AUTHOR: **Mr. Ben R. Kneppers** (MSc)

Co-Authors: **Mrs. Anna Jonasson** (MSc)
Mr. Brendan Moore (MSc)

Presenter: **Mr. Ben R. Kneppers** (MSc)

Title of Paper: A Principle-Based Decision Making Framework for Sustainable Electricity Infrastructures

Ben R. Kneppers
Student, Strategic Leadership towards Sustainability
Blekinge Institute of Technology
Karlskrona, Sweden
+64 27 238 4100
benkneppers@gmail.com

Abstract:

Electricity generation is both a major contributor to the root causes of environmental unsustainability, and an energy source that will likely play an important role in the transition to a sustainable society. Because renewable sources of electricity generation are seen as environmentally friendly as a group, there is a danger that investments will be made in technologies that do not effectively consider all environmental impacts and thus drive society towards additional unsustainable challenges.

The purpose of this study is to present a decision making tool that serves as a total-systems perspective of environmental impacts for electricity infrastructure options. The tool compares energy technologies on the basis of their contribution to our current, unsustainable society using a set of principles commonly referred to as The Natural Step framework. These principles are integrated into a qualitative life cycle analysis that gives a broad, strategic overview of each technology's strengths and weaknesses. For each life cycle stage, the tool is used to analyze the chosen technology's contribution to the systematic increases of materials from the Earth's crust and man made substances in the Earth's biosphere. In addition, physical degradation of the ecosystem and the effect on human well-being will also be analyzed.

The results are then used to create strategic bench-marking metrics that are presented to collaborating electrical utilities and governments. A concerted research effort could create a general guide for sustainable energy planning, which would compare all possible sources of electricity generation based on their total sustainability potential.

1. Zaricksson, M., M. Enroth, and A. Widing. 1999. "Environmental Management Systems: Paper Tiger or Powerful Tool. Stockholm: Industrial Research Institutes in Sweden.

1. Introduction

One of the key challenges of the 21st century is to move towards environmental and social sustainability while increasing human well-being. Modern technology often has contradicting effects on these two interdependent challenges, as illustrated by the current electricity generation system. Cheap, readily-available electricity is crucial to many of modern society's most important technologies and social advances. At the same time, the vast majority of the world's electricity is generated using fossil fuels and uranium, non-renewable resources with serious environmental and social effects. A transition to a sustainable, prosperous future requires sources of electricity that provide the benefits of today's generation system while minimizing its negative effects.

Creating a sustainable energy infrastructure will require the widespread deployment of renewable energy technologies, which draw their power from the continuous flows of the natural environment and have a number of major environmental benefits[1]. To encourage the adoption of these technologies, a number of regional and national governments offer financial and permitting incentives for renewable electricity projects. Exploratory research focusing on Swedish policy-making found that these incentives often do not distinguish between different types of renewable energy, leading to a situation where a majority of new investment goes to the cheapest alternatives[2]. In addition, current decision-making within the industry places a high value on financial return on investment, greenhouse gas mitigation, and increasing the percentage of electricity that comes from renewable sources. While this situation will most likely lead to greater adoption of renewable technologies, there is a need for tools that compare the environmental and social impacts of competing renewable electricity generation options.

This study presents a pilot decision-support tool, *Guide for Sustainable Energy Decisions (GSED)*, that is designed to compare renewable electricity generation options according to their effectiveness in moving society towards sustainability. This tool is designed to give strategic guidance to decision-makers in government, electric utility companies, consultancies, and other organizations involved in the electricity generation industry. It combines life cycle assessment with the Framework for Strategic Sustainable Development (FSSD), commonly referred to as The Natural Step framework. This framework uses the technique of backcasting, which consists of creating a vision of future success, and then asking "What do we need to do today to reach our desired future?"[3] While many backcasting studies, including those focusing on energy, use a specific future scenario as their reference point[4], the FSSD backcasts from four Sustainability Principles that use a scientifically-based understanding of the ecosystem to set the minimum requirements for a sustainable society[5]. The first three principles deal with how human society directly and indirectly damages the biosphere:

> In a sustainable society, nature is not subject to:
>
> 1. …systematic increases in concentration of materials from the Earth's crust;
> 2. …systematic increases in concentration of man-made substances; or
> 3. …systematic physical degradation.

---

[1] These renewable sources include solar thermal energy, solar photovoltaics, hydropower, wind power, bioenergy, tidal power, and geothermal energy (Twidell and Weir, 1986).

[2] Conny Hägg, Senior Adviser, Swedish Ministry of the Environment. Interview by authors, Mar. 28, 2008.

[3] K.H. Dreborg. "Essence of Backcasting." *Futures* 28: 813-828, 1996.

[4] See T. Johansson and P. Steen. *Solar Sweden.* Stockholm: Secretariat for Future Studies, 1978.

[5] J. Holmberg and K.H. Robèrt. "Backcasting from non-overlapping sustainability principles." *International Journal of Sustainable Development and World Ecology* 7: 291-308, 2000.

Also, a sustainable society does not:

4. … systematically undermine people's capacity to meet their own needs.

Two research questions were created to guide the development of the *GSED* tool. The primary question concerned the key attributes of the tool, while the secondary question focused on the efficacy of the resulting work.

Primary Research Question: What are the key attributes of a comparison tool that prioritizes investment in renewable electricity options using the Framework for Strategic Sustainable Development?

Secondary Research Question: What are the resulting comparison tool's strengths, areas for improvement, and inherent limitations?

2. Methods

The research was divided into two stages: development of the *Guide for Sustainable Energy Decision* tool; and a period of testing and feedback to measure the resulting tools's practicality. In the first stage, the tool was created with input from a literature review, interviews, and deductive reasoning within the research team. In the second stage, the practicality of the tool was evaluated by both attempting to compare three types of renewable electricity generation and gathering outside feedback on *GSED*'s strengths, areas for improvement, and inherent limitations.

Tool Development

Development of the comparison tool involved choosing a general framework for analysis, identifying relevant criteria, and creating a method for using the resulting tool to compare different technologies. Decisions relating to these three aspects of the tool were made in parallel and were significantly influenced by each other. The main outside sources of information for this process were literature reviews and outside interviews that focused on prior research related to decision-support tools and sustainability indicators. Four key success criteria were used to create a tool that had:

- A rigorous whole-systems perspective using a scientifically principled definition of sustainability as a strategic compass;
- An ability to compare electricity generation systems with different energy sources, costs structures, and levels of development;
- An analysis framework that takes the entire life cycle into account when analysing electricity generation options; and
- An interface and analysis process that is easy to use, flexible, and accessible.

Tool Testing and Feedback

To evaluate the comparison framework's effectiveness and ease of use, a pilot comparison was performed on three renewable electricity technologies: onshore wind energy, wave energy, and woodchip biomass energy. These three options were chosen in order to test *GSED* across a wide range of renewable technologies with differing fuel cycles, installed capacity, available test data, and future production potential. This phase of the study was not meant to create a definitive comparison of these energy types. Instead, it was designed to explore the secondary research question and reveal the tool's strengths, weaknesses, and inherent limitations.

In addition to the testing phase, the first version of the tool was sent to a group of expert advisers for feedback. Because *GSED* is still at an early stage of development, these advisers were chosen based on their experience with the Framework for Strategic Sustainable Development, life cycle assessment and, in some cases, their work on other decision-support tools. Their feedback was gathered through written comments and semi-structured phone interviews.

A Note on Limitations

This study was completed as part of a master's thesis that focused on the application of the Framework for Strategic Sustainable Development. Because the choice of the FSSD was a requirement for the thesis, the results should be viewed in that context, with its corresponding limitations.

3. Results

3.1 Tool Development Overview

The *GSED* comparison tool was designed around life cycle assessment (LCA), a cradle-to-grave approach to assessing industrial processes. LCA analyzes a product's environmental impacts from raw material extraction, through its production process, useful life, and disposal or recycling. Because this method captures environmental impacts throughout the life cycle, using LCA to compare electricity generation systems had important benefits. The most significant of these is the ability to compare options whose major environmental impacts come at different points in the product life cycle.

In order to combine the operational benefits of life cycle assessment with a strategic sustainability perspective, the *GSED* comparison tool compared electricity generation systems using a type of LCA commonly referred to as Sustainable Life Cycle Assessment (SLCA). SLCA integrates the Framework for Strategic Sustainable Development into the LCA method, giving decision-makers a strategic overview of how a product impacts movement towards the goal of a sustainable society. This method is under development, and has been employed by a large chemical production firm to guide strategic product development[6,7].

For the purposes of this study, a new version of the SLCA method was created to compare electricity generation options in a way that would be useful to decision-makers. The key attributes of this tool, as well as its differences with traditional LCA and SLCA, are described below within the framework of the LCA development process created by the International Standards Organization (ISO).

Goal Definition and Scoping

The goal the *GSED* tool was to allow decision-makers to make generic comparisons between renewable electricity options at the beginning of the planning process. Therefore, the tool was designed to compare generic models of renewable technologies. These models were created using data from two sources: site-specific information from previous life cycle assessments, and estimates based on an average expected generation system. This method made comparisons possible between mature technologies such as wind, which have been analyzed extensively, and

---

[6] Imperial Chemical Industries (ICI). 2007. "ICI Sustainability Review 2006" London, UK: ICI.

[7] Prior research on the integration of FSSD and LCA includes:

K. Andersson et al. "The Feasibility of including sustainability in LCA for product development" *Journal of Cleaner Production* 6: 289-298. 1998.

H. Ny et al. "Sustainability Constraints as System Boundaries: An Approach to Making Life Cycle Management Strategic." *Journal of Industrial Ecology* 10 (1-2): 61-77. 2006.

experimental technologies such as wave power, which do not have enough test data for a traditional life cycle assessment.

The second decision involved standardizing the life cycle stages in a way that allowed side-by-side comparisons of electricity generation methods. This type of comparison was especially challenging because of the differences between combustion, non-combustion, and nuclear electricity generation. Both nuclear systems and combustion systems such as coal and biomass generate electricity using a mined or harvested fuel. In contrast, non-combustion systems such as wind and wave produce electricity from the flows of the natural environment. Because non-combustion systems do not require a fuel to generate electricity, LCAs of these methods only consider the life cycle of the generation equipment. Combustion and nuclear assessments, by contrast, must include the life cycle impacts from both the generation equipment and the fuel source.

In order to rigourously compare these electricity systems, four standardized life cycle stages were created. These stages, raw materials, production, use, and disposal, were the same for all types of electricity generation. The raw materials stage captured all unsustainable impacts related to the extraction/harvesting, processing, and transportation of raw materials. The production stage focused on impacts related to producing components and transporting them to the electricity generation site. The use stage focused specifically on impacts during the generation of electricity. Importantly, the life cycles of the fuel used in combustion and nuclear systems were included in the use stage, since the vast majority of their impacts occur while the electricity generation system is operating. The disposal stage focused on impacts that occurred after the technology had passed its useful generating life. In addition to these modifications, it was necessary to standardize assumptions regarding energy and material use.

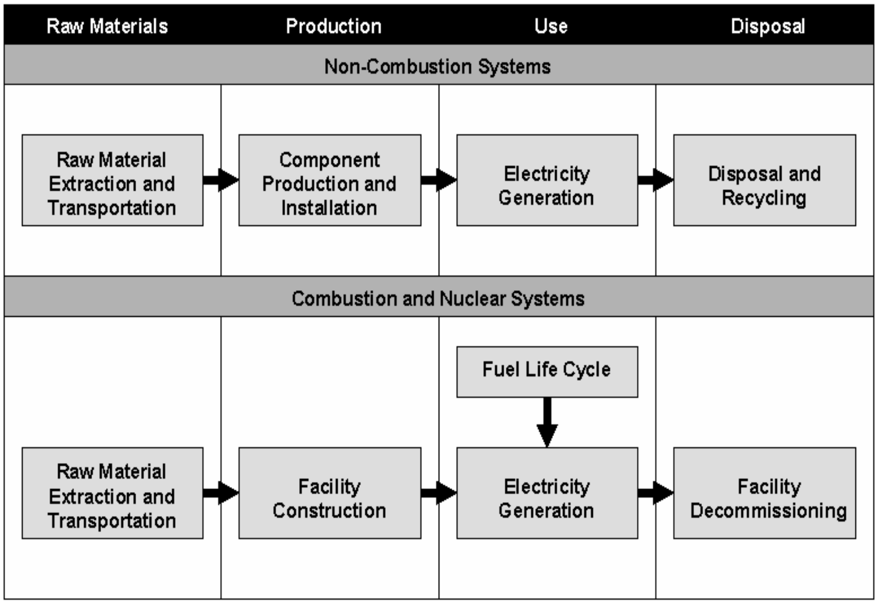


Figure 3.1. Standardized Life Cycles for Electricity Generation Comparisons

Defining *GSED's* scope required a decision on which activities within the electricity generation life cycle would be included in the LCA. Activities directly related to electricity generation systems, such as the production of steel for wind turbines, were included because of their direct impact on the production process. For other impacts, data were collected for those inputs and outputs that would not have been produced or used if the chosen electricity system was not being constructed. For example, when a wind turbine is being installed, a large construction crane is needed to lift it into place. Data on the diesel fuel in the crane is collected because the fuel is used specifically for the turbine's installation. In contrast, the materials that make up the crane itself are not considered because they can be used for other purposes, and are therefore outside of the scope of the analysis.

In order to expand the scope of the impacts that *GSED* considers, the four Sustainability Principles were integrated into the analysis process. For each life cycle stage, the chosen electricity generation technology was analyzed according to its contribution to unsustainable practices. The traditional environmental impact categories were included in this analysis within related Sustainability Principles. The process of identification and measurement of these impacts with be discussed further in the *Impact Iinventory* section below.

Life Cycle Inventory

The second stage of the LCA process is the life cycle inventory, where possible environmental impacts are listed. The first step in inventory creation is to build a flow diagram that visualizes the entire life cycle of the product. This diagram includes all necessary inputs to the life cycle (materials and energy) as well as all outputs (emissions, waste, and the finished product itself). Once the inputs and outputs are visualized, a data collection plan is created and quantitative data is gathered. At the end of this process, an inventory of relevant inputs and outputs to the life cycle is available to the decision-maker.

In a traditional LCA, after the inventory is completed the analysis moves on to impact assessment, where the product's contributions to environmental problems are analysed. In order to integrate a full sustainability perspective into the *GSED* tool, materials, energy sources, and emissions are first inventoried from the generic model of each electricity generation technology. They are then organized into impact categories according to the four Sustainability Principles, as referred in the introduction. All inputs and outputs related to the life cycle are included in one of the four categories. In the raw materials stage of wind power, for instance, the metals aluminium, copper, and steel are organized in the *Materials from the Earth's Crust* category.

These four impact categories are further divided into ten sub-categories. For example, the *Man-Made Materials* category is sub-divided into the two main activities that lead to a violation of Sustainability Principle Two: production and release of materials that are both persistent in the biosphere and foreign to nature, and overproduction of natural materials that systematically increase their concentration in the environment. These two activities do not overlap (i.e. are mutually exclusive) and together are the main drivers of violations of Sustainability Principle Two. This division into sub-categories serves the dual purpose of clarifying the violations of the four Sustainability Principles and categorizing potential unsustainable impacts in an easy to understand way.

Materials from the Earth's Crust
Q1: Use of fossil fuels?
Q2: Use of scarce metals and minerals?

Man-made Materials
Q3: Use of materials that are foreign to nature?
Q4: Overproduction of natural materials?

Degradation of the Biosphere
Q5: Over-harvesting of natural resources?
Q6: Manipulation of the ecosystem?
Q7: Decreasing Biodiversity?

Undermining the Social Fabric
Q8: Abuse of political power?
Q9: Abuse of economic power?
Q10: Abuse of structural power?

Figure 3.2. Sustainability Impact Sub-Categories

Once inputs and outputs are organized in their respective sub-categories, they are analysed for their potential to contribute to unsustainable impacts. This process begins with ten sustainability filter questions, one for each of the impact sub-categories. These sustainability filter questions are answered positively or negatively, and are designed to separate potentially sustainable inputs and outputs from those that have may have an unsustainable impact. The first sustainability filter question focusing on materials from the Earth's crust asks:

Within this stage of the life cycle [raw materials, production, use, or disposal], does this electricity generation method contribute to a systematically increasing concentration of substances from the earth's crust in nature through the use of ***scarce metals and other minerals****?*

To answer this question, a set of criteria are given for each of the sub-categories. In the case of metals and minerals, the unsustainable impacts depend on the size of human flows of the material compared to the natural flows. This indicator, human flows divided by natural flows, is referred to as the lithospheric extraction indicator. Within the *GSED* tool, this question is asked as:

Are any metals being used whose man-made flows are greater than natural flows?

In the analysis of the raw materials stage of wind power, there were three metals to study: aluminium, copper, and iron. In 2006, the annual human flows from mining and the burning of fossil fuels were greater than natural flows for both copper and iron[8]. In contrast, the human flows for aluminium were estimated at only 6% of natural flows. Therefore, while aluminium was included in the traditional life cycle inventory, it was filtered out of the *GSED* inventory because it did not have a high potential for unsustainable impacts. Copper and iron passed through the filter and were included in the *GSED* inventory of materials, energy sources, and emissions that contribute to unsustainable effects (Note: This does not include indirect effects of aluminium production such as the electricity needed for the aluminium smelter).

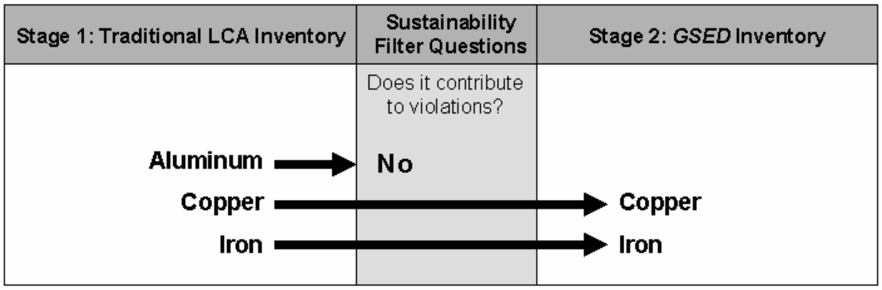


Figure 3.3. GSED Life Cycle Inventory Process

In this way, all inputs and outputs from the generic electricity generation model pass through a filter based on the four Sustainability Principles. At the end of this process, there are two inventories: a *Sustainable Inventory* of inputs and outputs that do not violate the Sustainability Principles, and an *Unsustainable Impact Inventory* of those materials, energy sources, and emissions that could potentially keep the chosen electricity generation system from being sustainable. After the filtering process is complete, impacts that would not be considered in traditional life cycle assessment, such as political power abuse and overharvesting of natural resources, are analysed and placed into the *Sustainable Inventory* or the *Unsustainable Impact Inventory.* If all of the inputs and outputs in a category or sub-category are in the *Sustainable Inventory*, then that category is in compliance with the four Sustainability Principles. If, on the

---

[8] Calculation is based on C. Azar, J. Holmberg, and K. Lindberg. 'Socio-ecological indicators for sustainability" *Ecological Economics* 18: 89-112. 1996.

other hand, a category has a large *Unsustainable Impact Inventory*, then it is flagged as a potential hot spot that may need more analysis.

Life Cycle Impact Assessment

The impact assessment stage is where two or more electricity generation systems are compared from a sustainability perspective. All comparisons are based on the impacts contained in the *Unsustainable Impact Inventory.* Put differently, *GSED* analyzes the strategic sustainability potential of electricity generation systems according to the amount and severity of their unsustainable impacts. These impacts are measured using criteria that are designed to be mutually exclusive, collectively exhaustive regarding the FSSD, and easily understood by decision-makers and the general public. Three decisions were important to meeting these guidelines: the choice of criteria, the choice of a reference point for success, and the method used to compare different options.

The choice of criteria is heavily influenced by the types of indicators that underlie the comparison process. It is possible to divide the majority of sustainability indicators into three main groups: *societal activity indicators* that measure activities occurring in society (i.e. the use of fossil fuels); *environmental pressure indicators* that measure human activities that will directly affect the environment (emission of greenhouse gases); and *environmental health indicators* that measure the quality of the environment (atmospheric CO_2 concentrations)[9]. Because *GSED* is designed to compare the sustainability of electricity generation systems from the perspective of a sustainable society, the comparison criteria were based on societal activity indicators or environmental pressure indicators.

The choice between societal activity and environmental pressure indicators were made depending on the nature of the unsustainable impact. Some impacts have been studied extensively and their effects are relatively well-understood. These include use of materials and processes that contribute to climate change, eutrophication, and acidification[10]. Extensive research and regulations have been created to deal with these well-recognized threats to long term ecological sustainability. In recognition of this fact, criteria that deal with these issues would most likely look at environmental pressure indicators that measure the direct emissions to the biosphere. The focus on pressure indicators allows greater compatibility with traditional LCAs, because they focus almost exclusively on these types of impacts. It also makes much more detailed plans possible, including precise benchmarks involving mitigation.

Despite the benefits of environmental pressure indicators, there are many unsustainable impacts whose effects in the biosphere are not well understood. These types of impacts tend to be complex, with dispersed, unpredictable effects. They also tend to be the impacts that traditional LCA does not measure, and that the *GSED* tool is attempting to capture. In the example of many scarce metals, it is extremely difficult to measure emissions to the environment because of their dispersal in society and unpredictable rates of disposal. Because of the uncertainty related to these impacts, comparison criteria were chosen that measure human activities (such as mining).

When sustainability impacts have been measured, it is important to create a Sustainability Reference Point for each indicator that defines the level of impact that would be acceptable in a sustainable society. Once Sustainability Reference Points are chosen, an electricity generation technology's contribution to the problem needs to be measured and how far it is from

---

[9] C. Azar, J. Holmberg, and K. Lindberg. 'Socio-ecological indicators for sustainability" *Ecological Economics* 18: 89-112. 1996.

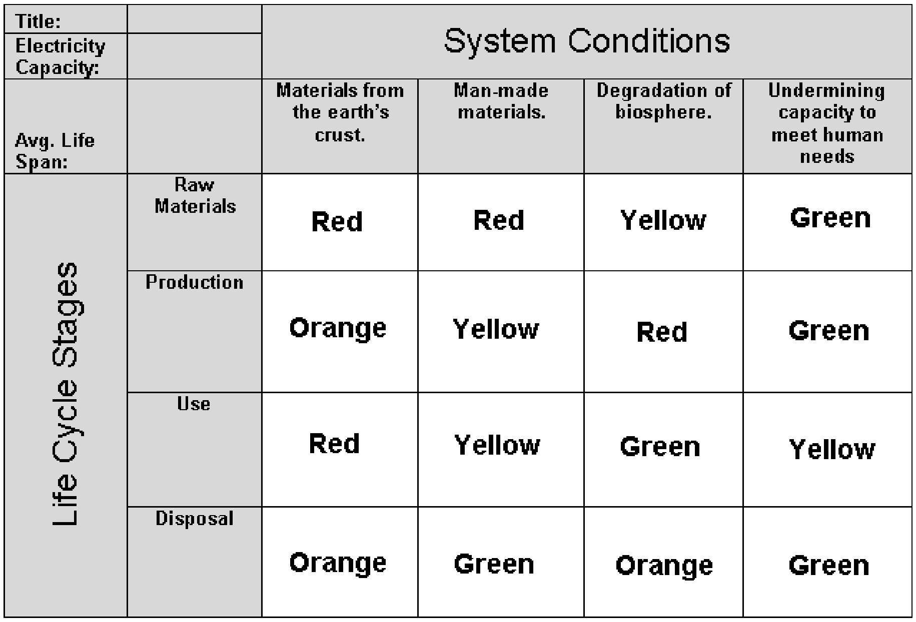
[10] U. Carlson, J. Holmberg, and G. Berndes. "Socio-Ecological Indicators for Sustainability for Gotland, Sweden" PhD Diss., Chalmers University. 1997.

sustainability needs to be decided. The contribution from the chosen technology is visualized on a continuum with the Sustainability Reference Point to give the decision-maker an idea of where the current reality is and where the technology needs to go.

Regardless of the choice of reference point, electricity generation options can be compared in a number of ways. For the GSED tool, a comparison process was chosen that uses an electricity generation option as a reference point. Within the comparison tool, this method focuses attention on the differences between electricity generation technologies and can give decision-makers useful guidance when choosing among different options.

Life Cycle Interpretation

The results of the life cycle comparison are presented in a sixteen-box matrix. The columns of the matrix represent the four Sustainability Principles. The rows represent the four standardized life cycle stages. Each sustainability principle/life cycle box is given a color depending on its relative unsustainable impacts. There are four possible output colors: green, yellow, orange, and red. Green is reserved for impact areas that do not make a major contribution to unsustainable activities. The other three colors are based on a comparative system where a generation method is given a red if it is worse than the method it is being compared with, orange if it is the same, and yellow if it is better. All colors other than green are therefore dependent on the electricity generation methods being compared. As a result, the results matrix can not be filled out without a point of reference with which to compare the chosen technology.



Title:		System Conditions			
Electricity Capacity:					
Avg. Life Span:		Materials from the earth's crust.	Man-made materials.	Degradation of biosphere.	Undermining capacity to meet human needs
Life Cycle Stages	Raw Materials	Red	Red	Yellow	Green
	Production	Orange	Yellow	Red	Green
	Use	Red	Yellow	Green	Yellow
	Disposal	Orange	Green	Orange	Green

Figure 3.4 GSED *Results Matrix*

3.2 Tool Testing and Feedback

To test the practicality of the *GSED* tool, an attempt was made to build general comparison models for three renewable energy technologies and test the comparison process described in Section 3.1. The goal of the pilot comparison was to build general models of the three renewable energy technologies, create unsustainable impact inventories with both quantitative and qualitative data, and use them to compare the overall sustainability potential of wind, wave, and woodchip biomass. Interviews and workshops were sufficient to build general life cycle models for all of the electricity generation technologies. In addition to the models, qualitative unsustainable impact inventories were also created. When set side by side, the inventories gave a general overview of where the serious impacts occurred, and which life cycle stages were in need of more detailed research.

Expert Feedback

To test the efficacy and ease-of-use of the *GSED* tool, interviews were conducted with nine outside advisers with expertise in the Framework for Strategic Sustainable Development and life cycle assessment. Feedback on the comparison tool was generally very positive and suggested that a complete version could be useful to decision-makers trying to choose sustainable electricity options. Key areas of strength included the application of the FSSD, the inclusion of a wide variety of impacts, and ease of use of the tool. The feedback also identified areas for improvement related to how trade-offs between technologies are handled, how the Sustainability Principles are presented, and additional issues to be considered in the tool, including scalability, future potential, and recycling. Inherent limitations of the tool were also identified, and included the difficulty of data collection and the possibility of a strategically questionable decision resulting from poor data or confusion related to the FSSD.

4. Discussion and Conclusions

The *Guide for Sustainable Energy Decisions* tool*,* while still in an early stage of development, can in theory compare renewable electricity technologies on their strategic potential to move society towards sustainability. The decisions made during tool development have helped *GSED* meet the key success criteria presented in the *Methods* section. The use of generic life cycle models and the standardization of the life cycle stages and energy/material assumptions made comparison of a wide variety of renewable technologies possible. In addition, integration of LCA and the FSSD made a whole-systems comparison possible throughout the life cycle. Finally, the visual interpretation of the results, as well as a simplified modeling process, increased the tool's ease of use and accessibility.

Despite meeting the success criteria, tool testing and feedback also identified a number of weaknesses that need to be addressed. This weaknesses fall into two categories: those that can be corrected through future research and refinement (areas for improvement) and those that cannot (inherent limitations). Further work related to areas for improvement will hopefully lead to the minimization of other, inherent limitations. Although further research is required, the authors have concluded that a tool integrating life cycle assessment and the Framework for Strategic Sustainable Development can provide useful strategic guidance for sustainable development to decision-makers and, along with existing decision-support tools, help plan and implement a long-term strategy for a sustainable electricity generation system.

Further Research

There are two major areas of future research possible in relation to the *GSED* tool: creation and refinement of tool components, and the testing and distribution of a final version. Research related to components would most likely focus on development of a detailed list of criteria, an e-learning module that would introduce users to the FSSD, and supporting data to help weight sustainability impacts and make effective comparisons. Testing of a completed software version of *GSED* could be carried out through a pilot distribution to decision-makers and collaborative relationships with other decision-support tool developers.