Principles-Based Comparison Framework for Renewable Electricity Options

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2008

Thesis submitted for completion of Master of Strategic Leadership towards Sustainability, Blekinge Institute of Technology, Karlskrona, Sweden.

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 move society towards sustainability. Therefore, this study presents a pilot decision-support tool, Guide for Sustainable Energy Decisions (GSED), designed to give investors, policy makers, and manufacturers strategic guidance on the most effective renewable technologies to invest in for sustainability. The tool is based on a modified version of life cycle assessment (LCA) that allows comparisons of the upstream and downstream effects of generation technologies from a whole-systems sustainability perspective. Early feedback by experts suggests that, with further research, GSED could serve as an effective comparison tool and help decision-makers make strategic investments for sustainability.

Keywords: Renewable energy, electricity generation, strategic planning
Statement of Contribution

This thesis was the result of a truly effective collaboration. The topic emerged from the research team’s strong shared interest in discovering solutions to today’s emerging energy issues. Each member of the team played an equal role in the investigation and discussion of the research design phase. The research methods were then carried out to provide balanced interviews and workshops while still effectively distributing additional areas in a fashion complimentary to each member’s background.

Anna focused on wave power research along with building an extensive network of knowledge and connections with researchers and advisers in Sweden. Ben looked into the method of biomass electricity generation while also using his technical engineering background to help define the system criteria and tool application strategies. Brendan focused on wind power and researched extensively to find data on previous work in the fields of life cycle assessment, sustainability indicators, and decision-making models.

All members participated in the planning of the written report and presentations. Brendan played the facilitating role on the written report by distributing tasks and compiling the results to help professionalize the flow of the completed document.

Karlskrona, June 3, 2008

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Acknowledgements

We would like to thank our thesis advisers, Pong Leung and Henrik Ny, for their valuable support and insights. David Cook at The Natural Step International provided us with our inspiration and steady guidance throughout the thesis period. Dr. Karl-Henrik Robert’s vision and encouragement were also extremely helpful.

We would also like to thank the practitioners and experts who gave their time to contribute to our thesis project, including:

Archie Kasnet; Benny Sindowe; Klaus Ronde; Paul Rijke; Mikael Lund; Georges Dyer; Shannon Lloyd; Jan Sundberg; Tony Thompson; Fredrik Lönngren; Ulrika Lundqvist; Per Svenningson; Sophie Hallstedt; and Staffan Niklasson.

Finally, we would like to thank our peer and shadow groups for their support, advice, and dedication to a sustainable world.
Executive Summary

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 system 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 benefits1. 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 (Hägg 2008). 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), which is designed to compare renewable electricity generation options according to their effectiveness in moving

1 These renewable sources include solar thermal energy, solar photovoltaics, hydropower, wind power, bioenergy, tidal power, and geothermal energy (Twidell and Weir, 1986).
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?” (Dreborg 1996). While many backcasting studies, including those focusing on energy, use a specific future scenario as their reference point (see Johansson and Steen 1978), 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 (Holmberg and Robèrt, 2000). 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. …systematically increasing concentrations of materials extracted from the Earth’s crust;

2. …systematically increasing concentrations of substances produced in society; or

3. …systematically increasing physical degradation.

The final principle deals with social sustainability and the importance of a strong social fabric when attempting to meet the first three principles:

Also, in a sustainable society:

4. … people are not subject to conditions that systematically undermine their capacity to meet their 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?
Methods

The research was divided into two stages: development of the *Guide for Sustainable Energy Decisions* tool; and a period of testing and feedback to measure the resulting tool’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 to a broad range of stakeholders involved in the planning and implementation of electricity generation projects.

**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. 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.
Results

Tool Development. The GSED comparison tool was developed to effectively compare the sustainability potential of renewable electricity generation options. It was built around life cycle assessment (LCA), a cradle-to-grave approach to assessing the environmental impacts of industrial processes. By building off past research that integrated LCA and the FSSD, GSED was able to evaluate renewable technologies throughout their life cycles using the four Sustainability Principles. To ensure that these evaluations could be effectively compared, the life cycles, assumptions for energy use and materials, and units of comparison were standardized for all types of electricity generation.

GSED’s comparison process is designed to evaluate renewable electricity options in four life cycle stages (raw materials, production, use, and disposal). In each of these stages, an inventory is created of the processes, materials, energy sources, and wastes that could lead to unsustainable impacts through a contribution to violations of the Sustainability Principles. Then each technology’s impacts are compared using a combination of quantitative and qualitative indicators. One of the possible renewable options is used as a benchmark, and alternative options are scored relative to that benchmark. The results are then presented in a sixteen box matrix that uses a series of colors (green, yellow, orange, red) to visualize the strengths and weaknesses of the chosen technology in relation to the Sustainability Principles.

Tool Testing. The GSED comparison process was tested on three renewable electricity technologies: onshore wind power, woodchip biomass power, and wave power. The results confirmed that general models of each technology can be created, and highlighted the challenges associated with trade-offs and data collection.

Expert Feedback. A summary of GSED’s key attributes was sent to nine outside experts. Feedback was generally very positive, and unanimously praised the tool’s overall design. Challenges encountered during tool testing were reiterated, and the experts highlighted issues related to recycling, technological development, and scalability.
Key Findings

Tool Strengths. Pilot testing and expert feedback confirmed that GSED met the key success criteria that were used as benchmarks throughout the thesis process. The integration of LCA and FSSD expanded the scope of the analysis and, in conjunction with standardization and generic models, made comparisons between every type of renewable electricity generation method possible. Once these comparisons were made, results were presented in an easy-to-understand, color-based format that could be useful for strategic planning.

Areas for Improvement. Feedback highlighted the importance of correctly presenting the FSSD and including issues such as future technological development and recycling in the comparison process. Tool testing revealed the need for further research into the most effective means of comparing renewable options.

Inherent Limitations. GSED’s inherent limitations included the difficulty of data collection and the risk of poor results stemming from improper use of the tool. While important, these problems are common to many types of decision-support tools and can hopefully be partially mitigated by further improvements in design.

Conclusion

The environmental sustainability challenge makes effective strategic planning extremely important, both for society as a whole and the electricity generation system in particular. To transition to a sustainable electricity system, rigorous and accessible decision-support tools are necessary. Testing, feedback, and discussion confirmed that GSED successfully met the key success criteria for this type of tool and could be a useful decision aide for a wide variety of stakeholders. Issues raised during the thesis period should be explored through further research on this topic.
Backcasting: Planning ‘from success’ by starting with the desired outcome in mind and then determining the steps required to achieve the outcome.

Carbon Capture and Storage (CCS): An approach to mitigate global warming by capturing carbon dioxide from large point sources such as fossil fuel plants and storing it instead of releasing it into the atmosphere.

Combustion-based electricity generation: Electricity generation that relies on a harvested or mined fuel whose life cycle needs to be considered along with the technology itself.

Framework for Strategic Sustainable Development (FSSD): A planning framework for sustainability that uses a combination of the backcasting method and a clear, scientifically-sound definition of sustainability.

Greenhouse gases: Gasses in the atmosphere which reduce the loss of heat into space. Human-induced emissions of greenhouse gases are believed to be a main driver of current global temperature increases.

Life cycle assessment (LCA): A cradle-to-grave approach to assessing the environmental impacts of industrial processes.

Non-combustion-based electricity generation: Electricity generation that relies on the flows of the natural environment.

Program for the Endorsement of Forest Certification (PEFC): A non-profit group involved in the certification of sustainable forestry practices.

Renewable energy: Energy generated from the natural flows of the environment.

Sustainability Principles: Basic principles for socio-ecological sustainability developed by the Natural Step, based on basic laws of science and reviewed by the international scientific community.

Sustainable society: A society that does not systematically degrade the ecosystem’s ability to provide life support services, and where all people have the capacity to meet their basic needs.
**The Natural Step:** An international non-governmental organization (NGO), of Swedish origin, which developed and promotes The Natural Step Framework for strategic planning towards sustainability.

**Wave power:** Wave power electricity generation consists of a magnetized generator placed on the seabed. A piston in the generator is driven by the motions from a buoy on the surface and can convert energy from waves to electricity.

**Wind power:** Renewable electricity generation method that relies on the physical force of the wind to turn generators.

**Woodchip biomass:** Forest products, untreated wood products, energy crops and short rotation coppice, which are quick growing trees like willow.
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1 Introduction

1.1 Electricity Generation and Sustainability

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. One possible answer to this problem is the widespread deployment of renewable energy technologies, which draw their power from the continuous flows of the natural environment\(^2\). To ensure that decision-makers invest in technologies that make a strategic contribution to sustainability, tools are needed to compare renewable electricity generation options. This study attempts to develop such a tool.

1.1.1 Electricity Generation Today

Since the mid-1800s, electricity has played a profound role in the development of human society. This energy source – clean, flexible, and easily controlled – makes up 40% of the world’s total energy use, with worldwide demand projected to increase sharply in the coming decades (Munson 2005, 3; IEA 2006, 1). The United Nations believes that access to electricity and other forms of energy is a key step in campaigns against poverty and global inequality (WSSD 2002, 9).

\(^2\) These renewable sources include solar thermal energy, solar photovoltaics, hydropower, wind power, bioenergy, tidal power, and geothermal energy (Twidell and Weir, 1986).
Today, fossil fuel and nuclear power generation account for more than 80% of total world electricity production, 65% of which comes from fossil fuels alone (EIA 2005). This is due to these methods’ superior properties in energy density, controllability, and historically, cost. Nevertheless, the fuels used for these types of generation are non-renewable resources and have serious environmental consequences (see Figure 1.1 for an overview). Fossil fuel generation is a major emitter of greenhouse gas emissions, scarce metals, and other air pollutants (Sims et al. 2007, 255; Azar, Holmberg, and Lindberg 1996, 96). Nuclear-based generation creates radioactive waste, carries a risk of nuclear accidents, and could be vulnerable to terrorism (Nielsen, 2006, 38; Barnaby and Kemp 2006, 24). Capturing and storing carbon underground, along with careful handling of nuclear waste, may help mitigate some of these environmental damages in the short term. However, the production of oil, coal, natural gas, and uranium is projected to peak at various times during the next 200 years, limiting these options’ usefulness in a sustainable future (Mason 2007, 1318).

![Figure 1.1 The current electricity generation system](image-url)
1.1.2 Electricity Generation in Context

The environmental problems associated with modern electricity generation have not occurred in a vacuum. They are part of a broader deterioration of the Earth’s ecosystem caused by human activities. This deterioration is especially important because the biosphere provides society with many essential goods and life-support services (Daily et al. 1997). These include purification of air and water, regulation of climate, and the production and maintenance of biodiversity. Ecosystem services are absolutely essential to technological society and general well-being. Historically, demand for these services was small enough that serious ecological effects caused by human activities were limited in scope and duration.

However, as global population and demand for resources has grown, pressure on the biosphere has increased dramatically. Human alteration of the Earth has led to massive land transformation, biodiversity loss, and a significant rise in atmospheric CO₂ levels (Vitousek and Mooney 1997). These environmental effects are creating increasing pressure on human society. As they get worse, the options and flexibility available to humans will systematically decrease, making a transition to an ecologically sound model much more difficult.

The metaphor of a funnel can be used to simplify the global situation while acknowledging the connections between environmental issues. Non-sustainable development can be visualised as entering a funnel where the space becomes narrower and more limiting. This narrowing of options is caused by the environmental and social crises that are becoming common occurrences, such as record droughts, climate change, resource depletion, and the weakening of the social fabric. Negative effects from these events can be visualized as hitting the walls of the funnel. A sustainable society, in contrast, will not only mitigate environmental and social problems, but will also give human society more options and flexibility to meet new challenges.
Figure 1.2. The funnel metaphor

The transition toward sustainability will require ingenuity, dedication, and access to energy. Without a reliable, clean, and safe source of energy, the flexibility and options available to move toward sustainability narrow considerably. Because of its flexibility and relative ease of use, it is reasonable to assume that electricity will play an important role in the sustainable society. Therefore, a key goal of sustainable development should be the creation of an electricity system that will provide energy for a transition to sustainability without contributing to large-scale environmental and social problems. The next section will discuss a strategic planning framework for moving towards that vision of sustainable electricity generation.

1.2 Framework for Strategic Sustainable Development

Creating a sustainable energy system requires a strategic planning focus that gives decision-makers a clear framework for success. As environmental problems have become more complex, energy planners have used the technique of backcasting to plan effectively for sustainability (Johansson and Steen, 1978; Dreborg 1996, 814; Holmberg and Robèrt, 2000, 294). Backcasting consists of creating a vision of future success, and
then asking “What do we need to do today to reach our desired future?” (Dreborg 1996, 813).

The Framework for Strategic Sustainable Development (FSSD) is a combination of the backcasting method and a clear, scientifically-sound definition of sustainability. While many backcasting studies, including those focusing on energy, use a specific future scenario as their reference point, 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.

1.2.1 Defining Sustainability

“Since there is probably no limit to the number of possible designs of sustainable societies, the definition [of sustainability] must be searched for on the principle level – any sustainable society would meet such principles.”

(Holmberg and Robèrt, 2000, 297)

The creation of a robust definition of sustainability requires an understanding of the system in which sustainability planning will occur, in this case, human society within the Earth’s biosphere. This system is extremely complex, and should only be studied enough to understand how society can damage the ecosphere. Therefore, a principled definition of sustainability should be derived from a scientific understanding of the natural world. The relevant areas of that understanding include:

- Matter and energy can be neither created or destroyed;
- Matter and energy tends to disperse spontaneously;
- The value of materials to human society is a function of their concentration, structure, and purity, and;
- Photosynthesis is the primary producer of this value in the biosphere.

Because the Earth is a closed system (i.e. energy enters and leaves, while matter by and large does not), human society and much of the biosphere depend on photosynthesis and energy input from the sun to build structure
and concentration. Current human practices endanger this process by damaging the biological foundation for society through direct and indirect means. Therefore, sustainability principles should be designed to reduce human pressure on the environment to a level that is sustainable for the foreseeable future.

Robust sustainability principles should be worded in such a way that they are:

- based on a scientifically agreed-upon view of the world;
- necessary to achieve sustainability;
- sufficient to cover all aspects of sustainability;
- concrete enough to guide actions and problem-solving; and
- mutually-exclusive to facilitate comprehension and monitoring

(Holmberg and Robèrt, 2000, Ny et al., 2006).

Holmberg and Robèrt have derived four Sustainability Principles that attempt to fulfill these conditions (Holmberg and Robèrt, 2000; Ny et al., 2006). 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. …systematically increasing concentrations of materials extracted from the Earth’s crust;

2. …systematically increasing concentrations of substances produced in society; or

3. …systematically increasing physical degradation.

The final principle deals with social sustainability and the importance of a strong social fabric while attempting to meet the first three principles:

Also, in a sustainable society:
4. … people are not subject to conditions that systematically undermine their capacity to meet their needs.

### 1.2.2 The ABCD Process

The Sustainability Principles articulated above serve as constraints that set out the minimum for a sustainable society, and can therefore serve as a vision of success when backcasting. Robèrt has developed a four-step “ABCD” tool that formalizes the process of backcasting from Sustainability Principles and facilitates practical application of the FSSD. An example of this tool being used for the electricity generation system is given below:

**Step A: Awareness.** A shared mental model is created around the Framework for Strategic Sustainable Development. This is important so that everyone has a common understanding of the definition of sustainability and the backcasting method.

**Step B: Baseline.** Planners ask the question “In what ways, and to what extent, does today’s electricity system contribute to violations of the Sustainability Principles?” A baseline assessment is created, and relevant tools to move towards sustainability are identified.

**Step C: Visioning.** Participants create a vision of a sustainable electricity system. Possible solutions to move towards that vision of sustainability are listed, regardless of their short-term feasibility.

**D: Strategic Program Design.** Solutions from step C are prioritized based on the following three guiding questions:

1. *Does this action lead in the right direction?* When planning for sustainability, actions must be evaluated on the basis of their contribution to the movement towards sustainability.

2. *Is this action a versatile platform for future improvements?* Financial, social, and intellectual investments should increase the options and flexibility available to society for adaptation in a changing environment.

3. *Does this action create a sufficient return on investment?* Return on investment can include the financial return to a private firm, the positive effects created by a government program, or the amount of energy that is created from the amount of energy invested.
1.2.3 Moving to Sustainable Electricity Generation

The current electricity system violates the four Sustainability Principles in a number of ways. The fuels used for generation are extracted from the Earth’s crust and lead to a systematic increase of carbon, scarce metals, and uranium in the biosphere. In addition, the combustion process produces man-made substances such as nitrous oxide, solid waste, and radioactive isotopes. Mining of materials contributes to the physical degradation of sensitive ecosystems, especially when practices like strip mining are used (Ward 2005). Finally, throughout the generation process there is a potential for negative health effects, poor working conditions, and other societal problems.

Figure 1.3. A sustainable electricity generation system

A sustainable electricity system would continue to provide the output of the current methods (electricity and heat), while insuring that electricity generation does not contribute to a systematic violation of the Sustainability
Principles (see Figure 1.3). Renewable electricity generation will play a key role in this new system, but choosing which technologies to invest in requires a strategic overview and an effective means of prioritization. In an ideal decision-making process, the ABCD process would be used to evaluate and prioritize investment in the renewable electricity options that would most effectively move the electricity generation system towards a future constrained by the four Sustainability Principles. In order for that process to begin, decision-makers throughout the electricity generation industry would need access to guidance and effective decision-support tools.

![Diagram showing backcasting from a sustainable electricity generation system]

**Figure 1.4. Backcasting from a sustainable electricity generation system**

A decision-support tool designed to give policy makers, investors, and manufacturing firms a strategic view of the electricity generation system would help create the ideal process outlined above. Decision-support tools are designed to give these stakeholders the data and analysis framework to help make solid decisions on which technologies to invest in. An ideal tool would look at competing electricity generation options from a holistic sustainability perspective and present the results in a format that is accessible to all relevant stakeholders. The current study explores the attributes of a comparison tool for electricity generation systems that can be used early in the decision-making process to decide if a technology has enough sustainability potential to invest money, build research and development programs, or create installation incentives. To build off the research and tool creation that has already occurred, exploratory research was carried out on the current decision-making process in the electricity generation industry.
1.3 Current Decision-Making Tools and Strategies

1.3.1 Overview

Current decision-making strategies and tools were studied using literature reviews, questionnaires and interviews. Questionnaires were sent to renewable energy consultancies, government energy departments, electric utilities, and the developers of current decision-support software tools for renewable energy. They consisted of four open-ended questions concerning renewable energy and decision-making. In addition, interviews were conducted with renewable energy consultants, Swedish government officials, and energy researchers at Swedish universities. The interviews were semi-structured, in that although a specific set of questions was used, interviewees were free to move to other topics.

These data collection methods focused on four main areas of interest: the interviewees’ role in electricity generation; comparison criteria for electricity generation systems; current decision-making tools and strategies; and possible areas of improvement of these tools. The three relevant questions included in the questionnaire to electric utilities and the Swedish government are given below:

1. What criteria do you use to compare renewable energy technologies?
2. Do you use outside tools and/or consultants to measure the environmental impacts of your renewable energy projects? If yes, please list the tools and consultants.
3. What are the gaps and weaknesses, if any, associated with current tools and methods? How could these gaps be filled?

Regional Focus. The exploratory research focused on decision-making tools and methods in Sweden, a nation of 9 million people in northern Europe. Sweden has a long history of governmental support for renewable energy, and in 2006, 54% of the nation’s electricity was generated from renewable hydro, biomass, and wind energy sources (Svensk Energi 2007, 3). This situation came about as a result of long standing government support for hydropower and an energy policy created after the oil crisis of the 1970s. In 1980, the Swedish parliament set up long term energy goals for the nation that called for the decommissioning of all nuclear reactors
and a transition to “an energy system based as far as possible on lasting, preferably renewable and indigenous, energy sources with the least possible environmental impact,” (Silveira, 2001, 85).

1.3.2 Current Areas of Strength

Organizations currently use a variety of criteria to choose between renewable energy options, including return on investment, environmental impacts, security of supply, and feasibility (Sims et al. 2007, 252; De Jager 2008). The choice of criteria and their relative importance depends on the type and size of the organization. Regardless, in many organizations the environmental benefits of renewable electricity generation are recognized, and in Sweden investment is supported by incentives from the national government (Tillenius 2008). In addition, many large corporations fund internal studies and research partnerships related to renewable electricity options (Örtenvik 2008). A variety of tools are available to these decision-makers that analyze feasibility, return on investment, and reductions of specific environmental effects such as greenhouse gas emissions and nitrous oxide (Bourque 2008).

1.3.3 Opportunities for Improvement

Whole-Systems Sustainability Perspective. Current tools can be used to consider the environmental impacts of most types of electricity generation. These analyses are usually limited to quantifiable, proven, and well-understood impacts such as the greenhouse effect and acidification. While these tools allow decision-makers to take a detailed look at some of the most obvious impacts of electricity generation, they omit other important environmental and social effects. Additionally, they are not sensitive to emerging sustainability issues that may be caused by widespread use of new technologies. The issues related to biomass electricity generation that are not covered by most current tools (deforestation etc.) illustrate how a whole-systems sustainability perspective could be useful. In order to develop criteria to ensure that a biomass project is moving electricity generation towards sustainability, the holistic sustainability potential of biomass generation projects could be determined through a whole-systems view.
“There is a need for (harmonized) biomass sustainability criteria.”

(de Jager 2008)

Strategic Outlook. There is an overall lack of strategic environmental planning tools in today’s organizations (Wrisberg et al. 2002, 80). In many cases, any type of renewable electricity generation is therefore seen as preferable to current fossil fuel and nuclear options. As a result, government incentives and many firms do little to differentiate between different types of renewable energy. This situation gives an advantage to the cheapest alternatives without a clear idea of relevant sustainability impacts. For this reason, decision-makers often choose the first renewable electricity option that is feasible and cost effective (Ullman 2006, 34; de Jager 2008).

“A problem with the electricity certificate [government incentive] system is that all of the renewable energy sources are treated equal. Some of them may cost a little bit more to start up and may then not have the same chance in the competition with others.”

(Melin 2008)

“It is important to develop a criterion that gives a direction of the types of energies environmental effects. This criterion hardly exists today but a vivid discussion is going on, for example within the EU.”

(Hägg 2008)

Another side effect of this situation is the lack of strategic constraints on project planning. There are a number of tools that allow users to optimize an electricity generation project’s energy output and return on investment. However, without clear criteria to assess the sustainability potential of a technology, there is a possibility that highly optimized but unsustainable projects will get approved.
1.4 A Tool for Electricity Decisions

“In energy modelling circles, there sometimes seems to be a perception that finding better algorithms or more accurate models is somehow going to be the key to improving energy and climate policy. But I think the way forward is not so much better algorithms (although these are of course also important). Rather, it is broadening access to energy policy, by making models more approachable and usable, so that instead of being used by a few dozen experts they can eventually be used by hundreds or even thousands of stakeholders.

(Heaps 2008)

1.4.1 Scope and Limitations of Current Research

To summarize the results of the exploratory research, current electricity generation decision-making places a high value on greenhouse gas mitigation, return on investment, and increases in the percentage of electricity generation that comes from renewable sources. A number of software tools and consultants are available to assist decision-making related to these priorities. This situation will most likely lead to a greater role for renewable electricity generation in the coming decades. Nevertheless, there is strong demand for strategic guidance related to the overall sustainability of electricity generation systems.

In the sense of prioritization of measures to move the electricity generation system to sustainability, the results of our survey were mixed. Current tools and methods effectively address the return on investment for renewable energy technologies. They also give guidance on certain environmental impacts, including greenhouse gases, one of electricity generation’s most serious unsustainable effects. But they do not take a whole-systems view of sustainability and can therefore miss emerging sustainability issues and lead to investments in technological and environmental dead ends.
Table 1.1 Generic Prioritization Questions in Current Decision-Making

<table>
<thead>
<tr>
<th>Generic Prioritization Questions</th>
<th>Does this measure move in the right direction?</th>
<th>Is this measure a versatile platform for success?</th>
<th>Does this measure have a sufficient return on investment?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answered in Current EGS Decision-Making?</td>
<td>Limited to improvements in known, quantifiable environmental damage.</td>
<td>No reviewed tools addressed this issue. The focus was on short-term, quantifiable environmental benefits.</td>
<td>Answered very well, numerous tools for financial and energy return on investment.</td>
</tr>
</tbody>
</table>

Therefore, it is reasonable to conclude that a decision-support tool designed to compare renewable electricity generation options from the perspective of the FSSD would be valuable from a sustainability perspective. As a result, this study focused on the development, testing, and improvement of a comparison tool called the Guide for Sustainable Energy Decisions (GSED). The tool will use quantitative and qualitative data to give a broad overview of current and emerging sustainability issues related to renewable electricity generation. GSED was designed for a number of audiences within the electricity generation sector. Renewable energy manufacturers, such as wind turbine producers, can use the tool to make the production and disposal of their products more sustainable. In addition, there is an opportunity to help influence public opinion and help decision-makers in government, municipalities, and private investment firms choose strategic sustainable electricity investments.

A complete, functional GSED tool would consist of:

- **An introductory section** that explains the Framework for Strategic Sustainable Development, including the current sustainability challenge, the four Sustainability Principles, and the importance of backcasting and whole-systems thinking;

- **A comparison section** where users evaluate the unsustainable impacts of electricity generation systems with the FSSD, using
models of the chosen technologies and data specific to the region where the decision is made;

- **A results section** where the comparison would be visualized in an easy-to-understand format; and

- **An explanation section** that helps the user understand the severity of specific materials and actions within the FSSD.

The current research will focus on the development of the main attributes of the tool’s comparison section. Further discussions on the other components can be found in section 5.1. In addition, the practicality and strategic usefulness of the proposed tool will be evaluated through testing and outside feedback.

![Guide for Sustainable Energy Decisions](image)

*Figure 1.5. Guide for Sustainable Energy Decisions*

### 1.5 Research Questions

In order to focus on the development testing of a sustainability comparison tool for electricity generation, two research questions were created. 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

2.1 Research Design

The research was divided into two stages: development of the GSED comparison tool for renewable electricity options and a period of testing and feedback to measure the resulting framework’s practicality. In the first stage, a pilot version of GSED was developed with input from a literature review, interviews, and deductive reasoning within the thesis group. In the second stage, the practicality of the pilot tool was evaluated by attempting to compare three types of renewable electricity generation and by seeking outside feedback on GSED’s strengths, areas for improvement, and inherent limitations.

Table 2.1. “Questions and Methods” matrix results

<table>
<thead>
<tr>
<th>Question</th>
<th>Literature Review</th>
<th>Outside Interviews</th>
<th>Deductive Reasoning</th>
<th>Framework Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Key attributes of a comparison framework for electricity generation?</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2  Is the tool a practical tool to move towards sustainability?</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

2.2 Comparison Framework Development

This phase of the study was designed to answer the primary research question:

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?
Though internal group processes and external consultation, the following critical success criteria were created for a pilot GSED tool. According to the criteria, the tool must have:

- **A rigorous whole-systems perspective using a scientifically principled definition of sustainability as a strategic compass.** The main goal of this study is to create a comparison tool that evaluates electricity generation options on the basis of environmental and social sustainability. For this goal to be realized, it was necessary to integrate a rigorous whole-systems view of sustainability into the analysis process.

- **An ability to compare electricity generation systems with different energy sources, costs structures, and levels of development.** The tool needs to be an effective prioritization aid that can compare the sustainability potential and unsustainable impacts of a wide variety of electricity generation technologies. For that reason, a design that allows users to compare a diverse range of electricity generation technologies is essential.

- **An analysis framework that takes the entire lifecycle into account when analysing electricity generation options.** With the continuous advancements in electricity generation technologies, the tool must be capable of not only considering the current options but the applicability of assessing any possible technology available in the future. By addressing it as a comparable system, rather than a specific type of technology, there will be an assurance in knowing the tool will be pertinent for the future, and provide clarity in which decision is the most sustainable.

- **A tool that is easy to use, flexible, and accessible to a broad range of stakeholders involved in the planning and implementation of electricity generation projects.** The usability and impact of the tool will depend in large part on its accessibility to stakeholders, the range of technologies it can compare, and its ease of use.
Development of the GSED pilot 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 conversations focusing on prior research and experience with decision support tools and sustainability indicators.

2.3 Framework Testing and Feedback

This phase of the study was designed to answer the secondary research question:

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

2.3.1 Tool Testing

To evaluate the comparison tool’s effectiveness and ease of use, a pilot comparison was performed using three renewable electricity technologies. There were at least nine different renewable generation methods that could be used for this phase of the research. To choose among these options, the nine technologies were compared using four variables: the nature of the primary energy source; current installed capacity in Sweden; theoretical potential for electricity generation in Sweden, and the difficulty of data collection. By choosing renewable technologies with a wide range of values for these variables, it was possible to test the tool in a number of situations that may arise during real-world decision-making. On the basis of this data, three technologies were chosen: onshore wind energy, wave energy, and woodchip biomass energy. This phase of the study was not meant to create a definitive comparison of these options. Instead, it served to highlight areas for improvement and inherent limitations in the comparison process.

Data for wind came from workshops with turbine manufacturers and operators, as well as review of the extensive environmental literature related to wind turbines. Biomass data was gathered through workshops with power plant supervisors and biomass providers, as well as limited literature review. Wave data was based on experimental designs, and so
depended largely on interviews and workshops with researchers directly involved in the design process.

**Nature of the Energy Source**

There are three main types of renewable electricity generation. Combustion-based electricity generation relies on the combustion of a mined or harvested fuel as an energy source. Nuclear generation systems also depend on the energy released from the nuclear fission of uranium. Non-combustion electricity generation rely on energy sources that are provided by the natural environment. Woodchip biomass is a combustion-based technology, while wind and wave are non-combustion.

**Current Capacity**

Another variable that was taken into account was the current installed capacity of the renewable energy technologies. Currently, wind energy and biomass energy have a large amount of installed capacity, while the type of wave power studied is still in the experimental stages.

**Table 2.2. Criteria used to choose renewable technologies for pilot**

<table>
<thead>
<tr>
<th>Question</th>
<th>Onshore Wind</th>
<th>Wave</th>
<th>Woodchip Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion/Non-Combustion</td>
<td>Non Combustion</td>
<td>Non Combustion</td>
<td>Combustion</td>
</tr>
<tr>
<td>Current Capacity&lt;sup&gt;3&lt;/sup&gt;</td>
<td>1.4 TWh</td>
<td>Negligible</td>
<td>50 TWh&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Theoretical Potential</td>
<td>29 TWh</td>
<td>15-20 TWh</td>
<td>8.8 TWh</td>
</tr>
<tr>
<td>Ease of Data Collection&lt;sup&gt;5&lt;/sup&gt;</td>
<td>Easy</td>
<td>Difficult</td>
<td>Difficult</td>
</tr>
</tbody>
</table>

3 Figures for installed capacity and theoretical potential refer to Sweden. Data comes from (Ebenå, 2007).
4 Includes electricity generation, biofuels, and heating.
5 This is a subjective measure arrived at through literature reviews.
Theoretical Production Potential

For the Swedish region, these three technologies covered a wide range of installation potentials. Although there is research into wave power within the Swedish community, the actual potential for this technology is somewhat limited compared to other nations, specifically Norway. However, it is still close to the potential for wind power, and about twice as large as the sustainable potential for woodchip biomass generation.

Ease of Data Collection

When using a quantitative comparison tool, it is important to address the issues of uncertainty and lack of data. Because the tool should be able to compare renewable electricity technologies that are at different stages of development, a method needed to be designed to compare options with widely varying amounts of available data. In this case, wind power has been studied extensively, biomass electricity has less information available, and wave power has none because the technology is still in the development stage.

2.3.2 Feedback

In order to gain outside feedback, a summary document explaining the first version of GSED’s comparison process was sent to a group of outside advisers. Because the tool was still at an early stage of development, these advisers were chosen based on their experience with the Framework for Strategic Sustainable Development and, in some cases, their work on other decision-support tools. Their feedback was gathered through written comments and unstructured phone interviews. The main topics of discussion focused on the appropriateness of:

- **The tool’s overall framework** (i.e. use of sustainable life cycle assessment, system boundaries, the division of the life cycle stages).

- **The divisions within each sustainability principle** (i.e. metals/minerals and fossil fuels for the first sustainability principle).

- **The analysis process** (general yes or no question followed by comparison between different energy options).

- **The criteria used to analyze energy options.**
3 Results

3.1 Overview

This section presents results arrived at through literature reviews, interviews, and deductive reasoning. It is based on the following structure:

- **Section 3.2**: An overview of the *Guide for Sustainable Energy Decisions* comparison tool that was developed to analyse and prioritize renewable electricity options using the four Sustainability Principles and the Framework for Strategic Sustainable Development. This section includes justification for the key attributes of the GSED tool.

- **Sections 3.3 and 3.4**: The results of pilot testing of the tool, as well as responses from outside experts who were sent a document explaining GSED’s criteria, comparison process, and overall framework.

3.2 The GSED Tool

3.2.1 Key Attributes

The first research question asked: *What are the key attributes of a comparison tool that prioritizes investment in renewable electricity options using the Framework for Strategic Sustainable Development?*

To explore this question, a pilot comparison tool, the *Guide for Sustainable Energy Decisions (GSED)*, was created through background research, deductive reasoning, and discussions with outside experts. The resulting tool was designed to meet the four key attributes of an effective comparison framework outlined in Section 2.2:

A rigorous comparison tool should include:

- 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 lifecycle into account when analysing electricity generation options; and

• An interface and analysis process that is easy to use, flexible, and accessible to a broad range of stakeholders involved in the planning and implementation of electricity generation projects.

3.2.2 Framework 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 and useful life, and finally to 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 was the ability to compare generation technologies whose impact on the environment came at different points in the product life cycle. For example, a comparison of wind and biomass generation required a tool that takes into account the wind turbine’s major impacts (which mainly occur in the raw materials and production stages) and those of biomass combustion (which are concentrated in the electricity generation stage). LCA allows a side-by-side comparison of these options throughout the life cycle, giving decision-makers an effective tool to compare electricity generation systems.

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 sustainable development. This method is under development, and has been employed by a large chemical production firm to guide strategic product development (Andersson et al. 1998; ICI 2007). 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). The four steps of this process are:

1. **Goal Definition and Scoping**: Define the goal of the LCA, what type of information is needed to reach that goal, and the boundaries of the system being studied.

2. **Life Cycle Inventory**: Identify and collect data necessary to measure the impacts of the product.

3. **Life Cycle Impact Assessment**: Assess the potential environmental and human impacts of the data collected from the life cycle inventory.

4. **Life Cycle Interpretation**: Present the results of the assessment.

(Adapted from ISO 1997; EPA 2006, 2)

### 3.2.3 Goal Description and Scoping

*Goal Description.* The GSED comparison tool was designed as a planning aid with the ability to compare a wide range of electricity generation technologies from a strategic sustainability perspective, while also remaining accessible to stakeholders (see section 3.1.1). In comparison to a traditional life cycle assessment, GSED measured the estimated impacts of emerging sustainability issues in addition to well-understood environmental effects such as global warming and eutrophication. The overall analysis process was therefore similar to the Sustainable Life Cycle Assessment used by Imperial Chemical Industries (ICI 2007; Ny 2006; Andersson et al. 1998). However, there were important modifications made to the SLCA method as well. SLCA was designed as a tool that could be used by specific organizations to get a strategic overview of a product life cycle. This technique could be used early in the design process to identify “hot spots” in the life cycle that warranted further research. For this reason, the analysis process was mostly qualitative in nature. In order to effectively compare electricity generation systems, this process was modified in GSED to include quantitative data and modelling. This made the comparisons more useful to decision-makers, who often prefer environmental decision-
support tools that are backed up by quantitative data (Wrisberg et al. 2002, 66).

In addition, GSED needed to compare significantly different processes in a way that was strategically useful. With this goal in mind, three early design decisions were made to ensure that the tool could be used to compare as many electricity generation technologies as possible. The first decision was to use generic models of electricity generation systems to estimate the average unsustainable impacts of a technology. This approach stood in contrast to many traditional life cycle assessments, which compared the unsustainable impacts of specific, real-world electricity projects (see Ardente 2004; Lenzen 2002; Michaelis 1998; Vestas 2006a). Using actual electricity generation sites as data sources allowed organizations to tailor results to specific products, cut down on uncertainty, and give an assessment academic credibility. These benefits led to a large number of detailed, project specific assessments. However, the focus on specific projects limited the usefulness of these assessments for general decision-making. As a result, a number of generic assessments have been attempted (Gagnon, Belanger, and Uchiyama 2002; Spitzley and Keoleian 2005). In a specific example, Gagnon compared 12 types of electricity generation using generic data that focused on the impact categories of emissions of greenhouse gases, sulphur dioxide, nitrous oxide, direct land requirements, and energy payback ratio (Gagnon, Belanger, and Uchiyama 2002, 1270). These types of assessments were often designed to give policy-makers and energy planners a broad overview of probable environmental impacts (Gagnon, Belanger, and Uchiyama 2002, 1267). When possible, the researchers still collected data for the assessment from real-world projects. However, those projects were chosen because they were representative of an average example of that electricity generation system.

For the GSED tool, a similar method was chosen, which focused on building a general model of an electricity generation system. First, a flowchart showing the types of material/energy inputs and the effects on ecosystems and society were created. Then this diagram was completed by adding quantitative data on materials, energy, and other effects, plus qualitative data on social effects. These estimates came from two sources: site-specific information from previous life cycle assessments, and estimates based on an average expected generation system. The use of a generic model meant that GSED could be used early in the planning process, when site specific data was not available. In addition, it made
comparisons possible between mature technologies such as wind, which have been tested extensively, and 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. Achieving this goal was especially challenging because of the differences between combustion, non-combustion, and nuclear electricity generation (see Spitzley and Keoleian 2005, 8). 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, LCA of these methods only considers 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.

![Standardized life cycles for electricity generation comparisons](image)

*Figure 3.1. Standardized life cycles for electricity generation comparisons*
In order to evaluate these electricity systems in a way that would allow strategic comparisons, 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 the 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. Because these stages were the same for all compared technologies, results could be visualized to show the life cycle stages that had the most serious impacts.

Generic technology models and standard life cycles ensured that both mature and experimental technologies could be compared in a way that could be visualized in a strategically helpful format. In addition to these modifications, it was necessary to standardize assumptions regarding energy and material use. The values that are chosen for these variables, such as the amount of electricity it takes to produce one ton of steel, have a significant effect on the results of a life cycle assessment. For example, in a study of 72 life cycle assessments of wind turbines, differing assumptions in a number of categories caused greenhouse gas potential to vary between 7.9 and 123.7 grams of CO2 equivalent per kilowatt hour (Lenzen and Munksgaard 2002, 346). If the same type of variation were to occur during a comparison of electricity generation systems in GSED, the results could not be effectively compared and the tool’s validity would be called into question. Therefore, an attempt was made to standardize these assumptions within the comparison tool.

**Scope.** 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, were included because of their direct impact on the production process. The question of scope is related to defining the limits of data collection. Choosing these limits is difficult because all processes that make up an electricity generation production life cycle are connected to many other processes by complex linkages. The decision was made to
collect data on the processes, materials, and energy sources used specifically for the chosen technology’s production, use, and disposal. For example, when a wind turbine is being installed, a large construction crane is needed to lift it into place. Within GSED, the data on the diesel fuel in the crane would be collected because the fuel is used specifically in the installation. In contrast, the materials that make up the crane itself would not be considered because they can be used for other purposes.

The other major area of scope definition involved which types of environmental and social impacts to consider with the comparison tool. Traditional life cycle assessments and other environmental measurement tools focus on a limited number of environmental impact categories, such as greenhouse gas emissions and acidification potential (Ny 2006, 68). These impacts are well understood, which allows detailed estimates of the potential impacts of the materials and energy used in a production process. However, the fact that this method focuses only on known environmental problems constrains a traditional LCA’s usefulness as a tool to compare electricity generation technologies from a strategic sustainability perspective. Many emerging sustainability issues are both dispersed and complex, and a traditional focus on the understood impacts could miss many of these problems.

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 will be discussed further in the impact inventory section.

*Functional Units.* Within the life cycle assessment, a functional unit is the unit of comparison between different alternatives that ensures that the options being compared provide the equivalent level of function or service. In the case of electricity generation, the service to the end consumer is the amount of electricity produced by the chosen system. One type of measurement for this unit is the installed capacity of a generation method. As an example, a wind turbine that has the capacity to produce 2 megawatts of electricity would be compared to an equivalent biomass plant. However, this comparison would be flawed, because intermittent renewable
technologies like wind power only produce an average of 30% of their rated capacity, while systems like biomass and nuclear at near total capacity for a large percentage of the time. For this reason, the functional unit chosen for the GSED tool was based on the actual amount of electricity produced over the estimated lifetime of the generation technology, measured in kilowatt-hours. The effect of this functional unit on the comparison process can be illustrated with a hypothetical comparison of wind and biomass electricity generation. The wind turbine may be expected to last for 20 years and produce at 30% of its capacity, while the biomass plant is expected to produce for 25 years at 80% capacity. Their sustainability impacts would be normalized to the total amount of electricity they produced, which would most likely be higher for the biomass plant. The choice of kilowatt-hours allowed an effective comparison between all types of electricity generation. In addition, it allowed the results to be compared to the majority of electricity system life cycle assessments, since this functional unit is widely used.

3.2.4 Life Cycle Inventory

The first 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. Depending on the specificity of this data, parts or all of the flow diagram are completed. 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: systematically increasing concentrations of materials from the Earth’s crust, systematically increasing concentrations of substances produced in society, systematic physical degradation of the ecosystem, and the systematic undermining of people’s capacity to meet
their own needs. 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 (see Appendix A for details on the analysis of wind power).

These four impact categories are further divided into ten sub-categories, shown in Figure 3.3. 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.

![Figure 3.2. Sustainability impact sub-categories](image)

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 (Azar, Holmberg, and Lindberg 1996). 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 (calculation is based on Azar, Holmberg, and Lindberg, 96). 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. If the electricity was generated from fossil fuels, then it would be included in the Fossil Fuels sub-category).

<table>
<thead>
<tr>
<th>Stage 1: Traditional LCA Inventory</th>
<th>Sustainability Filter Questions</th>
<th>Stage 2: GSED Inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>Does it contribute to violations?</td>
<td>No</td>
</tr>
<tr>
<td>Copper</td>
<td>Copper</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>Iron</td>
<td></td>
</tr>
</tbody>
</table>

*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 (for an overview of all sub-categories and comparison criteria, see Appendix A). At the end of this process, there are two inventories: a Sustainable Inventory made up 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. 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 other hand, a category has a large Unsustainable Impact Inventory, then it is flagged as a potential hot spot that may need more analysis.

3.2.5 Impact Assessment

The impact assessment stage enables comparison of two or more electricity generation systems are compared from a sustainability perspective. All comparisons are based on processes, materials, energy sources, and emissions 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 are important to meeting these guidelines: the choice of criteria, the choice of a reference point for success, and the method used to compare options.

The choice of criteria is influenced heavily by the types of indicators that underlie the comparison process. The majority of sustainability indicators can be divided into three main groups (see Figure 3.3): 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) (Azar, Holmberg, and Lindberg 1996, 90). 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 are 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 (Carlson, Holmgren, and Berndes 1997, 11). 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 related to these issues would include environmental pressure indicators that measure direct emission 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, their usefulness is limited when studying unsustainable impacts whose effects in the

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**Figure 3.4. Sustainability indicators, with examples**

The choice between societal activity and environmental pressure indicators are 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 (Carlson, Holmgren, and Berndes 1997, 11). 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 related to these issues would include environmental pressure indicators that measure direct emission 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, their usefulness is limited when studying unsustainable impacts whose effects in the
biosphere are not well understood. These types of impacts tend to be complex, with dispersed, unpredictable effects (Azar, Holmberg, and Lindberg 1996, 89). 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). This criteria framework causes some impacts to be measured with different criteria types within the same impact category. For instance, NO\textsubscript{x}, a heavily regulated pollutant, is measured using an environmental pressure indicator. In the same category, plastics are measured using a societal activity indicator (plastic produced for the electricity generation system) because of their uncertain dispersal rates and environmental effects.

When sustainability impacts have been measured, decision-makers must be given a Sustainability Reference Point for each indicator to show the ultimate sustainability goal and where the technology being studied currently lies. GSED has three types of Sustainability Reference Points:

- For well understood impacts such as greenhouse gases, the reference point is a level that would stabilize the impact at an optimal level (for instance, stabilization of atmospheric CO2 levels at 450 ppm). However, the decision on what the optimal level should be for a region or specific type of electricity generation is dependent on the context.

- For materials that are both foreign to nature and persistent in the environment, sometimes the goal would be zero (i.e. for the chlorofluorocarbons that damage the ozone layer). In that case, a goal for the electricity generation system would also be zero.

- For other impacts, the amount of production/use that would put human flows in line with natural flows. Again, however, the choice of a reference point for electricity generation is a value-laden decision.

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 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. The two methods considered for GSED focused on either an independent measure of impact severity or relative comparisons to a reference electricity option. In an impact severity comparison process, a scale would measure the impact of a technology based on the distance for the Sustainability Reference Point (Figure 3.5). This method has the advantage of providing clear contrasts between technologies and allowing decision-makers to get an idea of the magnitude of differences between options. However, an effective impact severity-based comparison process would require a degree of consensus on the definition of severe and less severe impacts.

![Figure 3.5. Comparison process focusing on impact severity](image)

For that reason, a comparison process that uses an electricity generation option as a reference point was chosen for GSED. Using this method, a certain technology is chosen as the benchmark, and the other options are rated in comparison to this benchmark (Figure 3.6). This avoids the need to agree on the definition of severity, and builds the comparison around the differences between technologies. Within the comparison tool, this method focuses attention on the differences between electricity generation technologies and can give decision-makers useful guidance on the type of electricity generation to choose.
The entire impact analysis process is pictured below. Within the metals and minerals sub-category, an electricity generation technology is analyzed according to whether it uses metals or minerals that have human flows greater than natural flows. If it does, then it is compared to other electricity options.

Figure 3.7. Comparison Flowchart, Metals and Minerals Sub-Category
3.2.6 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.

<table>
<thead>
<tr>
<th>Avg. Life Span:</th>
<th>System Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Materials from the earth’s crust.</td>
</tr>
<tr>
<td>Raw Materials:</td>
<td>Red</td>
</tr>
<tr>
<td>Production:</td>
<td>Orange</td>
</tr>
<tr>
<td>Use:</td>
<td>Red</td>
</tr>
<tr>
<td>Disposal:</td>
<td>Orange</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No Impact</th>
<th>Better</th>
<th>Same</th>
<th>Worse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>Yellow</td>
<td>Orange</td>
<td>Red</td>
</tr>
</tbody>
</table>

*Figure 3.8 GSED Results Matrix and color explanation*
For instance, if an electricity generation technology uses fossil fuels and scarce metals in the raw materials stage but the impacts are less severe than other options, a yellow is shown in the appropriate section of the matrix. 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.

3.3 Tool Testing

The secondary research question asked:

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

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 results of this process are given below.

3.3.1 Overview of Pilot Technologies

The three electricity generation technologies analyzed during the tool testing phase were wind power, woodchip biomass power, and wave power. Wind power generates electricity by harnessing the kinetic energy of the Earth’s wind currents (Boyle 2004, 244). The vast majority of wind-based electricity generation today is produced by large wind turbines made of steel, concrete, and a variety of synthetic materials. The key sustainability aspects studied for wind power were the energy and materials that go into the production of the turbine, and the fossil fuels that are necessary for transportation.

Woodland biomass supplies electricity through the burning of wood chips within an incinerator (Boyle 2004, 116). The smoke from the burnt wood chips generates heat to produce steam in the pipes running above the incinerator. The steam then passes through a turbine which produces electricity while also outputting heat for a district supply. The main industries involved in the biomass electricity production life cycle are the utility developers, operators and wood chip providers. The key sustainability aspects considered are the metals and fossil fuels used for
operations of the facility, the wood chip supply fossil fuel based transport and land degradation from wood waste via local saw mills.

Wave power is an experimental form of electricity generation that uses a buoy, a linear generator and magnets to generate power. The wave power construction is fastened to a concrete foundation in the bottom of the sea while a rope connects the generator to a buoy that is floating on the surface. Waves make the buoy move upwards while a piston with magnets is moving in the generator. A spring in the bottom of the generator is pulled out when the buoy is moving upwards and pulled back when the wave is on its way down. Because of this, electricity is generated both on the way up and on the way down. The major sustainability aspects that were studied for this type of wave power were the inputs used during production for both the generator and the undersea cables that transfer power to the mainland.

3.3.2 Building General Comparison Models

The first step of the tool testing phase was to compile various wind, wave, and woodchip biomass data sources into general life cycle models. Because these three technologies were at varying levels of technological development, the data for these models was gathered using significantly different methods. Data collection for wind generation, a mature and widespread technology, drew from existing environmental impact and life cycle assessments (Lenzen and Munksgaard 2002; Vestas 2006a; Vestas 2006b; Gagnon, Belanger, and Uchiyama 2002). In addition to this literature review, the full life cycle of common wind turbines was explored through workshops with two private firms. The first workshop, with the wind project developer Vindcompaniet, focused on the use and disposal stages of the turbine (Nicklasson 2008). The second workshop, with the turbine manufacturer Vestas, built off of this information and focused on the raw materials and production stages (Ronde 2008). The integration of the data from these workshops with the existing literature made the wind generation comparison model relatively complete and quantitatively detailed.

In contrast to wind generation, literature reviews for woodchip biomass, which uses waste wood from lumber yards and paper mills as fuel, found a relative lack of existing life cycle assessments. It was therefore difficult to obtain specific data on the lifecycle of the forestry waste used in woodchip
biomass, and, as a result, data collection focused on two workshops in the southern part of Sweden. The first workshop, with an executive at the biomass facility developer Järnforsen, collected data on the life cycle of the biomass fuel, which was included in the use stage (Lonngren 2008). The second workshop, with two employees of the Karlskrona district heating plant, focused on the use and disposal stages (Lund 2008). These workshops provided enough information to build a rough general model of the woodchip biomass life cycle and its sustainability impacts. However, the lack of quantitative data and guidance on the raw materials and production stages (when the electricity generation facility was constructed) hampered efforts to create a full comparison model.

The limiting factor for wave power data collection was a lack of actual generating stations to study. Most wave power technologies are still in the developmental stage (Boyle 2004, 324-330), and there is therefore a lack of test data. As a result, the majority of wave power data were collected through collaboration with the technology developers in Uppsala (Sundberg 2008a; Sundberg 2008b; Sundberg 2008c). This collaboration provided information on the production, use, and disposal stages. Data on raw materials and component production came from a variety of suppliers (Gustavsson 2008; Eriksson 2008; Bröderna 2008). This series of workshops and interviews made the creation of a general model possible. However, the technology was at an early stage of development, so any numerical estimates would be both very general and subject to significant change.

3.3.3 Key Life Cycle Findings for Wind

Because there were a number of previous environmental assessments of wind electricity generation, the results of the wind analysis are given here as an example of a general comparison model. The model was a combination of previous generic wind power LCAs and data gathered about the Swedish market in particular. As expected, the majority of the impacts occurred during the raw materials and production stages of the life cycle. The major raw materials used for the process were aluminium, iron (in the form of steel and cast iron), copper, plastic, fibreglass, wood, and concrete (Vestas 2006a, 16). Materials included in the Unsustainable Impact Inventory included copper and iron (Sustainability Principle 1), as well as plastic, fibreglass, and concrete (Sustainability Principle 2). Aluminium was not included in the inventory because of its extremely low lithosphere
Two types of wood were used in the blades, PEFC sustainable forestry certified birch wood from Finland and balsa wood from Ecuador (Vestas 2006a, 16; Nicklasson 2008). Although there was a general lack of information on the balsa wood, it was flagged as a possible unsustainable impact.

For wind turbines installed in Sweden, raw material extraction and component production often occurred domestically or in nearby Scandinavian nations (Nicklasson 2008). This had a number of important effects on the model assumptions. The first was that, because Sweden and Norway have low amounts of fossil fuel electricity generation, systematic increases in concentration of materials from the Earth’s crust would come disproportionately from transportation. Even so, domestic extraction and production led to lower transportation estimates than the Vestas study, which assumed a worse case scenario of inter-continental shipping (Vestas 2006a, 20).

Some synthetic lubricants and hazardous materials are used for the wind turbine during production. Transportation is also needed in this stage. Vestas has customers in all over the world and the turbines are transported either by boat or trucks. For all production that happens within Scandinavia, it is assumed that there are no direct contributions to Sustainability Principle 4 violations.

In the use stage, the wind turbine must be inspected twice a year and fossil-fuel based transportation is necessary for this process (Nicklasson 2008). During this inspection, oil in the turbines is also changed. In the disposal stage, most of the metals from all the sources are capable of being recycled. 90 percent of the metal counted to be recovered or recycled and the rest is disposed into landfills (Vestas 2006a; Larsson 2008). The metals from the cables can also be recycled but not to make new cables. The plastic is either used for energy extraction or put on landfills. The glass fibre can neither be recycled or reused today and has to be land filled as well (Ronde 2008).

Throughout the wind turbine life cycle, the majority of employees work in Sweden or nearby countries. Because of the high standard of living and strict worker protection laws in these nations, the model assumed that there were no contributions to Sustainability Principle 4 violations. Other issues commonly found in the public discourse, such as bird impacts, noise problems, and aesthetic problems stemming from turbines’ large size were
not considered to be important contributors to violations of the Sustainability Principles.

### 3.3.4 Comparison Results

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.

However, both qualitative and quantitative comparisons of the electricity generation systems were extremely difficult. The biggest reason for this was the general lack of data available for woodchip biomass and wave power. There was enough quantitative data collected for wind power to begin to make an assessment of major unsustainable impacts. However, because GSED’s comparison method is dependent on at least one other electricity generation option, it was not possible to complete a full analysis of wind power or visualize the final results. Despite this limitation, the pilot comparison played a valuable role in finding weaknesses and limitations of the comparison process that would have been difficult to discover without hands-on testing.

### 3.4 Expert Feedback

In addition to the testing process outlined in Section 3.3, a document containing an early version of the tool’s main attributes was sent to nine outside experts. Their feedback was then collected through semi-structured interviews. Interview respondents had expertise in life cycle assessment (Lloyd 2008; Thompson 2008), the Framework for Strategic Sustainable Development (Cook 2008; Dyer 2008; Hallstedt 2008; Kasnet 2008; Lundqvist 2008; Sidowe 2008; Thompson 2008), and energy systems (Svenningson 2008). Feedback was generally very positive and suggested that a complete GSED tool could be useful to decision-makers trying to choose sustainable electricity options. Interviews also revealed possible
areas for improvement in the comparison process, as well as inherent limitations of the chosen method. Common themes from the feedback sessions are outlined below, with representative quotes where appropriate.

### 3.4.2 Areas of Strength

There was a consensus among the surveyed experts that the overall structure of the GSED tool, based on life cycle assessment integrated with the Framework for Strategic Sustainable Development, would give decision-makers useful guidance when choosing between renewable electricity options.

"Using a tool based on a principled definition of sustainability that captures the granular problems of deciding on what type of system to employ in a simple to use model will be a significant value driver in the business case for sustainable solutions. Decision makers can quickly understand the environmental impacts of their potential choices before investing in a large capital expenditure. Understanding the life cycle will ensure the most effective and environmentally friendly source is chosen, significant information in a carbon constrained world. This tool will enable decision makers to understand the cost-benefit of their potential investment and choose the one that will be best for their bottom line while protecting the planet."

(Kasnet 2008)

A number of advisers specifically highlighted the fact that traditional environmental assessments do not evaluate some of the most important impacts that are included in the GSED comparison framework. An example that was mentioned frequently was biomass-based electricity generation and its effect on worldwide deforestation and food shortages. GSED’s focus on this area was seen as a valuable expansion of current practices (Cook 2008; Svenningson 2008).

“Regarding sustainability principle three, this is something that often is missed in LCA today so this is good.”

(Svenningson 2008)
Considering human impacts with Sustainability Principle Four was also seen as a valuable expansion of the scope of traditional life cycle tools. An LCA practitioner had never seen an LCA address human impacts in this way and reacted positively to the results (Lloyd 2008).

“You have areas that life cycle assessment doesn't capture, like [sustainability principle] four, and I think that's extremely valuable.”

(Lloyd 2008)

“Regarding the criteria and indicators, you are heading in the right direction. With more time and research these areas can offer a great value in the field.”

(Cook 2008)

GSED’s presentation of analysis results through a simple, color-coded matrix was seen as another of the tool’s key strengths. The visual presentation could give users a strategic overview of a technology’s impacts without getting lost in the details (Dyer 2008). This result was particularly important in light of past research in Sweden that revealed that, because of data complexity, even environmentally-conscious organizations, used the results of life cycle assessments in only 10% of their decisions. (Zaricksson 1999).

“I really like the break out of the LCA though – seems to capture it all without getting too bogged down, keeping it simple.”

(Dyer 2008)

### 3.4.3 Areas for Improvement

The interviewees had a number of suggestion on how to improve GSED and expand its scope. These fell into three main categories: clarifying the process for handling trade-offs between renewable options, refining the division and explanation of the Sustainability Principles, and expanding the scope of the tool to include recycling, scalability, and the potential for technological innovation.
**Further Work Related to Trade-Offs.** Two experts mentioned the importance of distinguishing how trade-offs should be handled, and how technologies with different but similar impacts should be compared (Lloyd 2008; Thompson 2008). The development process outlined above focused on both criteria and scope of comparison. However it was not clear how these criteria could be most effectively compared with each other (Lloyd 2008).

“Regarding impact analysis, if you are comparing two technologies and they are violating [a sustainability principle] in two different ways, how do you know which one is better? You need quantifiable data to clarify which is same, better, worse.”

(Thompson 2008)

**Refinement of the Comparison Framework.** Another area for improvement was the division of the Sustainability Principles into sub-categories to highlight important impact areas. The sustainable practitioners and LCA experts found that it was important to raise these questions related to the criteria. For instance, one adviser pointed out the need to clarify the term, “Use,” in the tools criteria and indicators. This was brought up due to the need for knowing if materials were being used and disposed of or a form of recycling was performed (Lundqvist 2008). A glossary providing these terms will be developed and to help clarify these issues.

“Regarding [Sustainability Principle Three], you need to include long term productivity. Display impacts of long term land use. Monocultures are not always bad; you can have them effectively working as long as they are not affecting biodiversity areas.”

(Lundqvist 2008)

Another illustration of this issue is shown with the comparison criteria used for the tool’s Scarce Metals and Minerals sub-category. These criteria are mainly based on the assurance that materials are not being used that have man-made flows higher than natural flows, but materials already known to be harmful could be more specifically addressed (Lundqvist 2008).
“Regarding a natural flows comparison, it is good to go with the indicators that ensure you are using lower societal use flows than natural flows BUT, also consider the use of more specifically materials already known to have severe affects to plants and animals.”

(Lundqvist 2008)

**Scalability, Recycling, and Technological Development.** Despite the fact that the GSED tool expands the scope used by the majority of current life cycle assessments, advisers pointed out additional issues that could be addressed. One of these was the issue of scalability, whether a technology can be produced at a large scale in a way that is as feasible and sustainable as small scale production. There is an importance in clearly stating at what degree the electricity generation’s impact will result with respect to the projected production. For instance, although a single wind turbine can be constructed today there needs to be predictions made on the scale of impact for expansion of the electricity generation system. The example was raised with the bio-fuels again; where the concept seemed feasible at a small scale but when increased massive impacts that were previously not considered were then highly significant (Lackner 2008).

“Consider feasibility of resources being used. Include resource scarcity and efficiency to consider if it is capable of being applied at a large scale.”

(Lundqvist 2008)

Recycling was another important issue, mainly because the Sustainability Principles focus on increasing concentrations in the biosphere and recycling in tight technical loops is one of the main strategies to move towards a more sustainable production system. If recycling is included in GSED, then many of the unsustainable impacts may change in surprising ways. For instance, in the initial analysis of wind power, iron (in the form of steel) was included in the Unsustainable Impact Inventory. However, it is important to note that steel, especially the steel used in wind turbines, has a very high rate of recycling (approaching 90%) (Vestas 2006a, 22). The importance of these issues has been recognized for a long time, and traditional life cycle assessments often take them into account. Therefore this is an area where the first version of GSED may have a more limited scope than its traditional LCA counterparts.
Advisers also suggested further research into the role of technological development, and how generation systems that are early in the innovation process (such as wave power) should be treated when compared to mature technologies (such as wind power). If this issue is not taken into consideration, the tool may not encourage sufficient investment in innovative solutions that are early in the development process (Dyer 2008).

### 3.4.4 Inherent Limitations

Because the comparison framework is based on generic, quantitative models of electricity generation technologies, an adviser with expertise with LCA-based tools raised the issue of data collection (Lloyd 2008). Data that is integrated into the framework’s design is essential because without it, users may make their best guess at what the data is and come out with a poor result. However, the amount of data that is available varies a great deal between mature technologies and experimental designs. Though steps can be taken to build data sets that are equivalent for these two types of technology, there is always a limitation to how effective comparisons using these ideas would be.

“*One concern is where you get your data; once you make the comparisons, there are a lot of data requirements. The user might not be able to answer the questions because of data constraints.*”

(Lloyd 2008)
4 Discussion

4.1 Research Validity

The research benefited from an iterative development process that used lessons learned from outside feedback and tool testing to continuously improve the GSED tool’s attributes. The results presented here are therefore the culmination of a number of outside influences and internal decisions. This situation allowed the research team to effectively incorporate new ideas and improve the tool.

One of the study’s major weaknesses was the lack of a fully functional version of the GSED tool. Without a working tool, it was difficult to effectively test the usefulness and accessibility of the comparison framework. In the past, tools using the FSSD have been created and tested with participants in a research setting (see Dyer, Mckay, and Mira 2006). In many cases, these tools have focused on qualitative capacity building, and could therefore be built and tested in a relatively short time. The GSED tool, in contrast, required quantitative data, as well as decisions on how that data would be weighted, to become a fully functional tool. This was difficult to accomplish in the research period, and so conclusions related to the usefulness and accessibility of the tool are preliminary.

4.2 Meeting the Success Criteria

The goal of this study was to build off of past research on electricity generation, decision-making, and sustainability to create a decision-support tool that could give clear guidance on the most effective options to move the electricity generation system towards sustainability. To build an effective and accessible tool, four critical success criteria were synthesized to guide development and testing. The first version of the tool was expected to have weaknesses, gaps, and limitations that could be addressed through further research and development. Therefore, the success criteria served as benchmarks to ensure that whatever the pilot tool’s shortcomings, it would provide a solid foundation for improvement and application in the electricity generation industry.
4.2.1 Whole-Systems Perspective

The first success criterion focused on the need for a rigorous whole-systems perspective using a scientifically principled definition of sustainability as a strategic compass. The integration of LCA and FSSD expanded the scope of the analysis and successfully gave GSED this important whole-systems perspective. The criteria areas of the GSED were built around this explanation of total-systems sustainability; defined through four Sustainability Principles. This format combined major benefits of a number of assessment tools, and could allow decision-makers to avoid costly, dead-end investments in certain methods of electricity generation.

4.2.2 Ability to Compare a Wide Range of Options

The second criterion focused on the ability to compare electricity generation systems with different energy sources, costs structures, and levels of development. A number of decisions revolved around the goal of meeting this criterion, including the standardization of life cycle stages and material/energy assumptions and the use of generic models that could theoretically be built for even experimental technologies. The above attributes expanded the possible scope of the tool, and its general ability to compare all types of renewable electricity generation was backed up by tool testing and expert feedback. The main challenge in this area related to the validity of comparing technologies with large differences in the amount and quality of available data.

4.2.3 Full Life Cycle Perspective

Third, the tool was expected to have an analysis framework that takes the entire life cycle into account when analysing electricity generation options. This was the easiest criterion to meet due to the extensive literature on life cycle assessment for electricity generation and past work on integrating the FSSD into this extremely powerful tool. The choice of scope and the integration of life cycle thinking in GSED were found to be effective ways to compare the most important impacts related to each generation technology.
4.2.4 Ease of Use, Flexibility, and Accessibility

The fourth criterion focused on the need for an interface and analysis process that is easy to use, flexible, and accessible to a broad range of stakeholders involved in the planning and implementation of electricity generation projects. From the project team’s work in the field, the results found that the current framework has been capable of benefiting the electricity generation field in two separate areas; one being the investor and consultant and the other being the technology developer and operator. The investors and consultant can apply GSED as a guide towards the most sustainable electricity investment and the technology developers and operators can apply the GSED to their current operations to discover unsustainable practices and possible areas of improvement. In addition, the presentation of comparison results appeared to be clear and easily accessible.

The validity of these positive findings for the final success criterion are weaker than the others, because the belief that this tool meets the minimum requirements is the opinion of FSSD, LCA, and other experts, but not any stakeholders or decision-makers that would be most likely to use the tool to make the decision. This is due in large part to the early stage of development of the tool and the fact that a working prototype has not yet been created.

4.3 Areas for Improvement

4.3.1 Guidance on Trade-Offs

The issue of trade-offs is central to decision-making; however GSED’s design brought up new and interesting permutations of this problem. This was especially clear in discussions related to the FSSD, which emphasizes the use of a shared language to decide between possible trade-offs. In this sense, the GSED tool may be used as only the first step in a process to decide between trade-offs within a group of decision-makers. However, it needs to be acknowledged that in the past, this type of consensus building was done after an interactive meeting with the participating organization. A number of firms and municipalities used this method successfully to create and implement sustainability plans. The process involved personal
interaction, training of a large number of participants, and the creation of solutions built from the knowledge of people within the industries.

In contrast, \textit{GSED} does not explicitly go through this process, making it more difficult to successfully communicate the thinking behind the FSSD. The four Sustainability Principles, along with the FSSD in general, do not necessarily conform to the types of analysis that decision-makers use regularly. For instance, in the analysis of wind power, steel was flagged as a possible unsustainable impact. This could be a strange, possibly debatable concept for many users. This raises the question of the most effective method to deal with these problems, and what role \textit{GSED} should play. The assumption coming into the research was that the tool would play a part in prioritizing investment in renewable options. However, a related question was not answered: how much of the decision process should be internalized in the tool itself? It will be interesting if further research can discover ways to effectively communicate and build sustainability planning capacity through an interactive tool such as \textit{GSED}.

4.3.2 Clarity Regarding the Sustainability Principles

It was a challenge to ensure that the presentation of the Sustainability Principles was both scientifically-sound and clear to users unfamiliar with FSSD. The implications of contributing to the root causes of sustainability had to be explained in a way that made it easy for decision-makers to understand the issues involved and also build their capacity to emerging unsustainable impacts that might arise with new designs or experimental technologies. Therefore, many of the terms applied to the Sustainability Principles are in a continual process of revision to meet these two goals. Definitions for terms such as, “Structural Power Abuse,” and “Nature-Like Materials,” need to be presented in a clear and concise language applicable to the practitioner who would be using the tool in the field. With the limits of the current research, these terms are still not complete in definition. The indicators addressing the Power Abuse Areas were more specifically raised as a challenge. It is not clear whether quantifiable or qualitative data should be used to measure these types of impacts. More research is necessary to answer these questions.
4.3.3 Additional Areas to Consider

Recycling, technological innovation, and scalability were areas that were overlooked in the initial design of *GSED*, but that need to be seriously considered in future versions. The inclusion of recycling gives users a clearer understanding not just about which materials are used, but also the likelihood of their emission into the biosphere where they can increase in concentration. In theory, human society can mine materials at a much faster rate than they are absorbed by the environment as long as they are kept in tight technical loops within society. The feasibility of this solution is unclear; however, it is important to include these questions in the comparison to increase the options available to move towards a sustainable electricity system.

Including possible technological innovation and scalability concerns in the comparison process would help give users a way of comparing the *future* potential of different options. It could also avoid serious environmental and social consequences stemming from overinvestment in technologies with limits to potential capacity (i.e. biomass) and myopic focus on a slightly cheaper option that has much less overall potential than a slightly more expensive, but technologically dynamic alternative.

4.4 Inherent Limitations

In general, the inherent limitations of the *GSED* tool relate to issues that are common to decision-making in general. Although these problems do limit the scope and usefulness of the tool, they are also useful limits in which to build strategically effective guidance for decision-makers. The possible difficulty of data collection, especially for experimental technologies and unsustainable impacts such as deforestation and the weakening of the social fabric, posed a significant challenge. This issue has been discussed at length by others in the field, and constrains the quantitative nature of the tool (Lundqvist and Holmberg, 2000, 13). On the other hand, it can be argued that access to too much data, from numerous sources, can lead to confusion, decision paralysis, and the loss of the big picture. So while the challenge of data collection can be seen as limiting, it is also useful to remember that using a whole-systems, less detailed perspective can lead to strategic insight and is compatible with the FSSD.
Because investment in a new, renewable electricity system is such a high priority, another major goal of GSED’s next version is to ensure that it does not become another procedural hurdle that slows down the critical transition to a sustainable energy system. By showing a clear assessment comparing the current unsustainable options to the renewable ones, the tool will present a case for the environment, business, and society as a whole.
5 Conclusion

The environmental sustainability challenge makes effective strategic planning extremely important, both for society as a whole and the electricity generation system in particular. To transition to a sustainable electricity system, rigorous and accessible decision-support tools are necessary. This study first found gaps in the current decision-making process related to a lack of a whole systems perspective, availability of comparison criteria, and a strategic overview. In response to this background research, the thesis team created the first research question:

**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?

The GSED tool was designed as a pilot project to test how the FSSD could be used to create a tool with a whole-systems view that would be easy to use and able to compare a variety of renewable electricity generation technologies. These success criteria were used to guide decisions related to the goal and scope, inventory process, and basic impact assessment framework.

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

Testing, feedback, and discussion confirmed that GSED successfully met the key success criteria for this type of tool and could be a useful decision aide for a wide variety of stakeholders. It also highlighted areas of improvement that could be used as leverage points to make the tool more effective, accessible, and rigorous.

5.1 Next Steps

The preliminary GSED comparison tool developed in this study has the potential to be turned into a functional decision-support program for a sustainable electricity system. The main focus on this thesis was the framework and decision tree connected with the analysis portion of the tool. In order to create a fully functioning version, a number of further sections
will need to be developed. A few areas that are important to reach this goal include:

*A clear, e-learning explanation of the FSSD.* To use the *GSED* tool effectively, decision-makers will have to have a clear understanding of the Framework for Strategic Sustainable Development. This will require a step-by-step explanation of the scientific foundations, principles, and implementation of the framework. In the context of a software tool, this goal can most likely be met by creating an electronic learning module within *GSED* to build an understanding of the framework. A clear integrated explanation of these concepts is especially important because not all users of the tool will be familiar with the framework or have access to facilitators from the relevant non-profit organizations. In the past, the FSSD has been used in a qualitative way to assist decision-makers trying to make choices in their own specific organizations. In contrast, this tool has been designed to be general and useable in many different situations.

*Guide Sheets.* The way that impacts will be measured in a full *GSED* tool will be different than most environmental practitioners and life cycle assessment leaders are used to. An extensive, well-researched explanation of the rationale for this method must be provided to users to increase buy-in and give them the tools to get effective results.

*A Method to Weight Impact Areas.* Since in reality only a few criteria are usually used in decisions, users need the ability to include their own weightings and make the analysis useful for them. This will involve interactive tools to let the user make decisions on the relative weights on the basis of the three prioritization questions (right direction, flexible platform, positive return on investment). For example, many decision-makers will be most interested in an electricity generation system’s effect on greenhouse gases.

### 5.1.1 Integration with Existing Tools

A number of outside advisers suggested that the *GSED* tool could be very effective if it was integrated with current decision-support tools that focus on project feasibility, energy modelling, and return on investment. In this way, the sustainability impacts of renewable technologies could be included in the existing decision-making process in a way that would be easier to understand. The ultimate goal would be the creation of an integrated decision-making platform that would allow users to consider economic,
technical, social, and ecological comparison criteria when choosing between renewable electricity options.

5.2 Final Thoughts

“If I have seen further, it is by standing on the shoulders of giants”

- Isaac Newton

This study is built on the work of the creators of the Framework for Strategic Sustainable Development and the experts who have built an extensive body of knowledge about energy systems over the past 30 years. The authors see this thesis as a small contribution to these fields. If this study is able to give concerned stakeholders in the electricity generation industry the beginnings of an effective decision-support tool to choose between renewable electricity options, then it will be considered a success. Hopefully, this is the first step in a larger research process that will contribute to society’s movement to a sustainable and equitable electricity generation system.
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Ronde, Klaus, Engineer, Vestas Energy. Interview by authors, April 11, workshop.


Sindowe, Benny, Human Resources Officer, Zesco Ltd. 2008. Interview by authors, April 18, phone interview.

Sundberg, Jan, Project Coordinator, Wave Power, Ångströmslaboriet. 2008a. Interview by authors, January 24, phone interview.

Sundberg, Jan, Project Coordinator, Wave Power, Ångströmslaboriet. 2008b. Interview by authors, April 4, in-person workshop.

Sundberg, Jan, Project Coordinator, Wave Power, Ångströmslaboriet. 2008c. Interview by authors, April 17, phone interview.

Svenningson, Per, Lund Institute of Technology. 2008. Interview by authors, May 2, phone interview.


Tellenius, Björn, Special Adviser, Swedish Energy Department. 2008. Interview by authors, April 22, phone interview.

Thompson, Tony, PhD Student, Sustainable Product Innovation, Blekinge Institute of Technology. 2008. Interview by authors, April 29, in-person interview.


Widstrand, Susanna, Energy Technique Department, Swedish Energy Agency. Interview by authors, April 21, phone interview.


Örtenvik, Mattias, Environmental Manager, E.on Energy. 2008. Interview by authors, April 22, survey response.
Appendix A: Analysis of Wind Power

**Sustainability Principle 1:** Does the electricity generation method contribute to a systematically increasing concentration of substances from the earth's crust in nature…

<table>
<thead>
<tr>
<th>Question</th>
<th>Comparison Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>...through the use of <strong>scarce metals and other minerals</strong>?</td>
<td>Averaged severity for all metals used in the process.</td>
</tr>
<tr>
<td>...through the use and combustion of <strong>fossil fuels</strong>?</td>
<td>Amount of fossil fuels used.</td>
</tr>
</tbody>
</table>

**System Condition 2:** …contribute to a systematically increasing concentration of substances from society…

<table>
<thead>
<tr>
<th>Question</th>
<th>Comparison Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>...through the use of <strong>materials foreign to nature</strong>?</td>
<td>Amount of man-made materials that are foreign to nature.</td>
</tr>
<tr>
<td>...through the overproduction and use of <strong>nature-like materials</strong>?</td>
<td>Amount of man-made materials that fit criteria.</td>
</tr>
</tbody>
</table>

**System Condition 3:** …contribute to a systematically increasing degradation of the biosphere…

<table>
<thead>
<tr>
<th>Question</th>
<th>Comparison Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>...through the <strong>over-harvesting of natural resources</strong>?</td>
<td>Amount of natural resource over-harvesting.</td>
</tr>
<tr>
<td>...through the use of <strong>monocultures and loss of biodiversity</strong>?</td>
<td>Amount of monoculture use.</td>
</tr>
<tr>
<td>…through <strong>land use changes</strong>?</td>
<td>Amount of land use changes in sensitive areas</td>
</tr>
</tbody>
</table>

**System Condition 4:** Within this stage of the life cycle, does the electricity method contribute to the systematic undermining of people’s capacity to meet their own needs…

<table>
<thead>
<tr>
<th>Question</th>
<th>Comparison Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>...through the <strong>abuse of political power</strong>?</td>
<td>Qualitative assessment of political power abuse.</td>
</tr>
<tr>
<td>...through the <strong>abuse of economic power</strong>?</td>
<td>Qualitative assessment of economic power abuse.</td>
</tr>
<tr>
<td>…through the <strong>abuse of structural/environmental power</strong>?</td>
<td>Qualitative assessment of the severity of structural power abuse.</td>
</tr>
<tr>
<td>Raw Materials Stage</td>
<td>Yes/No</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td><strong>Sustainability Principle 1:</strong> Systematically increasing concentration of substances from the earth's crust in nature…</td>
<td></td>
</tr>
<tr>
<td>…through the use of <strong>scarce metals and other minerals</strong>?</td>
<td>Yes</td>
</tr>
<tr>
<td>…through the use and combustion of <strong>fossil fuels</strong>?</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Sustainability Principle 2:</strong> Systematically increasing concentration of substances from society…</td>
<td></td>
</tr>
<tr>
<td>…through the production and use of <strong>materials foreign to nature</strong>?</td>
<td>Yes</td>
</tr>
<tr>
<td>…through the overproduction and use of <strong>nature-like materials</strong>?</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Sustainability Principle 3:</strong> Systematically increasing degradation of the biosphere…</td>
<td></td>
</tr>
<tr>
<td>…through the <strong>over-harvesting of natural resources</strong>?</td>
<td>No</td>
</tr>
<tr>
<td>…through the use of <strong>monocultures and loss of biodiversity</strong>?</td>
<td>No</td>
</tr>
<tr>
<td>…through <strong>land use changes</strong>?</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Sustainability Principle 4:</strong> Systematic undermining of people’s capacity to meet their own needs…</td>
<td></td>
</tr>
<tr>
<td>…through the <strong>abuse of political power</strong>?</td>
<td>No</td>
</tr>
<tr>
<td>…through the <strong>abuse of economic power</strong>?</td>
<td>No</td>
</tr>
<tr>
<td>…through the <strong>abuse of structural/environmental power</strong>?</td>
<td>No</td>
</tr>
<tr>
<td>Title:</td>
<td>Wind Power</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>Electricity Capacity:</td>
<td>1.6 MW</td>
</tr>
<tr>
<td>Avg. Life Span:</td>
<td>20 years</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Life Cycle Stages</th>
<th>Raw Materials</th>
<th>Man-made materials.</th>
<th>Degradation of biosphere.</th>
<th>Undermining capacity to meet human needs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
</tr>
<tr>
<td>Production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disposal</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Appendix B: Example of GSED Glossary

**Biodiversity:** The variation of life forms within an ecosystem, biome, or the entire Earth.

**Economic Power Abuse:** Manipulation of the economic system in such a way that benefits an organization at the expense of others' ability to meet their needs. This can be through channels such as unbalanced trade agreements or withholding funding needed for a project’s success.

**Ecosystem Manipulation:** Any change occurring within an ecosystem that is capable of undermining the ecosystem’s natural cycles.

**Environmental Power Abuse:** Misplacement of individuals or groups in spaces that are structured in a way that undermines their capacity to meet their own needs. This can manifest through the removal of green spaces, provisions of un-ergonomic work stations, or the creation of hazardous working or living conditions.

**Fossil Fuels:** Hydrocarbons extracted from the lithosphere by society to operate as a fuel source. Main types of forms being used: Oil, Gas and Coal.

**Lithosphere extraction indicator:** to measure the extracted rate of the elements divide with the rate of natural supply coming from weathering and volcano. The higher rate compared to the natural sedimentation the higher is the accumulation in the ecosphere.

**Man-made materials:** Materials foreign to nature and nature-like materials

**Materials Foreign to Nature:** Human-made substances that are unknown to nature and therefore are not capable of being assimilated into natural cycles.

**Monocultures:** The practice of producing or growing one single crop over a wide area thus leading to reduction of biodiversity within the ecosystem.

**Natural Resource Harvesting:** The extraction of resources provided by nature within the biosphere.
**Nature-Like Materials:** Substances based from materials in nature that are being emitted into the ecosystem at a rate faster than they can be reintegrated into natural cycles. (TNS Canada SC2 Doc)

**Political Power Abuse:** The misuse or exploitation of any position of authority. This can come in the form of governmental or organizational leadership that enact policies or regulations which (intentionally or not) disenfranchise some group or cause.

**Scarce metals and minerals:** Metals and minerals society has extracted from the lithosphere into the biosphere at a faster rate than they are naturally returned into the lithosphere.

**Sensitive Ecosystem:** An ecosystem at-risk or ecologically fragile in the provincial landscape. A highly sensitive ecosystem is listed as extirpated, endangered, or threatened.
## Appendix C: Exploratory Interviews

<table>
<thead>
<tr>
<th>Name, Position</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>David De Jager, Consultant</td>
<td>Ecofys, Sustainable Energy Consulting Firm</td>
</tr>
<tr>
<td>Tad Mason, CEO</td>
<td>TSS Consultant, Renewable Energy Consulting Firm</td>
</tr>
<tr>
<td>Jesse Gossett, Consultant</td>
<td>Emergent Energy Group, Renewable Energy Consulting Firm</td>
</tr>
<tr>
<td>Alexander Lackner, Consultant</td>
<td>Concurrent Technologies Corporation, Sustainability Consulting Firm</td>
</tr>
<tr>
<td>Charlie Heaps, Software Developer</td>
<td>LEAP, Energy Planning Software</td>
</tr>
<tr>
<td>Kevin Bourque, Software Developer</td>
<td>RET Screen, Renewable Energy Developers</td>
</tr>
<tr>
<td>Conny Hägg, Senior Adviser</td>
<td>Swedish Ministry of the Environment</td>
</tr>
<tr>
<td>Björn Tellenius, Special Adviser</td>
<td>Swedish Energy Agency</td>
</tr>
<tr>
<td>Erik Dahlström, Manager</td>
<td>Swedish Energy Agency</td>
</tr>
<tr>
<td>Tobias Persson, Analyst</td>
<td>Swedish Energy Agency</td>
</tr>
<tr>
<td>Susanna Widstand, Adviser</td>
<td>Swedish Energy Agency</td>
</tr>
</tbody>
</table>
## Appendix D: Workshop Participants

<table>
<thead>
<tr>
<th>Name, Position</th>
<th>Company, Role in Electricity Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paul Riyke, Facility Manager; Mikael Lund, Facility Administrator</td>
<td>Gullberna Park, Woodland Biomass Districty Heating Facility</td>
</tr>
<tr>
<td>Fredrik Lönngren, Development Planner</td>
<td>Janforsen, Woodland Biomass Facility Developer</td>
</tr>
<tr>
<td>Klaus Rønde, Safety and Environment Engineer</td>
<td>Vestas, Wind Power Developer</td>
</tr>
<tr>
<td>Staffan Niklasson, Project Management</td>
<td>Vindcompaniet, Wind Power Provider</td>
</tr>
<tr>
<td>Jan Sundberg, Developer</td>
<td>Division of Electricity and Lighting Research, Wave Power Developer</td>
</tr>
</tbody>
</table>
## Appendix E: Feedback Interviews

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>David Cook</td>
<td>Executive Director, The Natural Step International</td>
</tr>
<tr>
<td>Archie Kasnett</td>
<td>Sustainability Practitioner, Aedi Group</td>
</tr>
<tr>
<td>Benny Sindowe</td>
<td>Principal HR Officer, ZESCO Electricity</td>
</tr>
<tr>
<td>Ulrika Lundqvist</td>
<td>Professor of Energy and Environment, Chalmers University</td>
</tr>
<tr>
<td>Shannon Lloyd</td>
<td>LCA Practitioner, Concurrent Technologies Corporation</td>
</tr>
<tr>
<td>Tony Thompson</td>
<td>Sustainability PhD Student/Research, Blekinge Institute of Technology</td>
</tr>
<tr>
<td>Per Svenningsson</td>
<td>Professor of Environmental and Energy Systems Studies, Lund University</td>
</tr>
<tr>
<td>Sophie Hallstedt</td>
<td>PhD in Sustainable Product Development, Blekinge Institute of Technology</td>
</tr>
<tr>
<td>Georges Dyer</td>
<td>Sustainability Practitioner, Greenland Enterprises</td>
</tr>
</tbody>
</table>