships between the agriculture and energy systems, and between these systems and the broader economy and culture.

Broadening the scope of assessment allowed attention to more promising energy and agriculture options as well as about implications for peanut residue use. The case points to the possibly common advantage of beginning assessment work with a flexible unit of analysis that accommodates learning from the context and allows for unexpected insights to develop through recognizing a broader context, reformulating the core issue and expanding the range of response options.

8.7.2 Cooking options considered in the larger context

The research project discussed here began with a narrow question: how best to design cookstoves to be fuelled by peanut shells and other agricultural residues. Consideration of the larger context of soil fertility decline and deforestation led to an expansion of the question of how best to make use of peanut shells (and other such agricultural residues) in light of the current realities and needs for improvement of Senegal's energy and agricultural systems. That larger question call for comparisons of a range of promising options in the context of the full suite of sustainability-related issues at the conjunction of agricultural and energy systems in Senegal. The following discussion provides an outline of some of the options that might be assessed given the revision and expansion of the initial question.

Within the context developed in the rationale and Table 25, it appears that while burning peanut residues instead of wood or charcoal should usefully reduce some immediate pressures on forest resources, on the whole this option appears generally unadvisable because of the loss of a key means of preserving soil fertility and the consequent likelihood of indirect encouragement of further deforestation. As previously noted in the rationale, deforestation is tied to agriculture, as decreasing soil fertility and livelihood opportunities have encouraged farmers to abandon their fields and clear forests in the southeast so as to renew farming (Tappan et al. 2004). Using peanut shells (and other agricultural residues) as a fuel source removes their potential use as a soil amendment, and provides an incentive to keep removing residues from the fields, likely accelerating the rate of soil fertility depletion.

Despite these concerns, it may be advantageous to allow for the burning of agricultural residues in certain situations. For example, as a result of government centralization of agricultural processing, peanut shells currently collect outside processing plants in the cities, where there is no obvious use for them. Discussions with farmers and agricultural extension agents also indicated that peanut shells are often now simply burned as waste. The alternative of burning the shells in cookstoves would at least promise some beneficial use, though returning the shells to the fields as soil amendments might be even better. In such contexts, peanut shells may be a useful energy source for cooking or electricity production, but careful consideration of implications and broader alternatives – guided by the sustainability criteria set – is needed. For example, some of the peanut producer cooperatives in Senegal have begun to lobby for decentralized peanut processing, and it is important to ensure that centralized energy production from peanut shells does not hinder local agricultural processing, which may leave peanut residues closer to the fields for soil fertility applications.

The issue of burning peanut residues also opens the door to a deeper discussion of the future of peanuts in Senegal. The observations noted in Table 25 indicate many different facets to the centrality of peanuts in Senegal, including their historical importance, their relevance to Senegalese cuisine, their current economic decline, the difficulty in replacing peanuts with an alternative cash crop, the impact of intensive peanut agriculture on soil fertility, the impact of fluctuating world market prices for peanut oil, the relationship between cash-cropping and food security, and, of course, the combustion of peanut shells for energy purposes. To the extent that significant levels of peanut cultivation is not a desirable long-term agricultural path for Senegal, it makes sense to avoid energy systems that depend uniquely upon peanut shells as a source of bioenergy.

Addressing the relationship between soil fertility and deforestation, and the long-term role of peanuts requires attention to at least two other strategic options that are mutually compatible, operate on different timelines, and are already being explored in Senegal. The first option relates to the production and use of biochar as a soil amendment and/or the adoption of biocharcoal as a replacement for charcoal. Biochar, produced by the pyrolysis of biomass, is gaining popularity as a means to regenerate soils by increasing soil carbon storage and nutrient holding capacity, often more effectively than the original biomass could do as a soil amendment (Whitman and Lehmann 2009). Biochar can be produced from many different feedstocks and at multiple scales, proving flexibility in production on the input side and allowing peanut shells to play a role in bioenergy but be phased out over time. It would be possible to develop commercial operations of many sizes with the primary goal being the production of biochar. Biochar may also be produced in cookstoves that operate as biomass gasifiers (e.g. Anderson et al. 2007), although the science behind this appears to be still nascent.

Due to the importance of charcoal for cooking in Senegal (e.g. charcoal is largely used for brewing Senegalese tea), alternatives to this energy pathway must also be explored. In Senegal, various groups, such as the German development agency GIZ, are researching biocharcoal, which is effectively biochar that contains a binder (e.g. clay or sugar) to facilitate handling and combustion (GIZ 2011; VIE 2009). Similar to biochar, biocharcoal may be produced using various feedstocks (e.g. Typha, an invasive riparian weed), although it is likely only feasible under commercial production, as opposed to being a by-product from gasifier cookstoves.

Both biochar and biocharcoal allow for locally appropriate energy production, and do not lock Senegal into one specific type of biomass or agricultural residue. GIZ is promoting biochar as a means of youth employment for both men and women, indicating that mutually reinforcing gains are being sought, and more gains may be informed by a reading of Table 25. There are, of course, open questions regarding the long-term potential of both. First, the extent to which biocharcoal could feasibly replace charcoal depends on the scale of production (artisanal vs. commercial scale) and the availability of biomass, both of which require further analysis (e.g. Hrubesch 2011). Likewise, the energy return on investment of biochar is unknown and likely context dependent (e.g. affected by manual or machine production), indicating a degree of precaution is necessary.

Presently, neither biochar nor biocharcoal appears ready for large-scale adoption in Senegal. Biocharcoal is not considered as clean burning as regular charcoal, which has hindered uptake. Furthermore, Senegal lacks the high quality gasifier stoves needed to produce biochar, and promoting low quality biochar now may hamper future adoption of better stoves later. In effect, biochar appears to have greatest potential in the medium term.

The second alternative that merits discussion is liquefied petroleum gas (LPG), which the government has subsidized since 1988, but has been phasing out in recent years, resulting in increased charcoal and fuelwood consumption, especially in urban areas (CSRE 2008; Fall et al. 2008; Laan et al. 2010; Youm et al. 2000). The original impetus for the LPG subsidy – and one that is no less relevant today – is that it provides a means of reducing forest pressure by providing an alternative fuel source. The use of LPG helps decouple energy production and consumption from agriculture, which allows for greater flexibility in agricultural decision making. Furthermore, LPG stoves are clean-burning and culturally appropriate for cooking. On the other hand, the LPG subsidy has been criticized for various reasons, including its cost and equity effects (the rich tended to benefit the most), and the long-term implications of promoting reliance on fossil fuels (Laan et al. 2010). While the criticisms seem justified, no present option is likely to be problem-free and all serious possibilities need to be subjected to careful evaluation in light of a comprehensive set of sustainability criteria and approached as potential contributions to a long term strategy.

While an improved version of the LPG subsidy is not a potentially permanent solution, it could serve as a useful fossil energy bridge within a transition to more sustainable energy sources (e.g. biochar and biocharcoal). There are no doubt challenges to ensuring the effectiveness of an LPG subsidy, but given the international community is heavily involved in Senegal, LPG could be one means of promoting a more concerted approach to development efforts in Senegal guided by the full suite of requirements for progress towards sustainability.

Biochar and the LPG subsidy are unlikely to be the only promising options and both merit further attention and assessment. They do, however, illustrate the kinds of options that may emerge from context-specified, sustainability-based consideration of broader short- and long term energy/agriculture possibilities when a more narrowly conceived solution (in this case peanut shell fuelled cookstoves) proves unsatisfactory.

8.8 Conclusion

The research demonstrates both the importance of flexibility in defining the focus of sustainability-based assessment and the unavoidable complexity inherent in integrated consideration of things that matter. The research began as an assessment of using peanut shells and other agricultural residues for cooking applications in Senegal. The nature of the case required that the scope of assessment be increased from the project scale up to the strategic scale, in order to better define and address options in light of the interrelationships between the agricultural and energy systems of Senegal, and how they are situated within their economic, ecological and cultural contexts.

Guided by the sustainability assessment process and situating the discussion within both the centrality of peanuts in Senegal, and the key dynamics of energy and agricultural systems affecting soil fertility and deforestation, we have found that the development and use of cookstoves that burn agriculture residues, notably peanuts, for fuel appears generally undesirable. However, we recognize that under certain circumstances, such as where peanut shells are collecting outside urban areas, it may be advantageous to develop energy technologies (e.g. for cooking or electricity generation) based on agricultural residues, so long as they promote general progress towards sustainability, meeting the criteria elaborated in Table 24 and addressing the key considerations in Table 25.

Pending development of a more advanced, more suitably organized and more broadly endorsed set of sustainability criteria for the case, the criteria provided here may be useful for informing decision making for a wide variety of agricultural and energy undertakings. Regardless of what undertaking is proposed (e.g. Jatropha for bioenergy, market gardens for food security), the desirable end-goals for Senegalese society should be similar. Furthermore, the work illustrates a promising approach to more broadly informed deliberations and decisions at various levels, from cookstove design to an overall energy and agricultural strategy for Senegal. Ultimately, important and difficult decisions must be made, decisions that will be simultaneously technical, economic, ecological, social and ethical. This work contributes to that broader conversation.

<u>This is the end of the manuscript</u>

8.9 Key recommendations for sustainability assessment of energy systems emerging from the Senegal case study

This section describes some of the outcomes from the Senegal case study more generally relevant for the dissertation, and focuses on four points of note. First, the case points to the possibly common advantage of beginning assessment work with a flexible unit of analysis that accommodates learning from the context and allows for unexpected insights to develop through the reformulation of the energy problem. In this dissertation, Gibson's SA framework is proposed as the means of spanning the project-strategic divide in a flexible manner, while recognizing that other approaches have merit as well (e.g. Partidário et al. 2009; Rotmans and Loorbach 2008).

Second, similar to the sugarcane-ethanol case study in Chapter 7, this chapter highlights the importance of grounding the assessment within its broader context. Many of the dynamics, criteria and results discussed in this chapter are broadly relevant to Senegal's energy and agricultural systems, as well as the country as a whole. This implies that in certain instances (such as further exploratory research), a wide variety of starting points may be used to elaborate the same basic context. Furthermore, given the flexibility of Gibson's SA framework described in this dissertation and elsewhere, the potential remains to change the focal unit as necessary, assuming the terms of reference have not been imposed by inflexible authorities.

Third, this chapter provides another example of the importance of energy bridges. In this case liquefied petroleum gas is proposed as a temporary energy source that may provide the soil and forests some reprieve, and provide Senegal time to explore and develop alternative energy sources.

Finally, this chapter presents a case with no obvious ideal energy pathway. Rather, there are different alternatives that may be pursued, each with its own degree of uncertainty, path dependence, desirability, feasibility, degree of fairness, cultural sensitivity, etc. And the issues are not insignificant. For example, questions such as the degree of technological capitalization in the energy and agricultural sectors, the favouring of urban over rural regions, and the choice of export crops over local food security all have important implications for the future of individual life in Senegal as well as the country as a whole. What the case study provides is a starting point for a much deeper and more inclusive exploration of these issues; an exploration that must be undertaken by those affected by it, although researchers and other professionals may facilitate the process.

The themes discussed above – the benefits of a flexible unit of analysis, the importance of the broader context, the need for energy bridges, and the multiple future pathways – have all been incorporated in a generalized manner into the criteria set proposed in Chapter 4. Furthermore, these topics will be revisited in the next chapter (Chapter 9) in consideration with the insights emerging from the other case studies.

This completes the empirical component of the dissertation. The following chapter synthesizes the major insights from both the theoretical and empirical components of this dissertation.

Chapter 9 – Analysis and conclusions

Do not go gentle into that good night. Rage, rage against the dying of the light – Dylan Thomas, 1951

This research project set out to develop and apply a framework for assessing how energy systems may be structured to help society progress towards sustainability. The general intent was to outline a way for deciding upon the things that matter in order to make better decisions that will lead to positive near- and long-term outcomes.

There are various ways of reaching the goal described above, and the path chosen in this dissertation centred on Gibson's (2006) framework for sustainability assessment, a framework for integrated sustainability-based decision-making[13]. Gibson's SA framework has been applied to a variety of energy undertakings (including Duarte et al. 2013; Gaudreau and Gibson 2010; Gibson 2006c; Winfield et al. 2010), and this dissertation from these experiences as well as contributes to them.

The key theoretical contributions of this project centred on elaboration of Gibson's SA framework for energy undertakings through development of a theoretical framework grounded in the many forms of complexity and energy, and focused on four interrelated sub-objectives:

(1) the description of an assessment approach for a world characterized by uncertainty, incomplete knowledge and value conflicts;
(2) the preparation of two sets of guidelines for managing complex social-ecological systems relating to their general and, more specifically, metabolic characteristics;
(3) the preparation of two further sets of guidelines for defining the characteristics of an appropriate and constructive relationship with energy, and the necessary steps to foster sociotechnical systems change; and
(4) a synthesis of the above products sub-objectives into a unique, normative, and comprehensive set of sustainability criteria for energy undertakings.

The theoretical framework was applied in four case studies that took place between 2008 and 2012. The case studies represent a substantive contribution on their own, but also served as a means to continually improve upon the theory, particularly the sustainability criteria set for energy undertakings.

This chapter attempts to do two things. First, it summarizes the theory and casework contained in this dissertation. Following the summary, the second half of this chapter synthesizes the more general insights and discusses avenues for further research.

[13] I will refer to Gibson's (2006) framework for sustainability assessment as Gibson's SA framework.

9.1 Summarizing the conceptual framework

The following section summarizes the development of the conceptual framework that underpins this dissertation. A visual representation of the conceptual framework and the case studies is provided in Figure 4.

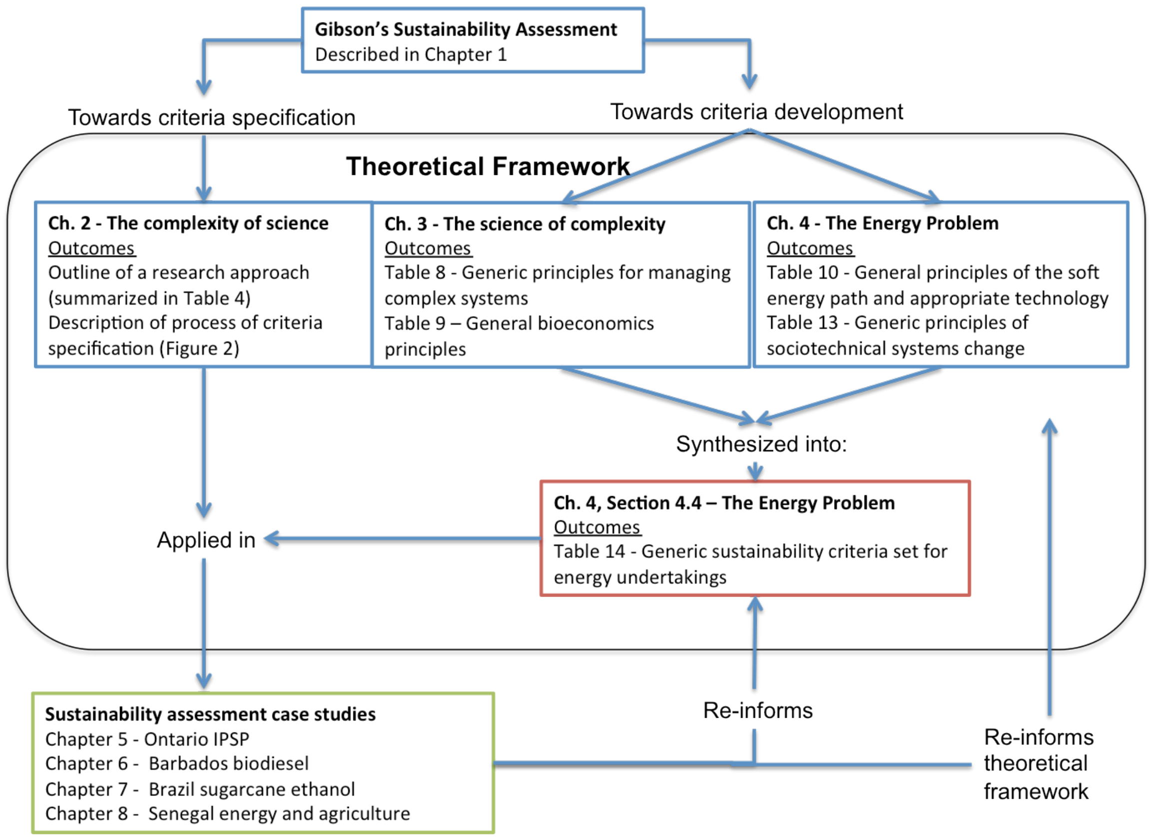

Figure 4 - The Conceptual Framework and Research Map

9.1.1 Grounding the research process in the complexity of science

Our journey began with an exploration of the complexity of science, the subject of Chapter 2. As Funtowicz and Ravetz (1993) note, we live in a world characterized by inherent uncertainty, multiple worldviews, conflicted values, power dynamics and a whole host of other challenges to science and decision-making. Many of the environmental and human challenges we currently are in part because we don't sufficiently respect the limits to knowledge and the personal biases we all bring to the table. In order to contribute to a new approach to science, this dissertation drew from various approaches to learning, particularly post-normal science, transdisciplinarity, integrated assessment, and science and technology studies. The intent was to develop a framework for knowledge generation and decision-making situated within its social context.

The theoretical explorations of this subject culminated into two specific outcomes. First, Chapter 2 proposed a set of guidelines for knowledge generation in a complex world. These guidelines are reproduced in Table 26 below.

Table 26 - A summary of eight guidelines for research and decision-making in a complex world

Be integrated and problem focused	Addresses difficulties with problem formulation, the presence of contradictions, multiple and incomplete views on the world, and incomparable and incommensurate factors.
Maintain a flexible approach to problem formulation	Addresses difficulties with problem formulation, the presence of contradictions, multiple and incomplete views on the world, and incomparable and incommensurate factors.
Emphasize the process of assessment over the substantive outcome	Proposed in response to disputed values, the presence of contradictions, multiple and incomplete views of the world, and incomparable and incommensurate factors.
Promote informed participation	Addresses disputed values, multiple and incomplete views of the world, power imbalances, and narratives and frames.
Foster social learning	Addresses disputed values, multiple and incomplete views of the world, power imbalances, and narratives and frames.
Be explicitly normative	Proposed in response to disputed values, power imbalances and scientific neutrality.
Be grounded in context	Addresses multiple and incomplete views of the world, disputed values, and difficulties with problem formulation.
Move from research to action and emancipation	Addresses power imbalances, narratives and frames, and scientific neutrality.

These guidelines are general, and serve to outline the worldview in which this dissertation is grounded.

The second outcome of Chapter 2 was the description of the criteria specification cycle, which serves as the approach to operationalize Gibson's SA framework. Drawing from multiple sources of data – particularly documentary analysis, semi-structured interviews and observation – the criteria specification cycle provides the means of deciding upon the things that matter in a given case and context. The cycle begins with a predetermined problem and a generic sustainability criteria set for energy undertakings (that will be discussed in section 9.1.4). Over the course of the analysis, the problem may be reformulated in response to new information. Likewise, the generic criteria set will be specified for the particular case and context. Further details on the process are provided in Chapter 2.

9.1.2 Developing a set of guidelines for and managing complex systems

The complexity of science is only half the story emerging from the complex systems literature. From a different perspective, it is evident that we live in a world of complex dynamics and interconnections, and it is important to ensure that whatever energy paths we set out on recognize these dynamics. Fortunately, there is a wide range of literature relating to the characteristics of complex systems, both in general and with regards to their energy and material flows. Furthermore, at the aggregate scale, it seems clear that society exhibits general and emergent patterns.

In Chapter 3 of the dissertation, the exploration of the science of complexity leads to the proposal of two sets of guidelines. The first set attempts to provide a basic understanding of complex systems in general, paying particular attention to the ecosystem approach, resilience thinking, and hierarchy theory. This first set of guidelines is provided in Table 27 below.

Table 27 - Generic guidelines for managing complex systems

Manage at the whole system and avoid sub-optimization Manage at the whole system level, and seek to understand the focal system's characteristics and dynamics to identify valued qualities as well as continuing and impending stresses and disturbances from internal and external sources. Promote full systems accounting and resource cascading
Manage at multiple levels while embracing contradiction System control occurs through reciprocal interactions at multiple scales and is often manifested in different ways. Manage hierarchies to promote redundancy and robustness, and optimize response diversity, while acknowledging that different hierarchies exhibit different goals and values, which often lead to contradiction. Promote top-down and bottom-up control
Allow systems to move in cycles that involve unexpected behaviour, death and renewal Work within the tendency of systems to grow, develop, collapse and reorganize. Anticipate and avoid catastrophic and chaotic behaviour when possible and desirable, while recognizing that human ability to predict and forecast is limited
Manage feedback to maintain desired system structures within their windows of vitality Aim to manage positive and negative feedback mechanisms so system structures remain within desired windows of vitality. Maintain or strengthen feedbacks that allow detection of thresholds before they are crossed (versus slow or delayed feedbacks with weak signals), while avoiding cascading collapse
Provide appropriate contexts for positive co-evolution of systems and their environments Influence systems by providing the appropriate context for their development and prosperity. Allow the system and its environment to co-evolve with one another, thereby changing the nature of both, all the while avoiding creating an overdependence of the system on its context. Anticipate and manage for changing contexts (e.g. climate induced species migration)
Avoid undesirable feedback mechanisms Reduce the gain of positive feedback loops so as to prevent undesirable dynamics, such as promoting gains to these who are already advantaged. Avoid the ratcheting effect where intensification from one side leads to intensification from the other side (e.g. the pesticide treadmill). Promote diversification, regulation, and other policies that level the playing field, and let go when necessary
Promote diversity, variability, redundancy and modularity Promote and sustain diversity in all forms (biological, landscape, cultural, social and economic) as a major source of future options and system capacity to response to change and disturbance. Embrace and work with ecological variability rather than attempting to control it. Favour largely self-reliant systems to avoid over-connectedness and overdependence
Follow systems over the long-term Seek to understand systems by following their long-term dynamics as opposed to understanding systems as a series of events. Look for emergent patterns at all scales. Develop the capacity to monitor changes (e.g. by providing baseline data, finding a balance between rigid and loose control)
Maintain the structures and services that underlie and support desirable systems Maintain and promote the functioning of critical systems structures (e.g. soil fertility, pollination) that underlie systems dynamics and support greater complexity

The principles, both individually and as a set, favour a humble approach to managing complexity, uncertainty and ethics, recognizing that social-ecological systems cannot be managed in fine detail at any scale. The principles also complement the resilience thinking 'no regrets approach' and Allen et al.'s (1999) management for context which prioritizes maintaining important structures (e.g. keystone species) that are necessary to provide the context within which systems self-organize.

Building from the generalized discussion of complex systems, the discussion shifted towards systems and society and drew primarily from Giddens' structuration theory and bioeconomics. Giddens' structuration theory focuses on the duality of structure, which implies that "[in] and through their activities, agents reproduce the conditions that make these activities possible" (Giddens 1984, ch. 1). Giddens' theory informed the discussions of sociotechnical systems change provided in Chapter 4.

The second approach to systems and society, bioeconomics, provided a powerful reinterpretation of economic systems through a complexity lens with particular focus on energy and resource flows. Bioeconomics provided a useful set of metrics for determining feasibility and desirability of energy systems based upon their metabolic patterns (i.e. energy return on investment, labour and resource requirements, and energy density).

The bioeconomics narrative is particularly relevant for considering how the physical characteristics of alternative energy systems may match or disrupt modern societies, which are currently predicated upon energy sources with a high energy-return on investment, high power energy sources, and low labour requirements. The insights from bioeconomics were synthesized into a set of guidelines reproduced in Table 28.

Table 28 – General guidelines for developing desirable bioeconomic systems

Favour energy sources with high energy return on investment and seek to close the energy-for-energy cycle Ensure anticipated energy systems have a sufficient energy return on investment to maximize net output from the energy-for-energy cycle. Over time seek to close the energy-for-energy cycle of renewable energy systems such that they may self-perpetuate
Optimize labour allocation in the economy Work within the current labour allocation requirements and return-on-investment of labour in complex societies (notably in the energy and agricultural sectors). Seek to reallocate labour back to the energy sector while minimizing disruption
Maintain non-energy resource consumption within renewable limits Ensure that land and other resource (e.g. water, minerals) requirements for energy production respect ecological and social limits, especially when attempting to close the energy-for-energy cycle
Encourage flexibility in societal metabolic patterns Favour energy systems that do not lock society into undesirable metabolic characteristics (in terms of resource consumption, labour allocation, and energy usage), but rather may respond to the changing nature of society's relationships with energy and resource consumption. Ensure that the proposed energy source matches both the metabolic characteristics (e.g., energy consumption, power density) and the constraints (e.g., land and labour availability) of society, both now and envisioned
Manage the rate, and rate of change, of energy supply and demand Ensure the rate at which society is supplied with energy avoids the collapse of current societal and economic systems. Likewise, maintain the rate of change of energy supply and demand within the adaptive capacity of society
Reduce societal complexity and its energy and resource cost Recognize that managerial complexity has a resource cost, and that individually rational and innovative responses to societal problems often increase societal complexity. Seek to manage complexity at emergent levels, and reduce complexity where feasible

9.1.3 Developing a set of guidelines to inform energy systems analysis

Building on the theory developed in Chapters 2 and 3 – with regards to knowledge generation in a complex world, and the characteristics of complex systems – the discussion in Chapter 4 began to develop an understanding of energy systems and energy decision-making. In many regards, the topics of Chapter 4 paralleled the previous discussions, but with energy as the dominant theme.

In order to develop an understanding of energy sustainability, Chapter 4 was structured around three general questions. The first question was simply what is the energy problem? This question grounded energy systems analysis and energy decision-making within the broader worldview presented in this dissertation. This section draws inspiration from Robinson (1982), who reviewed the energy literature and noted three broad framings of the energy problem that are commonly discussed:

(1) The energy problem is essentially a problem of developing new supplies and enhanced conservation measures to meet the energy demands of society
(2) The energy problem is a matter of the increasingly intolerable social-ecological impacts related to energy use.
(3) The energy problem is one manifestation of a far more fundamental crisis relating to the modern society.

The argument developed in this dissertation is that many of the challenges addressed by sustainability assessment deal with the first and second framings noted above, but, when taken collectively, recognize the relevance of the third problem framing.

Drawing from the discussion of the energy problem, the second question addressed in Chapter 4 is what are the characteristics of an appropriate and constructive societal relationship with energy? This second question, addressed through discussions of the soft energy path, was an important theoretical cornerstone to this dissertation and provided a means of energy decision-making grounded in the context of the complexity of science.

The soft energy path is a compelling approach to energy strategy that highlights the importance of *how* energy system change is implemented (through broadly democratic principles). Likewise, that soft path outlines a framework for conceiving of energy as a service and promotes matching energy supply with end-uses (in terms of scale, degree of centralization, and energy quality). Furthermore, the soft path promotes reflecting upon the needs and ends of individuals and societies with regards to energy consumption, and also more generally (e.g. Brooks et al. 2009a; Morrison and Lodwick 1981). To this end, the soft path provided an approach the goes beyond instrumental concerns (e.g. increased efficiency), to address systemic and ethical challenges and opportunities.

The discussion surrounding the soft path and appropriate technology culminated in a set of guidelines for achieving a soft energy path. These guidelines are reproduced in Table 29.

Table 29 – General guidelines for achieving a soft energy path

Promote end-use matching Match the scale and quality of the energy supply to the scale and quality of its final use. Seek opportunities for multiple uses of energy inputs (e.g. cogeneration)
Prioritize energy services in the pursuit of worthwhile ends Use energy a means for social ends that is valued for the services that it provides (e.g. comfortable rooms, light). Use energy policy as a vehicle for meeting end-use demands for those services in the most efficient, effective, ethical and elegant manner possible. Promote constructive discussions about means and ends in society, both with regards to energy policy and beyond
Design energy bridges that aim to close the energy-for-energy loop Design systems as bridges to more sustainable social structures, recognizing there is no ultimate energy or social end state. Bridging mechanisms should be minimally disruptive but will require societal and technical change and require seeking and developing means of production and consumption that do not (or minimally) rely on fossil fuels. Non-renewable goods must only be used if they are indispensable, and then only with the greatest care
Use energy policy to catalyze broader change in social values Recognize that energy strategy has implications far beyond energy supply and demand, and rather affects a wide variety of sectors (e.g. public health, food sovereignty). Design energy systems as a democratic means of constructively re-patterning society (e.g. promoting urban agriculture, fostering social learning). Ground quantitative calculations within qualitative narratives of desired future states
Maintain rate and scale of production and consumption within local limits Control the pace and rate of change of energy production and consumption to ensure that they remain within local capacity for system management and for change. Recognize that having too much energy too fast is as harmful as too little energy too late, and rapid expansion is harmful both to producing nations (e.g. resource curse and petrostates) as well as to consuming nations (fuel security)
Promote soft societal and political systems Seek structures and dynamics in society that reinforce and are reinforced by the feasibility and desirability of the soft energy path, including appropriately decentralized decision-making and energy production, and local self-reliance. Favour energy systems that promote sovereignty and minimize geopolitical risk
Promote reciprocity, responsibility and fairness in production and consumption Design energy systems that promote intrinsic responsibility, and foster greater reciprocity so as to allow people to become more involved in and aware of the production, consumption and operation of their energy technologies. Encourage the fair sharing of benefits and risks
Prioritize democratic participation to benefit both individual and public interest Favour energy technologies, employment opportunities and decision-making processes that promote informed and participatory decision-making and citizen engagement. Prioritize basic virtues, rights and the public good (e.g. liberty, justice, equality, fairness, self-realization)
Plan for the cumulative and emergent consequences of mass adoption Recognize that many of the important benefits and drawbacks of energy technologies emerge during mass adoption. To the extent possible, anticipate such cumulative and emergent effects and plan accordingly. Seek positive cumulative and synergistic impacts in energy systems
Foster an economics of permanence and non-violence Prioritize sociotechnical and energy systems that may be considered permanent, while recognizing the need for bridging technologies and practices. Favour energy technologies that are non-violent with respect to people and the environment. Favour technologies and technological systems that can fail safely and do not unduly depend on human infallibility
Design diverse, redundant and modular energy pathways Favour sociotechnical systems that ensure the ability of future generations to determine their own desirable futures. Promote energy technologies that are modular, incremental, diverse, redundant and with short lead times, so as to improve resilience and responsiveness. Favour precaution (e.g. safe fail vs. fail safe)

Where the soft path hits a rather hard barrier relates to implementation, and this led to the third question of how can sociotechnical systems change be achieved? The question of implementing change is a vexing problem in many disciplines and there is yet no panacea. However, there are still benefits to be found in drawing insights from previous conceptual research in this field, and the discussions in the third section centred on transition management, an approach to sociotechnical systems change (Kemp et al. 2005; Loorbach 2010; Rotmans and Loorbach 2008; Westley et al. 2011).

Transition management draws insight from Giddens' structuration theory, which was briefly discussed above. The intent of transition management is to provide a multi-level approach to change that can overcome the barriers to change through fostering appropriate co-evolution, overcoming lock-in, planning for the long-term, and addressing power imbalances. The discussions relating to transition management culminated in a set of guidelines for fostering change. These guidelines are based upon a previous synthesis by Gibson (2011b) and are reproduced in Table 30.

Table 30 – Generic guidelines for fostering sociotechnical systems change

Design for the long term Adopt a time scale for transition of at least 25 years for developing and evaluating options for immediate action while recognizing the need for short-term successes to maintain momentum. Allow for continued learning and adjustment, and work within economic cycles
Foster positive innovation and synergy in the broader economy Promote synergy among the various intersecting domains (e.g. health, energy, agriculture, waste) at all levels, and with attention to the current and potential participants. Foster co-evolution that leads to a more constructive relationship between technology and society. Where appropriate, build upon existing capital
Apply leverage when windows of opportunity are open Identify and prepare for windows of opportunity due to impending stresses and disturbances. Develop the capacity to apply leverage points so as to manage during disequilibria
Build supportive networks that promote participation Foster development of collaborative networks of interaction among current and potential participants, with emphasis on building an enabling environment, exploring many options, and ensuring experiential learning and responsive flexibility. Promote participation so as to build common ground among actors
Develop positive visions of the future Develop, test and compare alternative future scenarios to clarify long term objectives and their interrelations, identify apparently viable options for sustainability and resilience, and map pathways to reaching them. Combine visioning with analysis of current trends to identify key transition challenges, vulnerabilities and possibilities
Balance consistency and stability with adaptiveness during a transition Build transition strategy and policies on a foundation of well-defined and transparent objectives; ensure the supportive regime (legal, financial, etc.) is responsive to learning but also stable enough to provide a reliable base for investment of significant resources in longer-term initiatives
Create space for positive innovations to develop and mature Provide a safe and level playing for innovations (both technical and social) to experiment and grow. Avoid picking winners so as to keep multiple options open. Experiment with alternative system options with different structures, linkages, participants and roles, motivations, resources, knowledge bases and practices, while recognizing the cost of experimentation and failure. Promote successful innovations (e.g. publicizing results)

Favour adaptiveness and flexibility
Favour safe-fail, reversible and adaptable initiatives while recognizing innovation, adaptiveness and diversity may impact efficiency, stability, and increase uncertainty. Temper co-evolution to avoid lock-in
Strengthen democratic legitimacy and fairness
Favour policy and decision making processes that are inclusive, transparent, accountable, and democratically representative. Ensure attention to distributional impacts, power imbalances and trade-offs. Prioritize those vulnerable to loss of essential wellbeing, and seek to enhance intra- and inter-generational equity in transitions
Foster transformative learning
Focus on learning for innovation, with constant experimentation, monitoring, re-assessment and adaptation; integrate conventional scientific, local and traditional knowledge; focus on the process of learning
Challenge power structures through constructive conflict
Recognize that conflict with vested interests is an expected step towards positive change. Prioritize peaceful and constructive conflict that can overcome barriers to transition

Source: adapted from (Gibson 2011b)

Over time, as practitioners gain more experience with transition management and other approaches, perhaps the guidelines may become more prescriptive, while still recognizing that important aspects of systems change are likely inherently uncontrollable. For present purposes, however, the guidelines suffice to inform both Gibson's SA framework approach and criteria specification for energy applications.

The guidelines for fostering sociotechnical systems change provided above are the final set of guidelines related to the complexity of science, the science of complexity, and energy systems analysis. The following section describes how these four sets of guidelines were synthesized into a generic set of sustainability criteria for energy undertakings.

9.1.4 Proposing a generic set of sustainability criteria for energy undertakings.

The final step in the theoretical development was the proposal of a generic set of sustainability criteria for energy undertakings. The criteria set is provided in Table 31 below.

The criteria are integrated within Gibson's eight categories, while recognizing that in many instances a single criterion may be relevant to multiple categories. The transposition of the guidelines into sustainability criteria is not a simple linear process. In certain instances the guidelines are more directly and easily transposed into sustainability criteria, while oftentimes principles must be interpreted. The interpretations were informed by the casework. Furthermore, a single guideline may inform several criteria, and likewise a single criterion may be informed by multiple guidelines. The overlap between guidelines and criteria reflects both the complexity of the task being undertaken as well as the overlaps among the various theories that informed the conceptual framework of this dissertation.

Table 31 – Sustainability criteria for energy undertakings

Criteria
Socio-ecological system integrity
Promoting social-ecological integrity
• manage ecological integrity at the whole system level, including direct, indirect and induced effects (e.g. ecological connectivity, biodiversity)
• maintain critical ecological services, keystone species and culturally important species and ecotypes that provide necessary context (e.g. forest cover)
• anticipate and prepare for social-ecological systems change (e.g. climate induced species migration)
• maintain sufficient land available for ecological and societal uses (e.g. grazing, gathering medicine)
Anticipating and adapting to systems effects and thresholds
• allow ecosystems to move through necessary cycles, including growth, development, collapse and renewal, while avoiding undesirable dynamics (e.g. desertification)
• maintain and promote ecological life support systems (e.g. pollination, nutrient cycling)
• manage for cumulative impacts and thresholds while respecting uncertainty and vulnerable social-ecological components
• avoid escalation and other unwanted reinforcing cycles (e.g. energy poverty, desertification)
• manage rate of growth of energy and resource demand such that it stays with local and global ecological carrying capacity
Avoiding and addressing waste production
• where feasible and desirable, seek productive uses for wastes (e.g. anaerobic digestion of organic wastes)
• manage wastes in a way to avoid adverse social-ecological impacts (e.g. discharge of agricultural effluents)
Livelihood sufficiency and opportunity
Promoting meaningful employment opportunities and self-actualization
• promote respectful and fulfilling employment that respect workers' rights (e.g. fair wages, respecting migrant workers) and fosters their ability to self-actualize
• provide fair opportunities to all those seeking gainful employment (esp. poor, marginalized, youth)
• promote worker and user health and safety along the full energy supply chains and in the broader population (e.g., reduce indoor air pollution, promote biking as opposed to driving)
Fostering local economic development and capacity building
• support economic systems able to accommodate changing labour allocation due to the increase in renewable energy production and generally ecologically friendly practices
• support the provisioning of public services necessary for lasting economic and social development (e.g. schools, health facilities)
• control the pace and scale of energy production and consumption such that it remains within local capacity for management and avoids boom and bust effects
• provide opportunities for retraining in the transition towards sustainable energy practices
• create space for positive social and technical innovations to develop and mature
Promoting appropriate degrees of centralization
• promote local employment and capacity building (e.g. economic spinoffs) of both urban and rural regions in an appropriately decentralized economy
• promote economic self-sufficiency and energy sovereignty at all scales (e.g. facilitate domestic and decentralized ownership of production)
• promote small-scale and local energy production to improve resilience and counter current dynamics of centralization

Intragenerational equity
Fostering equality
• promote gender equality broadly in society (e.g. access to education, livelihoods, and decision-making powers) as well as employment within the energy system
• promote equitable energy pricing , while respecting that some groups have lower capacity to pay the true cost of goods and services
Promoting fair distribution of benefits and risks
• contribute to the maintenance of and access basic infrastructure and services (e.g. roads, schools, hospitals)
• promote fair distribution of wealth, income generating opportunities, and influence (incl. age, gender, ethnicity) both within and between societies and nations
• promote fair distribution of risks within local communities and by age, gender, ethnicity, respecting that some groups have less capacity than others to accommodate increased risks
• promote equitable distribution of resources and opportunities among and within urban and rural regions, while addressing different urban and rural needs
• promote internalized accounting of social and ecological costs of production and consumption
Promoting international equity
• promote responsible and equitable practices by the international community (e.g. fair trade)
• promote policies and consumption patterns that do not harm other nations, or prevent them from exercising their sovereignty
Intergenerational equity
Maintaining long-term social-ecological integrity
• maintain long-term resource availability (e.g. mineral resources) and ecological integrity (e.g. land productivity, water and other livelihood essentials)
• avoid economic boom and bust cycles and their associated social-ecological impacts
• promote long-term equitable distribution of wealth (incl. age, gender, ethnicity)
• maintain and enhance long-term social capital (e.g. traditions of mutual assistance, active engagement in addressing collective concerns)
Avoiding lock-in and perverse effects
• avoid energy undertakings with long-term legacy costs (e.g. nuclear wastes)
• maintain sufficient options for future generations to avoid lock-in
• avoid rebound effects that may cause long-term social-ecological harm
• avoid trading off long-term needs for short-term gains
Fairly distributing costs and benefits
• promote equitable long-term distribution of wealth, income generating opportunities, and influence (incl. age, gender, ethnicity) both within the energy systems and in society at large
• promote equitable long-term distribution of risks within local communities (esp. urban-rural) and by age, gender, ethnicity, respecting that some groups have less capacity than others to accommodate increased risks (e.g. elderly)
Resource maintenance and efficiency
Managing at the whole system level
• favour projects, plans and policies that reduce societal complexity and its consequent resource costs (e.g. governance burdens and regulatory costs)
• minimize whole system costs (e.g. GHG emissions, resource extraction) of energy systems by optimizing conservation resources and demand-management opportunities
• prioritize conservation, thrift, and demand management
• promote resilient energy supply systems with sufficient diversity, modularity and redundancy of energy pathways
Prioritizing system efficiencies
• match the quality of the energy and other resources (e.g. water) to the quality of the end-use
• focus on consuming energy only as necessary to provide services in the pursuit of constructive social ends

• seek opportunities for multiple uses of energy inputs (e.g. cogeneration) and for energy cascading
Fostering resource stewardship
• promote socially and ecologically beneficial energy system operations (e.g., energy crops that rebuild soil fertility)
• manage for total resource supply as well as rate of resource consumption
• promote the usage of locally available resources and avoid resource conflicts
• minimize the use of non-renewable resources along the entire lifecycle, and avoid extractive uses of renewable resources (e.g. water mining)
Matching current and future metabolic patterns
• promote renewable energy systems with a sufficiently positive Energy Return On Investment
• develop and plan for self-sufficient renewable energy systems that minimize and/or eliminate non-renewable inputs and close the energy for energy loop
• account for the resources and services that underlie the industrial and post-industrial societies (e.g. cloud computing)
• prioritize the use of non-renewable resources for the purpose of developing energy bridges to renewable and equitable energy systems
Socio-ecological civility and democratic governance
Providing a positive social-ecological regulatory environment
• promote an integrated regulatory environment that provides the necessary social-ecological and economic context for sustainability-based decision-making and actions while fostering creativity and individual choice (e.g. more stringent building codes)
• promote respect for social and environmental laws and regulations both domestically and internationally (e.g. corporate social responsibility
• ensure the supportive regime (legal, financial, etc.) is responsive to learning but also stable enough to provide a reliable base for investment of significant resources in longer-term initiatives.
Promoting good governance
• promote local decision-making and more broadly participative and decentralized local multi-stakeholder governance
• enhance collaborative and transparent governance, system legitimacy, accountability, and trustworthiness.
• favour policy and decision making processes that are inclusive, transparent, accountable and reflexive, linked closely to bodies of representative democracy.
Fostering responsible and virtuous individuals and societies
• promote responsible consumption understood as an ecologically and socially shared privilege as opposed to an intrinsic right
• promote respect for marginal members of society
• promote respect for, and maintenance of, desirable spiritual values, and traditional ways of knowing
• promote basic rights (liberty rights, security rights, gender equity)
Developing an awareness of means and ends
• increase awareness of the social ends being met by energy consumption and promote constructive dialogue of how best to meet those ends in the most effective, elegant and ethical manner
• promote open deliberation on means and ends (e.g. through forecasting and backcasting)
• promote a culture of conservation and resilience, and seek to delink welfare from energy and resource consumption
• promote energy systems that foster reciprocity such that people become more involved with and aware of the operation of their energy systems and the impacts of their lifestyles
Fostering individual and collective learning and understanding
• promote creative, virtuous and integrated thinking in the broader society
• promote learning to build individual and collective understanding of, and commitment to addressing, important societal challenges
• use energy policy as a means of catalyzing broader constructive social change (e.g. public transport and urban agriculture)
• promote active, informed and self-reflective participation in environmental management and other

environmental initiatives (e.g. public transit)
• use energy related conflicts (e.g. wind turbine siting) to explore broader ethical concerns in society
Promoting ecological literacy and responsibility
• contribute to improved public understanding of socio-ecological systems and their interdependencies, and to the protection and conservation of natural resources
• promote energy pricing that internalizes social and environmental costs, while ensuring fairness for the disadvantaged (e.g. poor, marginalized)
• promote appropriate means of valuing ecological services
Prudence, precaution and adaptation
Fostering resilience, reliability and adaptive capacity
• promote sufficient adaptive capacity in the broader social-ecological system, and at multiple scales, to maintain desired system structures in the face of changing conditions (e.g. drought, global economic recession)
• favour technological systems that are relatively insensitive to human error, and with low cost of technological failure and accidents
• promote diversity, flexibility, modularity, reversibility, fallback options, and safe-fail characteristics at all levels in the energy systems and in society at large
• seek mutual gains in resilience and efficiency
Avoiding lock-in
• avoid lock-in (e.g. one type of energy system) by favouring energy investments that are flexible, incremental, and with comparatively short lead times and appropriate lifetimes.
• promote economic diversification and reduce vulnerability to world market volatility
• favour energy options that minimize geopolitical risk (e.g. nuclear proliferation)
Developing anticipatory planning and managing for uncertainty and complexity
• manage for key social-ecological system thresholds, vulnerabilities and windows of vitality
• acknowledge and address key areas of uncertainty and recognize the presence of irreducible uncertainty
• promote anticipatory planning for risk management to avoid or reduce the risks of significant damage (e.g. high risk of minor damage, low or ill-understood risks of significant problems) as compared to alternative practices
• provide the capacity for monitoring changes in complex situations (e.g. by providing baseline data, finding a balance between rigid and loose control)
Mitigating perverse and other undesirable systems effects
• anticipate and prepare for cumulative impacts of mass adoption of energy and other technologies
• avoid rebound effects (efficiency gains facilitating more consumption in ways that add to sustainability problems, increasing supply and consequently requiring increased demand)
• avoid trading off long-term needs for short-term gains (e.g. cutting down mangroves for fuelwood)
• avoid and mitigate negative cumulative and escalating effects
Immediate and long-term integration
Promoting constructive co-evolution
• seek positive integration with other industries and stakeholders
• seek the appropriate combination of self-reliance and cooperative networks of support
• promote cultural-technological co-evolution favouring sustainability objectives
• promote positive indirect effects within the social-ecological system (e.g. public health, education)
Creating opportunity for multi-level change
• provide a level playing field so as to ensure fair competition between and amongst alternatives (e.g. organic farming, renewable energy)
• provide space to test, adapt and improve alternatives
• promote bottom up and top-down change at all levels
• favour peaceful and constructive means to achieve meaningful change
Harnessing key windows and players for change
• take advantage of avenues for rapid change and seek leverage points to obtain maximum net gains
• empower key stakeholders at all scales to promote positive change

• provide space for alternative structures of organization (shadow tracks) to develop
Developing energy bridges
• develop energy systems as a constant bridge to more sustainable societal structures and dynamics, and that match both current and desirable future societal metabolic patterns and that minimize consumption of non-renewable resources
• plan for the transition to more sustainable energy within longer cycles of change (e.g. economic cycles) and within the timeframe of capital stock turnover
• meet short-term and long-term needs, recognizing they may be different

There are several points of note regarding the sustainability criteria set, and these will be briefly discussed below.

Designed as a full suite

The criteria set proposed above provides an initial framework for assessing energy system options for the potential to promote progress towards sustainability. There are 107 criteria, which may seem an ungainly amount, but they are necessary if the assessment is to remain sufficiently general to accommodate all types of energy systems, and to ensure multiple benefits and interactive effects.

While the criteria set must be understood as a full suite, the criteria certainly can be – and indeed must be – organized and consolidated into packages and themes that relate to the local context such that decision-makers and stakeholders can make sense of the information, all the while ensuring the intent of the assessment is not undermined.

As they are currently presented, the criteria cannot be taken as individual, non-overlapping, and equivalently weighted. Important themes are double counted, and in specific contexts some criteria will be more important than others. This does not preclude the possibility of organizing the criteria to make them minimally overlapping and even apply weights or other means to recognize what criteria are most important.

Combining principles and goals into requirements for progress towards sustainability

The criteria set may be best understood as describing *requirements* for progress towards sustainability. The requirements include characteristics to be favoured (e.g. favour low risk approaches), and goals to be achieved based on predictions of what is to come (e.g., given anticipated future climate fluctuations, it is necessary to build adaptive capacity). The generic requirements are about moving in a desirable direction.

Seeking progress towards sustainability rather than defining an acceptability threshold

The criteria outline a set of generally desirable system attributes and actions for achieving *progress* towards sustainability, rather than defining an acceptability threshold. Conventional assessment practice generally prefers an acceptability threshold, whereby if a project meets the minimum requirement then it may be approved to proceed. Many of the concerns with environmental assessment – including inconsistent attention to alternatives, poor efforts to address cumulative and synergistic effects, and a focus on minimizing harm as opposed to promoting positive steps – are due in part to the acceptability threshold approach. While there are obvious cases where a proposed project is unacceptable, there is no clear delineation of acceptability at any point.

In order to avoid the threshold of acceptability, the sustainability assessment criteria should be applied primarily for the comparative evaluation of alternatives. The premise is that as societies move along choosing the best alternatives then they will move in the direction of sustainability.

Informed by the casework

The criteria set proposed above was significantly informed by the casework, even though the basic structure was present before the casework began. The criteria set evolved as insights from earlier case studies served to inform proceeding ones. The benefit of such an iterative approach is that it allows for insights and ideas explored through the theory and previous cases to be further explored and refined.

Focused on energy undertakings but more broadly relevant

Finally, the sustainability criteria proposed above are primarily intended for application regarding energy undertakings. These undertakings may be at a wide variety of scales. Indeed, the case studies include the assessment of individual operations (e.g. a small-scale biodiesel plant in Barbados; a sugarcane-ethanol mill in Brazil), all the way up to a provincial wide electricity system (the Ontario power system) and even linked national energy and agricultural systems (of Senegal). However, despite the energy focus, the criteria set is much more broadly relevant. The energy undertaking is used as a means of exploring the broader social-ecological context in which the undertaking is situated. Many of the important considerations addressed in the criteria set are by no means confined to energy systems. For this reason it is hoped that the criteria set may be applied to all manner of undertakings, requiring only a minimum of restructuring.

With the proposed sustainability criteria set, the conceptual development was effectively complete, and it was possible to apply the criteria towards the case studies. The results are summarized in the following section.

9.2 Summarizing the casework

The sustainability assessment framework and systems- and energy-informed criteria set developed in the theoretical portion of this dissertation were applied in four distinct case studies in four different countries (Barbados, Brazil, Canada, and Senegal), spanning multiple scales and various bioenergy systems. It is important to note the sustainability criteria set represents the iterative evolution between theory and casework. The criteria set has evolved as each subsequent case study had the benefit of being informed by the previous cases. The benefit of such an iterative approach is that it allows for insights and ideas explored through the theory and previous cases to be further explored and refined.

There is one final point of note before describing the individual cases. The theory presented above draws from theoretical frameworks that promote and describe fundamental change to the structure and function of society. Likewise, when understood as a full suite, the sustainability criteria proposed in Table 31 provide the foundations for a comprehensive critique of prevailing institutional assumptions and behaviour, and promotes consideration of broad alternatives. The intent was to recognize the important challenges facing society, and provide a unique and integrated means of addressing the challenges. Despite the more revolutionary undertone of the theory, it is evident in the casework that the results of sustainability assessment generally tend towards incremental change. To a certain extent this is a common occurrence when theory meets practice, especially so when the types of decisions related to sustainability assessment – were they to be implemented by those in power – would have far reaching consequences on livelihood opportunities, biophysical integrity, etc., both now and in the future.

The incremental nature of the case study insights does not detract from the revolutionary intent of sustainability assessment. Rather, the hope is that as societies move along incrementally the end result will be more radical. In other words, sustainability assessment must be demanding and practical, incremental and revolutionary.

9.2.1 Chapter 5 – The Ontario Power Authority's 2006 Integrated Power Systems Plan

Chapter 5 briefly reported upon a sustainability assessment of the Ontario Power Authority's (OPA) proposed 2006 Integrated electrical Power Systems Plan (IPSP). The research was undertaken in 2008 as a collaborative project between faculty and students at both York University (in Toronto) and the University of Waterloo. The results of the research were published as a report submitted to the hearings regarding the IPSP (Gibson et al. 2008) as well as an article in *Energy Policy* (Winfield et al. 2010).

The IPSP was found not to be a serious attempt for seeking progress towards sustainability. Overall, the IPSP appeared to promote business-as-usual and prioritize nuclear power in Ontario. The OPA framed its IPSP largely as a coal versus nuclear problem, as opposed to a critical appraisal of power systems planning; and in doing so it underplayed potential for conservation, demand management, increased renewable energy, and social change (Winfield et al. 2010). In response, the Waterloo-York research team attempted to apply Gibson's SA framework to both the IPSP as well as *Renewable is Doable*, an alternative power systems plan proposed by the Pembina Institute and WWF Canada (Peters et al. 2007).

The research project began with a collective process of criteria specification, and the general criteria set is provided in Table 34 in Appendix 2. The criteria set proposed in Table 34 provided a preliminary synthesis of resilience criteria with Gibson's SA framework. In this manner, the research highlighted the importance of concepts such as system reliability, modularity, path dependence, lead-time and lock-in, all of which are also considered within the soft energy path.

Once the sustainability criteria were finalized, each student applied them to evaluate of one or several components of the IPSP (e.g. wind, transmission, solar PV), and I focused upon bioenergy, notably energy cropping, agricultural residues, forest residues, on-farm biogas, digestion of solids and municipal wastes, and landfill gas. This section notes three relevant insights drawn from the general results.

First, the bioenergy assessment highlighted the importance of flexibility in energy supply systems. Bioenergy is particularly flexible through a variety of means. Notably, there are multiple energy pathways available for bioenergy production, including thermochemical, electrochemical, anaerobic digestion (biogas), and fermentation (Gaudreau 2009). Likewise, most bioenergy systems are also flexible in terms of dispatching. For example, most forms of solid bioenergy (e.g. residues) can be stored for significant lengths of time and can be brought on line relatively quickly. The ability to dispatch bioenergy throughout the day and year implies it may help support other renewable energy technologies, notably wind and solar.

Second, the bioenergy assessment of the IPSP highlighted importance of recognizing ecological limits to bioenergy production, particularly due to water and soil requirements, the overharvesting of wood and the increased capture of primary productivity. If undertaken improperly (e.g. in large monocultures, on ecologically sensitive lands), bioenergy may be harvested in a non-renewable manner. The limits to bioenergy production must also account for other uses of the bio-products, such as pharmaceuticals, liquid fuels, food and fibre.

Third, the assessment indicated how energy policy provides opportunities for pursuing broader societal goals. How bioenergy is developed in Ontario may have important implications for rural viability in Ontario, including providing rural employment opportunities, and improving the feasibility and desirability of agriculture. This presents an opportunity to pursue constructive rural development goals along with energy policy development, but one that must be properly undertaken in a broadly democratic manner. For example, for bioenergy to provide employment opportunities in rural areas in part depends on local ownership and the size of the energy systems (e.g. Morris 2007), both of which are themes noted in the discussion of the soft energy path. These insights all served to inform the assessment framework and criteria set.

9.2.2 Chapter 6 – A small-scale biodiesel operation in Barbados

Chapter 6 reported on a sustainability assessment of a small-scale biodiesel operation in Barbados that was undertaken in Fall 2008. The results of the assessment were published in the journal *Impact Assessment and Project Appraisal* (Gaudreau and Gibson 2010).

The plant owner collected used cooking oil from restaurants, roadside stands, and individual homes, and converted it into biodiesel using a first-generation processing technology known as transesterification. The output ranged from 250 to 400 gallons per week of finished biodiesel, which was sold on site.

The assessment process revealed that in terms of biophysical metrics, the operation was not overly successful. There were neither significant greenhouse gas reductions nor improvements to energy security, and the operation required large amounts of fresh water in one of the most water scarce countries in the world. However, to see this operation as a failure would be to miss some of the most important benefits it offered Barbados, which are discussed next.

First, the research highlighted the importance of seeking integration across sectors and domains. Biodiesel production from used cooking oil in Barbados involves and links a diversity of stakeholders, and the impacts of biodiesel production in Barbados relate to several issues of national concern, including diet (the high consumption of fried foods), waste and water management, energy security, economic diversification and livelihood opportunities. Integrating across sectors and domains provides an opportunity for seeking positive synergy, and in this case, it was proposed that the government might be best situated to seek such positive synergy.

Second, the research illustrated the potential for energy undertakings to promote social learning and capacity building. As a nexus for discussion, biodiesel initiatives can build social awareness of important issues. The social learning benefits of small-scale biodiesel are not related to the actual biodiesel produced, but rather to the characteristics of the biodiesel operation, notably the size of the operation, the relative simplicity and scalability of production, and the people involved.

Third, with appropriate implementation, biodiesel offers benefits as a transition fuel, facilitating a shift from the current transportation and energy infrastructure to more sustainable future options. Notably, biodiesel allows the characteristics of the supply infrastructure to change without unduly impacting current demand infrastructure (e.g. diesel engines, gas stations). Likewise, the potential to produce biodiesel at a small-scale provides the opportunity to foster a more broadly democratic energy transition, as promoted by the soft energy path.

Fourth, one topic not sufficiently addressed in the case study is the energy return on investment (EROI) of biodiesel. While no certain numbers are available, Giampietro and Ulgiati (2005) argue the EROI of large-scale biodiesel with current technology is below 2, implying biodiesel will continue to rely on fossil fuel subsidies for its production, and will be unable to meet the energy demands of modern society. As such, biodiesel should not be seen as the end goal of an energy transition, but rather an intermediary step in a dynamic process of change. While the low EROI does not detract from the benefits discussed above, it indicates that the indirect benefits alone are insufficient as an end goal. At some point, alternative sources of energy will need to be produced with a sufficiently high EROI for viability in a post-fossil era. Likewise, the metabolic characteristics of societies will need to change so as to match the new biophysical constraints (Hall and Klitgaard 2012; Hall et al. 2008).

9.2.3 Chapter 7 – A sugarcane-ethanol mill in São Paulo, Brazil

Chapter 7 reported on a sustainability assessment of a sugarcane ethanol operation located in the Tietê-Jacaré Watershed of São Paulo, Brazil. The assessment was undertaken as a team project between University of São Paulo and University of Waterloo. The principal investigators were Carla Grigoletto Duarte and this author, while Prof. Gibson from Waterloo and Prof. Malheiros from São Paulo supervised the work. The manuscript was published in the journal *Ecological Indicators* (Duarte et al. 2013).

The sugarcane ethanol mill harvests approximately 21,000 hectares of sugarcane crops from seven municipalities and produces hydrated ethanol for domestic markets, and sugar for domestic and international markets.

The assessment process illustrated four points of note particularly relevant for the dissertation. First, this chapter highlighted the importance of grounding the assessment within its broader context. Many of the impacts related to the mill can only be understood within the broader social-ecological system. For example, water supply and water quality depend upon, among other things, development in the watershed leading to other uses of water, rainfall variability, and point and non-point source pollution. These issues cannot be addressed adequately at the level of the individual mill, but rather require planning, regulation and monitoring at multiple scales (local, regional, watershed, state, etc.).

Second, the case study illustrated the difficulty of interpreting quantitative data, which arose in this case for several reasons. Notably, in many instances necessary data are unavailable, such as detailed and credible analyses of land-use change, measurements of greenhouse gas emissions, and ecological connectivity. To complicate matters, the data sets are often fragmented in various levels of government, and in certain instances, data are withheld for private reasons, such as proposed expansions of sugarcane production, which have financial implications. This is not to argue that informed decisions cannot be made, but they are hindered by data limitations at all scales.

Despite the data limitations, the sustainability assessment uncovered several important thresholds relating to land-use change and biodiversity, water and air quality and quantity, and livelihood opportunities. Uncertainty remains regarding which thresholds are most important, how they interrelate, and the time frame available to address them. The thresholds must be explored in relation to upcoming trends in Brazilian sugarcane ethanol, particularly efforts to expand sugarcane production and increase mechanization. A more rigorous analysis of these concerns was beyond the scope of the present case study.

Finally, this research illustrated the importance of government oversight in the energy industry. As noted by the Nuffield (2011), unfettered expansion of sugarcane ethanol – in large part due to rising international demand – risks overwhelming capacity for management. Governments, both Brazilian and beyond, must take responsibility for ensuring that sugarcane ethanol is produced in a constructive manner, and this requires regulating both the amount of sugarcane ethanol produced, as well as the manner in which it is produced. Some extreme consequences of unfettered market expansion include the use of slave labour (Nuffield 2011). Likewise, the key results note the mill under investigation has been fined for offences that include exceeding labour hours and illegally burning straw in protected areas. While the mill has also shown many progressive tendencies, current market forces encourage inappropriate activity, and local communities appear overwhelmed by the power of the sugarcane ethanol industry.

9.2.4 Chapter 8 – The agricultural and energy systems of Senegal

The final case study described in this dissertation is a sustainability assessment that originally focused on burning agricultural residues (primarily peanut shells) for cooking applications in Senegal, but ultimately explored the agricultural and energy systems of Senegal. At the time of writing (December, 2012), the manuscript will be submitted to a journal shortly.

In Senegal and elsewhere, using agricultural residues as a cooking fuel offers an apparently attractive means of reversing deforestation and reducing the adverse health impacts of cooking with traditional stoves. We set out to explore the potential for burning peanut shells in Senegal, with a particular focus on the country's Peanut Basin, an area that accounts for approximately 30 percent of Senegal's surface area and 75 percent of Senegal's grain and peanut production (ASPAB 2009). The objective was to determine whether, and under what conditions, cookstoves burning peanut-shell residues could promote progress towards sustainability.

As is typically the case, however, there are other factors involved, and the initial assessment process revealed that the general question of burning peanut shells in cookstoves in Senegal could not be addressed appropriately at the project scale. There are too many strategic level considerations, such as the historical importance and perils of reliance on peanuts as an export crop, and the complex interrelationship between deforestation and soil fertility. These represent key challenges and opportunities that must be addressed simultaneously, in an integrated manner, and at a sufficiently broad scale.

There are four general insights emerging from the case. First, the case pointed to the possibly common advantage of beginning assessment work with a flexible unit of analysis that accommodates learning from the context and allows for unexpected insights to develop through the reformulation of the energy problem. In this dissertation, Gibson's SA framework was proposed as the means of spanning the project-strategic divide in a flexible manner, while recognizing that other approaches have merit as well (e.g. Partidário et al. 2009; Rotmans and Loorbach 2008).

Second, similar to the sugarcane-ethanol case, Chapter 8 highlighted the importance of grounding the assessment within its broader context. Many of the dynamics, criteria and results discussed in this chapter are broadly relevant to Senegal's energy and agricultural systems, as well as the country as a whole. This implies that in certain instances (such as further exploratory research), a wide variety of starting points may be used to elaborate the same basic context. Furthermore, given the flexibility of Gibson's SA framework described in this dissertation and elsewhere, the potential remains to change the unit of assessment, assuming the terms of reference have not been imposed by immovable authorities.

Third, the case study provided another example of the important of energy bridges. In this case liquefied petroleum gas is proposed as a temporary energy source that may provide the soil and forests some reprieve, and provide Senegal time to develop alternative energy sources.

Finally, Chapter 8 presented a case with no obvious ideal energy pathway. Rather, there are different alternatives that may be pursued, each with its own degree of uncertainty, path dependence, desirability, feasibility, degree of fairness, cultural sensitivity, etc. And the issues are not insignificant. For example, questions such as the degree of technological capitalization in the energy and agricultural sectors, the favouring of urban over rural regions, and the choice of export crops over local food security all have important implications for the future of individual life in Senegal as well as the country as a whole. What the case study provides is ideally a start point for a much deeper and more inclusive exploration of these issues; an exploration that must be undertaken by those affected by it, although researchers and other professionals may facilitate the process.

9.2.5 Consolidating the insights from the casework

The previous four sections described the important general insights emerging from the individual cases. As may have been noted, there is a significant amount of overlap in these insights, indicating that even though the cases were unique in several regards (e.g. location, local context, type of bioenergy), they also shared important similarities.

Table 32 below provides the consolidated insights, with each insight listed normatively (keeping in line with the guideline tables in Chapters 2-4). Each insight is followed by a general comment, an example or two from the case studies, a description of how Gibson's SA framework addresses the insight, and, finally, a brief outline for further research and application. In the following section, the avenues for further research will be revisited.

Table 32 - Consolidating the insights from the individual cases

Promote a flexible unit of analysis and appropriate problem structuring *General comment* • The multiplicity of worldviews coupled with the uniqueness of every local context and the integrated nature of most problems implies that appropriate problem structuring is an important first step. *Examples from the casework* • Ch. 5 – Ontario IPSP framed primarily as coal versus nuclear, as opposed to a serious examination of power systems planning. • Ch. 8 – Original assessment focused on burning agricultural residues in cookstoves, but ultimately assessment expanded to entire energy and agricultural system. *How it is addressed in Gibson's SA framework* • The criteria specification process provides flexibility in problem framing. Determining the criteria that matter and organizing them into relevant thematic areas is essentially a process of defining problems and opportunities within their broader context. *Avenues for further research* • There is potential to incorporate other tools, such as backcasting or rich pictures (from soft systems methodology) to further develop this approach.
Develop the case and context in determining the criteria that matter *General comment* • The four case studies reported upon in this dissertation are representative of different contexts with different histories and trajectories, concerns and opportunities that led to different themes of exploration and different conclusions and recommendations. *Examples from the casework* • Ch. 7 – Many of the important biophysical dynamics surrounding the sugarcane ethanol mill related to the

broader context (e.g. pollution of the watershed, ecological connectivity).
- Ch. 8 – Peanuts are an important focal point for analyzing the energy and agricultural systems

How it is addressed in Gibson's SA framework

- The criteria specification process – as part of a mixed methods case study approach – is essentially aimed at determining the things that matter for case and context.

Avenues for further research

- It is important to ensure that the focus on case and context does not lead to relativism. Relativism can be avoided by constantly referring to the intent of Gibson's eight categories, or revisiting the generic sustainability criteria for energy undertakings.

Seek integration and promote indirect effects

General comment

- Energy planning has implications for other policy areas (e.g. agricultural policy, water quality, workers rights), and vice versa. Energy planning provides an opportunity to achieve broader societal goals.

Examples from the casework

- Ch. 6 - Biodiesel offered opportunities for social learning and capacity building. Its main benefits were not the end product itself.

How it is addressed in Gibson's SA framework

- Gibson's eight categories of progress towards sustainability were developed to avoid the usual reductionist triple bottom line and promote integration. The tabular nature of the criteria specification process allows for relevant themes to be explored by grouping related criteria as well as the initial observations.

Avenues for further research

- Energy systems must still be feasible and desirable in bioeconomic terms. At some point renewable energy systems will need to achieve their direct aim: provide society with sufficient surplus energy with the minimum of human labour. This will require both redesigning energy systems as well as restructuring societies and their energy and resource requirements.

Develop energy bridges towards feasible and desirable energy futures

General comment

- Rather than focusing on whether a given undertaking is sustainable or not, this assessment seeks *progress* towards sustainability, which provides an opportunity for exploring energy bridges. Energy bridges do not need to be renewable, but they must allow the time and opportunity for transition.

Examples from the casework

- Ch. 6 – Biodiesel allows the characteristics of the supply infrastructure to change without impacting demand.
- Ch. 8 – A renewed liquefied petroleum gas subsidy was proposed as a temporary energy source to give the forests and soils some reprieve.

How it is addressed in Gibson's SA framework

- The category "Immediate and long term integration" provides an opportunity to explore both the energy bridge and potentially what comes after.

Avenues for further research

- Gibson's SA may benefit from explicit use of tools such as backcasting and visioning.
- While the concept of energy bridges is well known, the particulars of the viable energy systems to which we must build bridges are still unknown.

Be cautious in the face of thresholds and uncertainty

General comment

- The basic premise underlying sustainability assessment is that as a world, we are facing a series of unprecedented challenges, many of which relate to trends towards undesirable thresholds. These thresholds may be biophysical, metaphysical, economic, etc., and are generally a combination. All the cases were grounded in recognition of thresholds relating to the particular context.

Examples from the casework

- Ch. 7 – Concerns regarding biodiversity, ecological connectivity, water availability and quality, workers rights, etc. Fragmented and missing data, and the complexity of the issues undermine the actual determination of the thresholds.
- Ch. 8 – In Senegal there are important concerns related to deforestation (and desertification) and soil

fertility, both of which are trending in undesirable directions.

How it is addressed in Gibson's SA framework

- Gibson's SA framework and preliminary criteria set described in this dissertation focuses on managing limits in the face of complexity, notably through the emphasis on prudence, precaution and adaptation, and the promotion of broadly informed democratic decision-making.

Avenues for further research

- In future research the approach to address limits may be supplemented through more formal backcasting and forecasting techniques (e.g. Robinson 2003). In other words, rather than focusing on avoiding thresholds, you can try to move positively away from them.

9.3 The road ahead

The philosophers have only interpreted the world, in various ways; the point is to change it. – Marx and Engels – Theses on Feuerbach

This research project has covered a lot of ground, both theoretically and geographically. This dissertation has attempted to synthesize a wide array of disparate, yet overlapping, conceptual frameworks and approaches. The end result has been the foundation of a comprehensive, powerful and flexible assessment approach to be applied to energy undertakings of all types, at all scales, and in all locations. That said, because of the push for greater reach, there are some details that will need to be ironed out by the next individuals and groups wishing to take up the mantle.

The first means of improving the assessment process developed above would be to explicitly incorporate other systems-informed techniques, such as backcasting and building rich pictures. These techniques could aid problem formulation and help in the criteria specification process.

Second, there is a need to better incorporate more quantitative metrics into the analysis. The individual cases drew from a wide range of indicators, both qualitative and quantitative, in order to determine the things that matter in each particular context. In all cases, however, there was significant uncertainty with regards to important thresholds and feasibility levels (e.g. EROI). While acknowledging that some of these metrics may not be possible to determine in a given context, and that operating with sufficient prudence and humility ideally obviates the need to know these thresholds in any fine detail, there are still benefits to attempting to determine thresholds in a given case. Furthermore, we can expect that the *process* of determining a threshold (or of calculating some feasibility metrics) will likely be as beneficial and insightful as the final numbers. To be fair, the absence of these more rigorous quantitative metrics is also indicative of the modest means of the assessments.

Third, one issue that has arisen in various places is the question of whether the sustainability assessment framework developed here is revolutionary or incremental/evolutionary. The response has been proposed that the casework tends towards incremental adjustments, with the expectation that these adjustments ultimately lead to more significant change. Clearly time and experience will dictate the extent to which this is the case, as well as the extent to which incremental changes in general can smoothly lead to significant change. In the meantime, however, it is clear that a better understanding of sociotechnical systems change is required, both for the sustainability assessment framework presented here, as well as more broadly in society. To this end, research into transition management is ongoing, similar to other organizations studying social innovation, entrepreneurship, social marketing, etc.

From a personal standpoint, I believe there is tremendous opportunity to explore the social learning benefits and implications of sustainability assessment. As was noted in Chapters 2 and 4, sustainability assessment provides people with a vocabulary and approach for exploring questions of the good life, and what it means to be a responsible citizen in a sustainable society. Criteria specification should not be some abstract undertaking but rather a general proposal for what all members of society to value and seek, while respecting the need for individual rights and freedom of choice. Traditionally, the focus on assessment practice – be it environmental impact assessment, strategic environmental assessment, etc. – has been understandably centred on improved decision-making for better long-term outcomes. While this goal is still clearly necessary, improved decisions alone are insufficient. It is ideally clear that at some point individuals will need to live significantly different lives, and part of the impetus for this societal change must come from the individuals themselves. The role of sustainability assessment in fostering such individual change is unclear, although there are many methodologies centred on the same goal (e.g. for social learning, double-loop learning, transformative learning) from which inspiration may be drawn. To this end, there is tremendous potential to bring sustainability assessment down to the community level and to use it as a means of collective visioning for a positive future.

At this point, however, the most pressing future need is simply to have more applications of Gibson's SA framework in general, or the energy-focused version developed in this dissertation. For both formal and informal processes alike, and by both researchers and practitioners, the time is ripe to apply the framework in a wide variety of cases and contexts, and to see the approach as valuable for both informing broadly democratic decision-making, as well as a means to provide individuals and groups a vocabulary for deciding and reflecting upon the things that matter. Without assuming that the current body of knowledge present in the world is sufficient for all future opportunities, dilemmas and decisions, it is reasonable to believe that a great deal of traction can be gained by integrating what is currently known into a normative and comprehensive framework for decision making and action; and this is precisely what the sustainability assessment approach described in this dissertation attempts to achieve.

9.4 Epilogue

We don't know where we're going, but we're on our way - (Winner 1986, p. 170)

Through the combination of theoretical and empirical research this dissertation developed and described a set of guiding principles and criteria for appreciating and acting within the world, particularly when one is interested in exploring and improving the relationship between energy and society, and means by which energy systems may help individuals and society progress towards sustainability. The individual principles and criteria appear reasonably credible on their own, although they must be continually negotiated as the world changes. When taken as a full suite, the principles and criteria transcend and transgress different worldviews, and outline an ethics-based approach to energy decision-making, one that conflicts with much current dominant discourse. However, perhaps the tides are changing, and maybe now is the time for the next generation to develop a new narrative, one grounded in the requirements for progress towards sustainability explored in this dissertation. Hopefully this research may have some part to play, however minor, in helping rewrite the history of the future.

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Appendix 1 – Sample interview protocol

This appendix provides a sample interview protocol for sustainability assessment. As noted in Chapter 2, it is difficult to have one pre-defined set of interview questions in research such as this. First, as was previously noted, the interviews were semi-structured, and the interviewees represented a wide range of expertise (e.g. farmers, energy managers, government officials, extension officers, etc.). In many instances some interviewees were more able than others to address different topics. Second, the process of criteria specification often uncovered important issues that were not previously anticipated, and therefore could not be included in the original interview protocol. Third, in certain instances – such as the Senegal case study – the research problem had to be reformulated in response to new information. For all these reasons it was necessary to remain flexible with the interview protocol.

Table 33 below provides a preliminary set of interview questions that were developed prior to the Senegal case study. Initially, the assessment centred on the use of agricultural residues for cooking applications in Senegal, while still addressing broader scale challenges and opportunities. As the assessment progressed and the scope of analysis changed to the broader energy and agricultural systems, the initial set of interview topics no longer addressed the primary concerns. Fortunately, the process of criteria specification provides an ongoing set of relevant topics for interviews. In effect, the sustainability criteria represent the important issues to be addressed in the given assessment.

Developing a more formal interview protocol represents a possible avenue for further research in sustainability assessment. In the meantime, the interview protocol may be guided by the generic sustainability criteria set for energy undertakings proposed in Table 14. Depending on the context of the interview, different themes and topics may be discussed, while still allowing for the conversation to guide itself.

Table 33 - Sample interview protocol for Senegal case study

Socio-ecological system integrity

Natural resources

- What local natural resources are available in Gambia and Senegal?
  - How are these resources being used?
  - Are they being used in a way that they will last for a long time?
- Who is harvesting the resources?
  - At what scale are they being harvest?

Ecological integrity

- What is the current status of biodiversity and ecological integrity in Senegal and Gambia?
  - What are the long-term prospectus for biodiversity and ecological integrity?
  - What is the relationship between cooking (via resource extraction) and biodiversity / ecological integrity?

Climate
- What are the important climatic and biophysical considerations?
  - Wet / dry seasons
  - Soil quality and soil erosion
  - Forest cover
  - Rainfall

Livelihood sufficiency and opportunity
Local employment and production of cookstoves
- How can cookstoves be used to promote local employment?
- Do local manufacturing facilities exist for the production of cookstoves?
  - If not, can the manufacturing infrastructure be developed?

Business models of cookstove development
- Will the cookstoves be produced elsewhere and assembled locally?
- Will the production be artisanal or mass-produced?
  - What are the impacts of these different business models on local employment, and the economic benefits of improved cookstoves?

Competition for fuel
- Are there other uses (fuel and non-fuel) for rice husks and peanut shells?

Intragenerational equity
Fair use of resources
- Will improved cookstoves create competition for scarce natural resources

Benefits of improved cookstoves
What are the desired benefits in changing cookstoves?
  - Who will benefit from these changes?
- What negative equity impacts can result from changing stove design and input fuels?

Gender equity and cooking
- Who is in charge of cooking?
  - How long does cooking take?
- What other tasks can the cook perform while cooking?
  - Is it possible to care for children?

Access to improved cookstoves
- Is there equal access to improved cookstoves?
  - Geographically?
  - Financially?

Intergenerational equity
Long-term biophysical capacity
- Do improved cookstoves help preserve biodiversity and ecological integrity for future generations?

Lock-in
- How do improved cookstoves impact the diversity of future options for fuel usage and agricultural practices?

Resource maintenance and efficiency
Changing designs of cookstoves
- What positive or negative biophysical impacts can result from changing stove design and input fuels?

Energy profile
- Current electricity usage
  - What the electricity is used for
  - How is the electricity produced?

Current use of non-renewable resources
- What the non-renewable resources are used for
- Where do the non-renewable resources come from?

Current use of renewable resources
- What the renewable resources are used for
- Where do the renewable resources come from?

Cooking system
- Are cookstoves being addressed independently, or as part of a broader cooking system?
- Do improved cookstoves represent the best means of addressing indoor air pollution and resource exhaustion?

Fuel supply
- Do the improved cookstoves represent the most effective means of using rice husks and peanut shells as a fuel?

Socio-ecological civility and democratic governance

Empowerment
- How can cookstoves be used to promote empowerment?
- Do the anticipated users have control of how improved cookstoves should be developed?

Balancing short and long-term goals
- How can short term needs (financial, family, etc.) be balanced with long-term goals (deforestation, indoor air pollution)?

Social learning
- How do improved cookstoves promote social learning?
- How do improved cookstoves promote discussion of broader social and environmental issues? (e.g. gender, resource use, materialization)

Precaution and adaptation

Changing biophysical conditions
- How stable is the long-term supply of fuels for the improved cookstoves?
- Are there anticipated changes to the agricultural industry in Senegal?
- What is the impact of extreme weather events on the availability of fuel?

Changing energy infrastructure
- What is the anticipated long-term energy system in Senegal?
- Will cookstoves have an increased or reduced role?

Monitoring of improvements
- What mechanisms will be in place to ensure that indoor air pollution has decreased?
- What mechanisms will be in place to ensure that resource exhaustion (e.g. deforestation) is being addressed by the improved cookstoves?

Indirect effects
- What types of indirect effects are anticipated due to improved cookstoves?
    - Will development (due to improved cookstoves) reverse the efficiency gains of improved cookstoves?

Local resilience
- How can improved cookstoves promote local economic and cultural resilience?

Immediate and long term integration

Lasting benefits of cookstoves
- What must be done to ensure the improved cookstoves are adopted both in the short- and long-term?
- What audiences should be targeted first with improved cookstoves?

External support
- How long must the development community remain involved in the cookstove operation?
- Can the cookstove operation succeed without external support (financial and otherwise)?
    - If so, how can the cookstove program be implemented so as to promote local self-reliance.

Implementation
- What type of stakeholders must be involved in the implementation of cookstoves? (NGOs, businesses, government)

Appendix 2 – IPSP criteria development

This Appendix provides the sustainability criteria set for the case study reported on in Chapter 5 – the Ontario Power Authority's 2006 Integrated Power Systems Plan (IPSP). The Appendix is comprised of six tables. The first table, Table 32, provides the final sustainability criteria developed by the Waterloo-York research team that is described in Chapter 5. This table represents a collaborative undertaking, and is provided below because it helped inform the systems- and energy-informed sustainability criteria set proposed in Appendix 1 and Chapter 4. The intent is not to take individual credit for the undertaking. Following Table 32, Tables 33-37 provide the individual assessments of various bioenergy options, including: energy cropping and residue harvesting; forest harvesting; on-farm biogas; biosolids and organic municipal solid waste; and landfill gas. These individual assessments were all performed by this author, and are provided in this Appendix to give context to Chapter 5.

Table 34 - Sustainability criteria for the IPSP

Criteria For application to development of an IPSP for Ontario or, now that the OPA's IPSP has been completed and proposed, for evaluation of • the anticipated and possible effects of the OPA's proposed IPSP, including each technology/component, the full system and alternative configurations; • other options for technologies/components and other full system configurations (e.g. the *Renewable is Doable* option); and • their comparative merits and deficiencies and overall desirability.
Socio-Ecological System Integrity *What is the nature and significance of* • overall effects on rate of growth of electricity demand and consumption and associated activities likely to add to local to global scale system stresses • effects on biophysical and socio-biophysical systems and the provision of ecosystem goods and services o atmospheric (GHGs, smog and acid rain precursors, heavy metals, hazardous air pollutants incl. POPS and heavy metals); o water quality (releases of radioactive, conventional and hazardous contaminants to surface and groundwater, thermal change, flow change); o water quantity (consumption, impacts on surface and groundwater storage, flows and cycling); o waste generation (radioactive, hazardous, high volume); o habitats, ecosystems and landscapes (new access/stresses, connectivity/fragmentation) • effects on livelihood system resources o foodlands (soil quality, access, fragmentation) o fisheries (sport, commercial) o forests (recreation, hunting and trapping) • effects on human health o occupational (construction, fuel cycle, operation, post-closure) o individual and community (construction, operational, fuel cycle, post closure, extreme events; consider impacts on vulnerable populations) • effects on important/valued ecological, social and socio-ecological systems and system components, characteristics and capacities, including o human appropriation of primary productivity

- communities' social and economic resilience including social capital, cultural and economic diversity, innovative and adaptive capacity, etc.)
- culture of conservation

• effects on qualities maintaining socio-ecological system integrity
  - biodiversity,
  - social capital, cultural and economic diversity, cooperative governance linkages, innovative capacity
  - monitoring/feedback/response systems,

• effects on areas of particular opportunity or concern (approaching thresholds, windows of opportunity, vulnerable sectors)

• local/regional effects on
  - capacity of biophysical systems to deliver valued goods and services reliably into the future
  - social capital and livelihood resilience
  - infrastructure capacity
  - governance requirements/capacities
  - landscape aesthetics

• provincial/national effects on
  - contribution to resilience/reliability of the power system and the Ontario socio-economy (including valuable ecosystem goods and services, durable employment, distribution of direct and induced opportunities and stresses, etc.)
  - air quality: smog, acid rain, air toxics, including transboundary pollutants, etc.
  - water quality, including contaminants/bioaccumulants, temperature, etc.
  - population and job distribution
  - economic development path/options
  - governance requirements/capacities

• global effects on
  - climate change (GHG emissions, adaptive capacity, etc.)
  - security and risks (weapons proliferation, terrorist targets, risk of accidents, risks of systems failures, etc.)
  - Ontario's appropriation of global biocapacity

Livelihood Sufficiency and Opportunity

What is the nature and significance of

• effects on reliable provision of energy services through system including consideration of CDM as well as supply

• effects on affordable provision of energy services, especially for crucial needs, disadvantaged interests

• employment/livelihood opportunities
  - number, durability, security, diversity, quality, accessibility/proximity to needs, equity/appropriateness of distribution, safety, flexibility, spin-off potential
  - direct and induced
  - fit with anticipated needs
  - potential for capacity building (learning, social capital)
  - potential for innovation for sustainable livelihoods in CDM and renewables (solar and wind performance gains, storage, etc.)
  - market access for small producers

• avoidance of boom and bust effects
  - plan/project design and scheduling
  - bridging provisions (capacity building, heritage funds)
  - diversification

• associated economic development opportunities/risks (directly linked and induced)
  - quality
  - location (where opportunities are needed vs. where growth is already a problem)
  - permanence vs. boom/bust
  - spin-off opportunities, multipliers

• local/regional effects
  - community solidarity and governance capacity

o adequacy and demands on local and regional services o growth management in GGH o job/development needs of rural and remote communities, First Nations o contribution to rural renaissance • provincial/national effects on livelihoods beyond Ontario (life-cycle effects, trade opportunities, etc.) • global effects on o transfer of beneficial technologies o opportunity for technology/trade advancement
Intragenerational Equity (distribution of costs and risks in the present) *What is the nature and significance of* • overall effects on consumption, wealth and resource access gaps between the first and fifth quintile of the population • equity effects of (re)distribution of risks, costs, benefits and opportunities among income groups, genders, age groups, regions, indigenous/non-indigenous people, areas of growth and decline, including o positive openings (e.g. durable economic development opportunities) o opportunities foregone (e.g. allocation of transmission capacity to one generation source) • distribution of effects on key quality of life considerations (health, valued employment, respected knowledge, community security, access to opportunity, influence in decision making, durable economic development opportunities, etc.) • allocations of costs/risks to those who benefit little or not at all from the system • effects on externalization or internalization of risks, costs and benefits on distribution of risks, costs and benefits among investors, suppliers, consumers and governments (i.e. taxpayers) • social and economic effects of electricity costs and pricing among suppliers, consumer groups (who wins, who loses) • local/regional effects on o employment for local or transient or outside people o opportunities for small producers o new governance burdens for local authorities and residents • provincial/national effects on o special needs of rural areas, First Nations, declining communities o concentration or dispersion of influence on energy policy and practice • global effects on o wealthy nations' responsibility for major GHG cuts and other reduction of energy, material and ecological system demand o food vs. fuel
Intergenerational Equity *What is the nature and significance of* • long term enhancements of opportunities (technological advantages, developed social capital, stimulation of innovation, resilient systems, etc.) • long term costs, risks and other burdens (costs, risks, debts, wastes requiring long-term/permanent management, decommissioning/rehabilitation needs, permanent damages (health, landscape, ecosystem productive capacity), security and safety risks, etc.) transferred to future generations • shrinking or foreclosure of options for future generations (e.g. depletion of non-renewable resources or renewable resource capital base). • distribution of long term positives and negatives (e.g. overall effects on future consumption, wealth and resource access gaps between the first and fifth quintile of the population) • capacity and provisions for use of near term benefits as bridge to more long term sustainable options (e.g. from non-renewable to renewable supply sources) • intergenerational distribution aspects of o residual gains and losses, openings and risks o long term effects on expanding or closing the gap between rich and poor • local/regional effects on o permanent changes (e.g. in landscapes, ecological system impairment)

o long term management responsibilities, risks, costs (e.g. wastes) • provincial/national effects on o decommissioning and rehabilitation costs o residual wastes/risks and associated management burdens o potential for residual debt • global effects on o overall and distributional results of long term climate effects, and effects on overall energy, material and ecological system demand o depletion of non-renewable resources, - impairment of biophysical and/or social system resilience o global (in)equities o global security (vs. armed conflict, scarcity/deprivation, vulnerability to economic and biophysical hazards,…)
Efficiency, Cost-Effectiveness and Resource Maintenance *What is the nature and significance of* • contribution to overall reduction of material, energy and ecological system demand with particular focus on maximum reduction of electricity demand and associated footprint • sustainability of primary energy sources • maintenance/enhancement of o ecological base for delivery of ecological goods and services o renewable resource base o non-renewable resources (including through effective bridging) o social capital and other community goods *Minimize costs (lifecycle, full costs basis including legacy, environmental, operating/maintenance and capital costs and risks) through* • full cost (beyond LUEC) calculation of most cost-effective supply/CDM option o internalization of costs and risks by electricity suppliers o minimizing overall public costs and assumption of risks and liabilities o avoiding subsidization of specific suppliers or technologies (directly or via transfer of risk and liabilities to government or government agencies such as the OPA) • maximization of efficiency of energy production, delivery and use including o exergy efficiencies through matching the quality of and with the needs of the use (end use matching) o maximizing primary to delivered energy efficiency including opportunities for multiple use (e.g. cogeneration); minimizing conversion and transmission losses, including attention to internalization and equitable distribution of risks, cost and impacts, quality of energy) o minimizing need for backups/reserve margin (recognizing desirable redundancy for system resilience) o stimulation of further conservation/efficiencies o maximizing use of underutilized existing facilities, resources and capacities and minimize requirement for additional supporting infrastructure, management o minimizing governance burdens/costs (regulatory, administrative, citizen monitoring, financial oversight, subsidies, acceptance of liabilities etc.) • maximization of flexibility to pursue and adopt new technologies/techniques o maximizing potential for incremental adjustment o avoidance of locked in obsolescence • local/regional effects on o max. multiple local/regional benefits from chosen options (e.g. desirable, diverse and durable employment, health and ecological enhancements, and infrastructure improvement) o contribution to growth redistribution o min. conflicts with current valued qualities, activities, opportunities o min. boom/bust effects • provincial/national effects on o maximization of electrical energy demand reduction (at full costs not significantly greater than supply options)

- min. econ/financial vulnerability
  - min. damages and risks to valued social and ecosystem components
  - max. potential encouragement of and benefit from domestic innovations
  - max. resources retained for other purposes
  - discouragement of direct and indirect expansion of energy, material and carrying capacity demand
- global effects on
- contribution to reducing overall energy, material and ecological system demand
- demonstration case/tools for global practice
- trade and aid implications

Socio-Ecological Civility and Democratic Governance

What is the nature and significance of

- contribution to enhancement of governance capacity, including
  - government capability (for consultation, planning, oversight, monitoring, and response) including supportive redundancy
  - diverse private sector opportunity and innovative culture
  - informed and enabled citizen engagement
  - accessibility and transparency of decision making (e.g. relative accessibility of nuclear approval process versus deliberations on conservation initiatives)
  - decision making transparency, comprehensibility and accessibility, process clarity
- contribution to understanding and capability, including
  - enhancing social capital
  - facilitating social learning
  - building a "culture of conservation" (demand reduction and efficiency)
  - accuracy of price message (e.g. full cost pricing)
  - open deliberation on objectives)/ends (e.g. through scenario building and backcasting)
- encouragement of
  - research and innovation
  - adaptive design including technology and system flexibility
  - capacity for response to opportunities and surprise
- minimization of
  - threats to valued community qualities, features
  - system (or component) vulnerability to security hazards (e.g. non-democratic security needs)
  - governance and oversight requirements
- local/regional effects on
  - demands on governance capacity (municipalities, NGOs)
  - contributions to or stresses on social capital
- provincial/national effects on
  - dependence on extra-provincial network (encouragement of interjurisdictional cooperation, vulnerability to decisions beyond local/provincial control)
  - demands on governance capacity (immediate and in perpetuity)
  - contributions for social capital
  - promotion of innovation
- global effects on vulnerability to geopolitical risk (e.g. security/terrorism, fuel/technology access)

Prudence, Precaution and Adaptation

What is the nature and significance of

- contribution to technology and system reliability
  - minimization of system vulnerability to risks due to catastrophic events, technology failures
  - minimization of opportunity for damaging human error
  - minimization of exposure to, or likelihood of, resource shortage (fuel, wind or water flow or other power resource) or programme failure (e.g. poor public or industry response to conservation/demand mgmt. initiatives)
  - minimization of vulnerability to grid upset
  - adequacy of measures to protect system security
  - ability to accommodate range of potential futures while promoting progress to a desirable future

- contribution to technology and system resilience
  - maximize modularity (distributed versus centralized components)
  - employ diversity of technologies, fuels, suppliers and facilities, etc.
  - maximize capacity to isolate failures and facilitate system recovery
  - minimize need for backups/reserve margin (recognizing desirable redundancy for system resilience)
  - availability of response options, including spare capacity (storage, back-up generation, additional temporary and longer term CDM), adjustable scale, etc.
  - effective monitoring and quick response capability (managerial and technical)
  - friendliness to innovation, minimum path dependence, ability to retain and pursue options
  - self-reliance combined with cooperative networks of support
  - contingency plans
- adaptive capacity and minimization of path dependency
  - ability to adapt to changing circumstances including externally generated ones , including environmental change (e.g. climate change impacts), economic recession or growth, structural economic change affecting electricity demand, political risks (e.g. policy shifts, geopolitical events)
  - ability to take incorporate new technological development
  - maximization of potential for incremental mid-course adjustment in face of changing circumstances (e.g. by adding system capacity in incremental steps with <5 year planning, approval and construction timelines
  - minimization of commitments to high path dependency large scale, capital intensive supply options with >5 year planning approval and construction timelines
- avoidance of economic risks
  - minimization of risk of project failure due to technological or management failure, regulatory, social licence, political factors
  - minimization of system level impact of individual project or technological failure through avoidance of over dependence on individual projects
  - minimization of risk of higher than predicted costs and delays (due to technical, management, economic, regulatory social, licence and political factors
  - retention of options to cancel/abandon individual projects that are seriously over budget or delayed via project modularity (minimize large centralized projects whose individual failure will throw the system/plan into crisis)
- avoidance of geopolitical risk
  - minimize political risk to fuel access or market risk where fuel is internationally traded commodity subject to international trade rules
  - minimize political risk to access to technology or market risks where there are competitive markets for technology and skills needed to deploy it
  - avoidance of choices that may contribute to proliferation of weapons of mass destruction,
- avoidance of security risks
  - minimize obvious targets for terrorist activity
  - minimize system dependence on individual facilities that may be vulnerable to terrorist attack or other failures/events
  - see minimization of geopolitical risks re: fuels or technologies above
- avoidance of extreme event risks that
  - minimize possibilities for catastrophic accidents or other events with catastrophic effects
- sustainability of primary energy sources
- avoidance of uncertain but possibly significant damages (e.g. climate change impacts, health damages, etc.)
- local/regional effects on
  - minimize vulnerability to boom/bust effects
  - minimize contribution/vulnerability to cumulative stresses
- provincial/national effects on
  - minimize risk of catastrophic failure
  - minimize path dependency
  - maximize component and system resilience

o maximize adaptive capacity o avoidance of network dependence but encouragement of cooperation and back up support • • global effects on o minimize contribution to global insecurity o minimize vulnerability to global insecurity o example for international adoption
Immediate and Long Term Integration *What is the nature and significance of* • potential to deliver multiple benefits (livelihoods/stewardship/equity/civility/precaution or environmental/economic/social/geopolitical) • potential for mutually reinforcing benefits • potential for avoiding trade-offs (see next section) • local/regional effects on o potential for multiple, mutually reinforcing livelihood benefits o risk of mutually reinforcing cumulative negatives (e.g. boom-bust of multiple associated/induced projects) o undesirable and avoidable trade-offs (e.g. short term development at the expense of longer term livelihood base) • provincial/national effects on o potential for multiple, mutually reinforcing benefits (e.g. centre for sustainable energy system innovations) o risk of mutually reinforcing negatives (e.g. contribution to growth concentration) o undesirable and avoidable trade-offs • global effects on o potential for multiple, mutually reinforcing benefits (e.g. building of sustainable energy model for global applications) o risk of mutually reinforcing negatives (e.g. contribution to climate change, larger material/energy footprint) o undesirable and avoidable trade-offs
Trade-off rules *Does the technology/component/system maximize opportunities for multiple mutually reinforcing gains?* • Are there likely to be significant adverse effects (e.g., damage or increased stress in a major area of existing concern, or reduction of prospects for resolving priority problems) that cannot be avoided without accepting more adverse effects elsewhere? • Are any trade-offs proposed where stronger mitigation efforts would be feasible? • Would any proposed trade-off displace significant adverse effects from the present to the future (and would this trade-off be unavoidable without displacing more serious adverse effects to the future)? • Have the proposed trade-offs been discussed in and accepted through an open, participative process? • Has each proposed significant trade-offs been explicitly and adequately justified by the proponent of the trade-off?

Adapted from (Gibson et al. 2008, Table A.13)

The criteria set provided above was applied to the assessment of various supply pathways, conservation and demand management opportunities, and transmission and generation concerns. For the purpose of the assessment this evaluated the potential for bioenergy production, notably: energy cropping and residue harvesting; forest harvesting; on-farm biogas; digestion of solids and municipal wastes; and landfill gas. The following tables provide the results of each individual assessment. The results contained in these tables represent this author's own work. Within the following tables, the results for each of Gibson's 8 categories are presented in terms of advantages and disadvantages. This is no longer the format proposed within this dissertation. However, given that these tables are already in the public domain (Gibson et al. 2008), they have not been altered other than basic formatting changes.

Table 35 - Assessment of energy cropping and residue harvesting (Gibson et al. 2008, Table A3.13)

Socio-ecological system integrity *Advantages* • Energy cropping has a low legacy cost, and there is little residual long-term ecological impact. Unharvested areas may be left fallow with no negative environmental harm. • Energy crops and residues have negligible upstream waste impacts (such as toxic emissions found in conventional energy resource mining), • Proper nutrient management may improve ecological system health (for example marginal lands). *Disadvantages* • Energy cropping often done as a monoculture, which harms biodiversity and increases risk of pest and disease outbreak • Ontario lacks available land, so energy cropping will need to spread to marginal lands. • Increased fertilizer and pesticide use required for energy cropping harms soil resilience and health. • Fossil fuels required for fertilizers and pesticides represent an indirect, yet substantial, upstream waste impact. • Energy crops require large amounts of freshwater, which many not be available and could reduce groundwater levels. • Weak social-ecological feedback (or positive feedback) may cause resource to be overused. • Greenhouse gas impacts depends greatly on past land use. Clearing land for energy cropping may incur a carbon debt over 100 years. • Uncertainty with respect to NO_x volatilization during cropping may in fact increase CO_2 equivalent emissions compared to fossil fuels.
Livelihood Sufficiency and Opportunity *Advantages* • Great potential for lasting employment benefits, especially in rural regions. Economic benefits, however, are largely dependent on local ownership. • Provides a stable income based on a stable price compared to food price volatility. Protect farmers against quota surpluses *Disadvantages* • Bioelectricity production competing for resources with pharmaceutical and liquid fuels. • Energy cropping may require changing land use from beef grazing • Electricity generated via energy cropping and residue collection is more expensive than traditional generation. While, this will increase the cost of electricity in the grid, it will not be a large increase.
Intragenerational Equity *Advantages* • Distributed and limited nature of energy cropping reduces any negative impact on other generating technologies. • Energy cropping has a great potential for distributed economic development, particularly in rural areas. *Disadvantages* • Internationally, energy cropping for biofuels is already causing a food versus fuel conflict. • On-farm biogas is subsidized through the standard offer program and increases the price of electricity, which unfairly impacts the poorer homeowners.
Intergenerational equity *Advantages* • If performed in an ecological sound manner, energy cropping may provide lasting employment in rural areas. *Disadvantages* • Bioenergy cropping and residue harvesting may reduce soil health for future generations. • Energy cropping may also remove food productive land from future generations, and create a food for

fuel conflict. • The uncertainty of greenhouse gas emissions may exacerbate climate problems for future generations. • The limited agricultural land availability could lead to agricultural clearing of ecologically significant lands. This would have long-term ecological impacts, and lead to significant GHG emissions.
Resource Maintenance, Cost Effectiveness and Efficiency *Advantages* • Solar energy is the ultimate energy source for energy cropping and residue harvesting, and thus represents a renewable energy supply. • Energy cropping offers multiple energy pathways and multiple end uses, thus increasing system flexibility and resilience. • May be stored and used when needed, therefore providing dispatchable power production. This allows for mutually benefiting gains with other renewable energies, such as wind power. • Electricity generation may be performed on a variety of scales (leading to increased modularity) and coupled with heat generation (for CPH) – this increases end-use efficiency • Modularity and energy pathways allows for better end-use matching of energy, with leads to greater resource and cost effectiveness. *Disadvantages* • Energy cropping is predicated on industrial agricultural techniques, which may be impacted by climate change and fossil fuel volatility. • Overuse of resource may lead to soil and resource mining. • Use of fertilizers may have long-term impact on resource availability. • Energy cropping and agriculture are acutely sensitive to climate change effects.
Social-ecological civility and democratic governance *Advantages* • Energy cropping and residue harvesting may help buffer small farmers from the deterioration of rural economies and provide them a stake in energy management. • Bioenergy offers potential for private investment, as well as new research and development. • May bring new value to agricultural lands, reducing the likelihood of further suburban sprawl. • By including farmers into the energy supply mix, increases the potential for stakeholder involvement. *Disadvantages* • OPA is currently favouring large-scale bioenergy projects, thereby reduces multi-stakeholder/community involvement.
Prudence, Precaution and Adaptation *Advantages* • Bioenergy is decentralized, modular, and offers grid voltage support increasing system reliability, resilience and adaptive capacity. • The multiple energy pathways for bioenergy reduce path dependency and increases long-term system reliability. • Energy cropping poses a low economic risks: the basic technologies and costs well established and understood. • Providing an income for farmers now will prevent a rural exodus that may deprive future generations of farmers. Therefore, there is great prudence in this regard. • Bioenergy has negligible geopolitical risk, as it relies on domestic fuel source. • Very low accident, security risks; no weapons proliferation risks. *Disadvantages* • There is a risk that the environmental feedback structures will be too weak, or too long, to prevent resource mining. • Similarly, there is the risk that as forest harvesting is increased, unit costs may decrease, which would create a positive feedback structure, and potentially lead to overuse. • Climate change may affect future agricultural production and impact the potential for bioenergy cropping and residue collection.
Immediate and long term integration • As a renewable solar derived energy source, energy cropping and residue harvesting have the potential to

provide mutually reinforcing gains by providing dispatchable, distributed power generation, as well as distributed economic development in an area where it is needed.

- The uncertain ecological impacts of energy cropping and residue harvesting, as well as the potential for unsustainable resource mining require a precautionary and modest expectation for long-term power supply.

Key trade offs

- Small-scale distributed energy cropping with increased stakeholder engagement versus greater cost efficiency with large-scale farms.
- Renewable resource versus need to maintain sustainable safety margin to account for change, ignorance, and surprise.
- Modular and dispatchable power source versus higher unit electricity costs

Table 36 - Assessment of forest harvesting (Gibson et al. 2008, Table A3.14)

Socio-ecological system integrity

Advantages

- Forest residue removal may reduce chance of forest fires.
- Biomass generally burns cleaner than their fossil fuel counterparts, thereby lowering atmospheric emissions impacts.
- Forest harvesting has a low legacy impact, especially compared to conventional generating technologies.
- Forest harvesting has limited upstream waste impact (such as toxic emissions found in conventional energy resource mining)

Disadvantages

- Forest harvesting may impact long-term ecosystem function.
- Forest residues collected needed for wildlife cover, erosion control, protection of emerging seedlings and moisture management.
- Forests residues also required for nutrient, carbon, and energy cycling, which is critical for forest health.
- Forest residue removal could harm biodiversity.
- Weak social-ecological feedback (or positive feedback) may cause resource to be overused.
- Greenhouse gas impacts depends greatly on past land use.

Livelihood Sufficiency and Opportunity

Advantages

- Great potential for lasting employment benefits, especially in rural regions. Economic benefits, however, are largely dependent on local ownership.

Disadvantages

- Bioelectricity production competing for resources with pharmaceutical and liquid fuels.

Intragenerational Equity

Advantages

- First Nations communities have the potential to benefit from forestry harvesting, if performed in an equitable manner.

Disadvantages

- Northern Ontario will bear the ecological impact of forest harvesting, while Southern Ontario will gain from power production.

Intergenerational equity

Advantages

- If performed in an ecological sound manner, forest harvesting may provide lasting employment in rural areas.

Disadvantages

- Forest harvesting is only renewable with respect to energy income. There is as risk that energy mining will take place, which will reduce productive abilities of forests for future generations.
- Future generations may be negatively impacted by the reduced ecological functions that are a consequent of forest harvesting.

Resource Maintenance, Cost Effectiveness and Efficiency

Advantages
- Forest harvesting offers multiple energy pathways and multiple end uses, thus increasing system flexibility and resilience.
- May be stored and used when needed, therefore providing dispatchable power production.
- Electricity generation may be performed on a variety of scales (leading to increased modularity) and coupled with heat generation for CPH) – this increases end-use efficiency.
- Forestry harvesting is economically competitive to oil and gas on an energy basis.
- Dispatchability allows for mutually benefiting gains with other renewable energies, such as wind power.

Disadvantages
- Overuse of resource may lead to soil and resource mining.
- Forest harvesting is acutely sensitive to climate change effects.
- Proper forest resource maintenance requires placing environmental concerns above economic efficiency.
- Forest energy harvesting may need to allow forest system cycling (including natural forest fires) at the expense of energy generating potential.

Social-ecological civility and democratic governance

Advantages
- Forest energy offers potential for private investment, as well as new research and development.

Disadvantages
- OPA is currently favouring large-scale bioenergy projects, which reduces multi-stakeholder involvement.

Prudence, Precaution and Adaptation

Advantages
- Bioenergy is decentralized and offers grid voltage support.
- The multiple energy pathways for bioenergy reduce path dependency and increases long-term system reliability.
- Forest energy has negligible geopolitical risk

Disadvantages
- Must plan for a minimum energy yield, which reduces potential short-term gains.

Immediate and long term integration
- As a renewable solar derived energy source, forest and residue harvesting have the potential to provide mutually reinforcing gains by providing dispatchable, distributed power generation, as well as distributed economic development in an area where it is needed.
- The uncertain ecological impacts of energy cropping and residue harvesting, as well as the potential for unsustainable resource mining require a precautionary and modest expectation for long-term power supply.

Key trade offs
- Forests as a biomass source versus forests as an energy source versus ecological service functions of forests.
- Renewable resource versus need to maintain sustainable safety margin to account for change, ignorance, and surprise.
- Modular and dispatchable power source versus higher unit electricity costs.

Table 37 - Assessment of on-farm biogas (Gibson et al. 2008, Table A3.15)

Socio-ecological system integrity

Advantages
- Biogas digestion prevents methane emissions and reduces odour problems on farms.
- Biogas gas is a GHG neutral energy source.
- Biogas digestate improves nutrient management techniques by converting manure into a more usable form. This reduces surface runoff effects, reducing organic and pathogenic loading of waterways.
- Biogas digestate reduces dependence on fossil fuel fertilizers, and thus reduces the upstream lifecycle impacts associated with fertilizers.
- Energy crops and agricultural residues may also be digested, and this improves nutrient cycling on the farm.

- On-farm biogas may accept limited amounts of off-farm organic material, reducing need for landfilling.

Disadvantages
- If using energy crops and residues as an input, the ecological limits must be understood and respected.

Livelihood Sufficiency and Opportunity

Advantages
- Biogas provides an excellent new source of revenue for farmers, and may reduce or reverse the current trend of economic hardship.
- The capital cost an on-farm biogas plant is in line with many farm investments, while the payback period is far quicker.
- The limited provincial potential for biogas will not reduce investment in other renewable energy technologies.

Disadvantages
- The potential for on-farm biogas in Ontario is currently limited by transmission capacity, as some grid capacity is being held aside for other generating resources.

Intragenerational Equity

Advantages
- If performed in an ecological sound manner, energy cropping may provide lasting employment in rural areas.

Disadvantages
- Biogas generated electricity is more expensive that traditional generating technologies, and thus the poorer homeowners must bear the added expense.

Intergenerational equity

Advantages
- Biogas helps improve soil conditions, which allows future generations the opportunity to continue using the soil.
- Biogas is a renewable resource and thus future generations are not impacted by the need to seek a new energy source.

Resource Maintenance, Cost Effectiveness and Efficiency

Advantages
- Biogas offers multiple energy pathways and multiple end uses, thus increasing system flexibility and resilience.
- May be stored and used when needed, therefore providing dispatchable power production.
- Dispatchability allows for mutually benefiting gains with other renewable energies, such as wind power.
- Biogas may also provide methane for the natural gas pipeline.

Disadvantages
- Biogas is predicated on industrial agricultural techniques, which may be impacted by climate change and fossil fuel volatility.
- On-farm biogas is closely coupled with agriculture, and therefore is sensitive to many of the same climate change variations as agriculture.
- Electricity generated via on-farm biogas is more expensive than conventional generating technologies. However, the positive externalities of biogas, such as being GHG neutral, counterbalance this added expense.

Social-ecological civility and democratic governance

Advantages
- Biogas offers potential for private investment, as well as new research and development.
- Biogas allows farmers a stake in provincial energy management.

Disadvantages
- Current government mandated transmission grid limitations prevent wider scale adoption of biogas, and therefore reduce stakeholder involvement.

Prudence, Precaution and Adaptation

Advantages
- Bioenergy is decentralized and offers grid voltage support.
- The multiple energy pathways for biogas reduce path dependency and increases long-term system

reliability. • Biogas energy has negligible security, accident or geopolitical risks, and represents a domestic energy supply.
Immediate and long term integration • As a renewable solar derived energy source, on-farm biogas has the potential to provide mutually reinforcing gains by providing, distributed power generation and voltage support, as well as distributed economic development in an area where it is needed. • The anaerobic digestion pathway also provides an alternative pathway to traditional energy cropping and residue harvesting that has greater respect for the environmental limits of agricultural soil, as well is lower GHG emissions. • On-farm biogas should be greatly encouraged through the standard offer program, and seen as a long-term viable alternative to combustion of energy crops and agricultural residues.
Key trade offs • Modular and dispatchable power source versus higher unit electricity costs • Investment in on-farm biogas versus investment in other farm related infrastructure. • Decentralized energy and voltage support versus need for increased transmission capacity in key biogas areas.

Table 38 - Assessment of digestion of biosolids and organic municipal solid waste (Gibson et al. 2008, Table A3.16)

Socio-ecological system integrity *Advantages* • Reduces organic loading of landfills, which in turn reduces methane emissions from landfills. • Treated biosolids and municipal organics may be used as fertilizers, and thus lead to nutrient management improvements in soil.
Livelihood Sufficiency and Opportunity *Advantages* • Digestion of biosolids and organic wastes provides value to an otherwise waste product. • Digestion of organic wastes promotes landfill diversion.
Intragenerational Equity • The limited provincial potential for biosolids and organic municipal waste will not reduce investment in other renewable energy technologies.
Intergenerational equity *Advantages* • Digestion of biosolids and municipal solid waste will aid to reduce future landfill needs. • Digestion of biosolids and municipal solid waste may be incorporated into a multifaceted waste management plan serving future generations.
Resource Maintenance, Cost Effectiveness and Efficiency *Advantages* • Electricity generation may be performed on a variety of scales (leading to increased modularity) and coupled with heat generation (for CPH). • Biosolids and organic municipal waste present a currently untapped resource. • Great potential for recycling nutrients and energy within the social-ecological system. • These plants may be located near populated areas, which reduces transmission requirements. • Biosolids and organic municipal waste are insensitive to climate change *Disadvantages* • May reduce incentive for source reduction of waste, as resource is contingent on continued organic supply. • On-farm biogas may compete for same resource base.
Social-ecological civility and democratic governance *Advantages* • Biosolids and organic digestion allows municipalities a larger stake in their energy management.

• There is great potential for private enterprise in the waste-to-energy sector. • Digestion may be part of a multifaceted waste management strategy.
Prudence, Precaution and Adaptation *Advantages* • Bioenergy is decentralized and offers grid voltage support. • Negligible geopolitical risk • Insensitive to climate change
Immediate and long term integration • The digestion of biosolids and municipal organic wastes should be integrated into the long-term energy supply plan due to the mutually reinforcing benefits of waste reduction, energy generation, nutrient cycling and local economic development.
Key trade offs • Dedicated biosolids and organic municipal waste biogas plants versus supplying biosolids and organic municipal waste to on-farm biogas and landfill gas.

Table 39 - Assessment of landfill gas (Gibson et al. 2008, Table A3.17)

Socio-ecological system integrity *Advantages* • Reduces methane emissions from landfills, thereby reducing global warming potential of current landfills.
Livelihood Sufficiency and Opportunity *Advantages* • Combustion of landfill provides value to an otherwise harmful waste product. *Disadvantages* • Dependence on landfill gas may cause boom and bust cycling as the energy supply is limited. • Landfill gas may deter organic diversion from landfills,
Intragenerational Equity *Advantages* • The limited provincial potential for landfill gas will not reduce investment in other renewable energy technologies.
Intergenerational equity *Disadvantages* • Initiates dependence on an ideally non-renewable resource.
Resource Maintenance, Cost Effectiveness and Efficiency *Advantages* • These plants may be located near populated areas, which reduces transmission requirements. • Landfill gas has a negative energy cost, and is therefore the cheapest form of available energy. *Disadvantages* • May reduce incentive for source reduction of waste, and thereby encourage continued landfilling. • Limited and finite resource.
Prudence, Precaution and Adaptation • Landfill gas is decentralized and offers grid voltage support. • Negligible geopolitical risk
Immediate and long term integration • Landfill gas provides mutually reinforcing benefits, including low-cost electricity, local economic development, voltage support, and GHG emissions reduction. • Landfill gas is ideally a non-renewable energy source and should therefore be included only into the short-term energy plan. Long-term energy plans should encourage waste recycling and diversion, so as to reduce future landfilling requirements.
Key trade offs • Development of future landfill gas versus increased efforts for source reduction and waste diversion.