LIFE CYCLE ASSESSMENT OF SOLAR UPDRAFT TOWER POWER PLANT: EROEI AND GWP AS A DESIGN TOOL

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

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Ikramuddin Ahmed, Committee Chair

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David Koert, Committee Member

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Glyn Rimmington, Committee Member

DEDICATION

To my wife, children and friends

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ABSTRACT

The Solar Updraft Tower Power Plant (SUTPP) is a simple proven concept capable of producing power from sunlight with relatively little complexity and few moving parts. Unfortunately, it requires a large investment to build huge greenhouse-like collector to feed heated air into a very tall chimney, where it rises due to natural convection and spins turbo-generators that provide electric power. Substantial research has gone into understanding its physics, modeling its performance, and optimizing its fundamental design aspects. Economic analyses indicate it is feasible, proposals have been made, and the proposal for the first commercial plant has been floated. This thesis considers a few well researched configurations, and examines their environmental impacts (via a Life Cycle Assessment) of Global Warming Potential (GWP), and Energy Returned On Energy Invested (EROEI), including some of the practical aspects of building and operating a SUTPP. The best glass SUTPP studied had an EROEI of 7, comparable to photovoltaic power generation. Use of ethylene tetrafluoroethylene (ETFE) raised that to 14, approaching wind power (18), and permitted an EROEI of 10 for an airflow regulated SUTPP capable of baseload power or of shifting some generation to peak demand times. The collector was the largest contributor to life cycle impacts. Sites with risk of damaging hail should be avoided. Glass and ETFE offer favorable combinations of durability and recyclability. Evidence is cited suggesting the collector needs a cleaning system. Design strategies to facilitate cleaning and employ ETFE are discussed. Areas requiring further research have been identified and recommendations have been provided, along with the most promising SUTPP configurations based upon this research.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

Chapter Page

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF TABLES (continued)

LIST OF TABLES (continued)

LIST OF TABLES (continued)

Table Page

LIST OF FIGURES

LIST OF PLATES

Plate Page

LIST OF ABBREVIATIONS / NOMENCLATURE

ASUTPP	Airflow Regulated Solar Updraft Tower Power Plant
BSUTPP	Baseline Solar Updraft Tower Power Plant
CO_2	Carbon Dioxide
cm	centimeter
EE	Embodied Energy
EROEI	Energy Returned on Energy Invested
ESRR	Economical Sustainable Robust Resilient
ETFE	Ethylene tetrafluoroethylene
ft	foot, feet
GJ	GigaJoule
GWh	Gigawatt Hour
GWh/y	Gigawatt Hours per Annum (year)
GWP	Global Warming Potential
GWP100	Global Warming Potential over 100 years (relative to CO_2)
in	inch
ISO	International Standards Organization
J	Joule
kg	Kilogram
km	kilometer
kWh	Kilowatt Hour

LIST OF ABBREVIATIONS / NOMENCLATURE (continued)

kWh/m^2	Kilowatt Hour per Square Meter
$kWh/(m^2y)$	Kilowatt Hour per Square Meter per Year
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m	meter
MJ	MegaJoule
mm	millimeter
MPH	Miles per Hour
MWh	Megawatt Hour
MWh/y	Megawatt Hours per Annum (year)
N	Newtons
psf	Pounds per Square Foot
RSS	(Square) Root of Sum of Squares
SCPP	Solar Chimney Power Plant
SUTPP	Solar Updraft Tower Power Plant
t	ton SI (1,000 kg)
t CO_2 Eq	ton CO_2 Equivalent
UV	Ultraviolet
WSUTPP	Water Storage Solar Updraft Tower Power Plant

LIST OF SYMBOLS

ρ	Density
°C	Degrees Centigrade
°F	Degrees Fahrenheit
(K)	Degrees Kelvin

CHAPTER 1

INTRODUCTION

Finite resources and fossil fuel supplies, along with concerns over anthropogenic (human caused) degradation of the ecosphere and climate change necessitate the development of reliable renewable power plants. Section 1.1 describes a Solar Updraft Tower Power Plant (SUTPP), a unique design that converts solar radiation into wind energy by employing natural thermal convection. Section 1.2 describes the contribution of this thesis to the potential development of SUTPPs and Section 1.3 outlines the contents of this thesis.

1.1 Solar Updraft Tower Power Plants

A solar Updraft Tower Power Plant (SUTPP), also known as a Solar Chimney Power Plant (SCPP), as illustrated in Figure 1.1, consists of a large transparent canopy "collector" that heats air below it much like a greenhouse, making the air less dense and buoyant, so it rises through a central "tower" or "chimney." A turbine or array of turbines are used to extract power from the rising air to produce electrical power. The ground under the collector is also heated and becomes warmer over time, allowing it to act as "thermal storage" releasing heat into the air at night, thereby maintaining some airflow and power production at night [1]. "Thermal storage" can be increased by trapping heat energy in "thermal mass" such as water sealed in black containers that more efficiently absorb and release energy to even out power production somewhat throughout a 24-hour cycle as illustrated in Figure 1.2.

The tower height provides the potential distance through which heated air buoyancy can act, whereas the collector provides a volumetric rate of heated air to provide the flow. The flow times the distance it acts through equals the potential power output of the power plant.

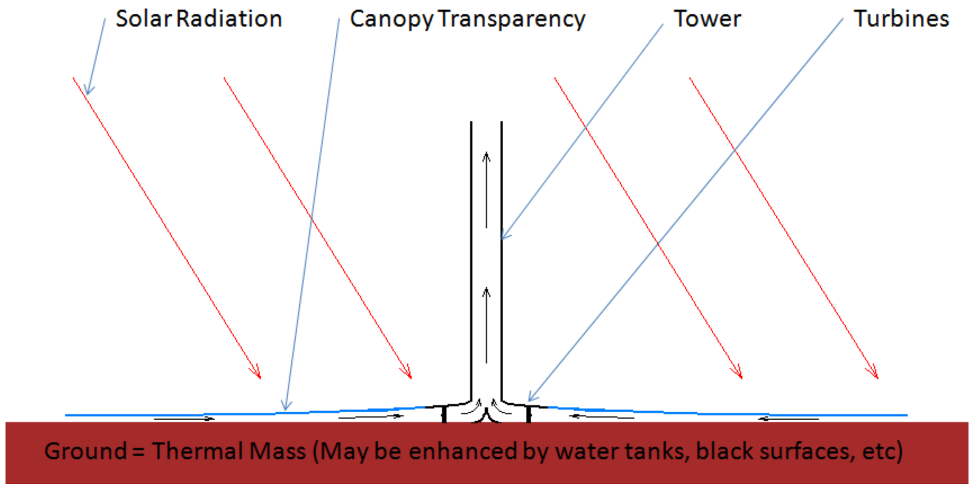

Figure 1.1. Solar updraft tower principle.

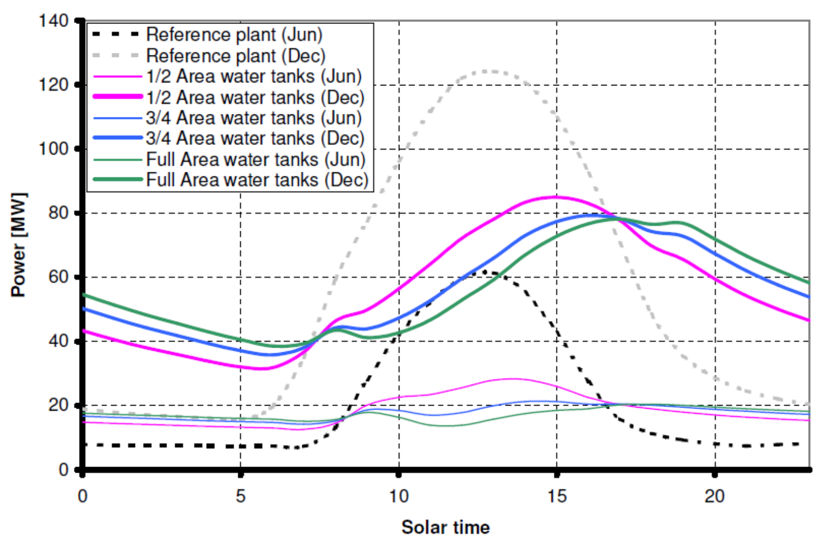

Figure 1.2. Effect of different amounts of water-thermal mass storage under collector (Pretorius, used with permission [2]).

Some variations from the basic design include:

- A sloped collector, that may be on a mountainside (Bilgen and Rheault [3]) (Panse et al. [4]) (Wei et al. [5]) (Zhou [6]), using a mountain to support a chimney (Proposed by Bernard Dubos in 1926, documented by Willy Ley in "Engineer's Dream" in 1954 [7]), (Serag [8]), or a manmade tunnel in a mountain used as a chimney (Zhou et al. [9]).

- Locating the turbine elsewhere in the tower or design (Gunther [10]) (Padki and Sherif [11]), multiple turbines around the base of the tower (Schlaich et al. [12]), and counter-rotating turbines (Denantes and Bilgen [13]).
- A "floating", lighter than air tower, or methods to create a vortex to act like a tower (Papageorgiou [14] [15] [16] [17]), or tower extension (Zhou and Yang [18]) (These cost saving ideas raise significant feasibility and safety issues.)
- Thermal storage in water (Kreetz [19]), soil or rock (Zheng et al. [20]) (Hurtado et al. [21]) (Pretorius [2]), or a vertical paraffin collector (Zhou et al. [22]).
- Other materials besides concrete for the tower (Castillo [23]) or glass for the collector (Smith for EnviroMission [24]), and the effects of glass with different characteristics and coatings (Pretorius [2]).
- Optimization of the collector roof shape (Pretorius [2]), turbine inlet and outlet geometry (Gannon [25]), and using tower supports as pre-whirl Inlet guide vanes (Gannon [25]).
- A collector consisting of many constant ceiling height East-West oriented canopy fingers feeding airflow duct veins that form a branched network converging at the tower. This greatly increases inlet perimeter, decreases internal wind speed and friction and permits use of North-South oriented ceiling vaults (parallel to airflow) that capture more solar energy near sunrise and sunset (Bonnelle [26]).
- Combining a SUTPP with other facilities, such as releasing heat from a power plant into the tower base (Zandian and Ashjaee [27]) or a desalination plant (Zhou et al. [28]).

The advantages and disadvantages of SUTPPs discussed by Schlaich [1], Gannon [25] and Pretorius [2] are paraphrased below.

Advantages:

1. The collector uses all direct and diffuse solar radiation, providing reduced power production on cloudy days.
2. The soil under the collector provides natural heat storage that keeps the updraft and limited power production going at night. This can be enhanced by placing additional thermal storage, such as tubes or bags of water under the collector to absorb more heat during the day to be released at night, to even out power production more over a 24 hour day to provide base load power. The gradual storage and release of energy avoids power spikes associated with wind energy, which increases turbine and generator life.
3. Solar updraft towers consist of simple robust structures, with turbines and generators exposed to slowly varying wind being the principal moving parts, resulting in a simple, highly reliable power plant requiring minimal maintenance, expected to provide a long operating life (possibly 80-100 years).
4. Unlike conventional power stations (and also some other solar-thermal power station types), solar updraft towers do not need cooling water.
5. The building materials needed for solar updraft towers, mainly concrete and glass, are widely available. They may even be available or producible onsite. These plants can be built today, in almost any country, without need for high tech parts and manufacturing, using local labor and currency.

Disadvantages:

1. Power output varies with season (more in summer, less in winter), time of day (most in afternoon, least in early morning,), and weather (less if overcast), and does not match power demand. (However, thermal storage and power regulation methods can somewhat mitigate this.)
2. Low thermodynamic efficiency (about 1 to 2 %) necessitates a large area of land for the collector and a tall (≈1 km) tower.
3. Commercial efficiency is only possible with a very large facility, requiring a large investment of capital resources and materials, financed until it repays the original investment. There may be difficulties acquiring or transporting the amount of materials required.

The first large commercial SUTPP will face some risks. While the basic physics is well understood, it is uneconomic to build intermediate sized plants, and a large plant may not meet performance estimates. Like any other large first of a kind project, there may be unforeseen issues leading to cost overruns or maintenance issues. Engineers have been actively researching construction, earthquake and wind hazards for such tall structures [12, 29-33], which appear to be feasible.

1.2 Contribution of this Thesis

This thesis evaluates SUTPP configurations (baseline, water thermal storage and airflow regulated power management), amount of collector structural material, and transparency material (glass or Ethylene tetrafluoroethylene (ETFE)), and identifies choices that minimize Global Warming Potential (GWP) and maximize Energy Return on Energy Invested (EROEI) to compete with other types of power plants. The collector was identified as the largest contributor to GWP and Embodied Energy (EE) which in turn determines EROEI (assuming power produced per lifetime remains the same). The collector's condition and cleanliness are important for maintaining plant performance. Losing a substantial part of a glass collector to hail will cause extended downtime and negatively affect its lifetime GWP impact and EROEI. ETFE, while easier to replace than glass, is even less hail resistant than glass. Therefore choosing a site with very low hail risk is important. Information is presented indicating an assumption the collector is self-cleaning may not be correct. Practical problems and considerations relevant to developing cleaning solutions are discussed. Rainwater will need to be retained and purified for cleaning. Excess rainwater will degrade performance if it is allowed to evaporate under the collector, and should to be directed away or captured for other uses. Additional areas where research is needed are identified. (These areas may be being addressed by those seriously considering constructing such a plant, but are probably considered too proprietary to be discussed in open literature.) A spreadsheet method is presented to evaluate SUTPPs configurations, which can be expanded to accommodate more detailed design and maintenance definitions developed by others. The potentially most reliable SUTPPs with the lowest GWP and best EROEI, optimized for either maximum output, baseload power, or power on demand are identified for further study and compared to other types of power plants.

1.3 Outline of this Thesis

Chapter 1 describes the need for such a power plant and how it works. Chapter 2 summarizes the results of a literature search and briefly discusses basic modeling equations. Chapter 3 addresses key considerations for developing infrastructure and power plants designed to endure future challenges, as well as specific considerations for SUTPP design and maintenance. Chapter 4 develops representative plant configuration definitions based upon considerable analytic and modeling work of others and practical considerations. Chapter 5 describes the Life Cycle Assessment (LCA) process, shows how LCA methodology is applied to the SUTPP configurations described in this thesis, and concludes with the spreadsheet tools used for analysis. Chapter 6 presents Global Warming Potential (GWP) and Energy Returned on Energy Invested (EROEI) of SUTPP configurations, evaluates the uncertainty of these results, and compares the results to the work of others and to other types of power plants. Finally, Chapter 7 identifies areas for further research and presents final conclusions. Appendices provide additional research, design development, analysis and calculations for those with a deeper interest, which was summarized in the main text for brevity.

CHAPTER 2

LITERATURE REVIEW AND MODELS

Section 2.1 summarizes selected items from the literature. Section 2.2 presents basic energy flow and some modeling equations for SUTPP performance.

2.1 Literature Review

One of the earliest applications of power from rising heated air may be a sketch by Leonardo da Vinci (1452-1519) illustrating a roasting split being rotated by a turbine in a fireplace chimney (Calder [34]). Marco Aurelio dos Santos Bernardes contributed an in-depth literature review chapter titled "Solar Chimney Power Plants – Developments and Advancements," to a book titled "Solar Chimney Power Plants – Developments and Advancements," [35] that has been the bases for many author's literature reviews. It begins with Cabanyes (1903) [36] "Protyecto de Motor Solar (Solar Engine Project), a household chimney device for generating electricity. (Gunther 1931 [10]) referred to a proposal by Bernard Dubos to construct a solar updraft plant in North Africa, consisting of a glass collector feeding a solar chimney on a mountainside with a turbine and generator at the top. The concept received little attention until the construction of the 50 kW prototype at Manzanares Spain in 1982 funded by the German Ministry of Research and Technology, and (according to Fluri [37]) designed, built and tested by Schlaich Bergermann and Partners. It consisted of a 195 m high tower and 240 m diameter collector, and operated for about 15,000 hours from 1982 through 1989 (Schlaich et al. [12, 35, 38]). The Manzanares prototype is the largest power output SUTPP facility completed to date, and has been a key source of experimental data used by researchers. Subsequently, there have been a few hundred scholarly and technical works on SUTPPs.

2.1.1 Computational Fluid Dynamic (CFD) Models, Experiments, Site Studies and Proposals

A substantial body of CFD modeling has been reported in the literature, including work to refine the optimal collector, tower, transition, and turbine area geometry, and investigate interaction with wind, humidity and cloud formation. The first known modeling work published was by Bernardes. Some other published research includes Daba [39], Maia et al. [40], Ming et al. [41], Sangi et al. [42], Shams et al. [43], Sun et al. [44], Xu et al. [45], Zhou et al. [46] and Zhou et al. [47]. Koonsrisuk [48] modeled a sloped collector. Fluri [37] discusses CFD work of others concerning the turbine and transition regions, and includes his own models.

Some small collector experimental work includes the following: A 12 m tall tower with a 10 m diameter collector that attained up to a 25 K temperature rise and up to 3 m/s (Kasaeian et al. [49]). A 60 m tall tower with a40 x 40 m square collector used to investigate maximization of solar energy power usage and compared to a MATLAB model code (Najmi et al. [50]). A 8 m tall tower with a 10 m diameter collector was used to map temperature within the collector, demonstrated up to 24 K temperature rise (Zhou et al. [51]).

Site proposals include a 200m tall 500 m diameter 190 kW plant Xia Hui Autonomous region of China (Dai 2003 [52]), 200 m tall 500 m diameter 140-200 kW Adrar Algeria (Larbi 2009 [53]), 350 m tall 1000 m diameter 1-2 MW in Iran (Sangi [54]), Mediterranean islands 550 m tall 1250 m diameter 2.8-6.2 MW with considerably higher levelized cost of electricity than other power sources (Nizetic 2008 [55]), sloped 5 MW plant in Lanzhou China(Cao 2011 [56]), 500 m tall 1,000 m diameter 8 MW plant in United Arab Emirates (Hamdan 2010 [57]), and 500, 1000 and 1500 m tall plants in Sishen South Africa by Pretorius [2]. Lorente, Koonsrisuk & Bejan 2010 [58] investigated the most optimal way to cover a desert with SUTPPs of varying sizes for optimal yield.

The German company Schlaich, Bergermann und Partners have published numerous papers on SUTPPs including a 2011 paper stating “The know-how is available with us” [1], suggesting they are looking for someone to invest and fund construction.

The multinational company EnviroMission is contracting with firms to construct the World’s first commercial SUTPP in La Paz County Arizona, and has explored options to build SUTPPs in Australia, China, and additional SUTPPs in the United States [59].

2.1.2 Design and Optimization Studies

Bernardes [60] presents a summary of convective heat transfer coefficients and Nusselt numbers for typical collector roof shapes, and notes the hyperboloid, which maintains constant flow from the collector entrance to chimney entrance, is the most appropriate for optimal heat transfer.

Fluri [37] performed a thermodynamic-economic optimization analysis showing large SUTPPs are best constructed with a multitude of large turbogenerators around the chimney entrance, and provided preliminary estimates of the number, sizes and specifications of the turbogenerator units.

Harte and Van Zijl [29] explored the natural frequencies of a solar chimney and its deflection and excitation by wind forces and vortex shedding. Alberti [30] investigated incorporating vertical ribs on the outside of a tower to avoid vortex shedding on opposites sides that can set up cross-wind oscillations, greatly simplifying design for wind induced oscillations.

Kraetzig et al. [31] provide an excellent overview of reinforced concrete conventional cooling tower and solar updraft tower design analysis, considering height, weight, wind, temperature, seismic and construction loads, and natural vibration modes. Niemann, et al. [32] provide a more thorough treatment of chimney design and analysis for wind. Rousseau [33] provides a very detailed treatise on the modeling of dynamic forces on a solar chimney. Harte et al. [61] discuss tower and collector wind and structural issues, including durability.

Kraetzig [31] and Niemann [32] employ some hyperbolic tower geometry when practical to enhance structural properties by taking advantage of the inherent strength and stiffness of its compound curvature.

2.1.3 Life Cycle Assessment (LCA)

Section 6.5 compares results of this thesis to the work of others. These include Bernardes' dissertation [60], the only well documented LCA of a SUTPP we have found in the literature. However, a statistic cited by Niemann, et al. [32], and a claim on EnviroMission's corporate Website [59] (see Section 6.5) suggest other LCA calculations have been made.

Hendrickson et al. [62] authored a manual explaining how the Economic Input-Output (EIO) approach to LCA works, its mathematics and how to apply it. General overviews of what LCA is and how to perform a LCA were written by Curran [63] and Jensen, et al. [64]. The internationally recognized standard for LCA is ISO 14000 Environmental Management, defined by the International Organization for Standardization (ISO) [65] which is listed in Appendix H.

2.2 Basic Energy Flow and Equations

While the basic physics of a SUTPP can be relied upon to produce power, it is very inefficient. Figure 2.1 illustrates the energy flow of the solar energy input. The maximum efficiency is limited to about 1% per km of height (Bernardes [35], Mullett [66]). To achieve commercially competitive power output vs. investment costs, a tall tower and large collector are required.

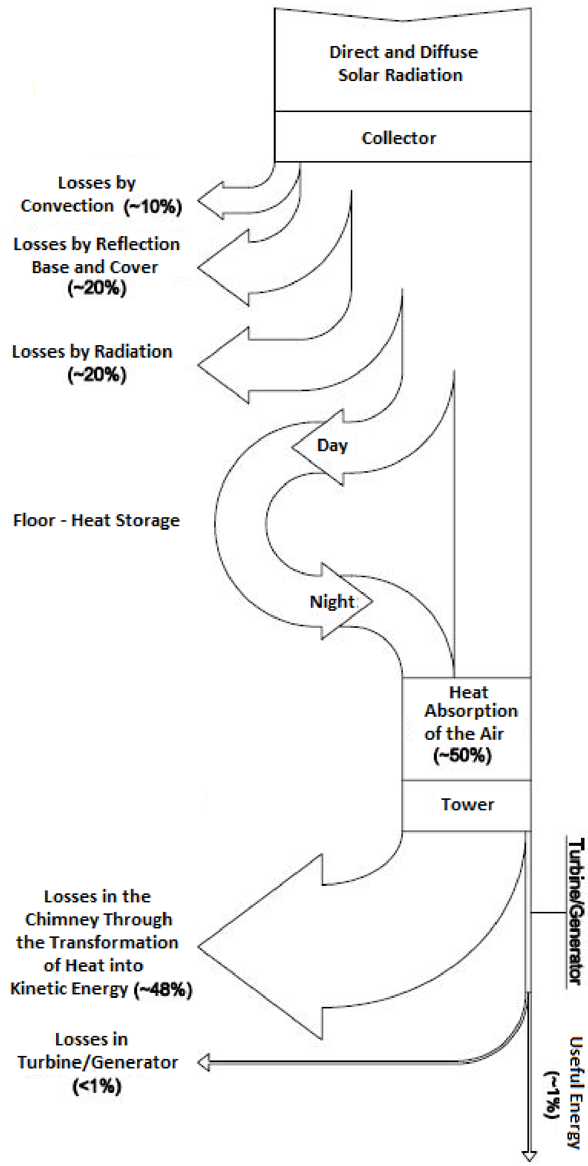

Figure 2.1. Energy flows (Bernardes, used with permission, translated to English [67]).

The heated air in the tower has a lower density than a nearby column of air outside the tower, imparting a buoyancy force to the air mass in the tower, whose own mass in turn resists acceleration. When these concepts are expressed mathematically, combined with the ideal gas law and solved for the velocity of air going up the tower (assuming no friction inside the tower), the ”Chimney” equation is obtained (Schlaich et al. [12]):

$$V_t = SQRT[2\ g\ H\ \Delta T / T_a)] \quad (2.1)$$

Where V_t = air velocity in tower (m/s), g = 9.81 (m/s), H = tower height (m), ΔT = temperature (K) increase at tower base vs. T_a, T_a = ambient temperature (K) at collector inlet.

The total electrical power output P is given by (Schlaich et al. [12]):

$$P = Q_s\ \eta_{collector}\ \eta_{tower}\ \eta_{turbine/Generator} = Q_s\ \eta_{\ plant} \quad (2.2)$$

Where P = Power (electric), Q_s = solar energy input = (Horizontal surface radiation)(Collector Area), $\eta_{collector}$ = efficiency of collector, η_{tower} = efficiency of chimney = $gH/c_p T_a$ [68] (where c_p = specific heat of air) , $\eta_{\ turbine/Generator}$ = efficiency of turbo-generator. Typical values for a 1 km tower might be about $\eta_{collector}$ = 0.60, η_{tower} = 0.03, $\eta_{turbine/Generator}$ = (0.80) (Bernardes [35]), and for the generator (.95) (Wentz [69]), giving $\eta_{\ plant}$ = (0.60)(0.03)[(0.80)(0.95)] = about 1.3.%.

For a more complete development of the equations, refer to Schlaich et al. [12] or Padki and Sherif [11].

CHAPTER 3

LIFE CYCLE AND DESIGN CONSIDERATIONS

Assessing the life cycle of a SUTPP requires an understanding the challenges faced with its three life phases: construction, operation and maintenance, and final disposal. These phases must be viewed within the context of future economic and technical infrastructure that will change as fossil fuels and some resources become less available and society adapts to solve emerging problems and live within new limits. This chapter will explore these considerations.

Construction requires a considerable amount of land that can be used without unacceptable ecological impacts and a huge investment to erect a very tall tower and vast collector area. Deserts can be ideal choices to minimize ecological impacts, but there may be species (such as the desert tortoise [70]) or habitats best left undisturbed. Environmental impact and site approval regulations may prove to be too strict to allow use of many sites. Perhaps new approaches are needed to better weigh the overall impact of a project against. the harm done by continued reliance on fossil fuels or other alternatives [71]. The plant has to last many decades to maximize return on cost, resources and energy invested. Decision makers and investors require confidence it can be built on schedule and budget, will perform as expected, and can be maintained without significant unexpected problems during its intended service life. A literature search (Chapter 2) indicated significant research has gone into understanding its physics, estimating and optimizing its performance, and optimizing many of its key components. Performance estimates can be compared to that of the 50 kW Manzanares pilot plant, which provided limited operational experience. Unfortunately, performance analysis indicates SUTPPs do not become economic until they become very large [1].

Intermediate sized test facilities tend to have lower efficiency and be uneconomic. This creates a motivation to jump directly to a multi-megawatt plant. Therefore it becomes critically important to understand as many of the problems and risks as possible before building the first large scale plant.

Maintenance has been quoted or presumed to be minimal [12]. This thesis explores the tradeoffs between design and maintenance to determine if common assumptions are justified and identify areas of potential concern for further research or guidance in future decision making.

Section 3.1 alludes to potential future infrastructure challenges humanity may face. Section 3.2 presents a design and lifecycle philosophy optimized to guide decisions to assure the SUTPP is a cost effective, reliable, robust power source in most future scenarios. Sections 3.3 through 3.5 address specific considerations for the construction, operation and decommissioning phases of the SUTPP life cycle. Chapter 4 draws upon these considerations to develop top-level plant design definition for life cycle assessment.

3.1 Infrastructure Environment

A power plant both supports and relies upon the rest of society's infrastructure. Contemporary Reliance on Fossil Fuels is not sustainable due to both finite exploitable supply and environmental impacts, including global warming. Renewable alternatives can reduce or avoid greenhouse gasses that contribute to global warming, but require substantial initial technology, infrastructure and energy investments that must be completed before fossil fuels are phased out or decline due to depletion. Renewable alternatives may not support the energy production rates, infrastructure, and standard of living we enjoy today. There will be a period of adaptation, which cannot be fully understood in advance that may prove quite challenging at times. The infrastructure of society and the economy is a complex interdependent system. Many aspects of this system may not cope well with disruptions. For example, the fractional reserve monetary system requires ever more money is loaned into existence to pay off old loans to avoid collapse, which assumes perpetual economic growth that may prove impossible. History includes many crises, shortages, hardships and declines. Disruptions and hardships may challenge society and its infrastructure as humanity makes the necessary changes to move beyond our current unsustainable practices. Humanity will do what is necessary with the means available to adapt and succeed, as they have throughout history. For a power plant to be a means to succeed during challenging times, it must be reliable and easily maintained with minimal support. Such a power plant, relying on freely available sunshine, may play a pivotal role in people's success. Section 3.2 defines the design philosophy of such a power plant.

3.2 The Need for Economic Sustainable Robust Resilient Design

Extensive review of energy and climate literature suggests for a SUTPP to be a reliable part of key infrastructure, it needs to a simple effective design that is Economic, Sustainable, Robust, and Resilient (ESRR).

a.) It needs to be "Economic", both "financially" and "energetically". Energetically, the plant must produce significantly more energy than is required to build, operate and decommission it (i.e. provide adequate EROEI). Financially the monetary value of the power sold must provide a profit above the costs to build, operate and decommission it after paying interest on any borrowed money.

b.) A SUTPP needs to be "sustainable" both "ecologically" and "practically." "Ecologically sustainable" is meant to be synonymous with "sustainable development," meaning it "meets the needs of the present without compromising the ability of future generations to meet their own needs" [72]. "Sustainable" as used in this thesis will also mean sustainable even if fossil fuels and many resources become scarce, uneconomic or unavailable. Practically "sustainable" means it can be easily maintained or fixed if the economy is smaller or infrastructure is stressed or compromised, which is best accomplished by making it "Robust."

c.) "Robust" means it endures over time, is not easily broken or rendered unusable, and has minimal problems or ways to fail. The ideal solution is it never breaks or needs maintenance. If it needs work, the work should be minimal and simple. Replacing a glass panel or recyclable metal beam is simpler than fabricating an exotic composite part with a complex supply chain, or a complicated cleaning or recoating procedure requiring exotic materials, high technology equipment and a staff of experts or excessive labor.

d.) "Resilient" is a term used by those advocating reliance on adequate basic local infrastructure that can survive setbacks and disasters to permit communities to endure hardships and fix or replace the larger infrastructure needed to recover or build new systems from what is left to serve future needs. Retaining electrical generating capacity in almost any situation is integral to resilience, as it powers key services and facilitates recovery or building new infrastructure. A SUTPP needs no fuel, only sunlight, a largely intact collector and chimney, and working turbines and generators. Unless heavily damaged, it is easily maintained or repaired with parts that can be kept onsite. It can be used to add power to the grid or to provide emergency power to fix and restart key infrastructure.

3.3 Construction

Construction of a tower reaching record heights, while challenging, appears to be feasible with contemporary engineering knowledge, and should be notably less expensive than skyscrapers of comparable height, such as the 2,717 ft (828 m) tall Burj Khalifa Tower in Dubai costing $1.5 Billion [73]. A literature search (Chapter 2) indicates most researchers believe reinforced concrete is the most appropriate construction material. Schalich states it is the most appropriate material in areas where the maximum earthquake acceleration is less than about 1/3 of the Earth's gravity [12]. Researchers are using established analytic tools to develop chimney designs to withstand earthquakes and high winds [29, 32]. Further research may be needed to determine construction and maintenance requirements to assure a long service life.

The collector inputs must be constrained for the project to be economically and energetically viable.

To facilitate analysis and attempt to minimize costs, this thesis assumes the collector consists of identically sized square "cells" that vary only in the height of the supported transparency. (The "cells" may be rectangular, hexagonal or of more than one type or size, but consideration of these possibilities will be deferred to detailed design, and ignored here to facilitate useful generic design evaluation sufficiently general to apply to other geometries.) Each "cell" is assumed to be supported by a structural "post" in each of its 4 corners (shared by 4 neighboring "cells). Each "post" is connected to each of its 4 neighbors by "major structural beams". One or more sizes of "secondary beams or structure" will span the space between major structural beams to form smaller squares or rectangles that will be covered by the "transparency" material.

Depending on how stiff the posts are, it may be necessary to add diagonal bracing. Estimating the total drag from all supports, as well as actual simulations by various authors, including Pretorius (p. 41 [2]), all show the few sparsely spaced supports have very little impact on plant performance. If the transparency is a membrane or film, it may be necessary to add features or components to keep the cell shapes from distorting before, during or after installation, or due to storm, maintenance, thermal expansion or cleaning activities. This life cycle assessment thesis will use a minimum of design information to define the amounts of material to construct the support structure.

The collector structure and transparency must withstand forces due to storms and any construction or maintenance activities, and the transparency must perform its intended function for decades to avoid or minimize replacement. Isolated damage at a very few sites (particularly not very near the tower) is expected to have acceptable impact on performance, and should be easily addressed by localized repairs or patches, however, large scale degradation due to weathering, UV damage, hail, or build up of dust or other deposits can present a large replacement or maintenance burden given the extremely large collector area, whereas a more robust transparency that resists some of these problems may be uneconomic and provide low EROEI or excessive life cycle impact.

The turbine area may consist of either one large vertical axis turbine installed in the chimney or many horizontal axis turbines encircling the base of the chimney. A single turbine will be very large and expensive, pushing the state of the art in size, which may be possible but constitutes undue technical risk. There will be no bending moment on the drive shaft but the bearings will have to support the weight of the turbine. Using many horizontal axis turbines will be much less risky and make each one less expensive. Non-operating turbines can be aerodynamically isolated from the moving airstream to permit maintenance or repairs while the remaining turbines continued providing power, thereby maximizing the plant's capacity utilization. The chimney will be supported by aerodynamically shaped (or shrouded) columns located between air ducts for each turbine. Ductwork for each turbine will blend into the collector to chimney transition fillet above the ducts. A central cone on the chimney floor will help to aerodynamically direct turbine outflows into the central chimney updraft. Airflow will be relatively steady, slowly changing velocity inside the SUTPP as environmental conditions change, unlike the extreme gusty conditions conventional wind turbines must be designed to handle [12]. This should increase service life and reliability. However, the ambient environment will be warmer, and the generators will require cooling. Cooling by shedding heat into the surrounding air may be the simplest solution, though it is compromised somewhat by the higher ambient temperature surrounding the turbine & generator. Some mechanism must be provided to isolate a turbine and generator from the warm airflow to allow personnel to perform maintenance.

The electrical hardware will be similar to any other power plant connecting to the power grid. The facility will require a control center building and whatever structure is required for maintenance repair and stocking supplies, roads and parking for workers and service vehicles and a visitor's center.

3.4 Maintenance

In the literature a number of authors claim maintenance will be minimal, possibly limited to servicing the generator and electrical parts and guards. These assumptions are examined in the sections that follow.

3.4.1 Tower Maintenance

Modern reinforced concrete structures often require repairs and maintenance at least every few decades. Moisture penetration leads to corrosion of the reinforcing steel and freeze-thaw damage, and pollutants can have a deleterious effect on the concrete [74]. Appropriate design and maintenance measures must be taken to assure the intended service life. Maintenance or repairs on such a tall structure may require specialized machines, coatings, and solutions that depend on modern infrastructure. Small chunks that come loose may damage the collector or endanger people below.

3.4.2 Collector Concerns

The collector must endure decades of sun exposure, heat, cold, wind, debris (mostly sand, also biological contaminants like droppings or occasional dead birds or insects), rain, dew, possibly hail, snow or frost, and any maintenance activity, like cleaning, in additional to occasional local damage from unforeseen causes.

Ice and Snow should be infrequent in most desert locations, and air underneath will be warmed by residual heat in the Earth below, accelerating melting, making snow on the collector a temporary condition, addressed by assuring the collector can support the worst expected snow loads and providing for drainage.

Rain will not immediately run off a large, barely sloped collector surface, and may collect in low areas, or form shallow pools on nearly flat panels bowed slightly due to gravity. Rain loads can be alleviated by providing proper drainage. Standing water or moisture under the collector will be evaporated by solar radiation and passing warm air, which wastes solar energy to overcome the latent heat of evaporation instead of heating the air. Reduced heating entails reduced buoyancy to draw air up the chimney, which reduces electrical power output. Therefore this thesis assumes this valuable desert rainwater will be collected by gutter-like shapes in the support structure around the edge of each transparency panel and drained to a system either used for transparency cleaning, retained for thermal storage as described in Section 4.4.1, or directed away from the SUTPP, possibly for other water uses.

Structural engineers will design the collector to withstand thermal expansion and contraction (with changing temperature). wind, and earthquake forces. This leaves any deterioration due to ultraviolet (UV) exposure, hail, debris contamination, the effects of windblown sand erosion, and the demands of any cleaning required as remaining collector concerns.

3.4.3 Hail

Hail can occur in many areas, and if large, poses the possibility that much of the transparency may have to be replaced before significant power can be generated. The risk of hail of a size large enough to damage or break the transparency can be estimated from meteorological or insurance actuarial models, (which is addressed in Appendix A and Appendix B). This can be used to estimate the frequency of transparency replacement due to hail. For an actual SUTPP the material, thickness, and panel size will be optimized with hail in mind if it is at risk. A better alternative is building the plant where there is no risk of damaging hail.

3.4.4 Cleaning

Schlaich stated "Glass resisted heavy storms for many years without harm and proved to be self-cleaning thanks to the occasional rain showers" [12]. However the work of Elminir et al. [75] and others cited by them indicates considerable variation in glass transmission loss at different locations due to local pollutants and dust, wind, glass angle (horizontal being the worst), rain (cleaning non-adhered contaminants), and dew. Dew attracts and adheres dust, salts and contaminants adhered after it evaporates, over months creating deposits that cannot be washed off of the glass. Michalsky et al. [76] obtained only a 1% transmittance loss in 2 months with rain at least every 10 days in Albany NY. Sayigh et al. [77] obtained a 64% transmittance reduction in 38 days in Kuwait. Elminir et al. [75] found horizontal glass transmission losses of 53% were found in Cairo over 7 months with 2 rain events (3 mm and 11 mm) during the test, that ended with the glass covered by a caked on dust & salt deposit that cannot be removed by subsequent rain. A 28% transmission loss occurred over the same 7 months for horizontal glass cleaned every month. Organic debris like droppings and dead organisms will add to this problem, creating small masses that may smear if improperly cleaned. Experiments should be conducted at any proposed SUTPP site over appropriate time intervals to determine the rate of accumulation and its effect on SUTPP performance, as well as to determine cleaning requirements and frequencies, and assess resulting plant performance.

Wind driven sand can cause tiny scratches that dull the surface. A severe sandstorm or several sandstorms may cause significant degradation. Cleaning can also cause scratches that dull the surface. Adequate sources to quantify the sandstorm dulling phenomena were not found. However single sandstorms have been known to degrade glass and car windows.

3.4.5 Transparency Replacement

Ideally the transparency should last the lifetime of the facility. If dulling, deposit buildup, and/or UV exposure degrade performance unacceptably, it may be necessary to replace large parts of, or the entire transparency area. For an actual plant an analysis must be performed to select the optimum transparency material to balance performance, durability replaceability, capacity utilization (lack of downtime), cost, environmental impact, and EROEI.

3.5 Decommissioning

Contemporary conventional decommissioning entails demolition and removal of most of the plant. The collector transparency and above ground supports may be disassembled, removed, and ideally recycled (instead of buried in a landfill), while concrete footers may be abandoned or buried in place. The tower may be brought down by explosives, broken up and used for new building or road construction, or possibly buried onsite. Generators may be refurbished or used elsewhere, and materials like copper wires can be used elsewhere or recycled.

The energy and infrastructure may not be available to decommission the power plant as envisioned under “contemporary” assumptions. The facility may be converted for alternative uses not envisioned today or its materials used to make other facilities onsite or nearby, or the facility may be scavenged for parts and materials and largely abandoned to disintegrate over future millennia.

The most extreme scenario entails “abandonment.” The consequences of this are probably minimal, aside from one or a few tower collapse events whose danger should occur over a limited area cordoned off to humans, that may temporarily disrupt local wildlife, after which the local ecology will continue on much as before. The area covered by the transparency will gradually open to the sky. The effects of this process are not well understood but do not seem to be a serious concern, though further research may be warranted. Concrete and glass should not be appreciably toxic, though a plastic transparency (such as ETFE) may not be as benign. Steel structure rusting and the small amount of copper on site will probably not have a serious impact, though it will cause highly localized chemical changes to the soil. The overall impact should be far less than a power plant with substantial amounts of nuclear or fossil residue materials, and considerably more infrastructure.

Life Cycle Assessment in this thesis considered both the “disassembly/recycling” and “abandonment” decommissioning options. It was difficult to fully evaluate disassembly and recycling. What could be evaluated contributed little to the life cycle impacts. Therefore after obtaining partial results (see appendices), the decommissioning phase was omitted in the final results.

CHAPTER 4

PLANT DEFINITION

This chapter defines the Solar Updraft Tower Power Plant (SUTPP) location, site characteristics, configurations to be evaluated, and necessary design definitions to permit a reasonable Life Cycle Assessment (LCA) of Global Warming Potential (GWP), Embodied Energy (EE), and Energy Returned on Energy Invested (EROEI) in later chapters.

4.1 Plant Site

For the purposes of this study, the site is assumed to be the same as the proposed EnviroMission plant to be built in La Paz county Arizona. Information for this site, described in detail in Appendix A is summarized in Table 4.1.

TABLE 4.1

LA PAZ SUTPP SITE DATA

Attribute	Value(s)
Location (Approx)	Latitude = +33.92°, Longitude = -114.29°
Terrain	Nearly Flat, Sandy Dessert
Elevation	900 (600-1,200) ft
Rainfall, Maximum Hourly	1.75 inches
Rainfall, Annual Average	5 (4 to 6) inches per year
Maximum Snow Load Expected	Zero
Wind, Maximum Gust Expected	120 MPH (54 m/s)
Hail	No significant risk of hail that can break 4mm tempered glass or dimple 0.2 mm EFTE.
Solar Insolation	Annual average 250 W/m^2, 2,194 kWh/m^2 per year

4.2 Plant Size and Performance

An attempt was made to size the plant to be studied to match EnviroMission SUTPP specifications, as advertised in several press releases (that often do not agree with each other) summarized in Table 4.2.

TABLE 4.2

ENVIROMISSION PUBLIC SPECIFICATIONS

Attribute	Value(s)	Source(s)
Tower Height	2,500 ft (762 m) 2,600 ft (792 m) 2,625 ft (800 m)	[24], [78], [79, 80]
Tower Diameter	120-130 m	[79, 80]
Collector Area (Diameter)	5,500 acres (= 5.3 km diameter)	[24]
Air Temperature Rise	From 40 °C ambient to 80-90 °C (Summer Peak)	[24, 79, 80]
Wind Speed	35 mph (56 km/h) (Summer Peak)	[24]
Watts (Rated) Capacity Factor Annual Output	200 MW, 60%, Implies 1,051 GWh/y	[24], [79], [80]
Service Life	80 years or more	[79, 80]
Maintenance Staff	40	[79]

EnviroMission did not respond to requests for additional design and performance information for this thesis. Combinations of performance (power, airflow, and temperature change) shown in Table 4.1 were not replicated using classical SUTPP performance equations by Schlaich et al. [12]. The performance seemed optimistic, in that adjusting internal system drag found no combination of airflow and heating that can produce the power output EnviroMission claims. EnviroMission claims their plant will have a 200 MW capacity and 60% utilization factor, implying it will produce 1,051 Gwh/y. Schlaich et al. [12] estimated for a site receiving 2,300 kWh/(m^2y), a 200MW rated capacity facility will need a 1 km tower and 7 km diameter collector, and will output 680 GWh/y, suggesting a capacity utilization of 39%. It is theoretically possible to achieve greater than 60% capacity utilization with suitably configured thermal management, as is shown by the double glazed secondary roof airflow regulated configuration (in Section 4.4.2) which is estimated to have a 64% capacity factor (Table 4.16, Section 4.8). Pretorius (pp. 99-101 [2]) describes a 1 km tower, 5 km diameter triple canopy collector configuration, estimated to provide 297 GWh/y, that may be capable of over 75% capacity utilization depending on the power rating of the generator(s) used. Alternatively, Pretorius (p. 84 [2]), presents another 1 km tower, 5 km diameter configuration optimized for maximum power output with a fully double glazed collector roof estimated to output 467 GWh/y (57% more power per year) with a summer day peak output of approximately 158 MW, which entails a capacity factor of 31% assuming the generator was rated 8% above the 158 MW expected summer power output maximum. (The 8% margin is typical of turbo-generator modeling in Appendix E based on Fluri [37]). Assuming the EnviroMission design has a 5,500 acre (5.4 km diameter) collector, and only a 750-800 m tower, and La Paz receives 2,194 kWh/(m^2y) (Appendix A), it will be difficult for them to meet their performance claims. An article about EnviroMission in the Sun and Wind Energy Journal entitled "Tall and Visionary" by Smith [24] is critiqued on the website "Meteorological Reactors" by Bonnelle [81], who pointed out EnviroMission must achieve a solar to electrical power conversion efficiency of 1.96% (assuming 2,400 kWh/(m^2y)) to meet their claims, yet the theoretical maximum efficiency allowed by the physics and thermodynamics is limited to 2.54%, meaning they can only lose 23% of theoretically optimal performance. This may be compared to Schlaich's performance estimates that indicate losses of 57% of what is theoretically possible. Bonnelle [81] then enumerates the expected losses: collector reflection, imperfect ground absorption, infrared reemission, canopy heat conduction, turbulent flow friction, kinetic energy losses at the chimney exit, turbine, generator and electrical system losses. Given the challenges of meeting EnviroMission's claims, this thesis takes the position that EmviroMissions's available design and performance specifications are incomplete and cannot serve as an adequate baseline for this study. However, the EnviroMission site location was retained for the purpose of this thesis.

The optimal choice for a baseline plant of comparable size in the literature was Pretorius (pp.18-19 [2]), which featured a 1 km tower "Reference Plant" with the performance modeled for many variations of this configuration, making it a valuable baseline for additional analysis. Fluri [37] built upon this baseline by further defining the optimal turbo-generator configurations for some of its variations. Therefore this thesis adopts the reference plant from Pretorius [2], with inputs from Fluri [37] and other sources as the "Basic" or "Baseline" Solar Updraft Tower Power Plant, which will be abbreviated "BSUTPP."

Pretorius specified a location near Sishen, South Africa, for his "reference plant," whose site data is summarized in Table 4.3.

An overall assessment of the performance of the Sishen SUTPP relocated to La Paz is presented in Table 4.4. Using the online Engineering Toolbox [84], ambient pressures are 99.1 kPa at 900 ft (La Paz) and 87.2 kPa at 3,900 ft (Sishen), making the air 1.14 times denser at La Paz.

Lower soil absorptivity may reduce performance by 10 – 15% (possibly more) according to Pretorius (pp. 46-48 [2]), which may be a concern at La Paz, which Google satellite maps show to be lighter than the reddish soil at Sishen, probably due to high iron content, given

TABLE 4.3

SISHEN SUTPP SITE DATA

Attribute	Value(s)
Location	Latitude = -27.67°, Longitude = +23.00° [2]
Terrain	Nearly Flat, Subtropical Dessert with shrubs, Iron mining nearby [82], soil may have red hue.
Elevation	Approx 1200 m (3,900 feet) (Near Sishen airport (1173 m) [83]
Ambient Pressure	87.2 kPa [84]
Rainfall, Annual	Approx 300 mm/yr (10 inches/yr) [85]
Hail	No significant risk of hail that can break 4mm tempered glass or dimple 0.2 mm EFTE.
Solar Insolation	Annual average 251 W/m^2, 2198 kWh/m^2 per year [86] (Refer to Appendix A of this thesis.).

TABLE 4.4

SITE PERFORMANCE RATIONALE

Aspect	La Paz	Sishen	Effect & Rationale
Solar Insolation	2,194 kWh/m^2 per year	2,198 kWh/m^2 per year	0% change.
Ambient Pressure	99.1 kPa [84]	87.2 kPa [84]	1.14 kPa higher suggests 2% more power according to Pretorius (pp. 51-53 [2]).
Soil Type	Sand	Sandstone	Pretorius (pp. 42-44 [2]) implies 7% more power
Internal Bracing Wheels	NO	YES (10 required)	Design enhancement by Kraetzig [31] Approx 3% gain according to Pretorius [2] (Described in text below)
Overall			About 13% more power at La Paz, without soil absorptivity is taken into account.

there is a major iron mine at Sishen [82]. This difference may be partly made up by a roughly 10% gain summarized in Table 4.4. There is also some question as to the accuracy of the survey data used to obtain kWh/(m^{2}y) in Table 4.1 and Table 4.4, which is discussed in greater detail in Appendix A, which suggests Shishen may have as much as 10-15% more solar insolation, even though the 2,194 (La Paz) and 2,198 (Sishen) values are each claimed to have less than 10% error. Unfortunately, without better insolation, climate and soil definition at La Paz, (which are probably not available without paying for a study), it is not practical to model and compare performance at La Paz by running simulations as offered by Pretorius [87] and Bernardes.[88]. Therefore this thesis assumes the performance expected at La Paz to be within 10% of that expected at Sishen. Given that the purpose of this thesis is to obtain a meaningful gross comparison of a SUTPP to other types of power plants, and to understand the main contributors to its GWP impact, and EROEI, the matter of more precise performance estimates can be appropriately deferred to those developing specific power plant proposals.

The generic tower design defined by Section 4.7, utilizes external stiffening rings (an innovation proposed by Kraetzig [89]) to avoid the need for 10 internal bracing spoke "wheels" of cables, thereby increasing performance about 3% according to Pretorius (pp. 50-51 [2]) as shown in Table 4.4. According to Appendix D of this thesis, each of the 10 external stiffening rings saves approximately 1632 tons CO_2 Equivalent (t CO_2 Eq) and 32,000 GJ per ring during construction, and saves an additional 290,000 GJ of energy not wasted overcoming drag during the estimated 80 year life of the SUTPP.

4.3 Baseline Solar Updraft Tower Power Plant (BSUTPP)

Pretorius' "reference plant", denoted "BSUTPP" (meaning "Baseline" or "Basic" SUTPP) by this thesis, is defined by Table 4.5 and Figure 4.1, and the results of his performance model for the "reference plant" are shown at "1. BSUTPP" within Plate 4.1, as Pretorius' "new equations," which reflect his updated performance models used in his dissertation.

TABLE 4.5

BSUTPP PLANT CONFIGURATION SPECIFICATION (Pretorius, used with permission [2])

Collector Roof (Glass)	
Emissivity of glass	$\epsilon_r = 0.87$
Roughness of glass	$\varepsilon_r = 0$ m
Extinction coefficient of glass	$C_e = 4\ \mathrm{m}^{-1}$
Refractive index of glass	$n_r = 1.526$
Thickness of glass	$t_r = 0.004$ m
Roof shape exponent	$b = 1$
Perimeter (inlet) height	$H_2 = 5$ m
Outer diameter	$d_2 = 5000$ m
Inner diameter	$d_3 = 400$ m
Inlet loss coefficient	$K_i = 1$
Support diameter	$d_{sup} = 0.2$ m
Support drag coefficient	$C_{sD} = 1$
Supports tangential pitch	$P_t = 10$ m
Supports radial pitch	$P_r = 10$ m
Ground	
Type	Sandstone
Emissivity (treated surface)	$\epsilon_g = 0.9$
Absorptivity (treated surface)	$\alpha_g = 0.9$
Density	$\rho_g = 2160\ \mathrm{kg/m^3}$
Specific heat	$c_g = 710$ J/kgK
Thermal conductivity	$k_g = 1.83$ W/mK
Roughness	$\varepsilon_g = 0.05$ m
Chimney (Concrete)	
Height	$H_c = 1000$ m
Inside diameter	$d_c = 210$ m
Bracing wheel (one) drag coefficient	$K_{bw} = 0.01$
Number of bracing wheels	$n_{bw} = 10$
Inside wall roughness	$\varepsilon_c = 0.002$ m
Turbine	
Turbo-generator efficiency	$\eta_{tg} = 80\ \%$
Inlet loss coefficient	$K_{turb,i} = 0.14$
Ambient Conditions	
Atmospheric pressure	$p_a = 90000\ \mathrm{N/m^2}$

Pretorius also presented double glazed canopy configurations, including ones with the inner 50% and 100% of the collector area double glazed, which this thesis denotes as “BSUTPP-½DG” and “BSUTPP-DG” respectively, whose performance estimates are shown at the graph for “2. BSUTPP-½DG” and “3. BSUTPP-DG” within Plate 4.1. Additional SUTPP configurations and variations presented in Section 4.4 give the six numbered SUTPP configurations in Plate 4.1

which are summarized in Table 4.10 in Section 4.4.3. These configurations will be combined with different transparency materials and amounts of collector structure for assessment.

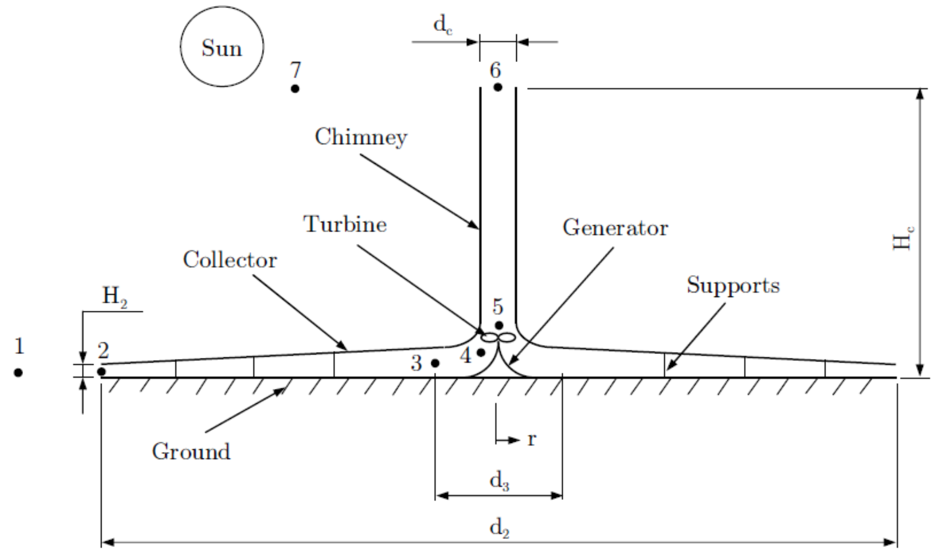

Figure 4.1. SUTPP schematic (Pretorius, used with permission [2]).

4.4 Power Output Regulation

The BSUTPP provides peak power slightly after local solar noon, and limited power at night due to residual heat being released from the ground that was stored during the day. However, the electrical grid or consumer(s) of this power may need round the clock baseload power or power at certain times. To provide power at other times, two fundamental configurations are presented. The first uses water for thermal storage, and will be referred to as the "Water Thermal Storage Solar Updraft Tower Power Plant," or "WSUTPP". The second regulates airflow near the ground to store or release heat, and will be referred to as the "Airflow Regulated Solar Updraft Tower Power Plant," or "ASUTPP".

All SUTPPs will require a water management system to provide purified water required for cleaning. Water will be obtained by a rainwater collection system.

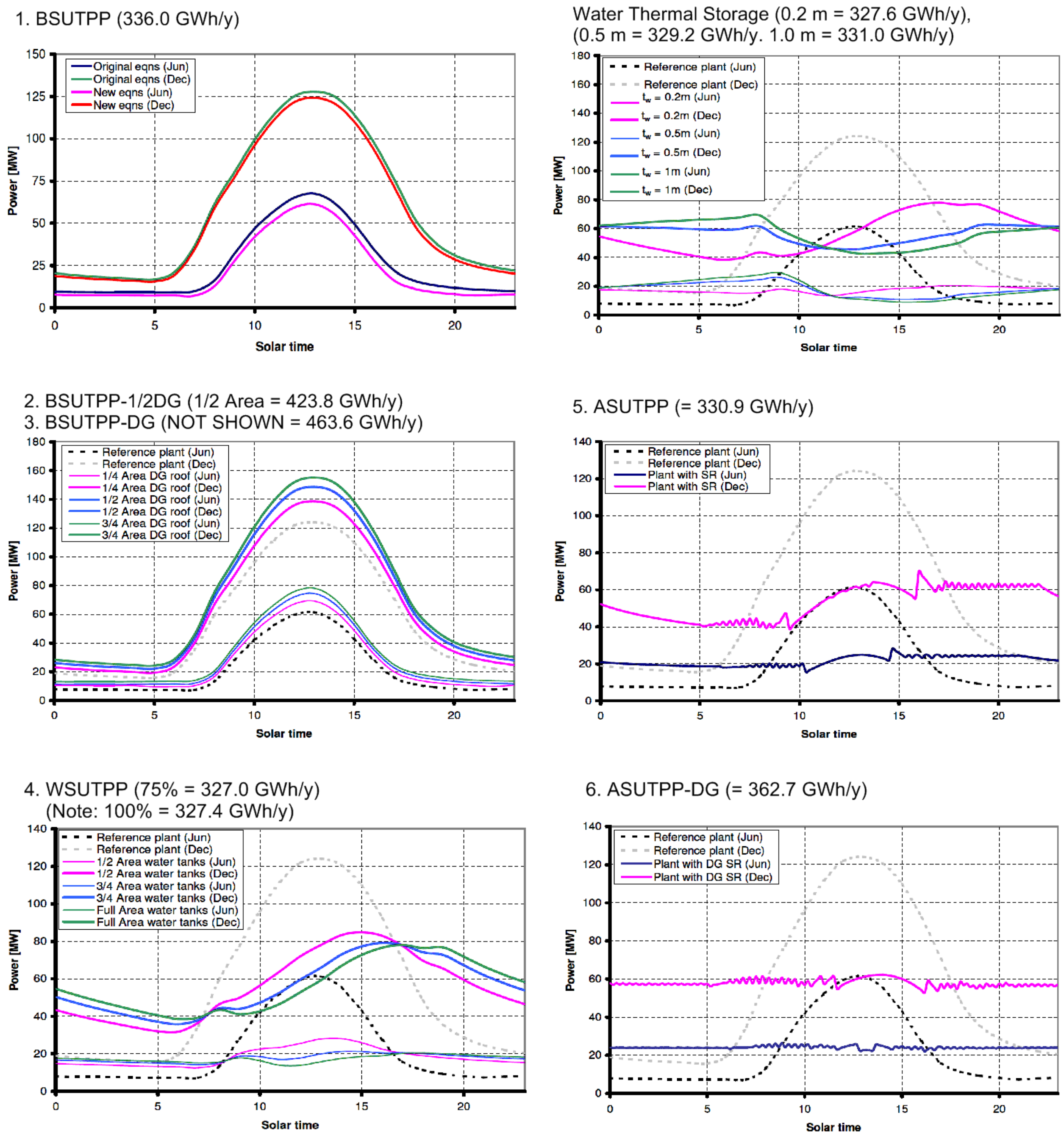

Plate 4.1.SUTPP performance models (Pretorius, used with permission [2]).

4.4.1 Water Thermal Storage SUTPP (WSUTPP) and Cleaning Water

Schlaich et al. [12] and many other authors discuss the option of enhancing thermal storage by placing water in sealed black tubes or bags under the collector. This evens out the power output across the entire day to a degree depending on the amount of thermal storage and how it absorbs and releases heat. The disadvantage is water is scarce in the desert and if the containers don't last the life of the plant, they may need maintenance or replacing and lost water may have to be replaced. Other authors, including Lombaard [90] (whose work is used and cited by Pretorius [2]), have suggested clear topped/black insulated bottomed shallow (0.2 to 1 m deep) water containers under part or all of the collector area.

The water may be part of a secondary process assisted by solar heating, or used to clean the glass. This thesis assumes rain and wash water runoff will be captured by a drainage system and processed to provide water for cleaning or thermal management to minimize or avoid importation of water. Pretorius [87] indicates further research is needed to determine how pure or clean the water needs to be to avoid contamination or biological activity that changes its optical properties and thus thermal performance, and whether this water may be suitable for cleaning or other potential applications. Therefore it is not clear if the water needs to be filtered, purified or treated or whether biocides must be used (which may somewhat negate the ecological benefits of the power plant), whether the plastic can retain the desired properties for the life of the plant or require replacing, and the scope of the effort to find and repair leaks. These questions are left for future research.

Pretorius modeled some water storage cases based upon water containers with transparent tops and black bottoms inside, with silvered insulated sidewalls, placed on the ground under the inner part of the collector. Specifications are shown in Table 4.6 and model results are shown at the graph for "4. WSUTPP" within Plate 4.1.

TABLE 4.6

WSUTPP SPECIFICATION (Pretorius, used with permission [2])

Water tanks (Plastic film and water)	
Thickness of film	$t_f = 0.0002$ m
Refractive index of film	$n_f = 1.6$
Emissivity of film	$\epsilon_f = 0.8$
Roughness of film	$\varepsilon_f = 0$ m
Extinction coefficient of film	$C_{fe} = 200$ m^{-1}
Refractive index of water	$n_w = 1.333$
Depth of water tanks	$t_w = 0.2$ m, 0.5 m or 1 m
1/2 Area outer diameter	$d_{wt} = 3528$ m
3/4 Area outer diameter	$d_{wt} = 4356$ m
Full Area outer diameter	$d_{wt} = 5000$ m

The upper right graph in Plate 4.1 shows Pretorius' performance estimates with water storage under the entire collector to various depths. Note how the daily curves show greater power production in the night and early morning for deeper water storage due to the near constant surface temperature of the larger thermal mass and the lower ambient air temperatures at those times, resulting in greater heat transfer to the air then, and correspondingly greater power production, as was pointed out by Pretorius [2].

This thesis assumes the "Water Storage Solar Updraft Tower Power Plant" (WSUTPP) configuration consists of a configuration that closely enough approximates 0.2 m deep water tanks under the 75% of the collector area nearest the tower to provide performance comparable to Pretorius' estimates. Larger amounts of water are not used to minimize the burden of constructing, filling and maintaining tanks. Some area must remain uncovered to provide space for paths, equipment, maintenance, and empty tanks to handle different purities of water if necessary. The water tanks may include different types of water, including fresh rain or cleaning runoff water, filtered water, purified water suitable for cleaning, or water used for other applications within or outside the WSUTPP.

Based on the reasoning in Appendix E, this thesis assumes the 0.2 m deep water tanks will be provided by grading to level the ground that leaves soil berms high enough to contain the water, lined with a 0.5mm layer of black plastic. This thesis does not go into the necessary level of detail to address site leveling requirements nor to provide detailed definition of the rest of the water management systems needed to fill and drain the tanks or route excess runoff water out of the collector to avoid wasting solar energy evaporating water under the canopy.

Filling of the water tanks ought to occur before summer operation, as the turbine/generator units will be designed for a peak output with water storage. Otherwise they will “overspeed” and need to “cut out” (shut down to avoid damage). If sufficient water has not been acquired by natural rainfall by first summer operation, water may be taken from the nearby Colorado River. Calculations in Appendix E show that to completely fill the tanks requires 2.926×10^6 tons of water, which is 0.16% of the minimum annual flow the US must provide to Mexico under the 1944 Mexican Water Treaty [91]. Hauling that requires about 108,000 truckloads, more tonnage than the rest of the plant combined, each traveling about 20 km by existing roads, with one truck arriving every 2 ½ minutes 12 hours a day for 365 days. Alternatively, the most direct a pipeline route is about 12 km long, but permission is required to cross the Parker Native American Reservation. The water may need to be filtered or purified. Provision will be needed to refill the tanks in the future if they need to be replaced or drained for overhead transparency replacement. Since trucking capacity may not be as readily available in the future, it may be wise to consider a pipeline as part of the plant infrastructure.

Purified water must be stored for transparency cleaning. Estimates in Appendix C show about 20,000 t of water will be required to clean the upper surface of a glass collector, (or 60,000 t to clean ETFE). This requires 352 tanks (15,000 gallons each) totaling 719 t of fiberglass, (2,157 tanks totaling 2,157 t of fiberglass for ETFE). If runoff water is not caught in the water thermal storage system, these tank requirements must at worst need be doubled to permit storage of the required water in either raw or purified form. If 25% of the 4-6 inch (10-15 cm) average rainfall (refer to Appendix A) were captured it can provide 500,000 to 750,000 t of water, or roughly 25-37 glass (8-12 ETFE) cleanings (according to Table C.2 in Appendix C), which exceeds the "high" estimates in Table 4.13 of Section 4.5.3 of 9 (glass) and 1.5 (ETFE) cleanings per year for SUTPPs with a secondary canopy.

The material requirements for water thermal storage and cleaning tanks are summarized by Table 4.7, water purification and transportation requirements are summarized in Table 4.8 and Table 4.9 respectively. The yellow cells in Table 4.7 denote the assumption of an average plastic value of 2.0 t/m^3 for generic plastic. "HERO" is an acronym for "High Efficiency Reverse Osmosis," system described by Hayter et al. [92].

This thesis assumes plants will not be grown under the canopy, nor will significant amounts of water be permitted to spill and evaporate there, as heat energy used to overcome the latent heat to evaporate water is not available to heat the air (including ambient water vapor) to decrease the gas density, which is the driving principle of natural convection in the chimney permitting power extraction by the turbines. Pretorius [2] models the reduction in performance caused by water evaporation to a baseline system.

Table 4.7

WATER TANK MATERIALS

WSUTPP	Material	Mass (t)	Other	(Units)
75% area is	ETFE (0.0002 m)	5,121	1.75	t/m³
14,631,968	Plastic (0.0005 m)	15,497	2.00	t/m³
	Fiberglass/Cleaning (Glass)	719	352	#Tanks
(m^2)	Fiberglass/Cleaning (ETFE)	2,157	1,056	#Tanks
ALL OTHERS	Material	Mass (t)	Other	(Units)
	Fiberglass/Cleaning (Glass)	1438	704	#Tanks
	Fiberglass/Cleaning (ETFE)	4,314	2,112	#Tanks

Table 4.8

WATER PURIFICATION REQUIREMENTS

	HERO # Units to fill in a year	HERO (MWh) to fill tanks
All WSUTPP Tanks	7.09	13,113
Single Cleaning Tanks (Glass)	0.048	90
Single Cleaning Tanks (ETFE)	0.145	269

Table 4.9

WATER TRANSPORTATION REQUIREMENTS

	Water	27t Truckloads
WSUTPP	2,929,394	108,496
Single Cleaning Tanks (Glass)	20,000	741
Single Cleaning Tanks (ETFE)	60,000	2,222
km		20

4.4.2 Airflow Regulated SUTPP (ASUTPP)

Another method to direct power production to the desired time of day is to regulate the passage of air under a “secondary” canopy (beneath the upper “primary” canopy) as shown in Figure 4.2 with a secondary inlet perimeter height of 2.5 m (half that of the primary above it) and secondary inner diameter of 584 m. Airflow is blocked or impeded under the secondary canopy to enhance greenhouse heating and increase ground thermal storage. Stored heat is then released by regulating airflow over the ground to meet power demand. “5. ASUTPP” within Plate 4.1 shows how this can be used to provide baseload power. Personal correspondence with Pretorius [87] confirmed this concept was originated by D.G. Kroger, and included in Pretorius’ dissertation [2]. This has the advantage of not requiring water or maintaining water in storage. Personal correspondence with Pretorius [87] indicated Pretorius and Lombaard assumed some type of louver system opened or closed incrementally, which this thesis presumes will be designed to be force-balanced to require minimal energy to operate. This adds cost and opportunity for maintenance issues, but a well-designed system may not be that difficult to maintain.

Pretorius modeled several airflow regulated configurations, including one with a double glazed secondary roof this thesis denotes as “ASUTPP-DG” with performance modeled as shown at “6. ASUTPP-DG” within Plate 4.1 to allow production of nearly uniform baseload power 24 hours a day.

Airflow regulation (ASUTPP) appears to offer a viable alternative to water storage that can be more readily tailored to redirect power to specific times of the day where it may be needed, that minimizes issues associated with obtaining and retaining large amounts of water in the desert. Instead lesser amounts of rain or cleaning runoff water will be required and retained for cleaning, while excessive amounts of rain runoff must be drained (or pumped if necessary) away from the collector to avoid performance loss due to evaporation under the collector. Alternatively, excess water may be provided for other uses.

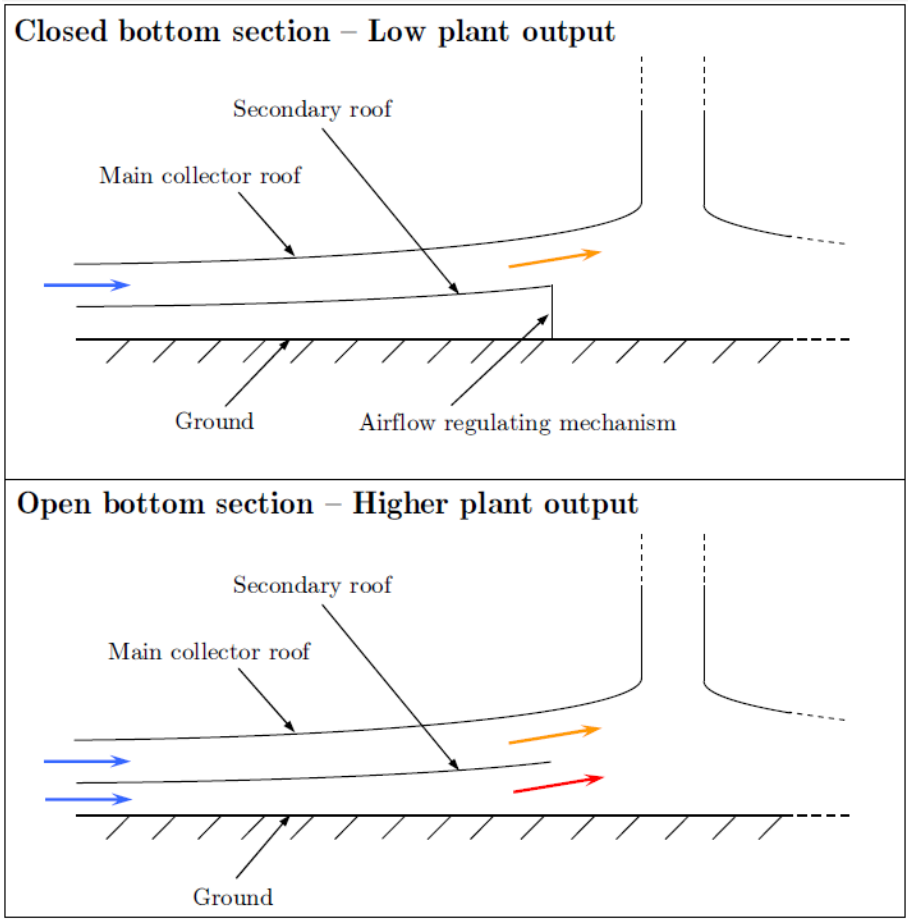

Figure 4.2. ASUTPP secondary collector roof concept (Pretorius, used with permission [2]).

4.4.3 Summary of SUTPP Configurations

The SUTPP configurations defined in Section 4.3 and Section 4.4 are summarized in Table 4.10.

4.5 Transparency Material

Section 4.5 discusses options for transparency materials, and defines the materials selected for LCA.

4.5.1 Glass

Regular green float glass can be used. However, clearer low iron types of glass are preferable [2]. Tempered glass, while more expensive and energy and GWP intensive, is

Table 4.10

SUTPP CONFIGURATIONS TO BE EVLAUATED

Abbreviation	Name	Comments
BSUTPP	Basic Solar Updraft Tower Power Plant	Pretorius "Reference Plant"
BSUTPP-½DG	50% Double Glazed BSUTPP	Inner 50% Double Glazed
BSUTPP-DG	100% Double Glazed BSUTPP	100% Double Glazed
WSUTPP	Water Storage SUTPP	0.2 m Deep, Inner 75% Area Clear Plastic Top Black Bottom Water Tank (Thermal Storage)
ASUTPP	Airflow Regulated SUTPP	Regulated Airflow Under Secondary Canopy Enhances/Releases Ground Thermal Storage
ASUTPP-DG	Double Glazed ASUTPP	Entire secondary Canopy is Double Glazed.

significantly more resistant to breakage, and will break into many small pieces, both of which reduce danger to people. Tempered glass, also called toughened glass, is also much more resistant to breakage from hail (see Appendix B), which can significantly reduce glass replacement rates over the life of the power plant, saving GWP impact, and reducing EROEI by saving both energy to repair and downtime. Coatings may be added to reduce reflection losses, but they cost more, and often are not as durable as the glass itself, so scratches from dust storms and cleanings, and any environmental degradation may compromise their value. Pretorius (pp. 32-37 [2]) simulated the results of different transparency characteristics, and decided to use 4mm glass. The literature survey for this thesis indicated other researchers typically assume float glass, often 4mm, preferably tempered and low iron, with concern about the extra cost of low iron glass & any coatings. A cost analysis by Fluri et al. (2008) assumed a cost of 11.49 Euros/m^2 [93], however, an informal online survey of glass for sale (wholesale) included many sources (many from China) for nearly clear tempered low iron glass for a few dollars per m^2. Therefore this thesis assumes 4 mm low iron tempered float glass is a viable choice for all configurations listed in Table 4.10.

The quantity of glass required for each SUTPP configuration is estimated in Appendix E and included with the collector structure in Section 4.6.

4.5.2 Other Transparency Materials

Time and resources permitted limited consideration of other transparency materials. Two materials are presented below. One was selected for LCA in this thesis.

Polycarbonate is impact resistant and has excellent optical properties, however, it is not as scratch resistant as glass, and tends to photo-degrade, causing it to yellow and/or become more susceptible to breakage, including by hail. (James and Wei [94] showed old UV degraded polycarbonate breaks more easily when it has warm greenhouse air under it and the air above is suddenly cooled by a hail producing thunderstorm.) This thesis considers polycarbonate an unacceptable choice due to its degradation over time.

EnviroMission plans to use Ethylene tetrafluoroethylene (ETFE) transparency material [24], however more specifics were not available as they were not willing to share what they may consider proprietary information to assist with this LCA effort. ETFE is a copolymer of ethylene and fluoroethylene. Robinson's Master's Thesis [95] provides an excellent introduction and summary of its capabilities and applications, and served as a motivation for much of what is said here. Robinson [95] describes the chemistry of its manufacture, which can be made from non-petrochemical feedstock. ETFE is a relatively ideal plastic film that has been used as an alternative covering for buildings, stadiums, walkways and greenhouses, most often in inflated/pressurized "pillows" two or more membrane layers thick, however it can also be used as a single tensioned layer membrane. Old and torn pieces can be recycled into new membranes. Different sources cite the estimated life as at least 30-50 years, as it does not suffer from the photo-degradation problems of many plastics. It is in the same chemical family as Teflon and has a non-stick surface. Exterior surfaces tend to self clean with rain, as dirt does not stick, so it may not require wiping, only spraying with proper drainage to clean. Judging by the snow loads ETFE can withstand, a 0.2 mm membrane of reasonable size should withstand reasonable spraying and possibly mild wiping forces. ETFE will get dimpled by hail a little over an inch (2.5 cm) in diameter, and can be penetrated by large hail. Damaged ETFE can be either patched or replaced. The source and recycling plants are probably in Europe. Fortunately the shipping bulk is only 1/20th that of glass (neglecting packaging or framing.)

ETFE pillows use air to assure proper tension, resist wind flapping, and form domes that will shed water and any non-adhering matter towards pillow edges. A clean transparency admits more energy and produces more power. Pillows also provide insulation to retain trapped heat and boost power output. Results (Chapter 6) show the power gain can more than offset the GWP and EE investment of the second layer of ETFE. Pillows will bulge into the airflow below, which will cause air drag and reduce performance. Pillows may be damaged if left deflated and exposed to winds (above and below). According to Tanno [96] for each 1,000 m^2, a typical building requires a 100 W primary fan used 50% of the time and a 220 W backup fan on standby. For a nearly 20 km^2 collector, that entails 20,000 primary and 20,000 backup fans, averaging 1 MW continuous power draw. This thesis questions the viability of pillows since the maintenance effort and supply chain required seem excessive and risk plant reliability.

A single layer of ETFE must be properly tensioned to stay taught across the expected temperature range of +127°F (+53°C) and +9°F (-13°C) (as measured in nearby Parker Arizona [97]), which will cause about an 0.8% length change given its coefficient of thermal expansion of $7.3x10^{-5}$ 1/°F ($1.3x10^{-4}$ 1/°C) [98]. A taught horizontal membrane will sag and trap a little water in a shallow pool at its center, complicating cleaning. However, the hyperbolic collector is sufficiently sloped near the tower to shed water without sagging and pooling. This suggests the rest of the canopy may be drained by incorporating shallow vaults as shown in Figure 4.3. (More extreme vaults are possible if one adopts the alternate design suggested by Bonnelle [26] mentioned in Section 1.1, that may prove superior for rain and machine cleaning of glass or ETFE. However this thesis limits its focus to disk shaped collectors.) Drainage may be enhanced by spraying water at an angle or blowing air to move wash water towards drains. The vault ridges should be parallel to airflow to minimize drag losses. A study may be required to determine how much vaulting is optimal and at what performance impact. However the losses may be less than that due to pillows that often bulge quite a bit, even though pillows offer the advantage of smooth round shapes. If a double glazing (2 ETFE layers) were used, the bottom layer need not be vaulted, alleviating the drag loss problem on the lower surface. This thesis assumes any ETFE "double glazing" consists of 2 layers of ETFE held at an appropriate spacing to be determined by subsequent research. Reasonable care must be taken to avoid permanent stretching leading to sagging, wind flapping and possibly damage. This appears quite feasible, given ETFE's resistance to stretching over time [99]. Most importantly, a membrane properly tensioned for long life is a simple passive installation with no motors, sensors or pressurization fault monitoring systems to fail, suggesting it may prove significantly more robust and reliable than pillows.

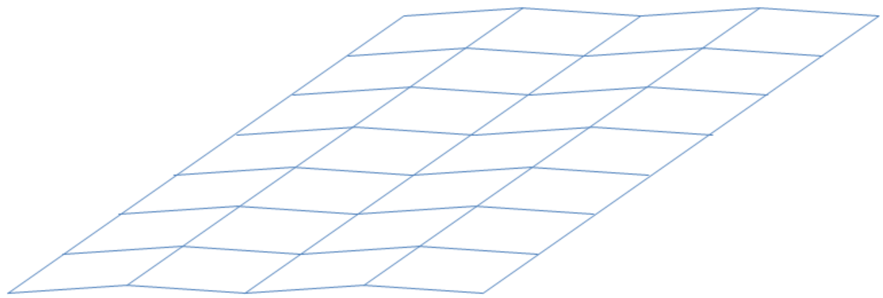

Figure 4.3. Shallow ceiling vaults to avoid water pooling.

For the reasons discussed above, this thesis assumes ETFE will consist of tensioned membranes. Other design concepts include replacing only the lower pane of double glazing with ETFE, or protecting a secondary canopy of ETFE under an upper glass primary canopy.

Glass may be more practical, durable and long lasting that ETFE. However, ETFE appears to offer easier cleaning, lower energy investment and higher EROEI that may be helpful or necessary to make a SUTPP a viable venture that is competitive with other power plants. There are many firms that design, install and service ETFE. Evidently EnviroMission concluded enough expertise exists to attempt to capture the benefits of ETFE. This thesis evaluates the glass and ETFE cases in Table 4.11, to determine whether preliminary LCA results justify considering ETFE instead of glass, while noting significant concerns about maintaining 20 km^2 of ETFE have not been fully addressed which are left for future research.

The effect of using ETFE instead of glass on SUTPP performance cannot be quantified for this thesis as adequate information was not be found to model it, or to submit all the required constants to Pretorius [87] or Bernardes.[88], who offered to run a SUTPP performance simulation. Other authors have noted the lack of data and models for ETFE [100, 101]. What work has been done suggests the performance will be similar to glass as ETFE allows slightly

Table 4.11

GLASS VS. ETFE TRANSPARENCY CASES

SUTPP Configuration	Material Used
BSUTPP, WSUTPP (1 Transparency Layer)	Glass
	ETFE
BSUTPP-½DG (1 ½ Transparency Layers)	All Glass
	Glass top protects ETFE immediately below.
BSUTPP-DG (2 Transparency Layers)	All Glass
	All ETFE
ASUTPP (Primary and Secondary Canopy)	All Glass
	Glass Primary protects ETFE Secondary
	All ETFE
ASUTPP-DG (Primary with Double Glazed Secondary Below)	All Glass
	Glass Primary, Glass top Secondary protects ETFE immediately below
	Glass Primary over ETFE Secondary
	All ETFE

more solar energy in at almost all wavelengths as glass, including significantly more long wave infrared, which will permit slightly more heating during the day and somewhat more heat loss at night [100, 101]. This thesis assumes roughly the same performance for glass or ETFE, however, the lack of substantiation for ETFE SUTPP performance must be considered when interpreting ETFE LCA results, which are therefore somewhat more uncertain. Consideration was given to omitting ETFE from this thesis over these concerns. However it was felt it was more appropriate to accept modest additional uncertainty to determine if the significantly lighter collector possible with ETFE offered enough GWP and EROEI advantages to be worth addressing the challenges of ETFE.

4.5.3 Replacing and Cleaning Transparency Material

Any transparency material will experience some loss, damage or degradation requiring replacement of some or all of the canopy transparency during its lifetime, possibly more than once. A few missing panels may barely reduce plant performance. A few localized holes can be patched with just about any material, (Even if it is not transparent), that keeps the air in to allow the plant to continue operating. To avoid performance degradation due to holes or numerous non-transparent patches, a store of transparent replacement panel material needs to be kept onsite, and means must exist to find and repair damage in a timely manner. ETFE may be useful as temporary or emergency patch material for a glass collector. The principal concerns are for sudden wide scale transparency loss and degradation over time. Risks of sudden loss comes from hail, which should not be a problem at La Paz, severe winds (the plant should be designed for worst winds cited in Appendix A) and sandblasting during a severe sandstorm, which is a risk that was not be adequately quantified by this thesis. Assuming the material does not photo-degrade, long term concerns include scratching from windblown sand and the potential development of caked on deposits that do not respond to cleaning.

One mitigation strategy may be to store enough material onsite to replace the entire transparency at any time. That entails a substantial upfront investment of money (with interest), energy and GWP impact, which must be weighed against the risk of needing transparency material on short notice or when it is difficult to obtain, and the criticality of continued output of the SUTPP. A risk assessment is required to address these considerations.

Consideration may also be given to the distance to the source of transparency replacement material, whether it can be recycled, and whether the recycling facility can be nearby to minimize risk of supply becoming unavailable if energy or transportation is constrained future. Unfortunately, locating a recycling plant nearby in the desert places it far from other markets, and it cannot be economically justified just serving the SUTPP. However, major cities in California are not far away, so if economic activity declined and became more localized (due to high energy and transportation costs) there may be enough demand to support glass recycling plants within at most a few hundred kilometers of the power plant. Preliminary research outlined in Appendix A suggests there may be adequate existing glass production and recycling facilities within a 600 km radius by road for initial construction.

ETFE production facility locations were not researched. Instead, EFTE was assumed to be trucked 3,000 km as that assumption embodies enough energy to account for either shipment from much of North America or a combination of intercontinental shipping by freighter and long haul trucking from a port in California. Given that the total mass of ETFE required is much smaller than that of glass, and the energy and global warming impact to transport it is a few percent of that required to manufacture it, this thesis takes the position the impact of ETFE transportation distance is small, and the principle concern is any critical material that requires long distance transport may be hard to obtain in the future, and therefore establishment of local or regional manufacturing capability may be in the regional or national interest, if it does not already exist at sufficient production capacity.

Appendix A determined that hail was rare and unlikely to be large enough to damage tempered glass at La Paz. Dulling due to scratches due to blown dust or cleaning, or caked on deposits that can't be removed by cleaning, may require partial or total glass replacements at times. (Refer to Appendix C for a discussion of glass cleaning). The overall average glass replacement rate is not clearly understood, requires additional research, and as at best a judgment call. Similarly, while ETFE has enough prior use and contractor experience to suggest a life of decades, possibly over half the 80 year life of the SUTPP, there is inherent uncertainty in its required replacement rate, which is compounded by lack of an installation design, concerns over maintaining an ETFE installation over 20 km^2, and any additional challenges posed by having nearly continuous winds inside the collector. Therefore the replacement rate cases in Table 4.12 are assumed by this thesis to explore the probable range of outcomes, based upon an overall judgment of risks. "Medium" cases will be used for generic LCA of SUTPP configurations. "High" and "Low" cases will be evaluated for selected configurations to estimate potential variation in LCA outcomes. ("DG" means Double glazed, "ETFE DG paired with glass" is ETFE directly under glass as a substitute for DG glass. "300%/lifetime" means it will be replaced 3 times per SUTPP lifetime.)

Table 4.12

GLASS AND ETFE REPLACEMENT RATES

Case	Glass	ETFE
Low	Top Surface 6%/lifetime	Top Surface 120%/Lifetime
	Secondary Surface 2%/lifetime	Secondary Surface 50%/Lifetime
	DG 40% of surface above it.	ETFE DG = Same as single layer
		ETFE DG under glass 25%/Lifetime
Medium	Top Surface 25%/lifetime	Top Surface 300%/Lifetime
	Secondary Surface 10%/lifetime	Secondary Surface 150%/Lifetime
	DG 50% of surface above it.	ETFE DG = Same as single layer
		ETFE DG under glass/Lifetime = 75% top, 50% bottom
High	Top Surface 100%/lifetime	Top Surface 800%/Lifetime
	Secondary Surface 50%/lifetime	Secondary Surface 400%/Lifetime
	DG 50% of surface above it.	ETFE DG = Same as single layer
		ETFE DG under glass/Lifetime = 300% top, 200% bottom

Section 3.4.4 discussed the need for cleaning. Substantial challenges of developing and maintaining a cleaning system for a 20 km^2 collector are considered in Appendix C, which outlines rough requirements for such a system, which support the generic definition of tankage and water purification requirements for cleaning derived in Appendix E. This thesis assumes

the cleaning rates in Table 4.13 span the range of probable outcomes, and 5 yrs stored water. ”Medium” cases will be used for generic LCA of SUTPP configurations. “High” and “Low” cases will be evaluated for selected configurations to estimate potential variation in LCA outcomes.

Table 4.13

GLASS AND ETFE CLEANING RATES

	Glass			ETFE		
	Frequency	Clean /5yr	5 yr Tanks	Frequency	Clean/ 5yr	5 yr Tanks
Low	Top Surface 5 x/decade	2.5	50 kt	Top Surface 1 x/decade	0.5	30 kt
	+ Secondary 2.5 x/decade	3.75	75kt	+ Secondary 0.5 x/decade	0.75	45 kt
Medium	Top Surface twice a year	10	200 kt	Top Surface 3 x/decade	1.5	90 kt
	+ Secondary 10 x/decade	15	300 kt	+ Secondary 1.5 x/decade	2.25	135 kt
High	Top Surface 6 x/year	30	600 kt	Top Surface yearly	5	300 kt
	+ Secondary 3 x/year	45	900 kt	+ Secondary 5 x/decade	7.5	450 kt
Multiply "5 yr Tanks" x 2 for all but WSUTPP to provide 2nd set of tanks to hold unpurified runoff water.						

4.6 Collector Structure

The collector structure is assumed by this thesis to consist of concrete footer, supports, and a “grid” or “matrix” that holds the transparency material, which Bernardes [67], Schlaich [68], and Kraetzig [89] assume is steel (supporting glass). This thesis makes the same assumption, and Appendix E derives the following specifications for potential configurations summarized in Table 4.14. Case 1, the “Light” configuration is an adaptation of the Work of Bernardes and his source (Schliach), whereas case 3, the “Heavy” configuration is a specific design provided by Kraetzig that can hold 5 or 6 mm glass and accommodate a 9 m wide glass cleaning machine that is not yet specified, however, the structure appears to be adequately robust. Case 2 adds aspects of case 1 when extra layers of glass are needed to minimize the extra mass required. Green font values are added together in the spreadsheet to calculate the amount of structural steel. The violet spreadsheet cells divided by bold horizontal lines address the transparency material options listed in Table 4.11. Yellow spreadsheet cells have the same values for all configurations for each case (case 1, 2 or 3). ETFE cases were omitted for cases 2 and 3 because it did not make sense to save GWP and EE by eliminating that much glass without also reducing the impact of a massive case 2 or case 3 structure. To further lighten the case 1 structure for ETFE, the BSUTPP-DG ETFE option assumes 2 ETFE membranes are inserted into a structure that is mass-equivalent to the BSUTPP case, and the ASUTPP-DG ETFE only option assumes the single layer primary and double glazed secondary are inserted into the mass-equivalent of the glass ASUTPP structure.

4.7 Tower Definition

Pretorius [2] specified a 1 km tall 210 m diameter tower, which was adopted by Fluri [37]. The literature review for this thesis yielded chimney design information on four configurations:

1. 1 km tall 150 m diameter cylindrical tower on a 280 m diameter base using external stiffening rings (shapes that double as access balconies) to avoid the need for internal bracing wheels by Kraetzig [31, 89].
2. 1 km tall slightly hyperbolic tower 145 m in diameter at the top, 133 m in diameter at the narrowest (500 m high), and 260 m in diameter at base, also with external stiffening rings, by Kraetzig et al. [31].
3. 1 km tall 110 m diameter tower by Schlaich et al. [102], briefly described by Fluri et al. in a cost analysis paper [93] that scaled down towers (by decreasing

diameter or cutting off extra height at the bottom) to obtain concrete volume estimates of smaller towers.

4. Scale up of a 750 m tall 100 m diameter tower shell by Kraetzig [89].

Table 4.14

MATERIALS NEEDED FOR COLLECTOR

Config	Item	Unit	Case 1 Qty	Case 2 Qty	Case 3 Qty
BSUTPP	4mm Tempered Float Glass (Low Iron)	(t)	195,093		195,093
WSUTPP	0.2 mm ETFE (Single Layer)	(t)	6,825		6,825
	Steel Grid Structure	(t)	90,626		408,756
	Steel Supports	(t)	14,351		87,893
	Structural Steel (Total)	(t)	104,976		496,649
Same	Steel Rebar	(t)	979	4,734	4,734
for all	Concrete C 70/85 (Supports)	(t)		32,504	32,504
Configurations	Concrete (Footers)	(t)	34,003	164,462	164,462
BSUTPP-1/2 D	4mm Tempered Float Glass (Low Iron)	(t)	292,639	292,639	292,639
	Glass on top only		195,093		
	0.2 mm ETFE Under 50% of Glass		3,413		
	Structural Steel (Total)	(t)	115,474	507,147	546,314
BSUTPP-DG	4mm Tempered Float Glass (Low Iron)	(t)	390,186	390,186	390,186
	Structural Steel (Total)	(t)	125,972	517,645	595,979
	ETFE DG, (2) 0.2 mm Layers		13,650		
	Structural Steel (Total)	(t)	104,976		
ASUTPP	4mm Tempered Float Glass (Low Iron)	(t)	390,186	390,186	390,186
	Glass on top only	(t)	195,093		
	0.2 mm ETFE Secondary	(t)	6,825		
	(2) Canopies 0.2 mm ETFE	(t)	13,650		
	Structural Steel (Total)	(t)	157,465	549,137	905,406
DG-ASUTPP	4mm Tempered Float Glass (Low Iron)	(t)	585,279	585,279	585,279
	Glass on top of each Canopy	(t)	390,186		
	0.2 mm ETFE bottom Layer Secondary	(t)	6,825		
	Glass on Primary (Outside) Only	(t)	195,093		
	0.02 mm ETFE DG Secondary	(t)	13,650		
	Structural Steel (Total)	(t)	188,958	580,630	1,004,736
	0.2 mm ETFE Top and DG Secondary	(t)	20,475		
	Structural Steel (Total)	(t)	157,465		

The above were used, along with a cost analysis by Fluri et al. [93] and personal communication with Kraetzig [89], in Appendix E to derive a representative specification of what is required to construct the tower, which is summarized in Table 4.15. Properly maintained, a concrete structure may outlast the intended life of a SUTPP in a dry dessert climate. However, this thesis does not model the concrete maintenance process. (Concrete designations such as C50/60 designate the cylindrical (150 x 300 mm) and cubical compressive strength in MPa after a 28 day cure.)

TABLE 4.15

TOWER AND FOUNDATION REQUIREMENTS

Item	Qty
Tower Concrete C50/60	682,738 t
Tower S500 Steel Reinforcement	21,831 t
Foundation Concrete C25/30	181,432 t
Foundation S500 Reinforcement	4,470 t
Foundation Excavation	130,947 m^3
Foundation Refills	44,491 m^3

4.8 Turbine, Generator and Electrical Systems

Multiple horizontal axis turbines offer a number of access and maintenance advantages described in Section 3.3. Fluri [37] showed multiple horizontal axis turbines were more economical overall, and provided optimized configuration information for the BSUTPP, ASUTPP, and BSUTPP-½DG configurations. Therefore this thesis assumes multiple horizontal axis turbines will be used according to Fluri [37], along with an under canopy access road, vehicles, and provision to erect an aerodynamic isolation partition around a turbine/generator requiring maintenance or replacement to provide a suitable work environment. The definitions of the BSUTPP-DG, WSUTPP, and ASUTPP-DG configurations were synthesized by extrapolating comparable values in Appendix E, to produce the specifications in Table 4.16, which are used in Appendix F to derive an approximation of the GWP and Embodied energy impacts of the turbines presented in Chapter 5.

TABLE 4.16

TURBINE/GENERATOR UNITS

Type		BSUTPP	BSUTPP	BSUTPP	WSUTPP	ASUTPP	ASUTPP
Subtype			1/2 DG	DG			DG
Power Regulation		Free	Free	Free	Base	Base	Base
GWh/y	Pretorius	336	423.8	463.6	327	330.9	362.7
	Fluri	328	415.5			332	
Peak	Summer	124	149	157	79	71	62
	Winter	62	76	78	20	28	27
Low (Est)	Summer	15	22	26	36	39	53
	Winter	6	12	14	15	16	23
# Turb		27	29	30	25	25	28
Power/Unit (MW)		5.09	5.57	5.65	3.41	2.77	2.33
(#Turb)*(Mwcap @)		137.43	161.53	169.56	85.32	69.25	65.1
Cap Factor		0.279	0.300	0.312	0.438	0.545	0.636

As was previously discussed in Section 3.3, Fluri [37] indicates multiple horizontal turbines are more economical than one large vertical axis turbine. Equally clear are practical arguments for this configuration to minimize risk and maximize capacity utilization with the more robust and resilient multi-turbine configuration that continues operating when one or a few turbo-generators are offline or being repaired. Fluri [37] advocates use of Direct Drive Permanent Magnet (DDPM) generators. It is assumed the system can be controlled to cut in different numbers of generators as airflow increased or decreased to operate each turbine/generator unit near is optimum operating conditions. Provision may need to be made to dump excess airflow out through one or more ceiling hatches if system capacity were exceeded or the plant needed to be taken offline to avoid turbine overspeed due to loss of electrical load caused by lightning strike or other electrical grid system failure. Consultation with Dr Wentz, Aeronautical Engineering professor emeritus at WSU, recognized wind energy subject matter expert [69], and thesis informal committee member, was sought to assure the top-level treatment of turbo-generators, while quick & approximate, was reasonably representative.

4.9 Other Infrastructure

This thesis assumes the SUTPP will at a minimum have the following, which are summarized in Table 4.17, with sizes chosen arbitrarily or as described below. An actual plant design will have much more specific, possibly larger requirements. This thesis assumes these are minimal requirements, included to determine if the impact they make is of a magnitude that can be accommodated.

- Control building to house control systems, offices, break/cafeteria room, and some overnight sleeping rooms.
- Visitor's Center with lobbies, restrooms, cafeteria, gift shop, of same size, materials and utility use as the control building.
- Workshop building for fixing items onsite.
- Onsite storage facilities, that may be a mixture of vacant land, platforms to support pallets and heavy items that can be covered with a tarp, and storage buildings to protect items from the weather and if necessary ambient temperature or humidity conditions. Only the permanent building storage will be modeled for LCA. The nominal, small building option will be the same size as the workshop, with minimal environmental controls. The large building option will be large enough to house a full change out of collector glass 4 mm thick at 30% space utilization stacked 6m high.
- Three lane concrete road from the entrance past the buildings to the center of the collector where either the tower footing or a circular road will allow access to replace failed power generating components.

- Perimeter fence, lights, and other items are deemed to be too ambiguous and insignificant to merit modeling for LCA.

4.10 Summary of Plant Definition

Table 4.18, lists the tables that provide inputs to the LCA.

TABLE 4.17

OTHER INFRASTRUCTURE

Item	Size	Area/vol/mass	Description
Control Building	One Story 30 x 20 x 3 m	Floor Area 600 m^2	Concrete slab, walls, commercial type roof. HVAC/Utilities demand for computers/offices/cafeteria/overnight rooms
Visitor's Center	One Story 30 x 20 x 3 m	Floor Area 600 m^2	Concrete slab, walls and roof, HVAC/Utilities demand similar to control building.
Workshop	One Story, High Ceiling 50 x 25 x 6 m	Floor Area 1,250 m^2	Concrete slab, walls and concrete or steel ceiling with 50% of control building utility use energy due to HVAC.
Storage (Minimum)	One Story, High Ceiling, 50 x 25 x 6 m	Floor Area 1,250 m^2	Concrete slab and walls, commercial type roof, with no environmental control, just lights and any inventory access equipment on intermittent demand.
Storage (Maximum)	One Story, High Ceiling, 260 x 26 x 6 m	Floor Area 67,600 m^2	Concrete slab and walls, commercial type roof, with no environmental control, just lights and any inventory access equipment on intermittent demand.
Road	5 km x 10 m x 0.2m thick	67,600 m^3 16,240 t	Approx 3 lane width road/freeway. Gate to & around center.
Other	N/A (Ignored)		N/A (Ignored)

TABLE 4.18

LCA INPUT TABLES

Table #	Title
4.7 4.8 4.9	Water Tank Materials Potential Water Purification Water Transportation
4.13	Glass and ETFE Replacement Rates
4.14	Glass and ETFE Cleaning Rates
4.15	Materials Needed for Collector
4.16	Tower & Foundation Requirements
4.17	Turbine/Generator Units
4.18	Other Infrastructure

CHAPTER 5

LCA METHODOLOGY AND IMPLEMENTATION

Section 5.1 introduces the standards, concepts and four phase methodology for performing a Life Cycle Assessment (LCA). Section 5.2 describes how the SUTPP LCA addresses each of those four phases. Section 5.3 introduces the spreadsheet used for LCA.

5.1 Life Cycle Assessment Methodology

ISO 14000 [65] is the widely accepted international standard for Environmental Management from the International Organization for Standardization (ISO) [65]. ISO 14000 consists of multiple standards, many of which have some relation to the process of conducting and documenting a particular LCA. The actual standards are too long to reproduce here, and are copyrighted and sold on the ISO website [65]. A list of standard titles with some relevance to LCAs appears in Appendix H. A literature search revealed some free uncopyrighted materials that provide a helpful and relatively comprehensive overview of the LCA process. Section 5.1 of this thesis is based on one of the most helpful guides, “Life Cycle Assessment: Principles and Practice” by Curran [63] at Scientific Applications International Corporation (SAIC), prepared for the US Environmental Protection Agency (EPA). Precise quotations appear in “quotes”, but otherwise this thesis presents a mere summary overview of Curran [63]. Those desiring more details are strongly encouraged to read the original document, or the ISO standards listed in Appendix H.

Life Cycle Assessment (LCA) is a method for comprehensive evaluation of the environmental impacts of all aspects and phases of a product, or process life cycle, from “cradle to grave”, including everything from acquiring raw materials, through its use, to its ultimate disposal. LCA can be conducted on parts, such as a screw, or entire systems, such as a SUTPP, and may include either the entire lifecycle or only part of it, such as the construction phase. Attempting to fully model even a simple system in a LCA usually results in inputs too numerous and ambiguous to fully understand, for which adequate information cannot be practically obtained to fully model the life cycle of the system. Therefore, depending on the intended use of the LCA results, simplifications are made, such as deciding what to include in the system boundary, how to approximate unknown, complex or ambiguous inputs or aspects, which impacts to consider and how they are grouped, or which alternative types of LCA may be used, such as a comparative LCA that examines only the difference between two otherwise nearly identical processes or products to provide decision makers with comparative information to select the most optimal choices.

Life Cycle Assessment consists of four phases: (1) Goal and Scope Definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation, which many authors, including Curran [63], portray in a diagram such as Figure 5.1. The process is typically iterative, such that prior work may be revisited or revised as work progresses. If the purpose of the LCA is to optimize a system, various aspects of the system may be varied to optimize the system, taking into account the limits to choice and practical tradeoffs, such as cost and technical risk.

5.1.1 Goal and Scope Definition

The goal for doing the LCA must be determined, which should be related to the target audience for the results and the type and quality of data needed or desired. The LCA may be intended to produce impact numbers for a known process, or product, which will collectively be called a system for brevity. The LCA may be a "comparative" LCA that compares systems to each other. It may also be used to weigh options and optimize the plan or design a system.

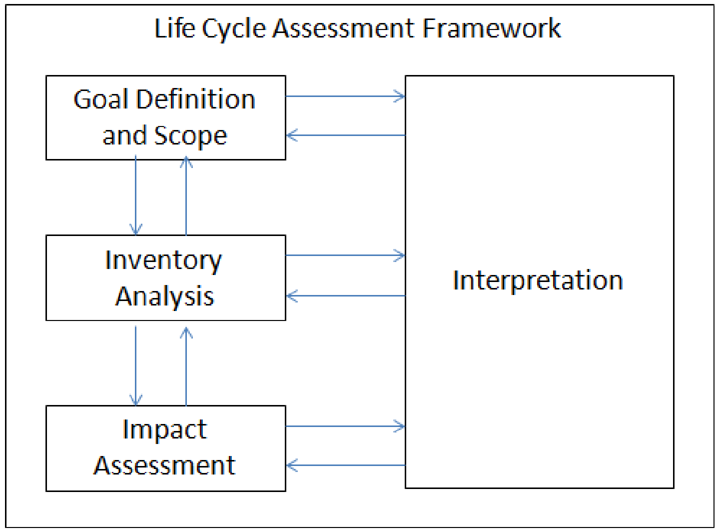

Figure 5.1. Life cycle assessment phases [63].

The scope of the LCA begins with a product (or process) "description." The demands the product must fulfill must be understood so its function can be defined, which leads to a "functional unit" of benefit it provides against which the lifecycle impacts can be weighed. For an electrical power plant the "function" is providing reliable electric power and the "functional unit" is GWh.

The impact of the system can be measured either in all its specific effects, both harmful and beneficial, including all the waste products and waste heat, or simplified into broad categories of impact such as global warming and human toxicological Impacts, which have been similarly defined by various organizations, including ISO and SAIC, which are summarized in Table 5.1

TABLE 5.1

COMMONLY USED LIFE CYCLE IMPACT CATEGORIES [63]

Impact Category	Scale	Examples of LCI Data (i.e. classification)	Common Possible Characterization Factor	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical Oxident Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Human Health	Global Regional Local	Total releases to air, water, and soil.	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications	Land Availability	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Water Shortage Potential	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.

These effects may occur on a local, regional, continental or global scale. It may be easy to spot a tenfold increase in the cancer rate in a small town consisting of 100 new cases, but impractical to discern that number of cases spread out over an country due to widespread airborne dispersal of a carcinogen. That does not mean the impact is not there, and it may only be apparent by knowing the effect of a tiny increase in background dose and the amount released over time. The relative weighting of all members of a category is determined by a combination of scientific comparisons when applicable and other methods, like computing monetary costs, increased mortality or incidence of sickness or disability as measured by average reduction in years of healthy life remaining, or some standard arrived at or derived by a committee of stakeholders or regulators based on collective judgment or other considerations that seem appropriate to the impact category. For more information on this, refer to Curran [63].

“Assumptions” and “System Boundaries” simplify the LCA by focusing on aspects of interest. The life cycle of a system includes many aspects, such as IT infrastructure to support product development, factories that build construction machines, and spending by employees, that connect to an interdependent world infrastructure. The standard LCA approach identifies and models specific contributions, such as tons of steel required, or extrapolates impact from an LCA on a comparable item, such as a similar generator.

A more comprehensive LCA approach may hybridize the classic LCA methods discussed here with Economic Input-Output (EIO) LCA methods, which employ correlations of currency units (such as dollars) of economic activity in each sector of the economy with activity in every other sector and data depicting the average environmental impact of currency spent in each sector of the economy, thereby capturing higher order effects such as workers using cars or health insurance. However, EIO-LCA methods require access to national or regional EIO databases and use of software to perform linear algebra with very large square matrices a few hundred rows by columns representing all the economic sectors. Additional steps are required to assure all relevant aspects of the system are included, yet not counted multiple times. A proper discussion of these concepts is beyond the scope of this thesis, which will rely on simpler standard methodology. Additional information may be found in [62].

Complexity can be reduced by either ignoring the larger economic system (implicitly assuming the rest of the economy won't be much different) comparing the system of interest to an alternative, or making simplifying assumptions. For example, a photovoltaic power plant may be compared to a coal power plant by comparing only the parts that are different and leaving out the fences, roads and power lines that are the same. This may require obtaining LCA data on a complete coal plant and "backing out" the contributions of the parts not modeled for the photovoltaic plant. Reasonable simplifications include assuming one representative shipping distance for all steel parts or an average value for many small plastic parts if plastic parts made a very small overall contribution.

System boundaries also include specific life cycle phases, such as "raw material acquisition" and "construction" (which may be combined as "construction"), "operation and maintenance" (often called "use") and "decommissioning". A "cradle to grave" LCA includes all these phases. A "cradle to gate" LCA may only include plant construction or construction and use. The system or process studied is often broken into sub-processes, like making steel, hauling billets and forming wire. System boundaries can exclude an intermediate process like transportation because the LCA may be comparing two wire making systems with identical transportation requirements.

Consideration should be given to the data quality, the practical need for accuracy and the ability to obtain the needed data for a desired level of accuracy. Consideration ought to be given to issues such as how precise the data is (variance), how complete the data is and whether it can be made representative of the range and behavior of the phenomena. Also of concern is whether the same methodology, standards and accuracy can be applied to all the components of the system being studied, and whether the results are likely to be reproducible by someone else using similar methods and data. If parts of the system can only be roughly quantified, they may cause a large uncertainty in the final values if they are large contributors or only a small variation if they are insignificant contributors. This may not become apparent until the LCA is well underway. The data quality, need for accuracy and resources available to perform the LCA, as well as its intended use must be weighed to choose system boundaries and any simplifying assumptions to provide the best practical meaningful results given the LCA goal, data and resource limitations. The system boundaries, assumptions, and other aspects of the LCA may have to be readjusted to address practical considerations as the LCA progresses and matures.

A formal LCA process should conclude its initial goal and scope definition phase with a definition of how the results should be presented, a definition of the overall format of the report, and definition of a formal review process, based on the needs of the end users or decision makers and their organizational, professional and ISO standards as applicable.

5.1.2 Inventory Analysis – The Life Cycle Inventory (LCI)

The inventory phase of the LCA identifies the system inputs, including raw materials and energy, and outputs, including energy (usable or waste heat), and airborne, water and solid waste emissions. The LCI is developed in part from a system process flow chart that also tracks valuable substances needed by, or produced by or used within the system under study. The LCI is required to proceed to the Life Cycle Impact Assessment (LCIA) step that determines the impact of the system under study.

The principal steps in the LCI phase include (1) Developing a flow diagram of the system, (2) Developing a data collection plan, (3) Collecting the data, and (4) Evaluating the LCI report results.

The flow diagram is an iterative process that assists with better defining what the system process is, what it consists of and how much detail is to be considered. Flow diagrams consist of boxes called "processes" or "steps", connected by arrows called "flows" that represent the "movement" of materials, products, energy, wastes, or other tracked items. The flow diagram may consist of many layers of flow diagrams that feed into one or more top-level diagrams, or the process may be intertwined with other processes so that inputs or outputs cannot be 100% attributed to the system under study. For example, waste heat water from a power plant cooling system may be used by the process under study and other processes, such that the percentage of power plant inventory and thus impact attributed to the system under study may vary, and need to be "allocated" in some representative manner. "Allocation" can be challenging, as some basis for it must be found, such as by cost, mass or volume, and may be complicated by variable flows. The system may produce co-products that are not part of the original intent, but that have value and can be sold rather than treated as wastes to discharge into the environment. For example, fly ash from a power plant may have use at another industrial facility.

The data collection plan (1) defines data quality goals (2) Identifies data sources and types, (3) identifies data quality indicators, and (4) a data collection worksheet and checklist. Data quality depends on the needs and accuracy requirements of the LCA. Sources need to be practical sources appropriate to the goals and accuracy requirements. Otherwise further iteration of the scope and methods may be required. Various techniques have been employed and discussed in the literature, including how to modify data available to the needs of the LCA, such as how to get the inventory data for a paper clip that is not yet bent to shape by subtracting what it takes to bend it from published data on the completed paper clip. Data Quality Indicators (DQI) may include "Precision, Completeness, Representativeness, Consistency and Reproducibility" [63].

Several standard databases exist that provide mostly generic data on common substances like steel wire, processes like transporting by truck, or electricity from the grid (US mix or a specific power plant type.) These save considerable time, and make LCA a practical undertaking for many applications of limited scope. However databases and software are often proprietary, requiring payment for access.

5.1.3 Life Cycle Impact Assessment (LCIA)

The LCIA phase assesses the environmental and human impacts of the energy and resource use and emissions from the LCI. A full formal LCA attempts to quantify things such as how many people died of cancer or were sickened by water pollution, as well as damage to land and water by acid rain, and many other estimated impacts. These involve complex causal chains, such as release of CFCs depleting ozone, causing crop damage and skin cancer. This quickly becomes quite complex. Therefore published standard approaches and results are used that greatly simplify this process.

The LCIA process standardizes the impacts of items obtained from the LCI into categories like global warming, acidification, ozone depletion and human health, characterized by quantifying impacts under a normalized unit of measure, such as t CO_2 Equivalent per unit of emission or per unit of useful substance produced. Commonly used impact categories include those shown in Table 5.1, reproduced from Curran, (p. 49 [63]). This thesis only addresses global warming via global warming potential (GWP) in t CO_2 Equivalent.

Published databases contain coefficients that when multiplied by the amount of material used, emission or energy provides the impact in a category like global warming. These databases include (among others):

- TRACI: US EPA "Tool for the Reduction and Assessment of Chemical and other environmental Impacts" [63]
- CML: Centre for Environmental Studies method which is similar and used in the European union.
- ICE: Inventory of Carbon and Energy by University of Bath by Hammond and Jones [103]
- EcoInvent: which requires paid access or access via a software package that uses some (or all) of the EcoInvent database, such as LCA Calculator, (which provides only very limited GWP data.)

The LCIA results can be grouped and weighed to simplify the important impacts and indicate which are deemed to be the most important.

Finally, the LCIA results are documented (listed and explained). It is important to describe "the underlying assumptions, simplifications and subjective value choices" [63].

5.1.4 Interpretation

The results need to be interpreted and presented in final documented form, including the assumptions and context within which the results must be viewed. Results may be complex and multi-dimensional, rather than a clear-cut recommendation. Key steps include:

1. Making the significant issues clear.
2. Checking for:
    a. Completeness: Is all needed data there?
    b. Sensitivity: One method is an uncertainty analysis. When the variation of inputs is poorly defined, another approach is to determine which inputs have the greatest effect.
    c. Consistency: Were all assumptions and approaches used in a consistent and appropriate manner?
3. Conclusions and recommendations.

The final report for a formal LCA must conform to the applicable standards, and pass critical review.

5.2 SUTPP Life Cycle Assessment Implementation

This thesis documents only the final results of the SUTPP LCA, after LCA iteration was carried out to provide the results for this thesis. The paragraph numbers and titles below mirror those in Section 5.1 as each paragraph below describes the results obtained through the methodology presented in Section 5.1.

5.2.1 Goal and Scope Definition

System Description: A Solar Updraft Power Plant (SUTPP) heats air under a transparent greenhouse-like canopy by solar energy, or energy released from thermal masses heated by solar energy, causing the air to rise by natural convection through a central chimney due to its lower density, thereby powering turbines at the tower base that turn generators to provide power to the electric power grid. The system includes a tower, collector, turbines, generators, electrical hardware to provide power to grid, control, maintenance and storage buildings and an onsite road. The system does NOT include power lines or roads beyond immediate area of plant or surrounding infrastructure.

Goals of Project: (i) Understand the overall environmental impact of a generic SUTPP, the main contributors to that impact, and the effects of certain design and maintenance assumptions on that impact. (ii) Provide Global Warming Potential (GWP), Embodied Energy (EE) and Energy Returned on Energy Invested (EROEI) estimates for a SUTPP to compare to other power plant types. (iii) Provide results to help determine if a SUTPP ought to be built, and how best to go about it.

Function and Functional Unit: The function is "to provide electrical power." The functional unit is gigawatt hours (GWh) of electrical energy.

System Boundaries: Cradle to Grave, including construction (raw materials acquisition and plant assembly), use (power production and maintenance), and decommissioning (demolition, removal and recycling or burial). The decommissioning phase will be broken into two alternatives: demolition & recycling vs. plant abandonment. (Decommissioning contributed little and cannot be adequately modeled, so the abandonment option, assumed to have no impact, was adopted for final results.)

Data Quality Requirements: Accuracy will be limited for a LCA of a generic SUTPP lacking more specific design definition. To assure the final overall SUTPP GWP and EROEI are certain enough for meaningful comparison to the work of others and other types of power plants, an uncertainty analysis will be conducted to show the GWP and EROEI have 90% confidence intervals within 20% of the expected (mean) value given the range of uncertainties of all input quantities (energy and materials used to construct, maintain or decommission) that neglects the uncertainty of impact coefficients. (Section 6.3 addresses impact coefficients.)

Comparison between Systems: The GWP and EROEI values obtained in this LCA will be compared to those of other power plant types found in the literature.

Results Format: All modeling assumptions and decisions must be documented as the LCA assessment model is created and refined. All data sources must be cited and appropriate in the context they are used. An attempt should be made to find good representative data and modeling methods within the time and resource constraints of this high-level study. All calculations must be presented in a fashion to permit understanding and verification of the math. (Appendices may be used to document details so the main body of the thesis can focus on overall reasoning and results.) Results formats must enable readers to fully view results for each case evaluated, and should at a minimum permit separation of construction, operation and decommissioning phases and the contributions of all aspects of the system modeled.

Review: The LCA must be sufficiently well formulated to make meaningful statements and support conclusions and suggestions for further research. (Additional review may follow as part of future extension of this research.)

5.2.2 Inventory Analysis – The Life Cycle Inventory (LCI)

Flow Diagram: The flow diagram for the SUTPP system appears in Figure 5.2. Construction and several maintenance activities include obtaining and transporting materials, and using equipment and energy to assemble them. Collector cleaning and repair involve runoff/cleaning water capture and recycling and ideally transparency recycling. Power generation results from solar energy entering a functioning SUTPP. Conventional decommissioning involves disassembly (or demolition) and either disposal (landfill or local burial) of materials or recycling of useful substances (for example metal or possibly crushed concrete). Decommissioning will be determined largely by the needs and resources of society at the time. The site may be rebuilt to produce power, or modified for use as a giant greenhouse, business or community structure, or it may be dismantled so its components and materials used for other applications. Alternatively, the site may by choice or circumstance (for example war or societal breakdown) have to be abandoned and allowed to degrade and ultimately be destroyed and reclaimed by weather and nature, as the materials used are not particularly toxic and will return to a relatively inert mineral-like state over time.

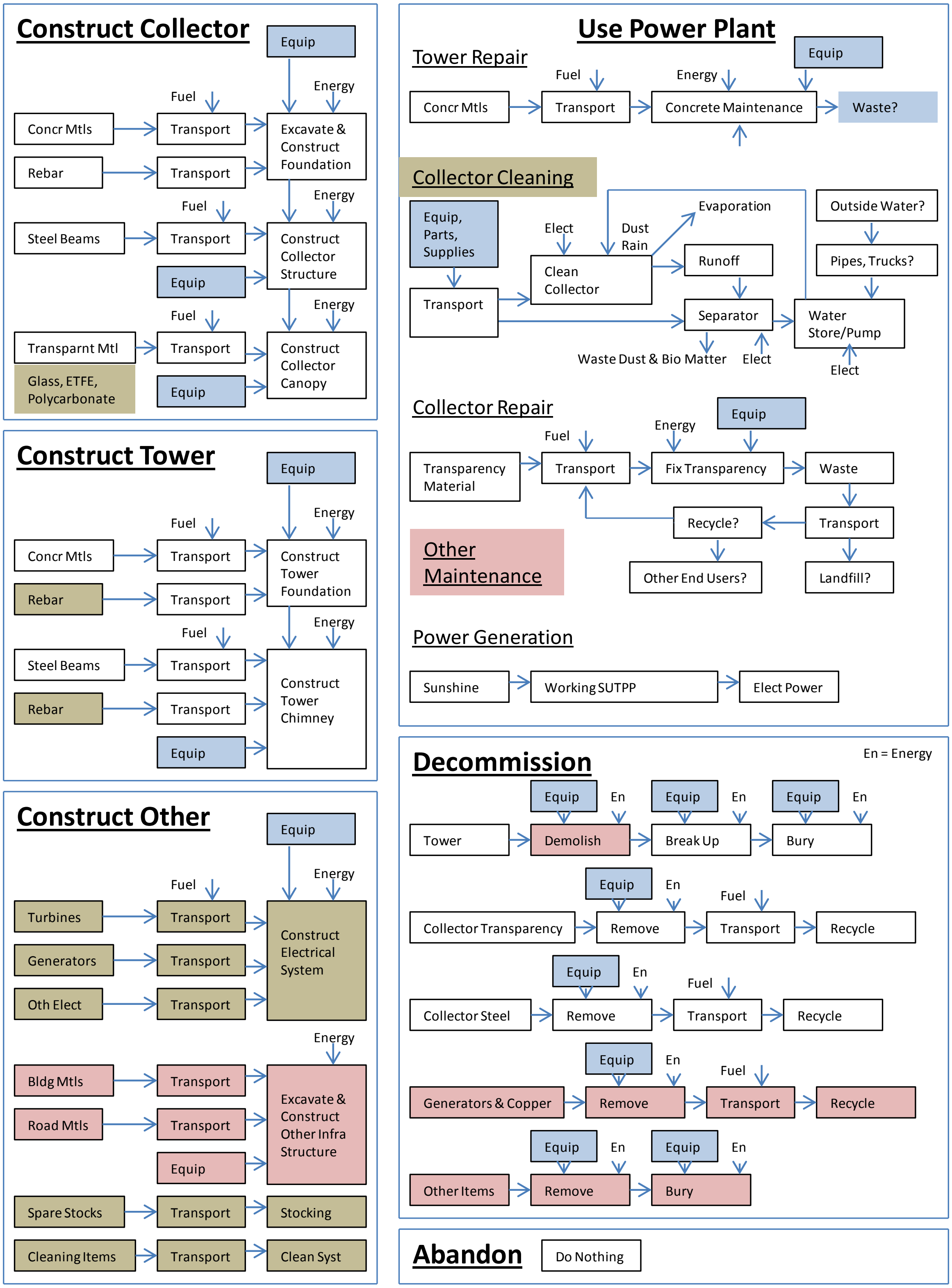

Figure 5.2. SUTPP life cycle assessment flow diagram.

Data Collection: The amounts of primary material (glass, steel, and concrete and its constituent components where necessary), and water (if needed to fill any water tanks) were obtained by determining the necessary volumes and masses from top-level design considerations. Transportation distances were estimated from Google Maps and information from the most credible sources online indicating where these items may be obtained in roughly the required quantity and quality.

The energy required to assemble the tower and collector was considered in Appendix E, found to be too complex and poorly defined to calculate, and shown to be very small relative to the energy required to obtain the steel, glass, and concrete. Assembly energy and GWP impact for the turbines, generators and other infrastructure considered was modeled by extrapolating more detailed studies of these components in Appendix F. Equipment used for tower and collector assembly and maintenance is often used for many projects, deemed too complex to model at this level of analysis, and like assembly energy, unlikely to be as significant as the large contributions made by the mass and energy intensive activities that were identified and modeled. Other authors found similar results for buildings and large civil engineering projects, thus it is accepted practice to ignore the contributions from assembly activities if they appear small and are too complex for practical analysis [104, 105]. Therefore it was decided to ignore many of the contributions of assembly equipment and assembly energy implied by Figure 5.2 to obtain useful rough total GWP and Embodied Energy (EE) impacts.

Since databases and peer reviewed reports were used to convert the SUTPP description into impacts, there was no formal LCI list in the sense intended by the standard methodology, listing the many emissions into water, air, or land to produce massive amounts of steel, concrete and glass. Instead, the tables listed in Table 4.18 define the material inputs to the SUTPP.

5.2.3 Life Cycle Impact Assessment (LCIA)

The impact coefficients per unit of input (summarized in Table 4.18) are listed in Table 5.2, Table 5.3 and Table 5.4, (for which more detail can be found in Appendix F.) Yellow cells in Table 5.4 denote the use of typical values for generic plastic and a generic plastic value for ETFE GWP, for which actual data was not found. No data was found for the red cells in Table 5.3. (Transportation energy was omitted from the LCA, as was energy to assemble, which was shown in Appendix E to be small relative to the energy embodied in the materials used.)

The impact of the turbine/generator units and electrical systems were estimated in Appendix F with results shown in Table 5.5, and the impact of Other Infrastructure was estimated in Appendix F with results shown in Table 5.6. Yellow cells in Table 5.6 denote the fact that road decommissioning was not included in this LCA.

Transportation distances were determined in Appendix A and the results are summarized in Table 5.7.

The amounts of steel, concrete, and glass, required transportation distances, support building floor areas, and work to be performed (known or merely assumed to be powered by electricity, since it was not known what was diesel powered), were multiplied by coefficients listed in Table 5.2, Table 5.3 and Table 5.4, to obtain the GWP and EE values which were summed in the spreadsheet defined in Section 5.3 and Appendix F to get the total t CO_2 Equivalent and EE for to compute EROEI for the SUTPP.

TABLE 5.2

ENVIRONMENTAL IMPACTS OF KEY MATERIALS (From ICE v 1.6a, Hammond and Jones [103])

	GJ/t	t CO_2 Eq/t
Concrete, High Strength	1.39	0.209
Concrete, Slabs, columns, Load Bearing	1.11	0.159
Concrete RC50	1.41	0.212
Concrete RC25 (C25/30)	0.95	0.128
for 25kg/m3 Rebar add	0.26	0.018
Road and Pavement	1.24	0.127
Glass, Tempererd	23.5	1.27
Fiberglass (Glass Reinf Plastic GRP)	100	8.1
Steel Bar	24.6	1.71
Steel Section (I-Beam)	25.4	1.78

TABLE 5.3

IMPACTS OF ELECTRICITY & TRANSPORT [106]

	GJ/	t CO_2 Eq/
Electricity /(MWh)	3.6	0.69
40t (27t payload) Truck /(km)		0.00007882
Container Ship /(km)		0.00001314

TABLE 5.4

ENVIRONMENTAL IMPACTS OF PLASTICS [103, 107]

	GJ/t	t CO_2 Eq/t
ETFE	26.5	3
Generic 0.5 mm Plastic	100	3

TABLE 5.5

TURBINE, GENERATOR, AND ELECTRICAL SYSTEM IMPACTS

		BSUTPP	B-1/2DG	B-DG	WSUTPP	ASUTPP	ASUTPP-DG	
Constr	GWP	78,999	92,852	97,468	73,566	79,614	74,843	t CO2 Eq
	EE	1,438,271	1,690,490	1,774,527	1,339,373	1,449,470	1,362,606	GJ
Oper	GWP	15,544	19,606	21,448	15,128	15,309	16,780	t CO2 Eq
	EE	297,448	375,173	410,407	289,480	292,933	321,084	GJ
Decom	GWP	3,566	4,191	4,399	3,321	3,594	3,378	t CO2 Eq
	EE	29,461	34,627	36,348	27,435	29,690	27,911	GJ
Total	GWP	98,109	116,649	123,315	92,015	98,516	95,000	t CO2 Eq
	EE	1,765,180	2,100,290	2,221,283	1,656,288	1,772,092	1,711,601	GJ

TABLE 5.6

OTHER INFRASTRUCTURE IMPACTS

						Intermediate Answer		Lifetime (Years) Impact	
Item	Area/vol/mass	Impact	Phase	Coefficient	Fraction	Estimate	Units	80	Units
Control	Floor Area	Embodied	Construct	5.17	1	3,102	GJ	3,102	GJ
Building			Operate	4.07	1	2,442	GJ/year	195,360	GJ
	600	Energy	Decomm.	0.924	1	554	GJ	554	GJ
	m2		Construct	0.381	1	229	t CO_2 Eq	229	t CO_2 Eq
		GWP	Operate	0.238	1	143	t CO_2 Eq/year	11,424	t CO_2 Eq
			Decomm.	0.0919	1	55	t CO_2 Eq	55	t CO_2 Eq
Visitor's	Floor Area	Embodied	Construct	5.17	1	3,102	GJ	3,102	GJ
Center			Operate	4.07	1	2,442	GJ/year	195,360	GJ/year
	600	Energy	Decomm.	0.924	1	554	GJ	554	GJ
	m2		Construct	0.381	1	229	t CO_2 Eq	229	t CO_2 Eq
		GWP	Operate	0.238	1	143	t CO_2 Eq/year	11,424	t CO_2 Eq/year
			Decomm.	0.0919	1	55	t CO_2 Eq	55	t CO_2 Eq
Workshop	Floor Area	Embodied	Construct	5.17	1	6,463	GJ	6,463	GJ
			Operate	4.07	0.5	2,544	GJ/year	203,500	GJ/year
	1,250	Energy	Decomm.	0.924	1	1,155	GJ	1,155	GJ
	m2		Construct	0.381	1	476	t CO_2 Eq	476	t CO_2 Eq
		GWP	Operate	0.238	0.5	149	t CO_2 Eq/year	11,900	t CO_2 Eq/year
			Decomm.	0.0919	1	115	t CO_2 Eq	115	t CO_2 Eq
Storage	Floor Area	Embodied	Construct	5.17	0.8	5,170	GJ	5,170	GJ
(Minimum)			Operate	4.07	0.1	509	GJ/year	40,700	GJ/year
	1,250	Energy	Decomm.	0.924	0.8	924	GJ	924	GJ
	m2		Construct	0.381	0.8	381	t CO_2 Eq	381	t CO_2 Eq
		GWP	Operate	0.238	0.1	30	t CO_2 Eq/year	2,380	t CO_2 Eq/year
			Decomm.	0.0919	0.8	92	t CO_2 Eq	92	t CO_2 Eq
Storage	Floor Area	Embodied	Construct	5.17	0.8	279,594	GJ	279,594	GJ
(Maximum)			Operate	4.07	0.03	8,254	GJ/year	660,317	GJ/year
	67,600	Energy	Decomm.	0.924	0.8	49,970	GJ	49,970	GJ
	m2		Construct	0.381	0.8	20,604	t CO_2 Eq	20,604	t CO_2 Eq
		GWP	Operate	0.238	0.03	483	t CO_2 Eq/year	38,613	t CO_2 Eq/year
			Decomm.	0.0919	0.8	4,970	t CO_2 Eq	4,970	t CO_2 Eq
Road	Mass	Embodied	Construct	1.24	1	20,138	GJ	20,138	GJ
			Operate	1.24	0.0125	252	GJ/year	20,138	GJ/year
	16,240	Energy	Decomm.	0	1	0	GJ	0	GJ
	t		Construct	0.128	1	2,079	t CO_2 Eq	2,079	t CO_2 Eq
		GWP	Operate	0.128	0.0125	26	t CO_2 Eq/year	2,079	t CO_2 Eq/year
			Decomm.	0	1	0	t CO_2 Eq	0	t CO_2 Eq

TABLE 5.7

TRANSPORTATION DISTANCES

Item	Km	By
Water	20	Truck
Glass	600	Truck
Steel Sections and Beams	900	Truck
"	2,400	Ship
Steel Rebar	900	Truck
"	2400	Ship
High Strength Concrete (Tower & Support Posts)	125	Truck
Foundation & Footer Concrete	100	Truck

5.2.4 Interpretation

Results are presented in Chapter 6 (and Appendix G.) Conclusions are in Chapter 7.

Assumptions, Completeness, Consistency and Uncertainty: The assumptions appear to be relatively consistent and appropriate. All the major contributors, such as concrete, steel, transparency material, turbo-generator/electrical systems, and other infrastructure were identified and representatively modeled by either multiplying the amount of material by appropriate impact coefficients or by extrapolation from roughly comparable baseline studies of similar facilities. An uncertainty analysis in Section 6.3 showed the uncertainty in the quantity of the largest contributors was deemed reasonable. The uncertainty due to input variations was less than the ±20% goal set in Section 5.2.1 prior to accounting for the ±30% uncertainty in the impact coefficients. The results obtained are sufficient to permit rough comparison of the SUTPPs assessed and rough comparison to other types of power plants. Further research would be required to achieve greater specificity and accuracy.

5.3 Spreadsheet Analysis Tool

The numerical LCA was carried out using a spreadsheet tool described in the last section of Appendix F, which was set up to permit case information to be entered from input files and outputs saved in output files that permit both full documentation of the cases evaluated and compact summaries of the results, all automated via simple “copy”, “paste” and “save” operations to assure data integrity and reproducible results. Results are presented and discussed in Chapter 6.

CHAPTER 6

RESULTS

This chapter presents all SUTPP LCA results, including variation of certain inputs and uncertainty analysis. Section 6.1 addresses all SUTPP configurations and collector transparency and structural cases and identifies the “Optimal SUTPPs”. Section 6.2 examines the effects of varying cleaning rates, transparency replacement rates, and the size of the storage building. Section 6.3 provides an uncertainty analysis for the “Optimal SUTPPs”, and provides “Corrected Results” for the “Optimal SUTPPs” by removing the asymmetry in the uncertainty estimates. Appendix G includes some additional results omitted from this chapter for brevity. Section 6.4 discusses and interprets the numeric results, clarifying the roles of the largest contributors and key variables (collector structure, transparency material, cleaning, replacement and storage requirements.) Section 6.5 compares results to others’ work, and Section 6.6 compares SUTPPs to other power plants

6.1 Configuration and Structural Case Results

This section presents the results of all the “Configuration” and “Case” combinations assessed, assuming “medium” collector replacement and cleaning rates as defined by Table 4.12 and Table 4.13 respectively. “Configuration” refers to choice of one of the following power plant types: BSUTPP, BSUTPP-½DG, BSUTPP-DG, WSUTPP, ASUTPP, or ASUTPP-DG described in Section 4.4 and summarized in Table 4.10. “Case” refers to one of the following collector structure “Cases”: 1 (Light), 2 (Medium) or 3 (Heavy) described in Section 4.6 and summarized in Table 4.14.

All unique combinations of the 6 "Configurations and 3 "Cases" were evaluated.)"Case 2" was not evaluated for the BSUTPP and WSUTPP cases because that case was not different from "Case 3". Hence "Case 2" was also omitted for these configurations in Table 4.14.) Results for "Case 1" are provided in Table 6.1, while "Cases" 2 and 3 are in Appendix G. Table 6.2 summarizes the GWP/GWh and EROEI of all glass combinations of "Configuration" and "Case" at the end of the "Operation" phase. The decommissioning phase was dropped from final results because (i) the portions of decommissioning that were modeled were incomplete and changed the results little, (ii) the abandonment option entails leaving the facility to degrade and return to nature with only modest impacts, and (iii) if rebuilding, conversion of the site for another purpose, or recycling provided greater value than it cost, the next project will justify and inherit the decommissioning costs and impacts. Therefore, as stated in Section 5.2.1 (under "System Boundaries"), final results were evaluated excluding the decommissioning phase. Gray highlighted text cells in Table 6.4 have no separate "Case 2".

Note the lighter "Case 1" structure has significantly more favorable GWP and EROEI performance than "Case 2" or "Case 3". Examination of the GWP and EE contributors for all "Cases" (Table 6.1 and Appendix G Table G.1 and Table G.2) showed the majority of the impacts came from the collector for "Cases 2 and 3", and further examination of the saved "Case 2 and 3" "Output" files showed this impact was dominated by the structure, not the glass. However, examination of the "Output" file for all "Case" 1 configurations (Appendix F, Table F.8) showed its collector impact was dominated by the glass, rather than the structure.

Therefore ETFE was only evaluated for "Case 1" structure as the GWP and EE savings gained by substituting ETFE for glass will be eclipsed by use of a heavier structure. ETFE LCA results are presented in Table 6.3, while Table 6.4 summarizes the GWP/GWh and EROEI of all ETFE SUTPPs evaluated at the end of the "Operation" phase (Neglecting "Decommissioning")

The 2 best glass, and 4 best ETFE SUTPPs (with performance shown in red font in Table 6.2 and Table 6.4) were selected as the "Optimal SUTPPs" for further study.

TABLE 6.1

CASE 1 STRUCTURE RESULTS WITH GLASS

#	St Case / Stats	Configuration	GWP / EE	Phase / Phase	(t CO2 Eq/GWh) / EROEI	Cum Tot (t CO2 Eq) (GJ)	Phase Tot (t CO2 Eq) (GJ)	Collector (t CO2 Eq) (GJ)	Water Sys (t CO2 Eq) (GJ)	Tower (t CO2 Eq) (GJ)	Turb/Gen (t CO2 Eq) (GJ)	Other (t CO2 Eq) (GJ)
	1	BSUTPP										
1	336	GWh/y	GWP	Constr		786,971	786,971	466,671	11,792	225,989	78,999	3,521
	80	yrs		Oper	34.12	917,136	130,165	65,402	9,884	0	15,544	39,335
	137.4	MW cap		Decom	34.27	921,147	4,011	0	0	0	3,566	445
	27	# Turbs	EE	Constr		10,736,336	10,736,336	7,312,903	144,122	1,803,066	1,438,271	37,974
	5.09	MW cap/turb		Oper	7.51	12,886,580	2,150,244	1,146,171	51,568	0	297,448	655,058
	0.279	CF		Decom	7.49	12,919,229	32,648	0	0	0	29,461	3,188
	1	BSUTPP-1/2DG										
2	423.8	GWh/y	GWP	Constr		951,390	951,390	617,237	11,792	225,989	92,852	3,521
	80	yrs		Oper	32.50	1,101,966	150,576	81,751	9,884	0	19,606	39,335
	161.5	MW cap		Decom	32.64	1,106,602	4,636	0	0	0	4,191	445
	29	# Turbs	EE	Constr		13,547,549	13,547,549	9,871,897	144,122	1,803,066	1,690,490	37,974
	5.57	MW cap/turb		Oper	7.60	16,062,038	2,514,490	1,432,691	51,568	0	375,173	655,058
	0.300	CF		Decom	7.58	16,099,853	37,815	0	0	0	34,627	3,188
	1	BSUTPP-DG										
3	463.6	GWh/y	GWP	Constr		1,106,572	1,106,572	767,802	11,792	225,989	97,468	3,521
	80	yrs		Oper	34.39	1,275,341	168,769	98,103	9,884	0	21,448	39,335
	169.6	MW cap		Decom	34.52	1,280,185	4,844	0	0	0	4,399	445
	30	# Turbs	EE	Constr		16,190,576	16,190,576	12,430,887	144,122	1,803,066	1,774,527	37,974
	5.65	MW cap/turb		Oper	7.02	19,026,865	2,836,289	1,719,257	51,568	0	410,407	655,058
	0.312	CF		Decom	7.00	19,066,401	39,536	0	0	0	36,348	3,188
	1	WSUTPP										
4	327	GWh/y	GWP	Constr		853,548	853,548	466,671	83,801	225,989	73,566	3,521
	80	yrs		Oper	45.62	1,193,413	339,866	65,402	220,001	0	15,128	39,335
	85.3	MW cap		Decom	45.76	1,197,179	3,766	0	0	0	3,321	445
	25	# Turbs	EE	Constr		12,297,792	12,297,792	7,312,903	1,804,477	1,803,066	1,339,373	37,974
	3.41	MW cap/turb		Oper	4.81	19,586,231	7,288,439	1,146,171	5,197,730	0	289,480	655,058
	0.438	CF		Decom	4.80	19,616,854	30,623	0	0	0	27,435	3,188
	1	ASUTPP										
5	330.9	GWh/y	GWP	Constr		1,148,003	1,148,003	827,087	11,792	225,989	79,614	3,521
	80	yrs		Oper	49.45	1,309,034	161,031	91,563	14,826	0	15,309	39,335
	69.3	MW cap		Decom	49.60	1,313,073	4,039	0	0	0	3,594	445
	25	# Turbs	EE	Constr		16,665,440	16,665,440	13,230,809	144,122	1,803,066	1,449,470	37,974
	2.77	MW cap/turb		Oper	4.94	19,295,422	2,629,982	1,604,640	77,351	0	292,933	655,058
	0.545	CF		Decom	4.93	19,328,300	32,878	0	0	0	29,690	3,188
	1	ASUTPP-DG										
6	362.7	GWh/y	GWP	Constr		1,464,123	1,464,123	1,147,979	11,792	225,989	74,843	3,521
	80	yrs		Oper	56.51	1,639,704	175,580	104,640	14,826	0	16,780	39,335
	65.1	MW cap		Decom	56.64	1,643,527	3,823	0	0	0	3,378	445
	28	# Turbs	EE	Constr		21,963,185	21,963,185	18,615,416	144,122	1,803,066	1,362,606	37,974
	2.33	MW cap/turb		Oper	4.20	24,850,506	2,887,321	1,833,828	77,351	0	321,084	655,058
	0.636	CF		Decom	4.20	24,881,604	31,099	0	0	0	27,911	3,188

TABLE 6.2

SUMMARRY OF GWP AND EROEI FOR GLASS SUTPPS

		Case 1	Cases 2	Case 3
BSUTPP	GWP (t CO2 Eq/GWh) EROEI	34.1 7.51	Identical to Case 3	62.9 4.19
BSUTPP-½DG	GWP (t CO2 Eq/GWh) EROEI	32.5 7.60	55.3 4.64	57.5 4.47
BSUTPP-DG	GWP (t CO2 Eq/GWh) EROEI	34.4 7.02	55.2 4.56	59.2 4.27
WSUTPP	GWP (t CO2 Eq/GWh) EROEI	45.6 4.81	Identical to Case 3	75.2 3.16
ASUTPP	GWP (t CO2 Eq/GWh) EROEI	49.5 4.94	78.7 3.23	104 2.47
ASUTPP-DG	GWP (t CO2 Eq/GWh) EROEI	56.5 4.20	83.2 2.98	111 2.28

6.2 Varying Cleaning, Transparency Replacement and Infrastructure

The 6 "Optimal SUTPPs" selected in Section 6.1 were used to evaluate the effect of varying between the Low, Medium, and High cleaning scenarios. The results are presented in Table 6.5. Very little difference was observed. The modeling of cleaning only took into account the energy (electricity) needed to operate the HERO machines, not any filters, chemicals, system maintenance, or power to run and service the washing machines. However, it is clear a significant multiple of what was modeled can be accommodated. Unfortunately, insufficient information and definition was available during the writing of this thesis for a more complete modeling of the cleaning process.

The 6 "Optimal SUTPPs" selected in Section 6.1 were used to evaluate and transparency replacement rates. Results are shown in Table 6.6. Clearly transparency replacement rate is a significant consideration, particularly for glass. Note that the GWP/GWh impact for ETFE is uncertain because its GWP was not be found, necessitating the use of a typical plastic value of 3 t CO_2 Eq/t of ETFE.

TABLE 6.3

CASE 1 STRUCTURE RESULTS WITH ETFE

	St Case	Configuration										
						Cum Tot	Phase Tot	Collector	Water Sys	Tower	Turb/Gen	Other
#	Stats		GWP	Phase	(t CO2 Eq/GWh)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)
			EE	Phase	EROEI	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)
	1	BSUTPP: All ETFE										
1	336	GWh/y	GWP	Constr		547,452	547,452	227,152	11,792	225,989	78,999	3,521
	80	yrs		Oper	24.93	670,081	122,628	66,266	1,483	0	15,544	39,335
	137.4	MW cap		Decom	25.08	674,091	4,011	0	0	0	3,566	445
	27	# Turbs	EE	Constr		6,332,513	6,332,513	2,909,080	144,122	1,803,066	1,438,271	37,974
	5.09	MW cap/turb		Oper	12.35	7,835,341	1,502,828	542,588	7,735	0	297,448	655,058
	0.279	CF		Decom	12.30	7,867,989	32,648	0	0	0	29,461	3,188
	1	BSUTPP-1/2DG: ETFE Under Glass										
2	423.8	GWh/y	GWP	Constr		831,631	831,631	497,477	11,792	225,989	92,852	3,521
	80	yrs		Oper	28.36	961,598	129,967	69,543	1,483	0	19,606	39,335
	161.5	MW cap		Decom	28.50	966,234	4,636	0	0	0	4,191	445
	29	# Turbs	EE	Constr		11,345,637	11,345,637	7,669,985	144,122	1,803,066	1,690,490	37,974
	5.57	MW cap/turb		Oper	9.00	13,563,686	2,218,049	1,180,083	7,735	0	375,173	655,058
	0.300	CF		Decom	8.97	13,601,501	37,815	0	0	0	34,627	3,188
	1	BSUTPP-DG: All ETFE										
3	463.6	GWh/y	GWP	Constr		588,010	588,010	249,241	11,792	225,989	97,468	3,521
	80	yrs		Oper	21.11	782,808	194,798	132,533	1,483	0	21,448	39,335
	169.6	MW cap		Decom	21.24	787,653	4,844	0	0	0	4,399	445
	30	# Turbs	EE	Constr		6,849,632	6,849,632	3,089,942	144,122	1,803,066	1,774,527	37,974
	5.65	MW cap/turb		Oper	14.82	9,008,006	2,158,375	1,085,175	7,735	0	410,407	655,058
	0.312	CF		Decom	14.76	9,047,542	39,536	0	0	0	36,348	3,188
	1	WSUTPP: All ETFE										
4	327	GWh/y	GWP	Constr		614,029	614,029	227,152	83,801	225,989	73,566	3,521
	80	yrs		Oper	36.50	954,759	340,730	66,266	220,001	0	15,128	39,335
	85.3	MW cap		Decom	36.64	958,525	3,766	0	0	0	3,321	445
	25	# Turbs	EE	Constr		7,893,969	7,893,969	2,909,080	1,804,477	1,803,066	1,339,373	37,974
	3.41	MW cap/turb		Oper	6.46	14,578,824	6,684,855	542,588	5,197,730	0	289,480	655,058
	0.438	CF		Decom	6.45	14,609,447	30,623	0	0	0	27,435	3,188
	1	ASUTPP: Glass Primary, ETFE Secondary										
5	330.9	GWh/y	GWP	Constr		908,484	908,484	587,568	11,792	225,989	79,614	3,521
	80	yrs		Oper	40.19	1,063,886	155,402	98,535	2,224	0	15,309	39,335
	69.3	MW cap		Decom	40.34	1,067,925	4,039	0	0	0	3,594	445
	25	# Turbs	EE	Constr		12,261,617	12,261,617	8,826,986	144,122	1,803,066	1,449,470	37,974
	2.77	MW cap/turb		Oper	6.51	14,638,675	2,377,058	1,417,465	11,603	0	292,933	655,058
	0.545	CF		Decom	6.50	14,671,553	32,878	0	0	0	29,690	3,188
	1	ASUTPP-DG: DG Secondary is ETFE Below Glass										
6	362.7	GWh/y	GWP	Constr		1,224,605	1,224,605	908,460	11,792	225,989	74,843	3,521
	80	yrs		Oper	47.75	1,385,550	160,945	102,607	2,224	0	16,780	39,335
	65.1	MW cap		Decom	47.88	1,389,373	3,823	0	0	0	3,378	445
	28	# Turbs	EE	Constr		17,559,362	17,559,362	14,211,593	144,122	1,803,066	1,362,606	37,974
	2.33	MW cap/turb		Oper	5.16	20,242,177	2,682,815	1,695,071	11,603	0	321,084	655,058
	0.636	CF		Decom	5.15	20,273,276	31,099	0	0	0	27,911	3,188

TABLE 6.3 (Continued)

#	St Case	Configuration										
						Cum Tot	Phase Tot	Collector	Water Sys	Tower	Turb/Gen	Other
#	Stats		GWP	Phase	(t CO2 Eq/GWh)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)
			EE	Phase	EROEI	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)
	1	ASUTPP: All ETFE										
1	330.9	GWh/y	GWP	Constr		646,877	646,877	325,961	11,792	225,989	79,614	3,521
	80	yrs		Oper	28.46	753,443	106,567	49,700	2,224	0	15,309	39,335
	69.3	MW cap		Decom	28.61	757,482	4,039	0	0	0	3,594	445
	25	# Turbs	EE	Constr		7,676,932	7,676,932	4,242,300	144,122	1,803,066	1,449,470	37,974
	2.77	MW cap/turb		Oper	10.54	9,043,465	1,366,534	406,941	11,603	0	292,933	655,058
	0.545	CF		Decom	10.50	9,076,343	32,878	0	0	0	29,690	3,188
	1	ASUTPP-DG: Glass Primary, ETFE Second										
2	362.7	GWh/y	GWP	Constr		985,086	985,086	668,942	11,792	225,989	74,843	3,521
	80	yrs		Oper	40.50	1,175,093	190,007	131,668	2,224	0	16,780	39,335
	65.1	MW cap		Decom	40.63	1,178,916	3,823	0	0	0	3,378	445
	28	# Turbs	EE	Constr		13,155,539	13,155,539	9,807,770	144,122	1,803,066	1,362,606	37,974
	2.33	MW cap/turb		Oper	6.60	15,832,042	2,676,503	1,688,759	11,603	0	321,084	655,058
	0.636	CF		Decom	6.58	15,863,140	31,099	0	0	0	27,911	3,188
	1	ASUTPP-DG: ETFE Primary & Secondary										
3	362.7	GWh/y	GWP	Constr		686,283	686,283	370,139	11,792	225,989	74,843	3,521
	80	yrs		Oper	30.23	877,154	190,871	132,533	2,224	0	16,780	39,335
	65.1	MW cap		Decom	30.36	880,977	3,823	0	0	0	3,378	445
	28	# Turbs	EE	Constr		7,951,793	7,951,793	4,604,025	144,122	1,803,066	1,362,606	37,974
	2.33	MW cap/turb		Oper	10.42	10,024,713	2,072,919	1,085,175	11,603	0	321,084	655,058
	0.636	CF		Decom	10.39	10,055,811	31,099	0	0	0	27,911	3,188

TABLE 6.4

SUMMARY OF GWP AND EROEI FOR ETFE SUTPPS

BSUTPP All ETFE	GWP (t CO2 Eq/GWh) EROEI	24.9 12.4
BSUTPP-½DG ETFE Under Glass	GWP (t CO2 Eq/GWh) EROEI	28.4 9.00
BSUTPP-DG All ETFE	GWP (t CO2 Eq/GWh) EROEI	21.1 14.8
WSUTPP All ETFE	GWP (t CO2 Eq/GWh) EROEI	36.5 6.46
ASUTPP Glass Primary, ETFE Secondary	GWP (t CO2 Eq/GWh) EROEI	40.2 6.51
ASUTPP All ETFE	GWP (t CO2 Eq/GWh) EROEI	28.5 10.5
ASUTPP-DG Secondary ETFE below Glass Top	GWP (t CO2 Eq/GWh) EROEI	47.8 5.16
ASUTPP-DG Glass Primary, Secondary ETFE DGs	GWP (t CO2 Eq/GWh) EROEI	40.5 6.60
ASUTPP-DG ETFE Primary, ETFE DG Secondary	GWP (t CO2 Eq/GWh) EROEI	30.2 10.4

TABLE 6.5

EFFECT OF LOW, MEDIUM AND HIGH CLEANING ON GWP AND EROEI

Configuration		Low	Med	High
BSUTPP All Glass	GWP (t CO2 Eq/GWh) EROEI	33.84 7.53	34.12 7.51	34.86 7.45
BSUTPP-½DG All Glass	GWP (t CO2 Eq/GWh) EROEI	32.28 7.62	32.5 7.6	33.09 7.55
BSUTPP All ETFE	GWP (t CO2 Eq/GWh) EROEI	24.89 12.36	24.93 12.35	25.06 12.32
BSUTPP-DG All ETFE	GWP (t CO2 Eq/GWh) EROEI	21.08 14.83	21.11 14.82	21.20 14.79
ASUTPP All ETFE	GWP (t CO2 Eq/GWh) EROEI	28.41 10.55	28.46 10.54	28.66 10.51
ASUTPP-DG ETFE Primary, ETFE DG Secondary	GWP (t CO2 Eq/GWh) EROEI	30.18 10.43	30.23 10.42	30.41 10.39

TABLE 6.6

EFFECT OF LOW, MEDIUM AND HIGH TRANSPARENCY REPLACEMENT ON GWP AND EROEI

Configuration		Low	Med	High
BSUTPP All Glass	GWP (t CO2 Eq/GWh) EROEI	32.27 8.05	34.12 7.51	41.42 5.93
BSUTPP-½DG All Glass	GWP (t CO2 Eq/GWh) EROEI	30.65 8.16	32.5 7.6	39.74 5.99
BSUTPP All ETFE	GWP (t CO2 Eq/GWh) EROEI	23.45 12.89	24.93 12.35	29.04 11.07
BSUTPP-DG All ETFE	GWP (t CO2 Eq/GWh) EROEI	18.96 15.98	21.11 14.82	27.06 12.34
ASUTPP All ETFE	GWP (t CO2 Eq/GWh) EROEI	27.29 10.84	28.46 10.54	31.59 9.80
ASUTPP-DG ETFE Primary, ETFE DG Secondary	GWP (t CO2 Eq/GWh) EROEI	27.34 11.19	30.23 10.42	37.84 8.83

The effect of increasing the onsite indoor storage volume from the minimum to the maximum scenario (enough to store all the BSUTPP glass at 30% volume efficiency, as defined in Section 4.9 and Table 5.6) is shown in Table 6.7. The impact of upgrading storage is a significant enough investment it will probably be avoided, as glass can be covered outside.

ETFE will not require as much volume if it can be stored flat, and there may be a way to store ETFE covered outside.

TABLE 6.7

EFFECT OF MINIMUM AND MAXIMUM STORAGE ON GWP AND EROEI

Configuration		Medium + Minimum	Medium + Maximum
BSUTPP All Glass	GWP (t CO2 Eq/GWh) EROEI	34.12 7.51	36.22 7.02
BSUTPP-½DG All Glass	GWP (t CO2 Eq/GWh) EROEI	32.5 7.6	34.17 7.20
BSUTPP All ETFE	GWP (t CO2 Eq/GWh) EROEI	24.93 12.35	27.03 11.09
BSUTPP-DG All ETFE	GWP (t CO2 Eq/GWh) EROEI	21.11 14.82	22.63 13.48
ASUTPP All ETFE	GWP (t CO2 Eq/GWh) EROEI	28.46 10.54	30.59 9.59
ASUTPP-DG ETFE Primary, ETFE DG Secondary	GWP (t CO2 Eq/GWh) EROEI	30.23 10.42	32.18 9.57

6.3 Uncertainty and "Corrected" Results

Insufficient information was available for a comprehensive uncertainty analysis. Therefore judgment was applied to what was known to assign approximate minimum and maximum limits to all modeled contributions to GWP and EE, which were arbitrarily assumed to roughly represent a 90% confidence interval for these input values, normally distributed about the midpoint of the minimum and maximum values. This input uncertainty model was used to estimate the uncertainty of GWP and EROEI (the latter being power produced divided by EE).

The GWP and EROEI of the 6 "Optimal SUTPPs" selected in Section 6.1 were determined by the sum of 10 contributors, each of which contributed to EE and/or GWP. These contributions were rescaled as percentages of the total GWP or EE, and arranged in roughly rank order by EE for a glass transparency, with water and cleaning items listed last, as shown in the left column of Table 6.8. A maximum and minimum percentage change value was assigned to each contributor using the reasoning in Table 6.8. The water management system was represented by only the fiberglass water tanks, yet it has to include significant plumbing, filters, valves, pumps, sensors and purification equipment (such as the HERO machines). Therefore the water management system is assumed to be 2 to 8 times larger than just the tanks in these “Corrected” results to attempt to account for the rest of the system. Similarly, cleaning will require more than just operating the HERO system to purify water, possibly including filtration, pumping, powering cleaning machines (locomotion, brushes), any water vacuuming that may be required, and maintenance for these systems, which it was assumed may add 50-700% more impact than was modeled.

TABLE 6.8

CONTRIBUTOR UNCERTAINTY RANGES

	Glass			ETFE		
Contributor	Min	Max	Reasoning	Min	Max	Reasoning
Glass or ETFE	0%	15%	Waste thrown out	-30%	15%	Thinner material vs. waste
Steel Collector Struct	0%	25%	Guttering cancels any savings	-50%	25%	Maybe much lighter with ETFE
Tower & Foundation	-15%	15%	Believable variation (Appendix E)	-15%	15%	Same as glass case
Turb/Gen/Electrical Package	-25%	33%	Believable variation (Appendix E & F)	-25%	33%	Same as glass case
Other Infrastructure	-30%	100%	Not well defined, maybe underestimated	-30%	100%	Same as glass case
Fiberglass Tanks & Water Syst's	100%	700%	Underestimated, maybe 2-5 times estimate	100%	700%	Same as glass case
Footing Concrete	-50%	100%	Design may change by factor of 2	-50%	100%	Same as glass case
Steel Rebar	-50%	100%	Design may change by factor of 2	-50%	100%	Same as glass case
Purify Wash Water (HERO)	50%	700%	Need to add rest of water treatment + Cleaning	50%	700%	Same as glass case
Transport Water	0%	0%	Too small of contribution to address	0%	0%	Same as glass case

The original percentage contributions and minimum and maximum changes for each of the 10 contributors were used to compute the “Mean” of the new minimum and maximum percentage values, as shown in Table 6.9 for the glass BSUTPP configuration. (The other configurations are shown in Appendix G.) Due to the asymmetric ranges used, the new “Mean” percentages add up a sum > 100%, which is multiplied by the original GWP or EE to obtain the new “Corrected” GWP or EE. “90% Intv” is the symmetric ± value for the 90% confidence interval. The square “Root of the Sum of the Squares” (RSS) of the “90% Intv” values appears under “RSS” below the “90% Intv” column. (RSS is the proper technique assuming the inputs are uncorrelated. While several inputs may be uncorrelated, two of the largest contributors, the amount of glass (or ETFE) and steel in the collector, are at least somewhat correlated.) The new “Corrected” percentage means and ± percentage values were used to find the new “Corrected” GWP (t CO_2 Eq/GWh) and EE (GJ) mean values and 90% confidence intervals. EROEI = (Energy Produced)/EE, therefore the symmetric uncertainty ranges for EE in the denominator of EROEI create somewhat asymmetric ranges for “Corrected” EROEI, which are averaged to produce a symmetric approximation to the 90% confidence interval for EROEI. Table 6.10 shows the “Original” and “Corrected” values of GWP along with the uncertainty ranges for the 6 “Optimal SUTPPs”. Table 6.11 provides the same information for EE and shows the averaged symmetric uncertainty range. The 90% confidence intervals for GWP and EROEI lie within the ± 20% goal established in Section 5.2.1.

Uncertainty is also increased by an unknown amount for ETFE because insufficient information was available to properly adjust performance to account for using ETFE in place of glass. Since the LCA summed up impacts, anything not included will make the final GWP and EE too low, and make EROEI too high. An effort was made to address this in the “corrected” results by assuming certain contributors may be significantly larger than originally modeled. The structure required to support ETFE is probably lighter than that required for glass (assumed to be 50% to 125% of the glass case in Appendix G, and may be even lighter, but no design or adequate evidence was found to support that.) The skewing of ETFE and steel structure contributions downwards compensates for most of the smaller contributors being skewed to higher values, such that the mean GWP and EE values for ETFE cases were between 103% and 106% of the original values. Since the major contributors have been identified and their variation has been reasonably accounted for, the ETFE results, while a bit more uncertain glass, ought to be meaningful.

TABLE 6.9

BSUTPP (GLASS) UNCERTAINTIES AND CORRECTED RESULTS

	BSUTPP									
	0.279	Capacity Factor				GWP	(t CO_2 Eq/GWh)	EROEI		
	96,768,000	GJ Produced/Lifetime				Corrected	± Uncertainty	Corrected	± Uncertainty	
	7.51	EROEI				**39.85**	**2.93**	**6.56**	**0.46**	
	34.12	(t CO_2 Eq/GWh)				90% Conf Interval		90% Conf Interval		Delta
						36.92	Min	6.14	Min	-0.42
	GWP	EE				42.77	Max	7.05	Max	0.49
	917,136	12,886,580							Avg	0.46
	(t CO_2 Eq)	(GJ)			90%					
	% GWP	**% EE**	Min	Max	Range	**Mean**	**90% Intv**	**Mean**	**90% Intv**	
Glass	35.66%	44.47%	0%	15%	15%	38.33%	2.67%	47.81%	3.34%	
Steel Collector Struct	21.55%	20.69%	0%	25%	25%	24.24%	2.69%	23.28%	2.59%	
Tower & Foundation	24.64%	13.99%	-15%	15%	30%	24.64%	3.70%	13.99%	2.10%	
Turb/Gen/Electrical Package	10.31%	13.47%	-25%	33%	58%	10.72%	2.99%	14.01%	3.91%	
Other Infrastructure	4.67%	5.38%	-30%	100%	130%	6.31%	3.04%	7.26%	3.50%	
Fiberglass Tanks & Water Syst's	1.28%	1.12%	100%	700%	600%	6.38%	3.83%	5.58%	3.35%	
Footing Concrete	0.62%	0.29%	-50%	100%	150%	0.77%	0.46%	0.37%	0.22%	
Steel Rebar	0.19%	0.19%	-50%	100%	150%	0.24%	0.15%	0.23%	0.14%	
Purify Wash Water (HERO)	1.08%	0.40%	50%	700%	650%	5.15%	3.52%	1.91%	1.31%	
Transport Water	0.003%	0.000%	0%	0%	0%	0.003%	0.00%	0.000%	0.00%	
	Sum	Sum				Sum	RSS	Sum	RSS	
	100.00%	100.00%				116.79%	8.57%	114.44%	7.92%	
						GWP/GWh (t CO_2 Eq/GWh)			EE (GJ)	
						39.85	2.93	14,746,927	1,020,267	
						Corrected	90% Intv	Corrected	90% Intv	

The glass and ETFE uncertainty estimates discussed above do not take into account the uncertainty in the coefficients obtained from the LCA databases that are multiplied by the amount of material used (or other quantities, such as electrical energy or distance transported). This is significant concern for all LCAs, as it is often the largest source of uncertainty. Hammond and Jones [103] state it is appropriate to assume an uncertainty of ±30% for most materials, specifically including glass, steel and concrete. Table 6.12 shows these 30% uncertainties RSS'd with the 90% confidence intervals to provide uncertainties that account for both the input and impact coefficient uncertainties. Note that Hammond and Jones do not provide a confidence interval for the ±30%, therefore it is not clear what the confidence interval is for the ranges portrayed in Table 6.12.

TABLE 6.10

OPTIMAL SUTPP CORRECTED GWP RESULTS

			BSUTPP Glass	BSUTPP -1/2DG Glass	BSUTPP ETFE	BSUTPP -DG ETFE	ASUTPP ETFE	ASUTPP -DG (Sec) ETFE
Original Values								
GWP	(t CO2 Eq/GWh)		34.12	32.50	24.93	21.11	28.46	30.23
Corrected Values								
GWP	Nominal		**39.85**	**37.46**	**26.49**	**22.08**	**29.73**	**31.05**
	± Uncertainty (90%)		2.93	2.52	3.69	2.89	4.87	4.66
	± Uncertainty (90%)		7.3%	6.7%	13.9%	13.1%	16.4%	15.0%
90% Uncert Range		Min	36.92	34.95	22.80	19.20	24.86	26.39
		Max	42.77	39.98	30.18	24.97	34.60	35.72

TABLE 6.11

OPTIMAL SUTPP CORRECTED EROEI RESULTS

			BSUTPP Glass	BSUTPP -1/2DG Glass	BSUTPP ETFE	BSUTPP -DG ETFE	ASUTPP ETFE	ASUTPP -DG (Sec) ETFE
Original Values								
EROEI	(Unitless)		7.51	7.60	12.35	14.82	10.54	10.42
Corrected Values								
EROEI	Nominal		**6.56**	**6.72**	**11.55**	**14.03**	**10.09**	**10.09**
	± Uncertainty (90%)		0.46	0.44	1.87	2.12	1.91	1.76
	± Uncertainty (90%)		7.0%	6.5%	16.2%	15.1%	18.9%	17.5%
Uncertainty Range		Min	6.14	6.31	9.97	12.23	8.53	8.63
		Max	7.05	7.18	13.71	16.46	12.35	12.16

TABLE 6.12

OPTIMAL SUTPP CORRECTED RESULT WITH IMPACT COEFFICIENT UNCERTAINTY

With 30%	Coeff	BSUTPP Glass	BSUTPP -1/2DG Glass	BSUTPP ETFE	BSUTPP -DG ETFE	ASUTPP ETFE	ASUTPP -DG (Sec) ETFE
GWP	Max	52.15	48.98	35.25	29.31	39.89	41.47
	Nominal	39.85	37.46	26.49	22.08	29.73	31.05
	Min	27.54	25.95	17.73	14.86	19.57	20.64
EROEI	Max	8.58	8.78	15.48	18.74	13.67	13.60
	Nominal	6.56	6.72	11.55	14.03	10.09	10.09
	Min	4.54	4.66	7.61	9.32	6.51	6.59

6.4 Discussion of Results

Table 6.13 lists results in Chapter 6 and Appendix G. Table 6.14 gives “Corrected” and “Uncorrected” or “Original” GWP and EROEI results for the 6 “Optimal SUTPPs”.

Among glass SUTPPs, the more robust collector structures (“Cases” 2 and 3), which may be used to support heavier cleaning machines, had poor GWP and EROEI due to the massive investment in structure (reference Table 6.2). Water thermal storage (WSUTPP, EROEI 4.8) and single glazed airflow regulated (ASUTPP, EROEI 4.9) configurations required significantly more GWP and EE inputs yet produce slightly less power, and double glazed airflow regulation (ASUTPP-DG, EROEI 4.2) did not produce enough extra power to offset the GWP or EE cost of the extra material required.

“Uncorrected” values are sometimes used in below to permit comparison of “Optimal” and “Non-Optimal” configurations. The EROEI of water thermal storage and airflow regulated systems using glass was not much above the minimum of 3 [108] to 5 [109] required to provide net benefit to people after accounting for thermodynamic inefficiencies and costs throughout society’s infrastructure. The single glazed secondary (ASTUPP) did insignificantly better than

TABLE 6.13

INDEX OF LCA RESULTS

Table	Title
6.1	Case 1 Structure Results with Glass
G.1	Case 2 Structure Results with Glass
G.2	Case 3 Structure Results with Glass
6.2	Summary of GWP and EROEI for Glass SUTPPs
6.3	Case 1 Structure Results with ETFE
6.4	Summary of GWP and EROEI for ETFE SUTPPs
6.5	Effect of Low, Medium and High Cleaning on GWP and EROEI
6.6	Effect of Low, Medium and High Transparency Replacement on GWP and EROEI
6.7	Effect of Minimum and Maximum Storage on GWP and EROEI
6.8	Contributor Uncertainty Ranges
6.9	BSUTPP (Glass) Uncertainties and Corrected Results
G.3	BSUTPP-½DG (Glass) Uncertainties and Corrected Results
G.4	BSUTPP (ETFE) Uncertainties and Corrected Results
G.5	BSUTPP-DG (ETFE) Uncertainties and Corrected Results
G.6	ASUTPP (ETFE) Uncertainties and Corrected Results
G.7	ASUTPP-DG (ETFE) Uncertainties and Corrected Results
6.10	Optimal SUTPP Corrected GWP Results
6.11	Optimal SUTPP Corrected EROEI Results
6.12	Optimal SUTPP Corrected Result with Impact Coefficient Uncertainty

TABLE 6.14

OPTIMAL SUTPP RESULTS (CORRECTED AND ORIGINAL)

		Corrected	Original
BSUTPP	GWP (t CO_2 Eq/GWh)	39.85	34.12
Glass	EROEI	6.56	7.51
BSUTPP-1/2DG	GWP (t CO_2 Eq/GWh)	37.46	32.50
All Glass	EROEI	6.72	7.60
BSUTPP	GWP (t CO_2 Eq/GWh)	26.49	24.93
ETFE	EROEI	11.55	12.35
BSUTPP-DG	GWP (t CO_2 Eq/GWh)	22.08	21.11
All ETFE	EROEI	14.03	14.82
ASUTPP	GWP (t CO_2 Eq/GWh)	29.73	28.46
ETFE Membrane	EROEI	10.09	10.54
ASUTPP-DG	GWP (t CO_2 Eq/GWh)	31.05	30.23
ETFE Membrane Primary	EROEI	10.09	10.42
FTFE Pillow Secondary			

Water thermal storage (WSUTPP) on EROEI (4.9 vs. 4.8 “Uncorrected”), but somewhat worse on GWP (50 vs. 46 t CO_2 Eq/GWh “Uncorrected”). However, this thesis asserts ASUTPP is preferable to WSUTPP because airflow regulation can permit some choice when to extract power whereas the WSUTPP LCA does not account for the GWP or EE investment to excavate and set up the plastic lined pit water tanks, investment in a design deemed robust enough to avoid substantial leak and maintenance problems, and concerns obtaining adequate refill water by truck or pipeline when fossil fuel becomes scarce. The Baseline (BSUTPP, EROEI 7.5 “Uncorrected”) and Baseline 50% double glazed (BSUTPP-½DG, EROEI 7.6 “Uncorrected”) configurations offered the best GWP and EROEI performance, and were selected as “Optimal” among the glass configurations evaluated. The 100% double glazed (BSUTPP-DG, EROEI 7.0 “Uncorrected”) was almost as good but not considered optimal because the 50% double glazed configuration required less investment and maintenance and provided slightly better EROEI.

Among the 9 configurations employing ETFE (or glass and ETFE), the 100% double glazed Baseline (BSUTPP-DG) on a structure comparable to that used for a single layer of glass (which in theory should still be overbuilt for ETFE) provided the best EROEI, at 14.8 “Uncorrected”), roughly doubling the 7.6 “Uncorrected”) of the best glass SUTPP (BSUTPP-½DG), while cutting the GWP about 1/3 from 32.5 t CO_2 Eq/GWh (“Uncorrected” for glass BSUTPP-½DG) to 21.1 t CO_2 Eq/GWh (“Uncorrected” for ETFE BSUTPP-DG). The investment in twice as much ETFE was more than repaid in both GWP and EROEI terms. Consequently, it is not surprising that the all ETFE Airflow regulated (ASUTPP, EROEI 10.5 “Uncorrected”) and (ASUTPP-DG, with ETFE DG secondary, EROEI 10.4 “Uncorrected”) came much closer to justifying the extra GWP and EE investment for additional transparency material than their glass counterparts did. However, water thermal storage (WSUTPP, EROEI 6.5 “Uncorrected”) did not perform as well as airflow regulation, and is regarded to be less desirable than airflow regulation by this thesis for the reasons given in the prior paragraph. Based upon the values in Table 6.4, the BSUTPP, BSUTPP-DG, ASUTPP, and ASUTPP-DG configurations using ETFE only (no glass) were selected as “Optimal ETFE SUTPPs”.

Varying cleaning rates (Table 6.5) had relatively little effect on GWP and EROEI, Significant research is still required to resolve practical cleaning concerns and understand the GWP and EE impact of solutions, which are quite probably several times higher than the what was modeled, which was limited to the fiberglass tanks needed plus the energy required to purify the water by High Efficiency Reverse Osmosis (HERO) Table 6.9 showed that even if the energy needed were 700% beyond that required for HERO, it account for only 1.3% of the total energy invested for construction and operation for the “Medium” cleaning case. Tables G.4 through G.7 in Appendix G show this drops to 0.3% to 0.4% for ETFE, due to the lower cleaning rates. This suggests that while cleaning impacts are not adequately understood, it is likely solutions with acceptable impacts can be found.

Varying transparency replacement rates (Table 6.6) had a significant effect, and emphasizes the importance of understanding what may determine replacement rates, especially dulling due to incomplete cleaning or scratching due to windblown sand. It is very important to avoid sites were large hail may damage much of the collector to avoid substantial downtime, as considerable GWP and EE is required to replace large areas of glass.

Table 6.7 showed having a storage building large enough to shelter a complete glass replacement was found to impact GWP and EROEI enough to discourage investing in such a structure if possible. It is suggested glass be stored under some type of protective cover outside instead if large scale glass storage were required, however given the negative impact of ever having to replace that much glass, it is highly preferable to minimize that probability. ETFE is much thinner and may permit more compact storage, unless ETFE is sorted as tensioned panels that include frames, in which case it may require more space than glass.

6.5 Comparison to Other's Results

When the results of LCA in this thesis were adjusted to the same service life as GWP and EROEI figures published by Bernardes [67], Niemann, et al. [32] and EnviroMission [59], the results were similar, though sometimes not as favorable as the other sources, possibly due to differences in modeling scope, SUTPP design or impact coefficients. This agreement suggests the results of this thesis can be used to compare SUTPP designs to each other and other power plant types.

6.5.1 Bernardes' LCA

Bernardes [67] performed a LCA on generic 5, 30 and 100 MW SUTPPs, with a 30 year life, and obtained the results shown in Table 6.15 and Table 6.16. The largest GWP contributors, in order of decreasing magnitude were the collector, tower and turbines, as was found in this thesis for the glass SUTPPs.

Bernardes' 100 MW plant is the closest to the cases considered in this thesis, at 73 t CO_2 Eq/GWh over a 30 year life. This compares to values ranging from 22.1 to 39.9 t CO_2 Eq/GWh for the "Corrected" results in Table 6.14 from this thesis for plants ranging in size from 65 to 170 MW capacity over an 80 life.

TABLE 6.15

ENERGY RESOURCES TO CONSTRUCT, OPERATE AND DISPOSE OF SUTPP [67]

Plant Size	[MWe]	5	30	100
Collector	MJ/Unit	6.67×10^8	2.55×10^9	6.39×10^9
Chimney	MJ/Unit	4.54×10^7	2.08×10^8	5.39×10^8
Turbine	MJ/Unit	2.42×10^7	1.45×10^8	4.83×10^8
Operating and Other	MJ/Unit	2.96×10^7	1.05×10^8	2.00×10^8
Total	MJ/Unit	7.66×10^8	3.01×10^9	7.61×10^9
Sum, area specific	MJ/m^2	381	391	395

TABLE 6.16

GWP100 FOR SUTPP [67]

Plant Size	[MWe]	5	30	100
Collector	t CO_2 Eq	51	195	488
chimney	t CO_2 Eq	5.8	22.5	57.5
Turbine	t CO_2 Eq	2.8	16.8	56
Operating and other	t CO_2 Eq	2.41	7.86	14.6
Total	t CO_2 Eq	62.01	242.16	616.1
specific	g/kWh	172	108	73

According to Fluri et al. [93], Bernardes 100 MW plant was estimated to output 281 GWh/y, which times a 30 year life equals 8430 GWh, or 30,348,000 GJ, that when divided by the 7,610,000 GJ in Table 6.15 gives and EROEI of 3.99. This thesis obtained an EROEI of 6.56 "Corrected" over the 80 year life of the BSUTPP, a 137 MW maximum capacity plant.

Table G.8 in Appendix G shows if the 137 MW capacity BSUTPP in this thesis were operated over 30 years and assumed to use 3/8 of the energy and GWP required to operate for its 80 year life, the "Uncorrected" EROEI decreases to 3.14, and "Uncorrected" GWP increases to 83 t CO_2 Eq/GWh (vs. EROEI 3.99 and 73 t CO_2 Eq/GWh Bernardes). Given somewhat different scope and design assumptions, and possibly somewhat different impact coefficients, the difference between these results seems reasonable.

6.5.2 Niemann

Niemann, et al. [32] claimed if all the CO_2 emissions from the materials used in construction were accounted for over an 80 to 120 year service life in an energy balance, the GWP was around ≈10 g CO_2 Eq/kWh (=10 t CO_2 Eq/GWh), and even if replacing the turbo-generators and part of the glass canopy is included, the GWP impact is still the lowest of all renewable energy sources.

Table G.9 Appendix G shows if the "Uncorrected" GWP impact of the lowest GWP/GWh glass configuration (BSUTPP-½DG) is evaluated as the GWP of construction phase only, (which also includes transportation), vs. power produced over 120 years, the result is 18.7 t CO_2 Eq/GWh. The language used by Niemann et al. implies glass, however, the same calculation for the lowest GWP ETFE plant yields 10.6 t CO_2 Eq/GWh.

"Around ≈10 t CO_2 Eq/GWh" seems a little optimistic for glass, but if taken to mean "on the order of 10 (rather than 100)", Niemann's figure is consistent with the results of this thesis.

6.5.3 EnviroMission

From EnviroMission's corporate Website [59] "Research and engineering modeling indicates a Solar Tower power station will operate efficiently for more than 50 years with a life cycle analysis (LCA) of approximately 2.5 years; LCA is the amount of time of clean operation needed to equalize the pollution associated with the manufacture and construction process, for example the carbon pollution resulting from the manufacture and transport of concrete."

Hammond and Jones [103] state US electricity production mix equates to 690 t CO_2 Eq/GWh. Dividing (t CO2 Eq to construct) for each of the 6 "Optimal SUTPPs" by (GWh/y produced x 690 t CO2 Eq/GWh) (both given in Table 6.1 and Table 6.3) gave the number of years for GWP savings to pay back construction in Table 6.17. Overall the 4 ETFE values compare well to EnviroMission's claim of 2.5 years, given they have not publicly disclosed most of their design details.

TABLE 6.17

GWP100 PAYBACK PERIODS

Configuration	Constr ($t\ CO_2$ Eq)	Pwr/y (GWh/y)	GWP/GWh ($t\ CO_2$ Eq/GWh)	Denominator ($t\ CO_2$ Eq/y)	Payback (years)
BSUTPP: Glass	786,971	336	690	231,840	3.39
BSUTPP-1/2DG: Glass	951,390	423.8	690	292,422	3.25
BSUTPP: ETFE	547,452	336	690	231,840	2.36
BSUTPP-DG: ETFE	588,010	463.6	690	319,884	1.84
ASUTPP: ETFE	908,484	330.9	690	228,321	3.98
ASUTPP-DG: ETFE	686,283	362.7	690	250,263	2.74

6.6 Comparison to Other Power Plant Types

Bernardes [67] presented the GWP100 results in Table 6.18 for other types of power plants. At 37 – 39 g CO_2 Eq/kWh (glass) and 22 – -30 g CO_2 Eq/kWh (ETFE) (both "Corrected"), the "Optimal SUTPPs" compare favorably with many energy sources. However wind energy in windy areas can do better.

EROEI for various types of electrical power plants shown in Table 6.19 was obtained from Inman (2013) [109]. With an EROEI of 7 the "Optimum" glass SUTPPs struggle to compete with photovoltaic, while the "Optimum" ETFE SUTPPs with an EROEI of 10 – 14 are potentially more competitive with other energy sources. However wind energy is a serious challenge to SUTPPs in both GWP and EROEI terms, and well ahead of SUTPPs in maturity of technology and ease of deployment.

TABLE 6.18

GWP100 OF OTHER POWER PLANT TYPES [67], (SUTPP replaced by Table 6.10 values)

Plant Description	g CO_2 Eq/kWh$_{elect}$
Photovoltaic (Multicrystalline Silicon)	226
PHOEBUS Solar Tower (100% Solar Fraction)	40
Wind power (4.5 m / s)	27
SUTPP (Glass) (Corrected mean values (Table 6.14))	37-39
SUTPP (ETFE) (Corrected mean values (Table 6.14))	22-30
Hydropower (Running Water)	14
Wind power (5.5 m / s)	18
Coal (Combined Cycle Power Plant Integrated Gasification)	835
Gas (Gas and Steam Turbine (CCGT) Power Plan)	421
Coal (Steam Power Plant)	874
Nuclear Energy (Pressurized Water Reactors)	20

TABLE 6.19

EROEI OFOTHER ENERGY SOURCES [109], (SUTPPs (Table 6.12) Added)

Source	
Photovoltaic	6
Hydro	40+
Wind Energy	20
Ethanol from Corn	1.4
SUTPP (Glass)	7
SUTPP (ETFE)	10-14
Natural Gas	7
Oil	16
Tar Sands	5
Coal	18
Nuclear	5

CHAPTER 7

FURTHER RESEARCH AND CONCLUSIONS

7.1 Further Research Opportunities

LCA can be enhanced with a more complete definition of each phase of the life cycle, and more details, use of better databases, or hybrid strategies using Economic Input-Output (EIO) methods in order to capture higher order effects due to what the company and workers buy.

Tower: Further define and model LCA for optimum concrete construction and maintenance, possibly including excavation and formwork or other key aspects of construction.

Turbo-Generator and Electrical Systems need to be more precisely defined and modeled.

Infrastructure needs to be better defined, including considerations for green building design.

ETFE: Expertise from architects and designers using ETFE is needed to define membrane systems appropriate for the SUTPP operating environment (which includes winds under the canopy), and establish the solutions that will be durable to not require excessive maintenance for a 20 km^2 area. Vaulting or other means may be required to facilitate rain and/or spray wash cleaning. An analysis is needed to determine the optimal degree of vaulting for drainage that does not significantly impact performance due to increased drag, whether it makes more sense to use a non-vaulted ETFE layer below the vaulted ETFE layer, and/or spray wash water at an angle or blow air to push wash water towards drains. Additional work is needed to to adequately model SUTPP performance with an ETFE transparency. (A number of investigators have noted the unavailability of sufficient ETFE solar gain information in the public domain [100, 101].)

Collector Structure: Design for actual glass and/or ETFE collector structures that meet all longevity and load requirements, including cleaning and servicing loads, that minimize GWP and EE (to provide higher EROEI.)

Transparency Logistics: Determine how much material should be stored onsite, with what protection, to permit recovery from damage. Include consideration for i) How far away are sources and recycling? ii) Would one or more SUTPPs justify the creation of glass or ETFE manufacturing or recycling capability in closer proximity to SUTPP site(s)?

Water Capture: Integrate a water catchment system into the collector structure to permit capture of rain and wash runoff water to be fed to the purification system(s) or diverted away from the collector to avoid wasting power evaporating water under the collector. The catchment system must resist corrosion and require minimal maintenance for many decades. To mitigate risk of clogged plumbing, water may be allowed to run down parts of the collector with adequate slope for washing and maximum rainfall events, and the required minimum percentage of the water (assumed to be 25%), can be captured (instead of evaporating) to ensure rainfall suffices for future cleaning needs. Excess water may be provided for other uses.

Water Purification: Define a reliable, low maintenance, cost effective system to purify rain water (and probably dirty wash water) for subsequent cleaning, (possibly employing reverse osmosis as one step). Determine to what extent use and impact of chemicals and disposable parts (including filters) can be minimized, including what could be done with the material separated from the purified water? (Could it be environmentally/agriculturally useful?)

Cleaning Systems: Define a reliable system capable of meeting operational needs with acceptable maintenance requirements. ETFE can probably be sprayed from overhead to wash contaminants into drains. Cleaning nearly horizontal glass will probably require mechanical wet wiping and a means to remove wash water, perhaps by wiping, moving it to drains and/or wet vacuuming. Trade studies are required to determine if onboard tanks that require stronger structure or hoses make more sense, and what the optimum distance between hose or refill ports is. The best architecture for water supply (plumbing and pump) systems below the canopy must be determined. The system must be robust, reliable and not require high maintenance a complex supply chain.

Water and Cleaning Power Requirements: Power requirements for the cleaning machines and water management and purification system need to be understood.

Sandstorm Risk, Effects and Mitigation: How often do sandstorms occur at an intended site? How severe are they and how much do they damage or dull candidate collector surfaces and coatings? What is the best choice of transparency material, expected replacement frequency, and impact of replacement (downtime, financial, GWP and EROEI?)

Excessive Soil Parching: Studies may be needed to determine the effects of heating and drying soil or sand for many decades. Does it blow away or become very hard? Does the soil become biologically sterile and unable to support an ecosystem after the SUTPP is removed and sol is periodically rehydrated by natural rainfall? Is this be a temporary or longer lasting condition? Can it be easily remedied? Is this a concern at the SUTPP location?

Wind Driven Performance Enhancement Device: Wentz [69] suggested performance of a SUTPP may be enhanced by prevailing winds by incorporating a conical annulus mounted just above the top of the tower as illustrated in Figure 6.1. Wentz [69] states: "Vertical exhaust systems (chimneys) frequently suffer performance loss when atmospheric cross-winds deflect the exhaust jet and cause flow separation within the tube. To avoid this problem, a cross-wind deflector ring may be attached to the exit area, as illustrated (in Figure 7.1). This ring deflects prevailing wind from any direction upward in the exit plane, inducing additional momentum to the exhaust and avoiding separation within the duct. Deflectors of this type are used in many chimney applications, including open return wind tunnel systems. While the device increases cost and weight, it often greatly reduces internal flow losses, and improves overall chimney performance" [69].

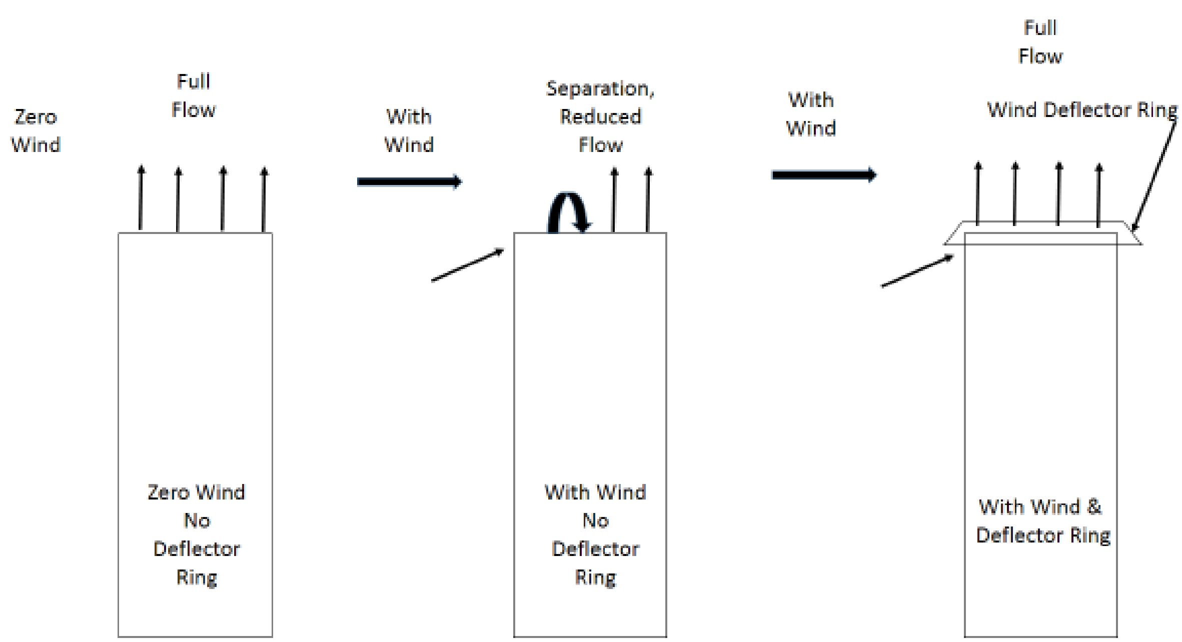

Figure 7.1. Wind driven performance enhancement device (suggested by Wentz [69]).

Further In-Dept Site Studies are required to assess ecological impact, solar insolation, weather, sandstorm risk and effects, soil thermal characteristics, contamination and cleaning method evaluation, estimated transparency life, and portion of rain and wash water captured vs. evaporated.

7.2 Conclusions

Global Warming Potential (GWP) and Energy Returned on Energy Invested (EROEI):

- EROEI of SUTPPs is between that of photovoltaic and wind power.
- SUTPP power has lower GWP than photovoltaic, and is comparable to wind power.
- The GWP impact of construction is repaid within the first 1.8 to 3.4 years of carbon free electricity production.
- For the SUTPPs studied, the collector was the largest GWP and EROEI contributor (larger than the rest combined), followed by the tower and turbine/generator/electrical systems.
- For the SUTPPs studied (excluding water thermal storage), the collector contributed over 50% to GWP and EROEI, followed by the tower and turbine/generator/electrical systems.

Design Guidance:

- SUTPPs need to use ETFE rather than glass to have acceptable EROEI and GWP, and compete with other renewable energy sources.
- The basic ETFE double glazed (BSUTPP-DG) configuration produces the most power.
- Water thermal storage is not worth the investment and practical problems of tank and water management.
- Airflow regulated power management permits enhanced ground heat storage and release to provide renewable baseload power or power at demanded times.
- The ETFE airflow regulated double glazed (ASUTPP-DG) configuration is most optimal for baseload power or for tailoring it’s design to provide power on demand.

- The physics makes intermediate sized SUTPPs uneconomic. The first SUTPP will face first of a kind practical and technical challenges.
- Tower external concrete stiffening rings offer better GWP, EROEI and power output than internal steel bracing wheels.
- Growing crops under a SUTPP is not recommended because it reduces power output due to evaporation from the plants and soil.

ETFE Conclusions:

- ETFE can be made without petroleum feedstock, can be recycled, resists UV, lasts for decades, and is easier to clean than glass, making it an attractive transparency material.
- ETFE should be deployed as tensioned membranes to avoid maintaining a pillow inflation system.
- Moderate optimized vaulting of the upper ETFE surfaces may be required, perhaps supplemented with directional spraying or blown air to assure proper cleaning drainage.
- A non-vaulted EFTE layer immediately below a vaulted layer can improve airflow and thermal insulation below, which may improve performance and EROEI.
- Avoid locations prone to transparency damage (such as hail) to avoid GWP, EROEI and downtime impacts.
- The risk and impact of sandstorms needs to be better understood.

Additional Research Required:

- Further research identified in Section 7.1 should be pursued, including site studies several years in advance to obtain enough data for planning and design decisions.

REFERENCES

REFERENCES

[1] Schlaich, J., 2011, "Solar Updraft Tower."

[2] Pretorius, J. P., 2007, "Optimization and Control of a Large-Scale Solar Chimney Power Plant," PhD, Stellenbosch.

[3] Bilgen, E., and Rheault, J., 2005, "Solar chimney power plants for high latitudes," Solar Energy, 79(5), pp. 449-458.

[4] Panse, S. V., Jadhav, A. S., Gudekar, A. S., and Joshi, J. B., 2011, "Inclined solar chimney for power production," Energy Conv. Manag., 52(10), pp. 3096-3102.

[5] Wei, J., Wang, F. H., and Zhao, L., 2007, Research on the best slope gradient of slope solar induced convective flows power generation system, Tsinghua University Press, Beijing.

[6] Zhou, X., 2008, "Study on Solar Chimney Thermal Power Technology and its Application in Western China."

[7] Ley, W., 1954, "Engineer's Dream," Viking Press, pp. 221-225.

[8] Serag-Eldin, M. A., 2006, "Analysis of a new solar chimney plant design for mountainous regions," Advanced Computational Methods in Heat Transfer IX, B. Sunden, and C. A. Brebbia, eds., Computational Mechanics Publications Ltd, Southampton, pp. 437-446.

[9] Zhou, X., Yang, J., Wang, J., and Xiao, B., 2009, "Novel concept for producing energy integrating a solar collector with a man made mountain hollow," Energy Conv. Manag., 50(3), pp. 847-854.

[10] Gunther, 1931, "In Hundert Jahren," p. 78.

[11] Padki, M. M., and Sherif, S. A., 1999, "On a simple analytical model for solar chimneys," International Journal of Energy Research, 23(4), pp. 345-349.

[12] Schlaich, J., Bergermann, R., Schiel, W., and Weinrebe, G., 2005, "Design of commercial solar updraft tower systems - Utilization of solar induced convective flows for power generation," Journal of Solar Energy Engineering-Transactions of the ASME, 127(1), pp. 117-124.

[13] Denantes, F., and Bilgen, E., 2006, "Counter-rotating turbines for solar chimney power plants," Renew. Energy, 31(12), pp. 1873-1891.

[14] Papageorgiou, C. D., 2004, External wind effects on floating solar chimney, Acta Press, Calgary.

[15] Papageorgiou, C., 2007, Floating solar chimney technology: A solar proposal for China, Tsinghua University Press, Beijing.

[16] Papageorgiou, C. D., and Katopodis, P., 2009, A Modular Solar Collector for Desert Floating Solar Chimney Technology, World Scientific and Engineering Acad and Soc, Athens.

[17] Papageorgiou, C., 2010, "Floating Solar Chimney Technology," Solar Energy" book of "InTech" edited by Radu D. Rugescu, pp. 187-222.

[18] Zhou, X. P., and Yang, J. K., 2009, "A Novel Solar Thermal Power Plant with Floating Chimney Stiffened onto a Mountainside and Potential of the Power Generation in China's Deserts," Heat Transf. Eng., 30(5), pp. 400-407.

[19] Kreetz, H., 1997, "Theoretische Untersuchungen und Auslegung eines temporären Wasserspeichers für das Aufwindkraftwerk," diploma thesis, Technical University Berlin, Berlin.

[20] Zheng, Y., Ming, T. Z., Zhou, Z., Yu, X. F., Wang, H. Y., Pan, Y., and Liu, W., 2010, "Unsteady numerical simulation of solar chimney power plant system with energy storage layer," Journal of the Energy Institute, 83(2), pp. 86-92.

[21] Hurtado, F. J., Kaiser, A. S., and Zamora, B., 2012, "Evaluation of the influence of soil thermal inertia on the performance of a solar chimney power plant," Energy, 47(1), pp. 213-224.

[22] Zhou, Y., Liu, X. H., and Li, Q. L., 2012, "Unsteady Conjugate Numerical Simulation of the Solar Chimney Power Plant System with Vertical Heat Collector," Physical and Numerical Simulation of Material Processing Vi, Pts 1 and 2, J. Niu, and G. T. Zhou, eds., Trans Tech Publications Ltd, Stafa-Zurich, pp. 535-540.

[23] Castillo, M., 1984, "A new solar chimney design to harness energy from the atmosphere," Spirit of enterprise: the, pp. 58-59.

[24] Smith, R., and Cohn, L., 2011, "Tall and Visionary," Sun & Wind Energy, 10/2011, pp. 24-29.

[25] Gannon, A. J., 2002, "Solar Chimney Turbine Performance," PhD, University of Stellenbosch.

[26] Bonnelle, D., 2004, "Solar Chimney, water spraying Energy Tower, and linked renewable energy conversion devices: presentation, criticism and proposals," PhD, University Claude Bernard - Lyon 1 - France.

[27] Zandian, A., and Ashjaee, M., 2013, "The thermal efficiency improvement of a steam Rankine cycle by innovative design of a hybrid cooling tower and a solar chimney concept," Renew. Energy, 51, pp. 465-473.

[28] Zhou, X. P., Xiao, B., Liu, W. C., Guo, X. J., Yang, J. K., and Fan, J., 2010, "Comparison of classical solar chimney power system and combined solar chimney system for power generation and seawater desalination," Desalination, 250(1), pp. 249-256.

[29] Harte, R., and Van Zijl, G., 2007, "Structural stability of concrete wind turbines and solar chimney towers exposed to dynamic wind action," J. Wind Eng. Ind. Aerodyn., 95(9-11), pp. 1079-1096.

[30] Alberti, L., 2006, "Flow Around Cylindrical Towers: the Stabilizing Role of Vertical Rib," MS, Stellenbosch.

[31] Kraetzig, W. B., Harte, R., Montag, U., and Woermann, R., 2009, "From large natural draft cooling tower shells to chimneys of solar upwind power plants," Proc. Symposium of the International Association for Shell and Spatial Structures (50th. 2009. Valencia). Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures: Proceedings, Editorial de la Universitat Politécnica de Valencia.

[32] Niemann, H., Lupi, F., Hoeffer, R., Hubert, W., and Borri, C., 2009, "The solar updraft power plant: design and optimization of the tower for wind effects," Proc. Proceedings of the 5th European and African Conference on Wind Engineering EACWE5, Florence, Italy.

[33] Rousseau, J.-P., 2005, "Dynamic Evaluation of the Solar Chimney," MS, University of Stellenbosch.

[34] Calder, R., 1970, Leonardo & the Age of the Eye, Heinemann.

[35] Bernardes, M. A. d. S., 2010, Solar Energy, In Tech, Online.

[36] Cabanyes, I., 1903, "Proyecto de motor solar," La Energia Electrica, 8(4), p. 2.

[37] Fluri, T. P., 2008, "Turbine layout for and optimization of solar chimney power conversion units," Stellenbosch: University of Stellenbosch.

[38] Schlaich, J., and Bergermann, R., 2002, "The Solar Chimney," p. 14.

[39] Daba, R., 2011, "Modeling and Simulation of Solar Chimney Power Plant with and without the Effect of Thermal Energy Storage Systems," MSME, Addis Abeba Institute of Technology.

[40] Maia, C. B., Ferreira, A. G., Valle, R. M., and Cortez, M. F. B., 2009, "Theoretical evaluation of the influence of geometric parameters and materials on the behavior of the airflow in a solar chimney," Comput. Fluids, 38(3), pp. 625-636.

[41] Ming, T. Z., Wei, L., and Xu, G. L., 2006, "Analytical and numerical investigation of the solar chimney power plant systems," International Journal of Energy Research, 30(11), pp. 861-873.

[42] Sangi, R., Amidpour, M., and Hosseinizadeh, B., 2011, "Modeling and numerical simulation of solar chimney power plants," Solar Energy, 85(5), pp. 829-838.

[43] Shams, E., Gross, A., and Fasel, H., 2011, "Performance Analysis of Solar Chimneys of Different Physical Scales Using CFD," Proc. International Conference on Energy Sustainability.

[44] Sun, J. M., Yang, M., and Shan, Y. G., 2007, The effect of the inclined angel on the output in a solar chimney power plant system, Zhejiang Univ Press, Hangzhou.

[45] Xu, G. L., Ming, T. Z., Pan, Y. A., Meng, F. L., and Zhou, C., 2011, "Numerical analysis on the performance of solar chimney power plant system," Energy Conv. Manag., 52(2), pp. 876-883.

[46] Zhou, X. P., Yang, J. K., Xiao, B., Hou, G. X., and Wu, Y. Y., 2009, "Numerical Investigation of a Compressible Flow Through a Solar Chimney," Heat Transf. Eng., 30(8), pp. 670-676.

[47] Zhou, X. P., Yang, J. K., Ochieng, R. M., Li, X. M., and Mao, B., 2009, "Numerical investigation of a plume from a power generating solar chimney in an atmospheric cross flow," Atmos. Res., 91(1), pp. 26-35.

[48] Koonsrisuk, A., 2012, "Mathematical modeling of sloped solar chimney power plants," Energy, 47(1), pp. 582-589.

[49] Kasaeian, A. B., Heidari, E., and Vatan, S. N., 2011, "Experimental investigation of climatic effects on the efficiency of a solar chimney pilot power plant," Renew. Sust. Energ. Rev., 15(9), pp. 5202-5206.

[50] Najmi, M., Nazari, A., Mansouri, H., and Zahedi, G., 2012, "Feasibility study on optimization of a typical solar chimney power plant," Heat Mass Transf., 48(3), pp. 475-485.

[51] Zhou, X. P., Yang, J. K., Xiao, B., and Hou, G. X., 2007, "Experimental study of temperature field in a solar chimney power setup," Appl. Therm. Eng., 27(11-12), pp. 2044-2050.

[52] Dai, Y. J., Huang, H. B., and Wang, R. Z., 2003, "Case study of solar chimney power plants in Northwestern regions of China," Renew. Energy, 28(8), pp. 1295-1304.

[53] Larbi, S., Bouhdjar, A., and Chergui, T., 2010, "Performance analysis of a solar chimney power plant in the southwestern region of Algeria," Renew. Sust. Energ. Rev., 14(1), pp. 470-477.

[54] Sangi, R., 2012, "Performance evaluation of solar chimney power plants in Iran," Renew. Sust. Energ. Rev., 16(1), pp. 704-710.

[55] Nizetic, S., Ninic, N., and Klarin, B., 2008, "Analysis and feasibility of implementing solar chimney power plants in the Mediterranean region," Energy, 33(11), pp. 1680-1690.

[56] Cao, F., Zhao, L., and Guo, L. J., 2011, "Simulation of a sloped solar chimney power plant in Lanzhou," Energy Conv. Manag., 52(6), pp. 2360-2366.

[57] Hamdan, M. O., 2011, "Analysis of a solar chimney power plant in the Arabian Gulf region," Renew. Energy, 36(10), pp. 2593-2598.

[58] Lorente, S., Koonsrisuk, A., and Bejan, A., 2010, "Constructal Distribution of Solar Chimney Power Plants: Few Large and Many Small," International Journal of Green Energy, 7(6), pp. 577-592.

[59] EnviroMission, 2013, "Corporate Website - Technology Overview - What is Solar Tower Renewable Energy Technology?," http://www.enviromission.com.au/EVM/Company/ShowPage.aspx?CPID=1073.

[60] dos Santos Bernardes, M. A., 2011, "Convective Heat Transfer Coefficients for Solar Chimney Power Plant Collectors," Heat Transfer - Mathematical Modeling, Numerical Methods and Information Technology, A. Belmiloudi, ed., InTech, p. 642.

[61] Harte, R., Hoffer, R., Kratzig, W. B., Mark, P., and Niemann, H. J., 2012, "Solar updraft power plants: A structural engineering contribution for sustainable and economic power generation," Bautechnik, 89(3), pp. 173-181.

[62] Hendrickson, C. T., Lave, L. B., and Matthews, H. S., 2006, Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach, RFF Press.

[63] Curran, M. A., 2006, Life-cycle Assessment: Principles and Practice, National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.

[64] Jensen, A. A., Hoffman, L., Moller, B. T., Schmidt, A., Christiansen, K., Berendsen, S., Elkington, A., and Dijk, F. v., 1997, "Life Cycle Assessment (LCA) - A Guide to Approaches, Experiences and Information Sources."

[65] 2009, "Environmental Management: The ISO 14000 Family of Standards," International Organization for Standardization (ISO).

[66] Mullett, L., 1987, "The solar chimney—Overall efficiency, design and performance," International journal of ambient energy, 8(1), pp. 35-40.

[67] Bernardes, M. A. D., 2004, "Technische, ökonomische und ökologische Analyse von Aufwindkraftwerken (Technical, Economic and Ecological Analysis of Solar Chimneys)."

[68] Schlaich, J., 1995, The solar chimney: Electricity from the sun, Edition Axel Menges.

[69] Wentz, W., 2013, "*Personal Communication*."

[70] Team, W. M. P., 2002, "Threats to Desert Tortoise Populations: A Critical Review of the Literature."

[71] Cameron, D. R., Cohen, B. S., and Morrison, S. A., 2012, "An Approach to Enhance the Conservation-Compatibility of Solar Energy Development," PLOS ONE, 7(6), p. e38437.

[72] Brundtland, G. H., 1987, "World Commission on Environment and Development," Our Common Future.

[73] Stanglin, D., 2010, "Dubai Opens World's Tallest Building," USA TodayWeb.

[74] Mehta, P. K., 1991, "Durability of Concrete--Fifty Years of Progress?," ACI Special Publication, 126.

[75] Elminir, H. K., Ghitas, A. E., Hamid, R., El-Hussainy, F., Beheary, M., and Abdel-Moneim, K. M., 2006, "Effect of Dust on the Transparent Cover of Solar Collectors," Energy Conv. Manag., 47(18), pp. 3192-3203.

[76] Michalsky, J., Perez, R., Stewart, R., LeBaron, B., and Harrison, L., 1988, "Design and Development of a Rotating Shadowband Radiometer Solar Radiation/Daylight Network," Solar Energy, 41(6), pp. 577-581.

[77] Sayigh, A., Al-Jandal, S., and Ahmed, H., 1985, "Dust Effect on Solar Flat Surfaces Devices in Kuwait," Proc. Proceedings of the Workshop on the Physics of Non-Conventional Energy Sources and Materials Science for Energy, pp. 2-20.

[78] Humphries, M., and Davey, R., 2011, "Solar Tower in Arizona to Power 150,000 Homes for 80 Years."

[79] Gutekunst, J., 2011, "Work on Solar Tower Progressing," Parker PioneerParker, Arizona.

[80] Blain, L., 2011, "Twice the Height of the Empire State - EnviroMission Plans Massive Solar Tower for Arizona," http://www.gizmag.com/enviromission-solar-tower-arizona-clean-energy-renewable/19287/.

[81] Bonnelle, D., 2011, "Solar Chimney Project in Arizona: An Energy Budget Basic Check," http://publications.solar-tower.org.uk/200_MW_La_PAZ_SCCP_in_Arizona.pdf.

[82] AngloAmerican, 2013, "Kumba Website," http://www.kumba.co.za/index.php.

[83] 2013, "Flightradar24 Live Air Traffic," http://www.flightradar24.com/data/airports/sis.

[84] 2013, "Air Pressure and Altitude Above Sea Level," http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html.

[85] 2013, "South Africa Rain Atlas," http://wsopuppenkiste.wiso.uni-goettingen.de/rainfall/.

[86] 2013, "Solar Energy Map (NOAA Data)," http://www.renewableenergyst.org/solar.htm.

[87] Pretorius, J. P., 2013, "*Personal Communication*."

[88] Bernardes, M. A. D., 2013, "Personal Communications."

[89] Kraetzig, W., 2013, "*Personal Communication*."

[90] Lombaard, F., 2002, "Performance of a Solar Air Heater Incorporating Thermal Storage," Stellenbosch: Stellenbosch University.

[91] Frisvold, G. B., and Caswell, M. F., 2000, "Transboundary water management Game-theoretic lessons for projects on the US–Mexico border," Agricultural Economics, 24(1), pp. 101-111.

[92] Hayter, S., Tanner, S., Urbatsch, E., and Zuboy, K., 2004, "Saving Energy, Water, and Money with Efficient Water Treatment Technologies," US Department of Energy, National Renewable Energy Laboratory (NREL), Federal Energy Managment Program (FEMP).

[93] Fluri, T. P., Pretorius, J. P., Van Dyk, C., Von Backstrom, T. W., Kroger, D. G., and Van Zijl, G., 2009, "Cost analysis of solar chimney power plants," Solar Energy, 83(2), pp. 246-256.

[94] James, M., and Wei, L., 1999, "Hail damage to polycarbonate roofing sheets," Proc. Proceedings of an International Conference on Case Histories on Integrity and Failures in Industry, Milan, pp. 715-724.

[95] Robinson, L. A., 2005, "Structural Opportunities of ETFE (ethylene tetra fluoro ethylene)," Massachusetts Institute of Technology.

[96] Tanno, S., 1997, "ETFE foil cushions as an alternative to glass for atriums and rooflights," Proc. International Conference on Building Envelope Systems and Technology 2nd, pp. 357-362.

[97] 2013, "The Weather Channel," http://www.weather.com/weather/wxclimatology/monthly/85344.

[98] 2013, "Tefzel (R) (ETFE Ethylene Tetraflouroethylene) Material Information," http://sterlingplasticsinc.com/materials/tefzel-etfe-ethylene-tetrafluoroethylene/.

[99] 2013, "Architecture of ETFE," http://www.makmax.com/business/etfe_advantages.html.

[100] Dimitriadou, E., and Shea, A., 2012, "Experimental Assessment and Thermal Characterization of ETFE Foil."

[101] Poirazis, H., Kragh, M., and Hogg, C., 2009, "Energy Modeling of ETFE Membranes in Building Applications," Proc. Eleventh International IBPSA Conference Glasgow, Scotland.

[102] Schlaich, J., Bergermann, R., Schiel, W., and Weinrebe, G., 2004, "Sustainable electricity generation with solar updraft towers," Structural engineering international, 14(3), pp. 225-229.

[103] Hammond, G., and Jones, C., 2008, "Inventory of Carbon & Energy (ICE) Version 1.6a," Sustainable Energy Research Team (SERT) Dept of Mechanical Engineering, University of Bath, UK (Downloaded from http://web.mit.edu/2.813/www/readings/ICE.pdf).

[104] Scheuer, C., Keoleian, G. A., and Reppe, P., 2003, "Life Cycle Energy and Environmental Performance of a New University Building: Modeling Challenges and Design Implications," Energy and buildings, 35(10), pp. 1049-1064.

[105] Buchanan, A. H., John, S., and Love, S., 2012, "LCA and Carbon Footprint of Multistorey Timber Buildings Compared with Steel and Concrete Buildings," World, 15, p. 19.

[106] 2013, "GaBi Software Website," http://www.gabi-software.com/america/index/.

[107] Robinson-Gayle, S., Kolokotroni, M., Cripps, A., and Tanno, S., 2001, "ETFE foil cushions in roofs and atria," Construction and Building Materials, 15(7), pp. 323-327.

[108] Hall, C. A., Balogh, S., and Murphy, D. J., 2009, "What is the minimum EROI that a sustainable society must have?," Energies, 2(1), pp. 25-47.

[109] Inman, M., 2013, "The True Cost of Fossil Fuels," Scientific American Magazine, 308(4), pp. 58-61.

[110] Sherry, K. F., 2011, "7 Wonders of the New World," New York PostOnline.

[111] 2013, "Google Maps," https://maps.google.com.

[112] 2013, "Arizona Elevation Map," http://geology.com/state-map/arizona.shtml.

[113] 1990, "Arizona Annual Precipitation 1961-1990," N. R. C. Service, ed., US Dept of Agriculture, www.google.com.

[114] "Rain Loads," 1611.1, I. C. Council, ed., International Code Council, publicecodes.cyberregs.com.

[115] "Snow Loads," Section 1608.2, I. C. Council, ed., International Code Council, http://publicecodes.cyberregs.com.

[116] "Wind Loads," 1609B, I. C. Council, ed., International Code Council, publicecodes.cyberregs.com.

[117] Schaefer, J. T., Levit, J. J., Weiss, S. J., and McCarthy, D. W., 2004, "The Frequency of Large Hail over the Contiguous United States," Proc. Preprints, 14th Conf. Applied Climatology, Seattle, WA, Amer. Meteor. Soc.

[118] 2013, "Community Collaborative Rain, Hail & Snow Network," http://www.cocorahs.org/ViewData/ListHailReports.aspx.

[119] 2013, "NAICS 327211 Flat Glass Manufacturing - Industry Statistics Sampler - 2007 Census Geographic Distribution," US Census Bureau, US Dept of Commerce, http://www.census.gov/econ/industry/geo/g327211.htm.

[120] Www.EngineeringToolBox.Com, 2013, "Concrete Mixtures,"http://www.engineeringtoolbox.com/concrete-sand-cement-gravel-mixtures-d_1547.html.

[121] Clute, D., 2003, "Title."

[122] 2013, "Cement Manufacturing," http://www.epa.gov/sectors/sectorinfo/sectorprofiles/cement.html.

[123] 2013, "Steel Industry Executive Summary: June 2013," I. T. A. US Dept of Commerce, ed.http://hq-web03.ita.doc.gov/License/Surge.nsf/webfiles/SteelMillDevelopments/$file/exec%20summ.pdf.

[124] 2010, "Steel Plants of North Amercia (Map)," http://www.steel.org/en/Making%20Steel/~/media/Files/AISI/Making%20Steel/2010_SteelPlant_NorthAmerica_HypocycloidVersion6.ashx.

[125] Leigh, R., 2007, "Hail Storm-One of the Costliest Natural Hazards," Proc. Coastal Cities Natural Disasters Conference.

[126] Lide, D. R., and Bruno, T. J., 2012, CRC Handbook of Chemistry and Physics, CRC Press LLC.

[127] Troshin, N., and Yaster, V., 1988, "Calculation of Resistance of Flat Glass to the Action of Hail," Glass and Ceramics, 45(10), pp. 372-374.

[128] Flüeler, P. H., 2007, "ETFE Membrane Structures: and What About Hail Impact Resistance?," Proc. RCI 22nd International Convention, Swiss Federal Laboratories for Materials Testing and Research, Flüeler Polymer Consulting GmbH, Zurich, Switzerland, pp. 29-37.

[129] Hoeffer, R., Wevers, C., and Gornendt, V., 2010, "Transport and Deposition of Dust on the Collector Surface," 2nd International Conference on Solar Chimney Power Technology Ruhr Universtiy Bochum, pp. 325-335.

[130] Blesi, R., and Wight, D., 2013, "*Personal Communication* with New Star Inc (Window Washer Manufacgturer)."

[131] 2013, "RainMaster 15,000 Gallon Fiberglass Rainwater System," http://www.rainharvest.com/rainmaster-15-000-gallon-fiberglass-rainwater-system.asp?gclid=CJr1xayjprgCFWIV7Aod_lwAvQ.

[132] 2013, "LCA Calculator," http://www.lcacalculator.com/.

[133] DeVilliers, P. F., 2001, "Sonkragstasie en skoorsteen konsepte vir 'n optimale versamelaar," Under-graduate, University of Stellenbosch.

[134] Doka, 2013, "Doka US Businesss Website (Concrete Formworks)," http://www.doka.com/web/home/index.us.php?startPageLanguage=US.

[135] 2013, "HP Dynaform System," http://www.comdynam.com/Natural-Draft-Cooling-Towers/.

[136] Papadopoulos, I., 2010, "Comparative Analysis of Electricity Generating Technologies with Regards to Environmental Burdens," University of Bath.

[137] Hammond, G. P., and Jones, C., 2008, "Embodied Energy and Carbon in Construction Materials," Proceedings of the Institution of Civil Engineers-Energy, 161(2), pp. 87-98.

APPENDICES

APPENDIX A

LOCATION AND SITE CHARACTERISTICS

The conclusions of research in this appendix are summarized in Table 4.1.

A.1 Location

The location of the SUTPP is assumed to be near the planned EnviroMission site in La Paz Arizona. A web search did not reveal its specific location, however it is possible to get very close with the information available on the Internet. It lies approximately 130 miles west of Phoenix Arizona and La Paz county near the California border [110]. A 130 mile radius arc around Phoenix on the Google map shown in Figure A.1 lies very near the Western border of the county at the Colorado River.

Figure A.1. Arizona [111].

Figure A.2 provides a closer view.

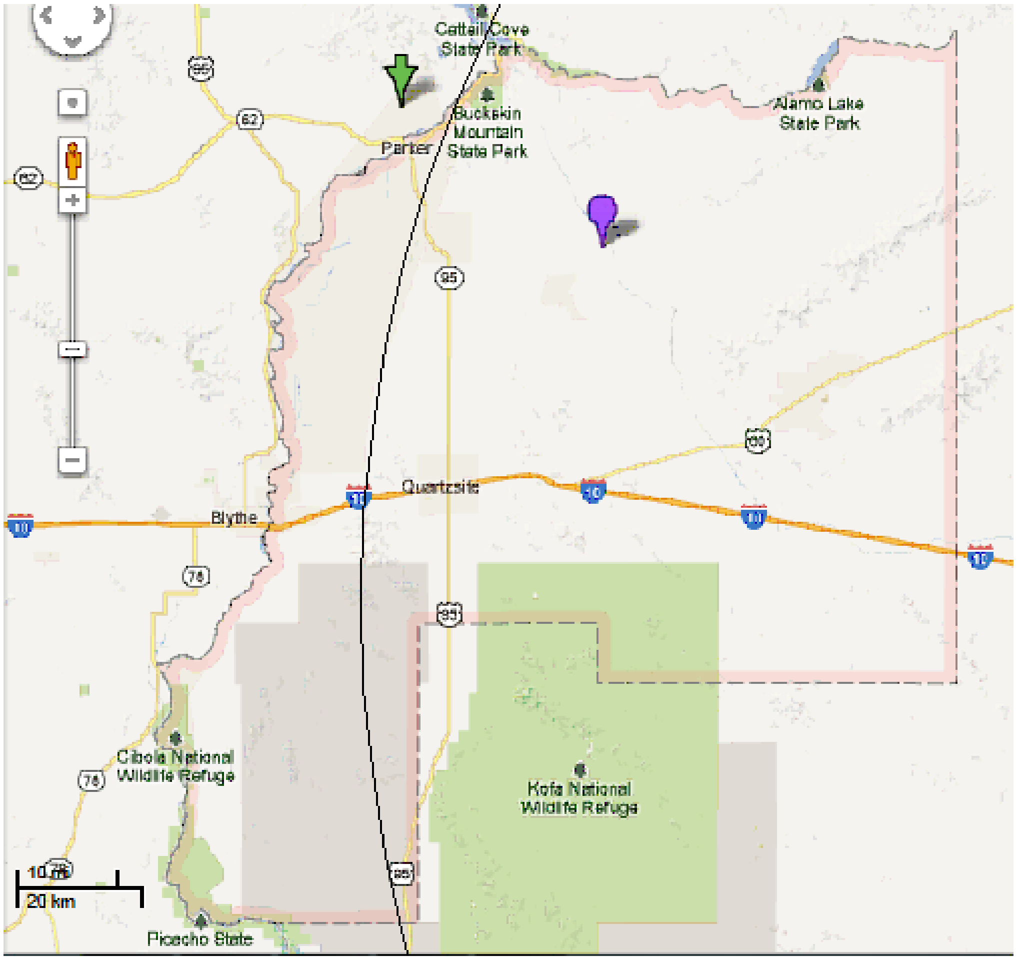

Figure A.2. La Paz County [111].

The site is unlikely to overlap any of the following:

Yuma Proving Ground (gray at lower left)
Kofa National Wildlife Refuge (Green below center)
Quartzite.
Highways
Fertile or inhabited areas within the Colorado River Indian Reservation (light gray upper left.)

This site is probably relatively flat and sandy. The claimed size of the EnviroMission collector is 5,500 acres [24], giving a diameter of 5.3 km, however, Schlaich estimates to achieve 200MW capacity, a 7 km diameter and 1km tower are needed[12]. Approximately 7 km diameter circles illustrate the most likely locations in Figure A.3. The red circle, appears to be on the best uniform flat terrain upon closer examination than shown in the Figure A.3, and is therefore assumed by this thesis to be the indented site, located at approximate Longitude -114.29, and Latitude +33.92.

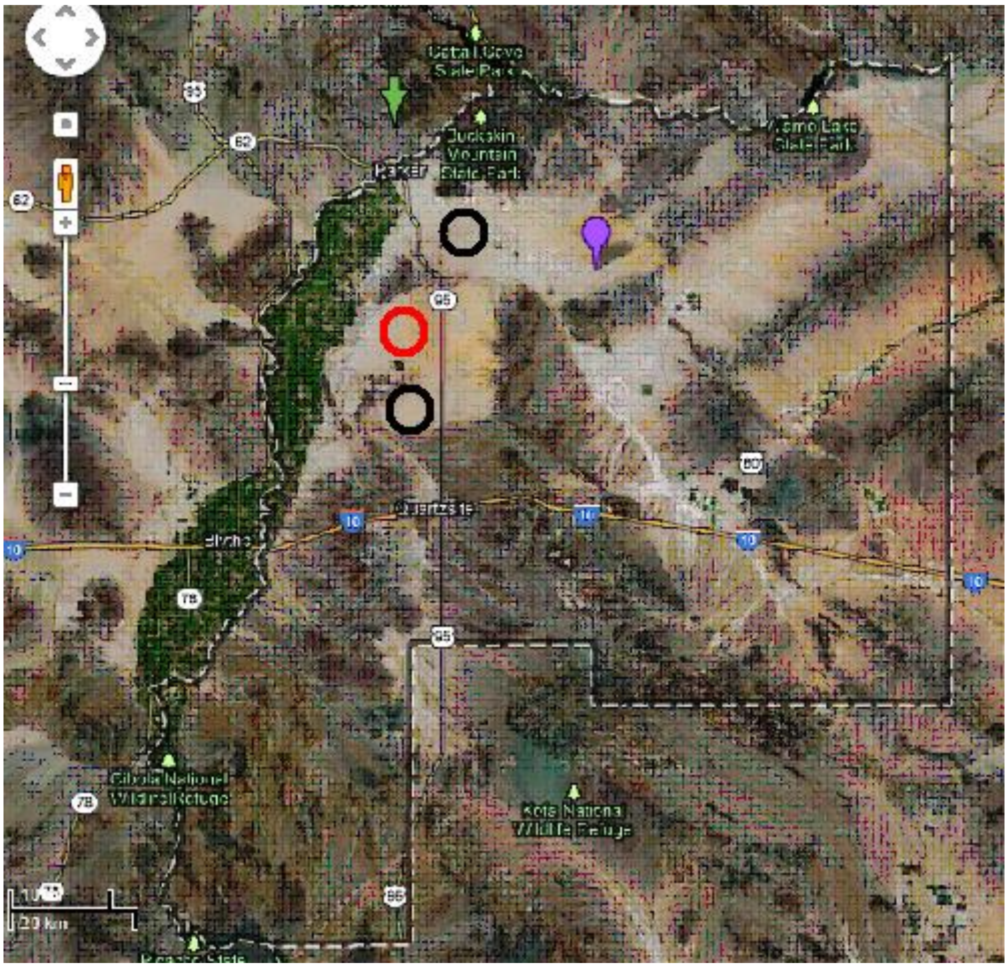

Figure A.3. SUTPP location map [111].

A.2 Elevation

The Arizona Elevation map available at http://geology.com/state-map/arizona.html [112] shows the elevation is in the 600 to 1,200 ft region, and is assumed to be 900 feet.

A.3 Rainfall

According to "Arizona Annual Precipitation" by US Department of Agriculture [113], the location is in the 4 to 6 inch per year Average Annual Rainfall region. "Figure 1611.1 100-year, 1-hour rainfall Western United States" from the National Weather Service, National Oceanic and Atmospheric Administration, Washington DC [114], shows the site is midway between the 1.5 and 2.0 inch per hour contour lines, and is assumed to be approximately 1.75 inches per hour. Should this all accumulate on the collector surface, it will exert a weight force of:

$$(1.75 \text{ in})(2.54 \text{ cm/in})(10{,}000 \text{ cm2/m2})(.001 \text{ kg/cm3})(9.81 \text{ m/s}^2) = 436 \text{ N/m}^2 \text{ (9.11 psf)}$$

A.4 Snow

"FIGURE 1608.2 Ground Snow Loads for the United States (psf)" by the International Code Council [115], shows the maximum snow load is zero at the proposed location.

A.5 Wind

"FIGURE 1609B Ultimate Design Wind Speed, V_{ult}, for Risk Category III and IV Buildings and Other Structures" by the International Code Council [116] shows the maximum wind gust will not exceed 120 MPH (54 m/s).

A.6 Hail

According to Schaefer et al., *The frequency of large hail over the contiguous United States*. [117], hail is expected less than 10 times per decade per 100 square nautical miles at the. 8.2% of hail reports in the contiguous 48 United States are 2" diameter or larger [117], implying the risk of 2" or larger diameter hail at the site is less than 0.8 times per decade per 100 square nautical miles. The incidence of hail at the 5 km diameter, 19.5 km^2 (5.68 nm^2)SUTPP itself is less than for 100 square nautical miles (suggesting less than 4% risk per century if areas are scaled, but is not valid reasoning because we don't know the average area of hail tracks in Arizona.) The Community Collaborative Rain, Hail and Snow Network, a volunteer organization used by the National Weather Service and Researchers maintains a web site [118] where anyone can query hail reports. Online records go back to June 1998 (roughly 15 years). During that time there were 189 hail reports for all of Arizona, only 10 indicated the largest stones were 1" or larger (5.3% of 189 reports), and only 1 report indicated the largest stones were 2" diameter (about 0.5%). None of the reports were for La Paz County, which consists of 4,500 of the 114,000 square miles in Arizona, suggesting it should have had 7 of those 189 reports, leading credence to the lower hail density for extreme Western Arizona indicated by Schaefer et al. [117]. Therefore this thesis concludes the probability of a 2" hail stone during up to a century of operation is essentially zero, though 1" hail is possible, but more likely not to occur than to occur during a century. 1" hail strikes have substantially less than 10 J impact energy according to Table B.1. A 1.7" diameter stone is required to have a 10 J impact. Therefore 1" stones will be significantly below the 13J required to dimple ETFE, and substantially below the impact force required to break a measureable fraction of 4 mm thick tempered glass per Table B.1. Therefore hail is deemed NOT to be a significant damage risk at La Paz.

A.7 Solar Insolation

The solar insolation of the La Paz and Sishen sites were obtained from Renewable Energy Science and Technology at www.renewableenergyst.org/solr.htm [86], a site providing data for total energy on a flat surface based on NOAA data. The website requires the user make a rectangular drag box across the area of interest, however at the La Paz site it was not possible to adjust the box smaller than a certain size, probably corresponding the smallest data grid resolution. Using the outputs from the website, the annual average power per square meter was estimated below.

La Paz: (1.126 x 10^{12} kWh/y) / (2,566 kt^2 *$1{,}000^2$ m^2/km^2 *.2) = 2,194 kWh/m^2y

Sishen: (4.841 x 10^8 kWh/y) / (1.101 km^2 *$1{,}000^2$ m^2/km^2 *.2) = 2,198 kWh/m^2y

The ratio of these values is 2,194/2,198 = 0.998, so this thesis will assume they are roughly equivalent.

Personal correspondence (Email copied below) with the above website clarifies the data source and accuracy of information from this site. Pretorius (Appendix H [2]) includes a table of hourly solar insolation averaged by Month that Table A.1 adds up to 2,340 kWh/(m^2y) direct and 446 kWh/(m^2y) indirect annual insolation. As discussed in Section 4.2, other sources cite 2,300 to 2,400 kWh/(m^2y) for La Paz, but time did not permit a more exhaustive search to confirm those numbers. Therefore this thesis takes the position the sites are similar enough for the gross evaluation purpose of this thesis. However, it must be noted the sites may NOT be as equivalent as is assumed.

> **From:** Quanhua Liu [mailto:renewableenergyst@yahoo.com]
> **Sent:** Saturday, July 06, 2013 1:10 PM
> **To:** James Zongker
> **Subject:** Re: Is this Direct or Total Solar Radiation per m^2?
>
> Answer to your question:
>
> 1. It is downward total radiation (direct + diffuse) at the surface.
> The annual solar power included efficiency factor in the right check box.
>
> 2. It used the same standard, but terrain wasn't considered.
>
> 3. The data is based on the NCEP reanalysis data. You may contact
> the NOAA NCEP scientists regarding to the accuracy of surface solar radiation.
> My own evaluation (not published) in the following figure shows that the NCEP surface solar radiation daily values agree with surface site measurements within about 10%. The annual mean should be much better, at least better.

TABLE A.1

SUM OF SISHEN DIRECT & DIFFUSE SOLAR RADIATION ON A HORIZONTAL SURFACE [2]

	Total	W/m^2 avg for that hour																	
	6	7	8	9	10	11	12	13	14	15	16	17	18	/mo	/yr	Days/mo	W/(m^{2}y)		
Jan	138	357	572	762	909	1003	1035	1003	909	762	572	357	138	8517		31	264,027		
Feb	68	279	496	691	845	942	976	942	845	691	496	279	68	7618		28	213,304		
Mar	0	190	406	604	763	865	900	865	763	604	406	180	0	6546		31	202,926		
Apr	0	100	299	489	644	745	780	745	644	489	299	110	0	5344		30	160,320		
May	0	35	220	407	562	664	700	664	562	407	220	35	0	4476		31	138,756		
Jun	0	19	190	368	517	616	650	616	517	368	190	19	0	4070		30	122,100		
Jul	0	35	220	407	562	664	700	664	562	407	220	35	0	4476		31	138,756		
Aug	0	99	295	483	636	735	770	735	636	483	295	99	0	5266		31	163,246		
Sept	0	182	388	578	730	827	861	827	730	578	388	182	0	6271		30	188,130		
Oct	66	272	483	673	822	917	950	917	822	673	483	272	66	7416		31	229,896		
Nov	135	348	558	743	887	979	1010	979	887	743	558	348	135	8310		30	249,300	W/m^2/day	
Dec	157	375	587	773	917	1009	1040	1009	917	773	587	375	157	8676	76986	31	268,956		W/m^2/hr
/hr	564	2291	4714	6978	8794	9966	10372	9966	8794	6978	4714	2291	564		76986	365	2,339,717	6,410	267
																	2,340		
																	kW/(m^{2}y)		

	Diffuse	W/m^2 avg for that hour																	
	6	7	8	9	10	11	12	13	14	15	16	17	18	/mo	/yr	Days/mo	W/(m^{2}y)		
Jan	52	89	108	126	136	140	135	140	136	130	114	82	40	1428		31	44,268		
Feb	46	86	109	124	144	151	156	160	161	145	114	75	24	1495		28	41,860		
Mar	0	72	102	121	130	138	144	138	145	133	102	54	0	1279		31	39,649		
Apr	0	50	84	112	129	134	148	142	129	108	78	31	0	1145		30	34,350		
May	0	18	66	85	101	106	105	100	96	77	48	11	0	813		31	25,203		
Jun	0	10	63	88	109	117	111	105	93	70	44	6	0	816		30	24,480		
Jul	0	17	66	90	107	113	112	106	96	77	48	12	0	844		31	26,164		
Aug	0	50	91	106	127	125	123	125	114	101	71	32	0	1065		31	33,015		
Sept	0	78	109	127	139	149	155	149	146	121	97	58	0	1328		30	39,840		
Oct	45	95	121	141	156	165	181	183	173	155	135	90	28	1668		31	51,708		
Nov	62	90	112	126	133	137	131	137	142	134	117	87	45	1453		30	43,590	W/m^2/day	
Dec	58	83	103	108	119	121	114	131	128	124	116	86	49	1340	14674	31	41,540		W/m^2/hr
/hr	263	738	1134	1354	1530	1596	1615	1616	1559	1375	1084	624	186		14674	365	445,667	1,221	51
																	446		
																	kW/(m^{2}y)		

A.8 Proximity & Transportation Distances

The transportation distances in Table 5.7 were determined via the rationale below.

Water:

The nearest large source of water is the Colorado River, which the US is required to provide 1,5 million acre feet (1.8 x 10^9 m^3) per year to Mexico under the 1944 Mexican Water Treaty [91]. Much of the Colorado River flow never makes it to Mexico because it is used for agriculture, industry, and major cities along the way, including Los Angeles and Southern California via the Colorado River Aqueduct which takes water to the North of the proposed SUTPP site at Lake Havasu. This thesis assumes that any flow diverted for this project must not exceed 1% of the flow promised to Mexico under the treaty, under the slightly optimistic assumption most of the flow can come from other upstream users taking less water or the water can be taken during periods or higher flow rate. Examination of a Google map (See Figure A.3) suggests a trip of roughly 20 km from the site center, to I-95, north and then Northwest to the Colorado River may be the shortest distance to truck in water by main highway. Thus this thesis assumes water can be trucked in from 20 km away. Alternatively, the most direct pipeline route is 12 km long, but requires permission of landowners, and permission to cross the Parker Indian

Reservation. Permission may also be required to drive many truckloads of water across the reservation. It may be necessary to drive a few km farther to get water north of the reservation.

Glass:

2007 US Census data [119] shows the value of Shipments produced in US was $3,273,652,000, with $281,152,000 produced in California from 6 establishments. If cost were $1 per square meter (it is unlikely to be that cheap) that is $19,500,000 worth, or about 7% of annual production of California. At $5/m^2, that amounts to about 1/3 of a year's production, (or 1/6 if spread over 2 years.) Therefore it was somewhat optimistically assumed all glass can be obtained from California (or possibly Arizona or Mexico), and since most populated area in California, is near Los Angeles, the average shipping distance is 600 km by highway according to Google maps.

ETFE:

Shipping distances for ETFE are discussed in Section 4.5.3.

Concrete:

Concrete is made up of cement, sand, gravel, and water. By determining the approximate mass fraction of each, and distance to a source for each, it is possible to approximate the ton*kilometers of hauling needed to yield one ton of concrete at the worksite.

The Engineering Toolbox website [120] was used to obtain the relative volumes for the 3 types of concrete listed in Table A.2, and to determine the density of concrete was typically between 2,240 and 2,400 kg/m^3, for which the average value of 2,320 kg/m^3,was assumed, as much of the difference comes from how much air or water is trapped in the concrete is (after curing). The specific gravity of water, cement, sand, and gravel was taken from "Fundamentals of Concrete Mix Design" by Dennis Clute (Civil Engineer) [121], and used for the calculations shown in Table A.2 where the relative volume of water was iterated to get a density of 2,320 kg/m^3. The mass fractions were then computed for water, cement, sand and gravel, and the sand and gravel were added together, giving the 3 yellow highlighted values for water, cement and (sand + gravel). Since it was not clear whether the foundation or basement case most closely resembled the tower foundations and collector footings, it was decided to average those two concrete types and round to the nearest 1%, giving the red font values. Similar rounding was done to the high strength values. Thus this thesis assumes the values shown at the bottom of Table A.2 are suitable approximations of the concrete mass fractions.

APPENDIX A (continued)

TABLE A.2

CONCRETE MASS FRACTION CALCULATION

Water	Mass	Cement	Mass	Sand	Mass	Gravel	Mass	Tot Mass	S.G.	Mass Fractions			
Vol	S.G.	Vol	S.G.	Vol	S.G.	Vol	S.G.	Tot Vol		Water	Cement	Sand	Gravel
Foundations and walls, normal static loads, exposed													
	2.4659		3.15		6.575		13.25	25.441 =	2.32	0.0969	0.1238	0.2584	0.5208
2.4659	1 +	1	3.15 +	2.5	2.63 +	5	2.65 =	10.966					0.7793
										0.1	0.14		0.76
Basemennt walls, waterproof													
	2.0909		3.15		6.575		9.275	21.091 =	2.32	0.0991	0.1494	0.3117	0.4398
2.0909	1 +	1	3.15 +	2.5	2.63 +	3.5	2.65 =	9.0909					0.7515
High Strength, floors, columns										0.11	0.25		0.64
	1.3636		3.15		2.63		5.3	12.444 =	2.32	0.1096	0.2531	0.2114	0.4259
1.3636	1 +	1	3.15 +	1	2.63 +	2	2.65 =	5.3636					0.6373

Mass Fractions:	Water	Cement	Sand & Gravel
Foundation Concrete	0.10	0.14	0.76
High Strength (Tower) Concrete	0.11	0.25	0.64

According to the Portland Cement Association website, in 2008, the US consumed 93.6 million metric tons of Portland cement, of which 11.5 metric tons was imported, mostly from China, Canada, Columbia, Mexico and the Republic of Korea. A map on the US EPA website [122] identifies the locations of US cement manufacturers as of January 2011, and notes California as one of the top producers. This project is expected to require less than 1 million tons of concrete, which is mostly sand and aggregate, so it is unrealistic to attempt to acquire the amounts required over 1-2 years from local producers within 300 km (throughout southern California and south central Arizona), transported via highways shown on Google maps.

The sand, gravel and crushed rock will probably be taken from the closest environmentally and economically viable sources, possibly even on site, so it is assumed the average shipping distance is about 75 km or less.

This thesis assumes ton kilometers for hauling concrete ingredients to the site can be characterized as shown in Table A.3.

APPENDIX A (continued)

TABLE A.3

TON-KILOMETERS FOR CONCRETE

	Foundation Concrete			High Strength Concrete		
	Water	Cement	Aggregate	Water	Cement	Aggregate
Fraction	0.1	0.14	0.76	0.11	0.25	0.64
Distance (km)	20	300	75	20	300	75
(t+km)	2	42	57	2.2	75	48
(Avg'd t*km)		101			125.2	

Therefore this thesis will assume the materials for foundation and footer concrete will need to be trucked in 100 km, and the materials for high strength concrete will need to be trucked in 125 km.

Steel:

According to the US Department of Commerce [123], the US has consumed about 8 million metric tons of steel a month over the most recent year of data, about 23% is imported, and the largest foreign source is China. Therefore it will be assumed 23% of the steel comes from China, thus the mean distance by boat is 0.23*10,500 km = approx 2,400 km. Trucking distances are assumed to be 350 km in China + US combined if imported,50% is assumed to come from more distant US plants and trucked 1,500km, and the remaining 27% is assumed to come from the 2 closest steel mills at www.steel.org [124], located near Rancho Cucamonga CA and Mexicali, Baja, Mexico, with most of that coming from the higher capacity Mexicali plant, assumed to be an average shipping distance of 160 km. Thus the average steel transport distance is the combination of:

(0.23*350 + 0.5*1,500 + 0.27*.160) = 874 km, rounded to 900 km by truck
2,400 km by ship.

Turbine, Generator, Electrical and Other Infrastructure:

The data on turbine/generator assemblies comes from entire wind turbine installations and already includes transportation as such a small percentage of the total, that is was not deemed worth attempting to isolate it for separate recalculation, given that the uncertainties in turbine/generator units will be far greater due to elimination of the wind turbine tower and tower's foundation, and recomputation of the turbine contributions due to use of an entirely different turbine design for use inside a duct.

APPENDIX B

HAIL SUCEPTABILTY

The effect of potential large hail on the collector “canopy” or “transparency” material must be understood to facilitate an appropriate choice of material and to assess the life cycle impact of having to replace damaged transparency areas.

The terminal fall velocity V_t of hail near sea level is maximized for smooth round solid ice hailstones with minimum drag and maximum density. V_t is given by the equation [125].

$$V_t = 14.04(d)^{0.5} \quad (V_t \text{ in m/s, } d = \text{diameter in cm})$$

The mass of a pure ice sphere is the product of the density of ice and spherical volume:

$$M = \rho(4/3)\pi(d/2)^3 \quad (M \text{ in kg, } \rho = 0.9167 \text{ kg/m}^3 \text{ density of ice at 0 °C [126]})$$

Assuming a vertical fall at terminal velocity, the kinetic energy is given by the equation.

$$KE = ½MV_t^2 \quad (KE \text{ in Joules, } M \text{ in kg, } V_t \text{ in m/s})$$

These equations were utilized to compile Table B.1 giving the mass, terminal velocity and kinetic energy of perfectly round pure ice hail stones (containing no air or water pockets) of the sizes needed to get KE that is a multiple of 10 Joules. Actual vertical kinetic energy at impact is typically less due to higher drag of imperfect spherical shapes.

TABLE B.1

HAILSTONE KINETIC ENERGY

Diameter		Volume	Mass	Velocity	KE	4mm tempered glass Breakage
(cm)	(in)	(cm^3)	(kg)	(m/s)	(J)	Probability (1 = 100%) (Troshin and Yaster [127])
4.400	1.73	25.09	0.02300	29.45	10.0	
5.236	2.06	42.28	0.03876	32.13	20.0	
5.795	2.28	57.32	0.05254	33.80	30.0	.13
6.227	2.45	71.11	0.06519	35.04	40.0	.45
6.584	2.59	84.06	0.07706	36.03	50.0	.70
6.891	2.71	96.38	0.08835	36.86	60.0	.84
7.162	2.82	108.20	0.09919	37.57	70.0	.92
7.405	2.92	119.59	0.10963	38.21	80.0	.98

APPENDIX B (continued)

B.1 Glass:

The probability of a horizontal annealed or tempered 4mm thick glass plate breaking when hit by a hailstone was investigated theoretically and experimentally by Troshin and Yaster [127], which was expressed as a graph of hail impact energy vs. breakage probability of a 1,280 x 740 mm, panel supported along all 4 edges, with practical ultimate strength of 190MPa (tempered) vs. 80 MPa (annealed.) The Annealed glass had about 50% probability of destruction with a 5 to 6 Joule impact, vs. about 42 Joules for a 50% destruction probability for tempered glass. The probabilities of destruction of tempered glass were added to Table B.1.

This can be compared to insurance company research summarized by Figure 6 in Leigh [125] indicating automotive glass damage begins with 3.0-4.9 cm diameter hail (consisting mostly of cracks), whereas hail over 7.0 cm size causes extensive glass and metal damage, which has been known to include penetration of the windows. Automotive glass, while struck at more unfavorable angles than typical vertical building windows, is more shatter resistant due to its curvature and safety glass construction consisting of 2 tempered layers bonded together by a plastic film. The 3-4.9 cm diameter range cited is too broad to implicate smaller sizes in that range, and the 1.0-2.9 cm range showed zero glass damage reports. This supports the implication of Table B.1 it that 5 cm diameter hail usually does not break glass but 7 cm diameter hail usually does break glass.

Therefore Table B.1 may be roughly indicative of glass replacement rates for typical glass panes of one or a few square meter sizes, although the probabilities of such hail stones per year must be known to estimate glass replacement rate.

B.2 Polycarbonate

James and Wei [94] investigated hail damage to greenhouse in a disputed insurance claim and established that weathering of polycarbonate dramatically reduces its impact strength, and that being exposed to warm air in a greenhouse below while being exposed to the cooled air typical of such storms, further exacerbates the susceptibility to crack or break under impact loads. Given this behavior and the well known tendency of polycarbonate to yellow and degrade in 1-2 decades if used for a greenhouse, as well as it lack of hardness to resist scratching due to windblown sand, polycarbonate is a poor choice for transparency material. Therefore this thesis concludes polycarbonate is not a suitable material for use on a SUTPP collector.

B.3 ETFE

According to Flueler [128], 0.2 mm ETFE membranes become dimpled with hail impacts of about 13 Joules, with penetration at about 36 Joules, when tested as the upper layer of an inflated “pillow” panel.

APPENDIX C

CLEANING

C.1 The Need to Clean

Lose sand and fine grit will be lofted by winds and deposited on the collector transparency surface. Bits of organic matter, including windblown matter droppings and occasional dead organisms will also be deposited on the upper transparency surface. Wind may blow some of this material about, concentrating it in some areas while removing it from others. Water (from precipitation, dew, and organic matter) tends to hold this material, may attract more of it, and tends to cause this material to adhere to and cake on to a surface as the water evaporates, along with any substances previously dissolved in the evaporated water.

Section 3.4.4 discusses the contrast between the experience of Schlaich et al. [12], that the glass transparency at the Manzanares prototype received sufficient rainfall to be self cleaning vs. the work of others suggesting significant reductions in light transmission may be observed in months, which are summarized in Table C.1, which indicates a wide variation in loss of transmission experiences depending on site, weather, and contaminant mix. Without an appropriately designed multi-year study of contamination rates at La Paz, it is not clear what the contamination accumulation rate will be at La Paz. The rate of cleaning required may vary from less than once a year to at worst monthly, and probably varies significantly between seasons and years.

TABLE C.1

DIRTY GLASS LOSS OF TRANSMISSION

Source	Location	Reduction	Comments
Schalich	Manzanares	Little Reduction	
Michalsky	Albany NY	-1% in 2 months	
Sayigh	Kuwait	-64% in 38 days	
Eliminir	Ciaro	-53% in 7 months	Not Cleaned, 2 rain events (14 mm)
Eliminir	Cairo	-28% in 7 Months	Cleaned Monthly

Hoffer et al. “Transport and Deposition of Dust on the Collector Surface” [129] (Conference Paper) examined the mechanics of dust movement on top of the collector, which will form shallow drifts around certain features, convert some direct radiation to diffuse radiation, and reduce overall performance by an amount that varies significantly at different locations and times. They also discussed concerns about scratching and dulling over decades and in sandstorms, but did not quantify it.

C.2 The Cleaning Process

This thesis does not define a specific cleaning system and associated cleaning machines, however, a generic discussion of the considerations is presented here to explore the ramifications of needing and using such a system, to better understand the LCA and practical implications.

The experience of commercial window glass cleaners indicates caked on deposits are best removed by a wet process, using water, which is an ecologically safe solvent, and some type of scrubbing or mechanical wiping action that greatly enhances the dislodging and removal of contaminant material while also significantly reducing the amount of water required for dislodging and removing the contamination, that otherwise requires cleaning chemicals and/or additional water to dissolve and dilute contaminants. Given the rarity and value of water in a dessert, and undesirability of using and discarding other cleaning substances, it is prudent to capture rain and possibly used wash water, purify it as needed, and use it for subsequent washings, to minimize or avoid reliance on imported water at the sight. Therefore this thesis assumes the collector will need drain holes leading to troughs or tubes (possibly integrated into the structure to save cost) that bring water to collection tanks, where it can be provided to purification devices and stored for subsequent use, including cleaning.

Using air to clean the transparency seems less promising, as blowing scatters the dust somewhere else nearby. Vacuuming (which attempts to remove and capture material) is unlikely to dislodge a caked on coating on glass. There may be some cleaver solution, such as combining air with wiping or ultrasound to dislodge contaminants, however research is required to develop such technology and demonstrate is was both effective and did not scratch and dull the surface worse than a well designed wet wiping system. Such a system may prove complex to deploy and maintain, violating the ESRR philosophy appropriate to a SUTPP discussed in Section 3.2.

A transparency cleaning system consisting of cleaning machines requires these machines move about on top of the transparency to perform the cleaning operation, suggesting the following design and logistical concerns need to be addressed:

- Contemporary window washers operate on a vertical surface, that builds up less contamination than a horizontal surface that promotes more settling and the adhesion of contaminants as any non-flowing water evaporates. A vertical surface also allows excess water to flow away from the cleaning process, whereas horizontal cleaning works best if the wiping action can remove all water between cleaning passes. However, the contemporary emphasis on a spot free window requires a purified water rinse that is largely wiped away, which ought to be applicable for horizontal cleaning of a SUTPP.
- The machine must be supplied with water by hose or carry a tank of cleaning water. A hose drags or needs support, and a tank adds weight above the collector.

- Machines require power, which can come from electricity the SUTPP produces (requires electrical power line, or onboard battery) from onboard solar panels (which provide little power per unit area and become another deployment and maintenance burden, or from a pressurized water (or air) source (which probably requires a hose). Powering the machine by electrifying the structure poses issues with practicality, safety and losses given its size and working around water.
- Machines must be controlled by humans and/or microprocessors to avoid hazards, connect and disconnect from hoses or cables, and navigate certain situations. Sensors or cameras may be used, and/or humans may be onsite, possibly requiring vehicles (to transport them and equipment, or to protect them from heat under the collector.
- Hoses and cables for water or electricity, (and possibly waste or air) may need extend across the transparency, which may promote transparency scratching and dulling, hoses getting tangled, run over, losing protective coatings or worn out, or may need to be suspended from above. Shorter hoses or smaller water tanks may mean more frequent hook ups. Water at ground level must be pumped up to the cleaning machines at many locations because they are too high for pumps to suck up water from below. Either pumps have to be moved or additional stationary pumps are required. The large collector area and distances multiply infrastructure requirements. About 9,900 hook up points will be required to access the entire area with 50 m hoses. That is potentially 9,900 sets of hardware, possibly including pumps. A 100 m hose will need only about 2,400 hook ups, however, dragging the hose (transparency dulling and pulling force required or wear and tangling considerations may require using only a 25 m hose (requiring about 39,000 hook ups) or it may make more sense to use overhead support systems. Without careful planning, the cost and impact of transportation may compete with the actual service and maintenance required.
- Machines can be made wide to span multiple transparency panels and ride on primary structure that may serve as “guide rails” that also support the machine and its water tanks, leaving only minimal down force required for cleaning concentrated in a small strip as the machine moves along. This ought to work well with a stiff transparency material such as glass, of a reasonable span, but may prove more challenging with a thin plastic membrane like ETFE. Large machines that span primary structure may alleviate the need for hoses by carrying onboard tanks, once an optimal power scheme is worked out. This may allow machines to stop at a limited number of widely spaced service ports spaced out across the collector, thereby minimizing the overall infrastructure required.

Repeated connections and disconnections, dragging hoses, monitoring, servicing, cleaning, and replacing cameras, sensors, pumps, valves, processors, purification equipment, fault monitoring systems, batteries, specialized parts, filters, metal parts that rust or corrode, plastic and rubber that degrades, troughs and tubes that clog with debris, lifts, vehicles, and other infrastructure needed for cleaning capability, and the larger infrastructure in the economy needed to support these systems, constitute a life cycle burden to deploy and maintain. A system with tens of thousands of items to be monitored, serviced or replaced that often needs work, with parts that can't be easily fixed onsite, goes against the need for Economic Sustainable Robust Resilience (ESRR) described in Section 3.2. A less automated system using more human labor requires a larger staff that becomes less economic and sensible if many people have to live in the middle of a dessert away from infrastructure, water and food. Based on the reasoning presented above, it appears a modest fleet of large, robust, durable, easily maintained machines may be an optimal solution, however, further research is required in this area.

C.3 Machine Performance and Water Estimates

The following summarizes personal communication with Ryan Blesi and D. Wight at New Star Inc [130], which builds window washing machines:

- Wet mechanical wiping, such as with a rotary brush, is a highly effective way to dislodge most caked on material.
- Two passes are needed.
- Their brushes have a 10 year life when used on buildings, and in theory the brushes should not require cleaning if they are used in a 2 pass cleaning process.
- Commercial units are designed for use on a vertical or sloped surface, where water can run, so there is some concern about removal of waste and dirty water on a horizontal surface. A vacuum system may be required.
- Water for spot free cleaning is treated by carbon filter, reverse-osmosis and then de-ionized. The apparatus they use consumes a lot of filters and the other two steps may not be very cost effective at the scale of a SUTPP.
- Their 12 foot wide SkyPro rotary brush unit uses 5 GPM (18.9 L/min) water as it advances at 34 ft/min (34*12 = 408 ft^2/min = 37.9 m^2/min). Therefore its water use is 0.50 L/m^2.
- Their 8 ft wide Skydrowasher (brushless jet spray cleaner) uses 8 GPM (30.3 L/min) water as it advances at 26 ft/min (26*8 = 208 ft^2/min = 19.3 m^2/min). Therefore its water use is 1.57 L/m^2.

Assume:

- The rotary brush process requires 2 passes at 0.5 L/m^2 is suitable for glass.
- The brushless spray process requires 2 passes and 1.50 L/m^2 after it is readjusted to a lower pressure and flow to clean ETFE, which should require less forceful water and hopefully less water to clean than glass.
- A vacuum or other system will have to be added to either system to pick up or remove waste water.
- Enough machines must be provided to clean the entire collector in 30 days if operated continuously.

Then:

- Glass washing will require 1 L/m^2.
- ETFE washing will require 3 L/m^2.
- Cleaning 19.5 km^2 in 30 days (451.4 m^2/minute) will require 11.9 12 ft Skypro equivalents, or 23.4 8 ft Skydrowasher equivalents, assuming non-stop operation, which is unrealistic, but suggests a reasonable number, possibly twice that many machines, may suffice to account for down time and availability. This is consistent with the goal or a reasonable number of wide cleaning machines.
- Cleaning 19.5 km^2 of glass at 1 L/m^2 (0.001m3 water / m^2 area) requires 19,500 m^3 (19,500 t) of water. This thesis will assume 20,000 t of water.
- Cleaning the same area of ETFE will require 60,000 t water.

Water requirements for each cleaning are summarized in Table C.2.

TABLE C.2

WATER TO CLEAN COLLECTOR AREA ONCE

	Glass	ETFE
Water (t)	20,000	60,000

Given that on each cleaning pass, 0.5 L/m^2 (glass) to 1.5 L/m^2 (ETFE) are needed, and a spacing between primary support girders of 9 to 15 m, that equates to 4.5 to 22.5 kg of water to clean as the machine moves fwd 1 m. If the service ports were spaced to work with 50 m hoses, the machine will have to move about twice that far if were using tanks instead, which equates to 450 to 2,250 kg of water on a single pass, and each machine will have to make 2 passes per unit area, and multiple parallel passes to clean subsequent strips of area adjacent to the strip that actually contained the service port, such it must either move sideways or be serviced by a hose to avoid moving sideways, or carry even more water to minimize the number of tank fill ups.

APPENDIX D

TOWER "EXTERNAL RING" VS "BRACING SPOKE WHEEL" REINFORCEMENT

This appendix establishes external stiffening rings, proposed by Kraetzig, provide lower Global Warming Potential (GWP) and Embedded energy (EE) impact than internal bracing spoke wheels, in addition to saving substantial energy over the life of the power plant.

An internal spoke bracing wheel of the nominal tower diameter of 210 m is estimated by Fluri et al. [93] to consist of 72 0.063 m by 0.6 m radial elements of length 210/2 m, of density 8 t/m3, giving a total steel mass/spoke wheel of

(72 spokes)*(.063m)*(.6m)*(210/2 m)*(8t/ m^3) = 2286 t m^3

According to Table 5.2, the EE of steel is 25.4 GJ/t and its GWP is 1.78 t CO_2 Eq/t, thus per spoke wheel:

(2,286 t steel)*(25.4 GJ/t steel) = 58,068 GJ (per internal spoke wheel)
(2,286 t steel)*(1.78 t CO_2 Eq/t steel) = 4,069 t CO_2 Eq (per internal spoke wheel)

A comparable external stiffening ring shown in Figure E.3 adds 2.1 t/m^3 concrete with a profile whose area was estimated under "stiffening" in E.4 as 8.03 m^2, which must be multiplied by the circumference the center of this area is revolved through of roughly 215 m, giving

(8.03 m^2)*(215 m)*(Pi)*(2.1 t concrete/m^3) = 5,424 t concrete (per external ring)

Personal communications with Kraetzig indicated (by calculations shown in E.4 of this thesis) that 0.135 t steel is required per t concrete, thus each ring requires

(5,424 t concrete)*(0.135 t steel/t concrete) = 732 t steel (per external ring)

Table 5.2 lists the EE of high strength concrete as 1.39 GJ/t and its GWP as 0.209 t CO_2 Eq/t, thus per external ring:

(5,424 t concrete)*(1.39 GJ/t concrete) = 7,539 GJ (per external ring)
(732 t steel)*(25.4 GJ/t steel) = 18,593 GJ (per external ring)
Total = 26,132 GJ (per external ring)
(Less than 58,068 GJ per internal spoke wheel)

(5,424 t concrete)*(0.209 t CO_2 Eq/t concrete) = 1,134 t CO_2 Eq (per external ring)
(732 t steel)*(1.78 t CO_2 Eq/t steel) = 1,303 t CO_2 Eq (per external ring)
Total = 2,437 t CO_2 Eq (per external ring)

(Less than 4,069 t CO_2 Eq per internal spoke wheel)

Therefore the external rings have lower construction EE and GWP, in addition to providing a performance gain of approximately 0.3% (refer to Table 4.4) of the 336 GWh/yr power output of the BSUTPP over its estimated 80 year life:

(80 years)*(0.003)*(336 GWh/yr)*(3,600 GJ/GWh) = 290,304 GJ Saved/external ring

These calculations are summarized in Table D.1 to give the total EE and GWP differences. These differences need to be multiplied by expected number of the number of bracing wheels converted to external rings (1) to obtain an estimate of the difference for the SUTPP. The actual difference will be larger for a tower with a mean diameter greater than the nominal 210 m diameter suggested by Pretorius thesis.

TABLE D.1

INTERNAL BRACING WHEEL VS. EXTERNAL RING

	EE (GJ)	GWP (t CO2 Eq)
Internal Bracing Wheel	+58,068	4,069
External Ring	+26,132	2,437
Energy Saved	-290,304	
Net Savings (per Ring)	322,240	1,632

APPENDIX E

PLANT DEFINITION

This appendix includes supporting sources, calculations and rationale for the plant definition presented in Chapter 4.

E.1 WSUTPP Water Tank Filling

The amount of water to fill the tanks

= (Area collector)*(0.2 m depth) * (0.75 of Area)

= Pi*[(5000 m/2)^2 – (400 m/2)^2]*(0.2 m)*(0.75)

= (19,509,290 m^2)*(0.2 m)*(0.75)

= 2,926,394 m^3 water

= 2.926 x 10^6 t water

If it were hauled by 40t trucks with approx 27 t payloads, it will take about 108,385 truckloads, or one every 2 ½ for 12 hours a day for 365 days. 2.9 x 10^6 t water is almost 1 ½ times the mass of the entire tower (0.7 x 10^6 t, Section E.4), foundation (0.2 x 10^6 t, Section E.4), and heaviest collector considered by this thesis, with a robust structure and 3 full layers of glass (1.2 x 10^6 t, Section E.3).

Even without the water, the amount of truck traffic required to build this power plant suggests the main road should be built first, and truck traffic managed and directed to avoid trucks getting stuck or unacceptable impacts of heavy truck traffic on unpaved areas.

Large areas may need to be drained for tank or collector maintenance. Hopefully strategies can be devised to avoid or minimize that, and save the water. However, it may be necessary to refill a large area in the future, possibly at a time when fossil fuels and transport are scarce. Rainwater is an option, as it becomes available, but may entail reduced or curtailed power production at times until adequate water is secured to level out summer power production to levels the turbo-generators can absorb, given they are probably sized for reduced power ratings using water thermal storage to save the investment, maintenance and inefficiency issues of having an otherwise oversized turbo-generator design.

Another option is a water pipeline from the Colorado River, pumped by power from the grid or the SUTPP to onsite storage or the SUTPP water tanks as needed. However, a roughly 12 km pipeline requires permission to cross into and take water from the Parker Reservation, or a longer (approximately 25km) pipeline route may be required.

Appendix A cites the flow of the Colorado River to be at least 1.8 x 10^9 m^3) per year supplied to Mexico per treaty, with the actual upstream water available much more, but used for agriculture, industry and cities. Therefore it is assumed at most this project should not take more than 1% of 1.8 x 10^9 m^3) per year, thus:

$(1.8 \times 10^9\ m^3/y)*(0.01) = 1.8 \times 10^7\ m^3/y$

$(2{,}926{,}394\ m^3\ \text{water}) / (1.8 \times 10^7\ m^3/y) = 0.163$ or 16% of the proposed 1% maximum.

This thesis does not investigate the pipeline option further, and conservatively assumes the worst case of having to truck the water roughly 20 km as described in Appendix A. Therefore the requirements to fill the water tanks is as given in Table E.1.

TABLE E.1

WSUTPP WATER TANK FILL HAULING REQUIREMENTS

(km) haul (one way)	20
(t) Water	2,926,394
40t/27t payload truckloads	108,385

Another concern is the quality of the water needed. This requires further research beyond the scope of this thesis. The water may need to be filtered, then possibly purified by reverse osmosis and/or some other process. The actual requirements for this water depend on whether it will be and remain clear and pure enough to perform as needed in the clear top, black bottom tanks, any requirements it must meet to be suited to clean the collector, and its ability to be returned to the environment. If the water is also used for some valuable secondary process, like making hot water or growing something in the covered tanks (possibly an anaerobic environment) then there may be other requirements for this water to meet.

Given an adequate specification of water requirements is beyond the scope of this thesis, one representative process is briefly looked at as a potential baseline for a generic analysis: A High Efficiency Reverse Osmosis process called "HERO", for which information was found at the US National Renewable Energy Laboratory website [92], which includes the pertinent numbers summarized in Table E.2.

TABLE E.2

HERO OPERATION STATISTICS

	In Units Given	SI Units
Power Use	1,849,760 kWh/y	1,849,760kWh/y
Feed Water	116,817,000 Gal/y	442,199 m^3/y
Waste Water	7,767,000 Gal/y	29,401 m^3/y
Net Water Output (Difference)	109,050,000 Gal/y	412,798 m^3/y
Chemicals (acid and caustics)	56,871 lb/y	25,797 kg/y

For simplicity, this thesis ignores the other purification steps, and chemicals (which are an important considerations, environmentally. In fact the entire water purifying system, whether used to fill or obtain cleaning water, is a significant infrastructure burden and liability that contradicts the need for Economic and Sustainable Robust Resilience (ESRR) discussed in Section 3.2.

If all the water had to be put through this process in one year, it will require 2,926,394 m^3 / 412,798 m^3 = 7.089 times the output of one HERO unit for a year, therefore it will need 13,113,258 kWh of electric power. Therefore potential water purification requirements assumed by this thesis are summarized in Table E.3.

TABLE E.3

POTENTIAL WATER PURIFICATION REQUIREMENTS

Electric Power	4.481 kWh/(m^3 water)
Electric Power to Filter All Water in Tanks	13,113,258 kWh
# HERO installations to filter in a year	8 (7.09), plus spares?
# Hero installations to Filter annual rainfall (5” (12.5cm) per year average, in Appendix A)	6 (5.908), plus spares?
Equipment, maintenance, chemicals	Necessary, but not included here

E.2 WSUTPP Water Tank Construction and Maintenance

Water tanks include both thermal storage tanks for the WSUTPP configuration and conventional water storage for cleaning. Thermal storage will be covered first, then cleaning.

Thermal Storage:

It is assumed to minimize costs the water tanks consist of whatever is needed to level the ground, a sheet of black plastic of unspecified type laid over the ground, walls formed by scope sand/soil or a cheap material, covered by a clear plastic top. The plastics have to not degrade enough to need replacing for at least 40, preferably 100 years. 0.2 mm thick ETFE may be suitable for the top [95]. Sufficient time was not available to properly research a material for the bottom, thus a generic plastic 0.5 mm thick of density 2 t/m^3 was assumed.

Options considered for tank walls assumed a “L” or inverted “T” shape section will be used along tank boundaries, which were initially established to fit under 9m canopy support spacing as 8 x 44 m rectangular tanks to provide 1m wide berm foot paths, keep each tank a manageable size and maximize both ability to walk around and the ratio of tank area to tank perimeter, which is thus 9x45 = 352 m^2 vs. 2*(8+44) = 104 m. The “L” or “T” was arbitrarily considered to be the equivalent of a 0.5 m wide strip of material of some type and thickness. Choices considered are shown in Table E.4. Soil Cement uses the existing sand to make a low grade cement. That may be useful for reinforcing berm tops to reduce incidence of damage or rupture of dirt dams, but it is difficult to remove and thus not entirely site eco-friendly. Wood had a low impact, but cannot be counted on to last, and may need replacement too often. Recycled aluminum may make sense. This thesis assumes since the ground will probably have to be leveled anyway, simple dirt/sand dams will suffice for a rough estimate, though reliability demands consideration be given to actual walls, possibly of recycled aluminum or a better material.

TABLE E.4

WATER TANK WALL OPTIONS

Tank Perimter		104					
Tank Area		352					
Perimter/Area		0.2954545					
Water Area		14,631,968	m²	=(19,509,290 m² Coll Area)*(0.75)			
		Thickness	X-Sect A	Dens	Mass/L	Mass/A	Mass
		(m)	(m²)	(t/m³)	(t/m)	(t/m²)	(t)
Soil Cement		0.05	0.025	8	0.2	0.05909	864,616
					Source		
	GWP		0.139	t CO2/t	[Bath]	gives	120,182
	Emodied Energy		0.85	GJ/t	[Bath]	gives	734,924
Sawn Wood		0.01	0.005	0.6	0.003	0.00089	12,969
					Source		
	GWP		0.46	t CO2/t	[Bath]	gives	5,966
	Emodied Energy		7.6	GJ/t	[Bath]	gives	98,566
Steel (Galv)		0.000635	0.00032	8	0.00254	0.00075	10,981
					Source		
	GWP		2.81	t CO2/t	[Bath]	gives	30,856
	Emodied Energy		39	GJ/t	[Bath]	gives	428,244
Stainless Steel		0.000635	0.00032	8	0.00254	0.00075	10,981
					Source		
	GWP		2.48	t CO2/t	[Bath]	gives	27,232
	Emodied Energy		56.7	GJ/t	[Bath]	gives	622,602
AL Prod Mix		0.001	0.0005	2.8	0.0014	0.00041	6,052
					Source		
	GWP		8.79	t CO2/t	[LCA calc]	gives	53,200
	Emodied Energy		0	GJ/t		gives	0
Recycled AL		0.001	0.0005	2.8	0.0014	0.00041	6,052
					Source		
	GWP		1.49	t CO2/t	[LCA calc]	gives	9,018
	Emodied Energy		0	GJ/t		gives	0

Energy to construct it difficult to estimate. Plastic has to be laid down and anchored, however the biggest energy requirement is probably for grading the site to create so many leveled tank bed and berms, which will probably entail far more energy and topsoil disruption than merely erecting a collector over less level, often natural terrain. Estimating the work and energy required is far too site specific and ambiguous, so this thesis will omit estimating energy to construct the water tank system, while acknowledging this is not an insignificant contribution, and ought to be addressed in follow on work, possibly for a specific site.

Tank maintenance will assume the entire tank system is taken up and replaced at least every 20 years, given the propensity for leaks and potential finite life of the plastic. It is possible this assumption oversimplifies and underestimates the magnitude of the problem, given that more work may be required to do this than is implied by the embodied energy of the materials.

The Embedded energy and GWP impact of acquiring and serving the HERO systems and all the tubes, pumps, canopy drains, and water handling systems is also not accounted for, due to the complexity and lack of time and specifics to refine its definition. It cannot be assumed to be insignificant, though it may be relatively rather small compared to the overall plant investment.

<u>Cleaning Water Tanks:</u>

Appendix C determined the quantity of water needed to clean the 19.5 x 10^6 m^2 upper surface of the collector was 20,000 t for glass, and 60,000 t for ETFE. A quick web search turned up a 15K gallon (56.78 L) fiberglass rainwater catching system tank weighing 4,500 lb (2041.2 kg) by RainHarvest Systems [131]. Table 4.7, Table 4.8 and Table 4.9 summarize tank material and purification and transportation requirements respectively, in terms of the entire thermal tank system and in terms of ONE glass or ETFE cleaning. Table 4.13 gives the cleaning frequencies, number of cleanings in 5 years, and purified water tank capacity required, which must be doubled for all but the WSUTPP to provide equal tankage to hold unpurified rain and wash runoff water to be purified and subsequently stored in the clean wash water tanks.

No allowance has been made for the rest of the water system hardware, which probably exceeds that of just the tanks. Substantial tubing and quite possibly pumps may be required to remove excess water from the collector during a maximum rain event of 1.75 inches (4.5 cm) of water in an hour (cited in Appendix A), and/or significant water weight and water flow will occur near the outer edges of the collector. However, many topology and design details need to be considered to make a reasonable estimate of materials required, which was deemed to be beyond the scope of this thesis. Therefore this thesis assumes undefined significant energy and material is required, probably exceeding that required for the fiberglass water tanks.

E.3 Collector

The collector outer edge is 5 m above the ground at 2500 m radius, and rises toward the center to provide a constant cross section for the flow converging at the center. The roof height is defined by Pretorius (p. 39, equation 3.1 [2]), which can be integrated to obtain the average roof height as follows:

$$H = H_2\left(\frac{r_2}{r}\right)^b = 5\left(\frac{2{,}500}{r}\right)^1 \qquad \text{(as } H_2 = 5\text{ m, } r_2 = 2500\text{ m, } b = 1\text{)}$$

$$\overline{H} = \frac{\int_A H da}{\text{Area}} = \frac{\int_{200}^{2500} \frac{12{,}500}{r}\, 2\pi r dr}{\pi(r_2^2 - r_1^2)} = \frac{\int_{200}^{2500} 25{,}000\pi dr}{\pi(2{,}500^2 - 200^2)} = \frac{25{,}000\pi r \Big|_{200}^{2500}}{\pi(6{,}210{,}000)} = \frac{(2{,}500 - 200)}{248.4} = 9.26\text{ m}$$

Note the height at the inner transparency radius is 62.5 m, which while tall, is in accordance Pretorius [2], and the turbine diameters and inlet duct design in Fluri [37] matched to this canopy height, so the canopy will require very tall supports near the tower. This thesis does not go into the level of detail required to determine if the tallest supports must be of a different design.

<u>Transparency Material:</u>

The quantity of transparency material in a single glazed (single layer) canopy is approximately the collector area in m^2, which can be approximated as the area of an annulus and converted to m^3 with a material thickness, and mass with a density, as shown in Table E.5.

TABLE E.5

SINGLE LAYER TRANSPARENCY AREA AND MASS OF GLASS

Area		Pi	(OR)^2	(IR)^2
19,509,290	(m^2)	3.14159	6250000	40000
			5000	400
		Glass	ETFE	
Thickness	(m)	0.004	0.0002	
Volume	(m^3)	78,037	3901.858	
Density	(t/m^3)	2.5	1.75	
Mass	(t)	195,093	6,828	

This thesis assumes:

- The BSUTPP and WSUTPP require 195,093 (t) of glass.
- Each additional full layer of transparency adds this much glass or ETFE yet again. For example a glass ASUTPP that introduces a secondary glass canopy requires 2*195,093 = 390,186 (t) of glass. A 50% double glazing adds half as much as a second layer of transparency.
- The transparency layers required are described in Table 4.11 and the corresponding total amounts of transparency material required are listed in Table 4.14.

- APPENDIX E (continued)

Structure:

Overall Considerations:

The collector structure must support the transparency, which in the baseline case is assumed to be 4mm thick tempered low iron float glass with a density of 2.5 t/m^3. Snow loads can be considered to be zero (as no snow is expected according to Appendix A), and rain loads can be computed at something less than 1.75" standing water (one hour's maximum rainfall according to Appendix A, assuming proper drainage is designed into the collector.) Earthquakes can be dealt with using appropriate design and analysis utilizing the inherent flexibility of the structure and properly cross bracing it to keep it from being damaged while allowing it to move to absorb the accelerations. Wind loads can likewise be modeled and accounted for. The details of this level of design are within contemporary engineering knowledge, but not directly addressed in this high-level thesis.

This thesis uses structural designs or generic information on them provided by other sources, and assumes the engineers originating these designs have considered appropriate load cases, though it may not be known what cases they have considered. If additional requirements are placed on the structure, such as supporting people or hardware to facilitate cleaning or other maintenance activities, it may be necessary to increase the structural requirements, and the associated materials, energy, and environmental impact.

The following sources were provided enough information to attempt to model some of what is needed for LCA:

1. Bernardes (2004) "Technische, ökonomische und ökologische Analyse von Aufwindkraftwerken" (Technical, economic and ecological analysis of Solar chimneys) [67] provides tons of materials, with personal communications with Schlaich cited as a significant source.

   Collector = 99,370 t steel, 257,900 t glass, 1,440 t concrete for 4,950 m diameter 4mm glass
   NOTE: The tons of glass is more consistent with 5mm glass.
   Tower = 3,840 t steel, 146,900 t concrete, 1,245 t diesel
   Turbine/Generator Area = 1,560 t steel, 63,000 t concrete, 16 t plastic
   Shipping by truck 200 km steel, glass and diesel, 50 km concrete
   Density (t/m^3): Concrete 2.1, Steel 8, Glass 2.5
   GWP Coefficients Not given, suppressed in discontinued "Balance" Software (according to personal communication with Bernardes [88])

From LCA Calculator [132] (t CO_2 Eq/t): Concrete 0.228, Steel 1.6, Glass 1.09
From ICE [103] (t CO_2 Eq/t): HS Concrete 0.209, Steel 1.71 Bar *& 1.78 Section,
Glass (Tempered) 1.27
From LCA Calculator [132] 40 t trucks with 27 t payloads shipping is .000107 t CO_2 Eq /km.

It was not feasible to obtain enough of the source material of Bernardes, including personal communications with Schlaich, to fully understand an replicate Bernardes results. However, a crude spreadsheet summation of the materials for the entire plant listed above, using shipping and trucking data listed above from LCA calculator gave 60 g CO_2 Eq/kWh and using ICE v1.6a gave 67 g CO_2 Eq/kWh, vs. the 73 g CO_2 Eq/kWh Bernardes found. Bernardes also accounted for some energy to excavate, lift and assemble that is not included in the 60 and 67 g CO_2 Eq/kWh numbers. None the less, the basic GWP calculations of Bernardes have been roughly replicated, so they are relatively reproducible.

2. Personal communications with Kraetzig [89] provided and gave permission to use a report “Solar Updraft Power Plants with 750m power towers and collector diameters of 3000m to 4000m”, “750m Solar Chimney Power Plant” drawings and advice for scaling 750 m towers to 1000m height, from which material volumes and masses can be obtained.

Collector
Glass 5 or 6 mm
Support post spacing 9 x 9 m square pattern
Specific post and girder designs – can get steel and concrete per unit area
Sized to allow unspecified cleaning machine to ride on 9 m spaced primary girders.
Details will be addressed below after presentation of 3rd Source, results are:

This deign definition is complete enough to simply adopt by this thesis, with the understanding it is a concept not accompanied by the associated loads and assumptions about the cleaning machine. However, upon estimating material masses it was found this design is very massive, which results in a lot of embodied energy and GWP impact.

3. Fluri et al. (2008) “Cost Analysis of Solar Chimney Power Plants” [93]
The Cost analysis paper gives enough numbers and definition to determine the materials for the collector foundation and supports, but not the what they call the “matrix” that supports the glass panels. That additional information may be provided in De Villiers, P. F., 2001. “Sonkragstasie en skoorsteen konsepte vir ‘n optimal versamelaar.” [133], which could not be obtained from the University of Stellenbosch library.

Support post spacing 15 x 15 m square pattern, average roof height 5.3 m
Calculations (details to follow) on data provided showed this design with 5 km diameter gave:84,971 support posts.
Footers each 0.8 x 0.8 x 0.3 m = 0.192m^3 giving total of 34,003 t concrete, 979 t rebar
Support Posts IPEAA120 I-Beam Grade 350WA steel,
Steel Diagonal Angles (2) per (5) posts “L” beams 0.1 x 0.1 m, 0.008m thick
Steel Diagonal cables (2) per (5) posts, 0.008 diameter
10559 t steel total (structure plus rebar.)

34,003 t concrete + 10,559 t steel + steel glass matrix, compares with
Bernardes Collector = 99,370 t steel, 1,440 t concrete

The 3 Cases:

Given the sources and observations above, it was decided the 1,440 t concrete for foundations for Bernardes may be a bit “optimistic” given the much larger masses (computed below) from Fluri et al. (34,003 t) and Kraetzig (164,462 t). Given that the robust collector design by Kraetzig is heavier and may be less ideal for overall plant EROEI, whereas the lighter one is poorly defined in this thesis, and may not support cleaning equipment, and lack of other designs or time to derive one, this thesis elects to assume Bernardes with the Fluri et al. amount of footer concrete as “Case 1” (or the “Light” case) and the Kraetzig design as “Case 3” (or the “Heavy” case). Case 2 was created by adding values from case 1 for a secondary collector and/or double glazing to case 3 values to create lightweight additions to the basic case 3 structure. It should be noted that case 1 and 2 lack actual design detail. The numbers for the cases are derived below.

Case 1 (Light: Modified Bernardes/Schlaich):

From Fluri et al. Cost Analysis [93]
Support post spacing 15 x 15 m square pattern
Implies for BSUTPP area of 19,509,290 m^2 (Table E.6) are 86,708 support posts.
Footers each 0.8 x 0.8 x 0.3 m
Footers have 0.060 t/m^3 rebar

Support Posts are IPEAA120 I-Beam Grade 350WA steel,
Steel Diagonal Angles (2) per (5) posts "L" beams 0.1 x 0.1 m, 0.008m thick
Steel Diagonal cables (2) per (5) posts, 0.008 m diameter
Average roof height 5.3 m in Fluri et al., but is 9.26 m for BSUTPP

This permits a rough calculation of steel for support structure beneath the matrix or grid that holds the glass canopy, as shown in Table E.6:

TABLE E.6

CASE 1 (LIGHT) COLLECTOR SUPPORTS (BENEATH CANOPY)

			Pi	(OR)^2	(IR)^2									
Area	19,509,290	(m^2)	3.14159	6250000	40000									
Thickness	0.004	(m)		5000	400									
15	m	Spacing between posts (X and Y directions)												
225	m^2/post						Avg Heig	9.26	m					
86,708	Posts						Steel	8	t/m^3					
Support Column (Post)														
	IPE$_{AA}$120 Grade 350WA I-Beam				X-Sect	0.007936	Ht * Wide				Avg Ht	9.26	m	
		m	m					Height2	0.1144		Avg Vol	0.0095	m^3	
	Ht of I	0.124	0.0036	Web Thick		0.00690976	Subtract	Width2	0.0604		Dens	8	t/m^3	
	W Cap	0.064	0.0048	Cap Thick	Area =	0.00102624	m^2				Avg Mass	0.076	t	
					kg/m	8.20992	Above x	8000	kg/m		Posts	86,708	qty	
					Vendor	8.36	kg/m				**Tot Mass**	**6,592**	**t**	
						(Assume rest is Zinc - Galvanaized)								
Diagonal Angle					X-Sect	0.01	Ht * Wide				Length	(m)	Span	Ht
						0.008464	Subtract				Diag	17.628	15	9.26
	0.1	m	Each Leg			0.001536	Area				Qty = 2	35.256		
	0.008	m	Thick		kg/m	12.288	Above x	8000	kg/m		1 in 5	7.0512	Avg Length per Post	
Diagonal Cable		7.05121	Avg Length per Post								Area	0.0015		
		5E-05	Xsect	0.008	m dia						Avg L/P	7.0512		
	Avg Vol	0.00035	m^3/post								Vol	0.0108	m^3	
	Dens	8	t/m^3								Dens	8	t/m^3	
	Mass	0.00284	t								Mass	0.0866	t	
	Posts	86,708	qty								Posts	86,708	qty	
	Tot Mass	**246**	**t**								**Tot Mass**	**7,513**	**t**	
14,351	**t**	**Total Support Steel Mass (Under Collector, NOT counting glass support grid/matirx)**												
10,775	t	(Work not shown - is mass if change avg post height from 9.26 to 5.3 to match original Berardes case.												
101,401	t	vs Bernardes												
				Bernardes	99370	t	Based on area of					Pi	(OR)^2	(IR)^2
90,626	**t**	**Est'd For Glass Grid/Matrtix**							Area (m^2)		19,118,555	3.1416	6125625	40000
		101,401	minus	10,775					Thickness (m)		0.004		4950	400
104,976	**t**	**Total Mass of Collector Structure**												
		Adjusted up to account for greater height (9.26 vs 5.3 (if linear)) and area (5 km dia vs 4.95 km dia)												

APPENDIX E (continued)

Case 3 (Heavy: Kraetzig):

From Kraetzig [89]

Support post spacing 9 x 9 m square pattern

Implies for BSUTPP area of 19,509,290 m2 are 240,855 support posts.

Footers each 0.6 diameter x 1.15m deep concrete

Posts o.102m OD, 0.094 ID S235 Steel tube filled with HS Concrete C70/85

Girders are defined in a drawing shown in Figure E.1

Calculations in Table E.7 estimate specifications required for LCA.

Cases 1 and 3 are expanded as follows to cover all transparency configurations, which results in case 2 consisting of lightweight case 1 additions to the basic case 3 structure.

For Collector Case 1 (Light):

BSUTPP (Defined Above)

WSUTPP = BSUTPP Order

BSUTPP-½DG requires 1.1 times as much steel

BSUTPP-DG requires 1.2* times as much steel (if glass), 1 times as much if ETFE double glazed (DG)

ASUTPP requires 1.5* times as much steel as BSUTPP

ASUTPP-DG = (1.5)*(1.2) = 1.8 times as much steel

*These are the same assumptions made in Fluri (pp. 84-85[37]).

For Cases 2 and 3

BSUTPP (Defined Above)

WSUTPP = BSUTPP

BSUTPP-½DG:

Case 2 = 1.1 times as much steel

Case 3 = Add 0.1 * (Case 1 total structural steel).

BSUTPP-DG

Case 2 = 1.2 times as much steel

Case 3 = Add 0.2 * (Case 1 total structural steel).

ASTUPP:

Case 2 = Same as Case 2 except add weight of an entire new glass matrix.

Case 3 = Add .5 * (Case 1 total structural steel).

ASUTPP-DG has versions

Case 2 = 1.2 * BSUTPP + (Grid Structure added again (not supports)

Case 3 = BSUTPP + 0.8 * (Case 1 total structural steel).

The specifications for the Collector cases are summarized in Table 4.14, which also includes scenarios for swapping out some or all glass for ETFE as defined in Table 4.11.

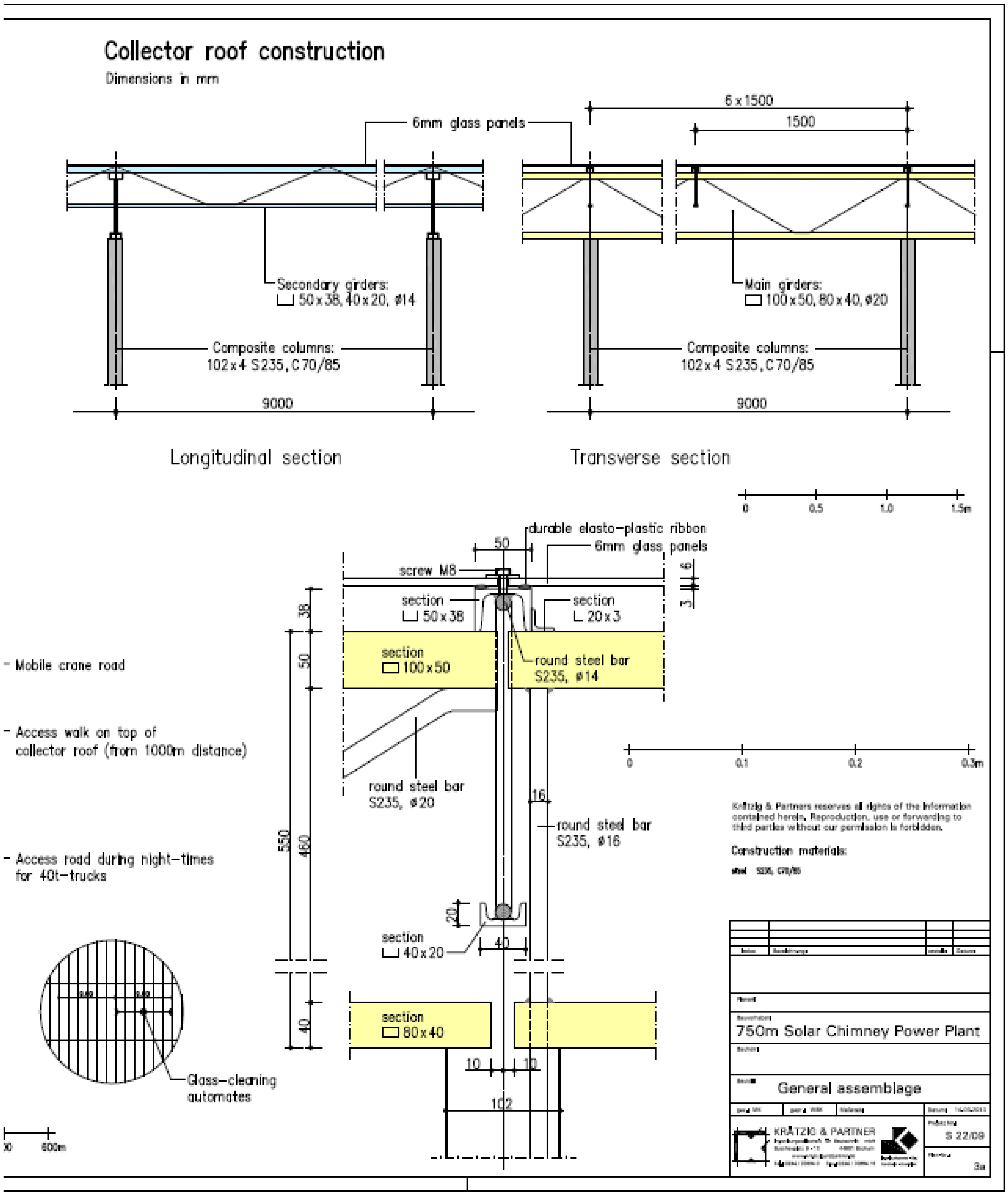

Figure E.1. Kraetzig collector design [89] (used with permission).

APPENDIX E (continued)

TABLE E.7

CASE 3 (HEAVY) COLLECTOR SPECIFICATION DERIVATION

		Pi	(OR)^2	(IR)^2		9	m	Spacing btwn posts (X & Y direct)				Avg Heig	9.26	m
19,509,290	(m^2) Area	3.1416	6E+06	40000		81	m^2/post					Steel	8	t/m^3
0.004	(m) Thickness		5000	400		240,855	Posts					Concrete	2.1	t/m^4
Main Girder		Top Section								**Footer**				
0.077117	(m^3)	0.045	0.045	9	0.1	0.05				**Concrete**				
2	Qty	Vol	Out Vol	L	W	H					0.6	Dia		
0.154234	(m^3)		0	9	0	0					1.15	Height		
1.23387	(t) Each		Inside V	L	W	H					0.325155	(m^3)	Vol	
240,855	#/BSUTPP										2.1	t/m^3	Dens Concrete	
297,184	**(t) /BSUTPP**	Bottom Section									0.682825	(t)/Post		
		0.0288	0.0288	9	0.08	0.04					240,855	qty	Cells	
		Vol	Out Vol	L	W	H					**164,462**	(t)	Footer Concrete per BSUTPP	
			0	9	0	0				**Rebar**				
			Inside V	L	W	H					0.060453	(t/m^3)	Rebar	
											4,734	(t)	Footer Rebar per BSUTPP	
		Diagonal bars												
		0.0033	10.558	12	0.75	0.46	0.000314	0.02		**Post**				
		Vol	Length	Multiple	Diag L	Diag H	X-sect A	Dia		**Concrete**				
											0.094	(m)	Dia	
											0.00694	(m^2)	X-sect A	
Secondary Girder		Diagonal bars									9.26	(m)	Avg Ht	
0.011581	(m^3)	0.002	9.8816	12	0.75	0.34	0.000201	0.016			0.064262	(m^3)	Avg Vol	
5	Qty	Vol	Length	Multiple	Diag L	Diag H	X-sect A	Dia			2.1	t/m^3	Density	
0.057904	(m^3)										0.134951	(t)	Mass/Post	
0.463233	(t) Each	Top Section									240,855	qty	Cells	
240,855	#/BSUTPP	0.0064	0.0171	9	0.05	0.038					**32,504**	(t)	Post Concrete per BSUTPP	
111,572	**(t) /BSUTPP**	Vol	Out Vol	L	W	H								
			0.0107	9	0.037	0.032				**Steel**				
			Inside V	L	W	H					0.102	(m)	OD	
											0.094		ID	
		Bottom Section									0.004926	(m^2)	X-sect A	
		0.0032	0.0072	9	0.04	0.02					9.26	(m)	Avg Ht	
		Vol	Out Vol	L	W	H					0.045615	(m^3)	Avg Vol	
			0.0041	9	0.03	0.015					8	t/m^3	Density	
			Inside V	L	W	H					0.364919	(t)	Mass/Post	
											240,855	qty	Cells	
408,756	**(t)**	**Steel Matrix per BSUTPP**									**87,893**	(t)	Post Steel per BSUTPP	
496,649	**(t)**	**Steel, Structural, Non-Rebar / BSUTPP**					**32,504**	**(t) HS Concrete C70/85**			**501,384**	**(t)**	**Steel, All types per BSUTPP**	
4,734	**(t)**	**Steel, Rebar / BSUTPP**					**164,462**	**(t) Footer Concrete**			**196,966**	**(t)**	**Concrete, All types per BSUTPP**	

Energy to Construct:

The entire scope of mechanical operations needed to position and use machines, cut drill, screw, weld and lift is unknown and ambiguous. The energy to lift the average height of mass in the collector canopy, which is 9.26 m, is:

$$PE = mgh = \text{approx } (0.3 \text{ to } 0.6 \times 10^9 \text{ kg})*(9.81\text{m/s}^2)*(9.26415 \text{ m}) = 27.2 \text{ GJ}$$

Add to this, digging the foundations, and assuming even 20 times the above amount requires only about 600 GJ, which is insignificant compared to the 195,000 t of glass for a single glazing times 23.5 GJ/t equaling roughly 4,500,000 GJ of embedded energy, or the few million more GJ more for the lightest canopy support structure. Therefore this thesis does not include collector construction energy.

E.4 Tower and Foundation

<u>Materials:</u>

Three 1 km tall towers were considered in developing a roughly representative tower for the SUTPP, which was further justified by comparison to scale up of 750 m tower by Kraetzig discussed after Table E.8. (The advantages of hyperbolic over cylindrical tower geometry are briefly mentioned in Section 2.1.2.)

1. Figure E.2 1 km tall 150 m diameter cylindrical tower .on a 280 m diameter base using external stiffening shapes that double as access balconies to avoid the need for internal bracing wheels by Kraetzig [89].
2. Figure E.3 1 km tall slightly hyperbolic tower 145 m diameter at top, 133 m wide and narrowest (500 m high) and 260 m diameter at base with external stiffening rings by Kraetzig [31].
3. 1 km tall 110 m diameter tower by Schlaich [68], briefly described by Fluri et al. in a cost analysis paper [93] that scaled down towers (by decreasing diameter or cutting off extra height at the bottom) to obtain concrete volume estimates of smaller towers.

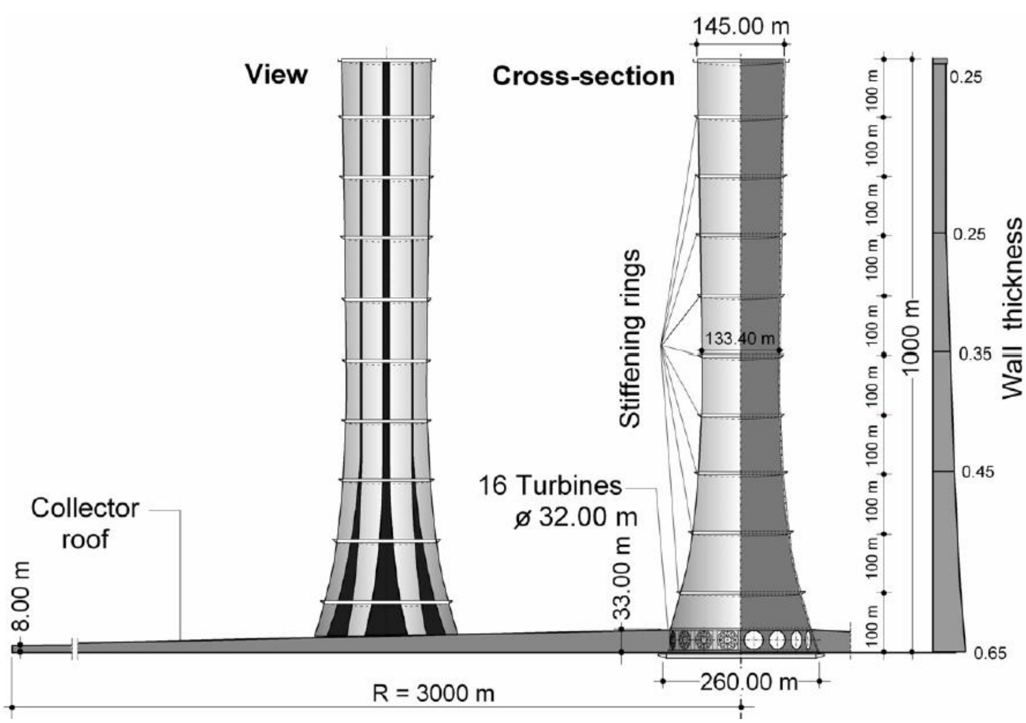

Figure E.2. 1 km tower design concept by Kraetzig (used with permission) [89].

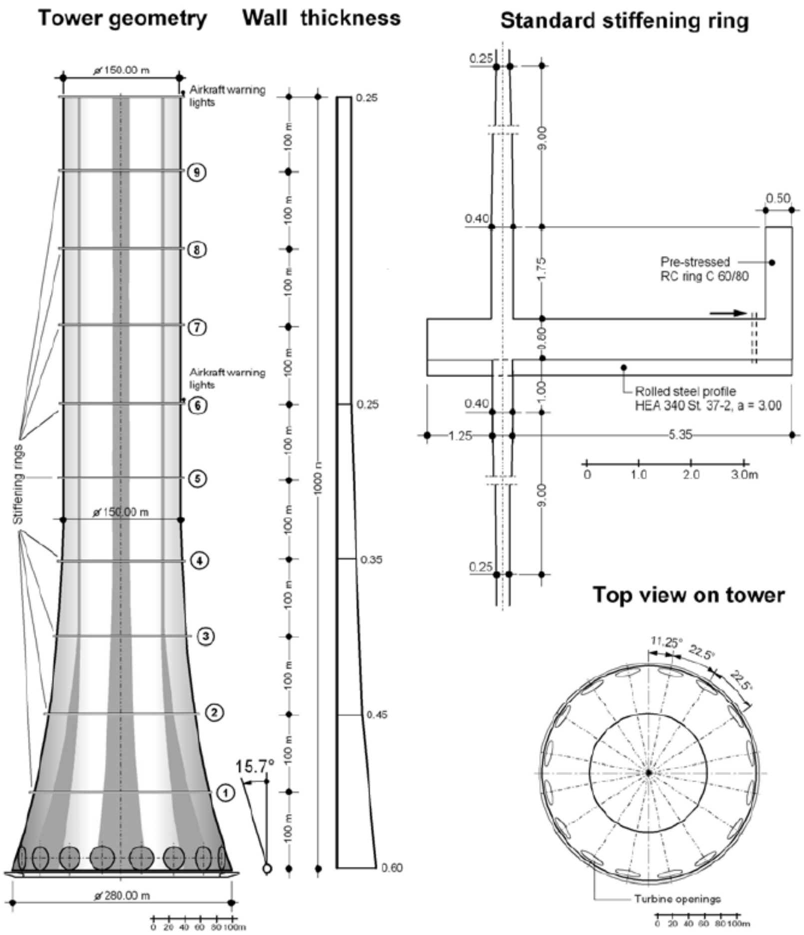

Figure E.3. 1 km tower design concept by Kraetzig (used with permission) [89].

Scaling down a tower as described in #3 above is a conservative approach, as it probably overestimates the actual concrete volume required for a smaller diameter. Scaling up the diameter, as will be done in this thesis, entails some uncertainty because while the main consideration, thickness required to support the weight from above, is unchanged, the effects of side loads and modes of oscillation initiated by winds (vortex shedding) and earthquakes may require some adjustment of wall thickness. This thesis assumes the required adjustments will not be large enough to be of concern for generating generic material volume estimates.

Diagrams of towers 1 and 2 above included a view showing the thickness at various heights, from which volume can be estimated in Table E.8, which also shows the same thickness profiles rescaled to a constant 210 m diameter tower thought to best embody the specifications of Pretorius [2].

The mass fractions and densities of subsurface foundational and above ground high strength concrete and steel rebar were estimated from the following assumptions stated in the cost analysis by Fluri et al. [93]:

- Rebar is 8,000 kg/m^3 concrete is quoted as 2,100 kg/m^3 (which is lighter than the density of concrete found at many other sites on the web, possibly because a Solar Updraft Tower can benefit from low density concrete to minimize the weight supported near its base.
- Foundation consists of 60 kg/m^3 rebar, whereas tower consists of 120 kg/m^3 rebar
- Foundation Concrete is 100 Euro/m^3 whereas tower concrete is 125 Euro/m^3.
- Rebar costs 125 Euro/ton.
- Foundation volume is proportional to tower volume. The basis for determining the ratio of volumes was from the relative prices of materials of Schlaich's tower and foundation being 36.19 million Euros for the tower (without bracing wheels) and 9.23 million Euros for the foundation.
- Internal bracing wheel stiffeners consist of 72 radial steel elements 0.63 x 0.6 m cross section from the center to the tower wall. (These were avoided by using external ring stiffeners. Appendix D shows it is worthwhile to exchange out this steel and add the concrete for the external rings for the gain in performance.)

These assumptions are embodied in the calculations which resulted in the estimates in bold boxes in Table E.8.

APPENDIX E (continued)

TABLE E.8

TOWER & FOUNDATION MATERIAL ESTIMATES

Baselines							**Resized Up**							
														Times V
Design 2	(1 km high, 133 m dia Kreatzig)						Design 2	(1 km high, 133 m dia Kreatzig)					Avg	Sum
Height	Thick	Dia	Pi	Product (m^3)			Height	Thick	Dia	Pi	Product (m^3)		Height	/Vol
300	0.25	141	3.1416	33,222			300	0.25	210	3.141593	49,480		850	42058072
200	0.3	135	3.1416	25,447			200	0.3	210	3.141593	39,584		600	23750440
200	0.4	140	3.1416	35,186			200	0.4	210	3.141593	52,779		400	21111503
300	0.55	185	3.1416	95,897			300	0.55	210	3.141593	108,856		150	16328428
				189,752	Sum						250,699	Sum		103248443
Design 1	(1 km high, 150 m dia Kraetzig)						Design 1	(1 km high, 150 m dia Kraetzig)					Avg Ht	411.84211
Height	Thick	Dia	Pi	Product (m^3)			Height	Thick	Dia	Pi	Product (m^3)			
400	0.25	150	3.1416	47,124			400	0.25	210	3.141593	65,973		800	52778757
200	0.3	150	3.1416	28,274			200	0.3	210	3.141593	39,584		500	19792034
200	0.4	165	3.1416	41,469			200	0.4	210	3.141593	52,779		300	15833627
200	0.525	225	3.1416	74,220			200	0.525	210	3.141593	69,272		100	6927211.8
				191,087	Sum						227,608	Sum		95331629
													Avg Ht	418.84058
Design 3	Schlaich`	Ht 1000, Dt 110					Schlaich`	Ht 1000, Dt 110						
Delta H	Thick	OD	ID	Pi	Vols (m^3)		Delta H	Thick	OD	ID	Pi	Vols (m^3)		
450	0.3	110	109.7	3.1416	46,525		450	0.3	210	209.7	3.1416	88,937	775	68926111
550	0.645	110	109.36	3.1416	121,874		550	0.645	210	209.355	3.1416	233,322	275	64163539
					168,399	Sum					Sum	322,259		133089650
													Avg Ht	412.98986
Based on red #s Assume Tow Vol				275000	(m^3)									
													Avg Ht	414.55752

Deconstructing "Cost Analy" paper - get Foundation Size and fractions concrete vs Steel:

TOWER						FOUNDATION					
120	120kg/m^3 Tower Rebar					60	120kg/m^3 Tower Rebar				
8000	Kg/m^3 Dens Rebar					8000	Kg/m^3 Dens Rebar				
0.015	Rebar vol fraction Tower					0.0075	Rebar vol fraction Tower				
0.985	Concr vol fract					0.9925	Concr vol fract				
125	Euro/m^3 High Strength Concr					100	Euro/m^3 High Strength Concr				
123.125	Euro/m^3 HS Concr					99.25	Euro/m^3 HS Concr				
90	Euro/m^3 Rebar in Tower at 750 Euro/ton					45	Euro/m^3 Rebar in Tower at 750 Euro/ton				
213.125	Euro/m^3 Tower					144.25	Euro/m^3 Tower				
26680000	Euro Tower Mtls					7580000	Euro Foundation Mtls				
125,185	M^3 Tower					52,548	M^3 Foundation				
Tower is						Foundation is				Foundation is	
0.985	Concr vol fract					0.9925	Concr vol fract			0.4198	Multiple of Tower Volume
0.015	Rebar vol fraction Tower					0.0075	Rebar vol fraction Tower				
Thus Tower and Foundation are:											
Tower			Dens			Foundation			Dens		
568,838	(t)	Concrete	2100			240,594	(t)	Concrete	2100		
33,000	(t)	Rebar	8000			6,926	(t)	Rebar	8000		
Bracing Wheels											
	Qty	Spokes	Rad	Ht	T						
22,861	10	72	105	0.63	0.06	8000					

Scaling up the 91,480 m3 concrete C50/60 volume for a 750 m high 100 m diameter tower provided by Kraetzig in a report via personal communications, shown in Figure E.4 as shown in Table E.9, assuming extra material was added below to a thickness profile averaging 0.75 m thick from 0 to 50 m high (which is thicker than the other examples), and taking a guess at diameters, yielded a rough estimate of about 289 x 10^3 m^3 of concrete, which when averaged with the 228 251 and 323 x 10^3 m^3 obtained in Table E.8, gives 273 x 10^3 m^3 which further supports the 275 x 10^3 m^3 estimate selected for further evaluation in Table E.8. However, none of these estimates address stiffening features.

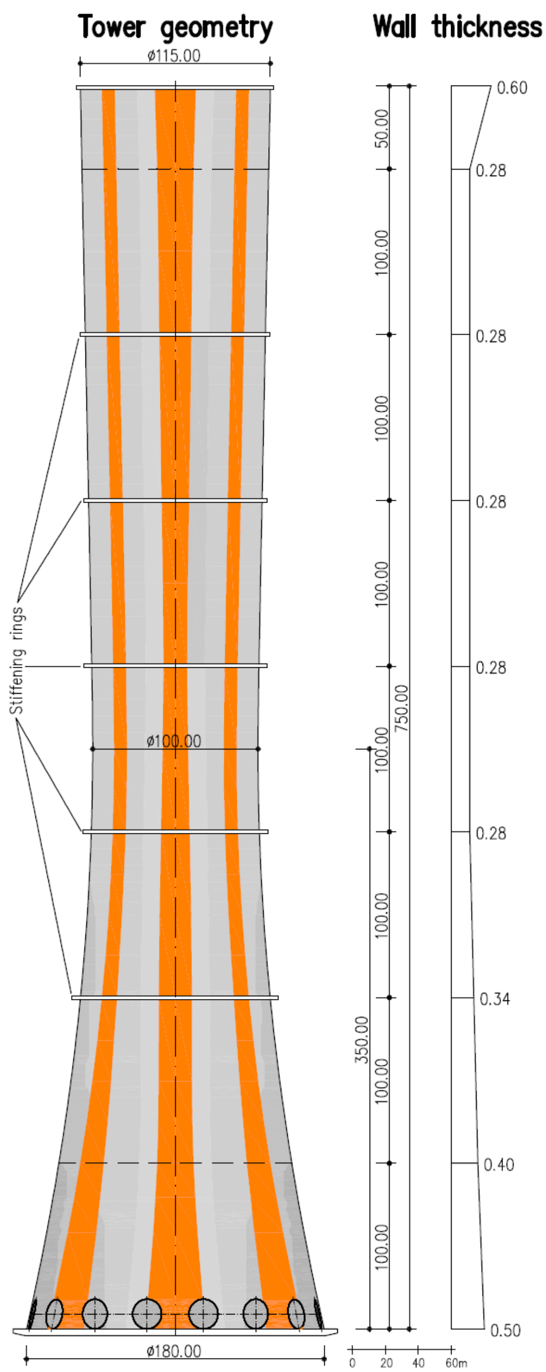

Figure E.4. 750 m tower design concept by Kraetzig (used with permission) [89].

TABLE E.9

2ND TOWER MATERIAL ESTIMATE

Design 3, (750 m high ,100m dia Kraetzig Report & Drawings)								
			Avg					
Height		Height	Wall	X Sect	750 m	Plus	Volumes	
From	To	Interval	Thick	Area	dia	110 m		
(m)	(m)	(m)	(m)	(m^2)	(m)	(m)	(m^3)	
950	1000	50	0.44	22	114	224	15,482	
850	950	100	0.28	28	110	220	19,352	
750	850	100	0.28	28	105	215	18,912	
650	750	100	0.28	28	103	213	18,736	
550	650	100	0.28	28	100	210	18,473	
450	550	100	0.31	31	103	213	20,744	
350	450	100	0.37	37	105	215	24,991	
250	350	100	0.45	45	110	220	31,102	
150	250	100	0.55	55	120	230	39,741	
50	150	100	0.65	65	135	245	50,030	
0	50	50	0.75	37.5	160	270	31,809	
							289,372	Sum

Stiffening:

A large thin shell chimney has some natural stiffness, which can be increased by using a hyperbolic shape, however to get the required strength and stiffness at acceptable mass and cost it requires stiffening with either internal bracing spoke “wheels” (of cables meeting at the central axis) or External stiffening rings (Kraetzig et al. [31]). Appendix B shows the GWP and embedded energy impacts are worth the improved plant performance of external stiffening rings due to the elimination of aerodynamic drag caused when internal bracing wheels are used.

Using the close up in Figure E.3, (which was selected because it is for a 1 km tower) a typical ring stiffener can be approximated by:

Inner and Outer Annulus and “railing”: 0.8*(1.25+5.35) +1.75*0.5 = 6.155 m^2
Wall Thickening: 0.15*(1.75+1.75) + 2*(1/2)*9*0.15 = 1.875 m^2
Total 8.03 m^2 times (minimal) circumference approx 215*Pi = approx 5,423.8 m^3
Times (10) stiffening rings = 54,238 m^3
At 2.1 t/ m^3, mass of 113,900 t.

Personal communication with Kraetzig [89] indicated one should multiply the 0.117 t/m^3 steel reinforcement estimate he made for a 750m tower by 1.15, giving 0.135 t/m^3. Multiplying by 54,238 m^3 gives 7,298 t S500 steel (rebar plus any bracing under the ring implied by Figure E.3.)

Applying the same rebar density to the tower Kraetzig recommended and using his 750 m high tower as a baseline, for which he lists 91,480 m^3 concrete and 6,315 t S500 steel, one obtains

.0690 t rebar / m^3, times 1.15 giving .0794 t rebar / m^3, and times 275,000 m^3 gives 21,831 t steel instead of the 33,000 t obtained in Table E.8. Adding the concrete from Table E.8 of 568,838 t to 113,900 t for the rings gives 682,738 t concrete, and adding steel reinforcement of 22,381 t to 7,298 t for the rings gives 29,679 t S500 steel, some of which may be beams instead of rebar.

The Foundation requirements of the 750 m tower by Kraetzig [89] are excavation of 43,560 m^3, refills or 14,800 m^3, and 28,740 m^3 of C25/30 concrete with 1,380 t of S500 steel reinforcement. When linearly volumetrically scaled to a 275,000 m^3 tower this gives excavation of 130,947 m^3, refills of 44,491 m^3, and 86,396 m^3 of C25/30 concrete (times 2.1 t/m^3 = 181,432 t), with 4,148 t of S500 steel reinforcement. According to Kraetzig [89], the steel is multiplied up by 1.15 giving 4,470 t S500 Steel. This compares to 240,594 t concrete and 6,926 t steel obtained in Table E.8 by reverse engineering the cost analysis. Given that there are ample opportunities for the cost analysis numbers to be too approximate, the scaled estimates from Kraetzig are assumed to be the more accurate numbers, and are adopted by this thesis.

Therefore the material requirements for the 1 km high 210 m diameter tower are assumed to be in accordance with Table 4.15.

<u>Formwork and Energy to Construct:</u>

Concrete shell towers are often built with forms that are adjusted up the face of the tower as it is poured [134, 135], which ought to allow a very modest investment in materials for forms and scaffolding. Whether this type of system can be adapted to a tower with external stiffener rings is a question this thesis leaves to for others to determine in design planning studies.

The entire scope of mechanical operations needed to set up machines and scaffolding and manipulate all material into final form is unknown and ambiguous. The energy to lift the average height of mass in the tower, which according to Table E.8 is about 415m, is:

$$PE = mgh = \text{approx } (0.6 \times 10^9 \text{ kg})*(9.81\text{m/s}^2)*(415 \text{ m}) = 2{,}443 \text{ GJ}$$

Assuming 10 times this value may approximate the total work, even 25,000 GJ is insignificant compared to the 195,000 t of glass for a single glazing times 23.5 GJ/t to get roughly 4,500,000 GJ of embedded energy, or the few million more GJ more for the lightest canopy support structure. Therefore this thesis does not include tower and foundation construction energy.

E.5 Turbine, Generator and Electrical Infrastructure

The SUTPP configurations for potential LCA are shown in Table E.10. The data provided by Pretorius [2] and Fluri (p. 88 [37]) is shown in black font. Red font identifies the configurations not addressed by Fluri, and values that were assumed to fill the data gaps. Blue font indicates items that were calculated:

Row 13 = “Max/Min Ratio” = Summer Peak/Winter Low
Row 14 = “Cap Factor” = (Pretorius GWh/y (Row 7)) / (Row 16)
Row 16 = (Turb)*(MWcap @) = # Turb (Row 5) * Power/Unit (Row 37)
Row 17 = Compare to Peak = Row 16 / Row 9
Row 35 & Row 37 are linear interpolation

Plate 4.1 in Section 4.3 shows Pretorius’ graphs of the estimated performance models of these configurations Pretorius [2] to aide in conceptual understanding of the configurations.

Review of the sources cited above and use of Table E.10 and Plate 4.1 resulted in the estimates for the configurations not addressed by Fluri [37] indicated in Table E.10 which was shown in simplified form in Table 4.16. Sufficient time was not available to determine blade count or mass, so this thesis assumed 16 blades of 2 tons each. A more accurate value for these numbers is preferable, however, the overall contribution of them is quite small relative to the rest of the power plant.

APPENDIX E (continued)

TABLE E.10

TURBINE CONFIGURATION DEFINITION DETERMINATION [2, 37]

Potential	Case	1	2	3	4	5	6
Type		BSUTPP	BSUTPP	BSUTPP	WSUTPP	ASUTPP	ASUTPP
Subtype			1/2 DG	DG			DG
Power Regulation		Free	Free	Free	Base	Base	Base
# Turb		27	29	30	25	25	28
Pretorius	Page #	31	85	85	103	89	93
GWh/y	Pretorius	336	423.8	463.6	327	330.9	362.7
	Fluri	328	415.5			332	
Peak	Summer	124	149	157	79	71	62
	Winter	62	76	78	20	28	27
Low (Est)	Summer	15	22	26	36	39	53
	Winter	6	12	14	15	16	23
Max/Min Ratio		20.6667	12.4167	11.2143	5.26667	4.4375	2.69565
Cap Factor		0.279	0.300	0.312	0.438	0.545	0.636
(#Turb)*(Mwcap @)		137.43	161.53	169.56	85.32	69.25	65.1
Compare to Peak		1.11	1.08	1.08	1.08	0.98	1.05
Init Capital Cost (ME)		96.1	102.2			88.8	
Rotor dia (m)		38.75	37.46			41.83	
Blade Length (m)		11.62	11.24			12.55	
Turbine Speed (rpm)		21	22.8			13.7	
Max Tip Speed (m/s)		42.61	44.72			30.01	
Turb Load Coef		0.24	0.25			0.3	
Turb Flow Coef		0.29	0.28			0.29	
Deg of React (@mid)		0.77	0.77			0.77	
Turb Efficiency (tt)		0.89	0.89			0.9	
IGVs/turbine		32	32			32	
Rotor Blades/Turb		15	15	16	16	16	16
Rotor Blade Mass (t)		1.81	1.67	2	2	2.17	2
Generator Length (m)		1.49	1.49			1.4	
Generator Dia (m)		5.96	5.97			5.61	
Generator Mass (t)		70.93	71.39	73.3729	63.6395	61.33	59.7312
Torque, MNm		2.31	2.33			1.93	
Power/Unit (MW)		5.09	5.57	5.652	3.4128	2.77	2.325
Specif PCU cost E/kW		700	633			1284	
Diffuser Area Ratio		1.3	1.29			1.2	
Efficiency of PCU (tt)		0.78	0.79			0.8	
Ann Pwr Output (GWh)		328	415.5			332	
COE (E/kWh)		0.139	0.121			0.169	

APPENDIX F

CALCULATION SETUP

This appendix shows additional steps required to determine input values for the SUTPP LCA.

F.1 Impact of Key Materials

The impacts of key materials in Table 5.2 were obtained from Hammond and Jones [103].

The impact of electricity in Table 5.3 was obtained from GaBi 5.0 Educational Software, which returned 69 t CO2 Eq/MWh from both the TRACI and CML databases [106]. The GWP potential impacts of 40t truck in Table 5.3 were obtained by averaging the impacts obtained from LCA Calculator (0.000107) (which uses mostly EcoInvent data) [132], and the average output of GaBi 5 (0.00005064), using the average of the CML, TRACI and ReCiPe database outputs [106]. The GWP potential impacts of Container Ship were obtained by averaging the impacts obtained from LCA Calculator (0.0000108) (which is mostly EcoInvent data) [132], and the average output of GaBi 5 (0.00001548), using the average of the CML, TRACI and ReCiPe database outputs [106].

F.2 ETFE and Water Tank Plastic

By the reasoning in Appendix E, this thesis assumes 0.2 m deep water tanks will be provided by grading to level the ground that leaves soil berms high enough to contain the water, lined with a 0.5 mm layer of generic plastic, with embodied energy and GWP taken as average for plastic materials in Hammond and Jones [103], topped with a 0.2mm layer of clear ETFE, for which Embodied energy is taken to be 26.5 GJ/t [107], but GWP data was not found, thus the average of 3 t CO_2 Eq/t for all plastics is assumed to get a rough impact estimate for ETFE. These results are summarized in Table 5.4.

The embodied energy to set up the water tank system for the WSUTPP is to be omitted, as it is too complex to estimate, and highly dependent on unquantified site leveling work that can be of much less scope if a collector were simply be erected above the land. A more rigorous assessment ought to address the additional impact of required grading, and should look at the installation of the water management systems, including canopy drains, pond to pond plumbing and pumps to send wash and rain water for purification or dump excess rain water beyond the collector, as required, which is beyond the scope of this thesis.

F.3 Turbine, Generator and Electrical Infrastructure

Table F.1, Table F.2, Table F.3 and Table F.4 show the derivation of turbine, generator and electrical infrastructure impacts.

APPENDIX F (continued)

TABLE F.1

TURBOGENERATOR IMPACTS (ONSHORE)

Onshore

				EE	2,630,000	GJ	p168	
25	yr life	p153			210	MW	p133, Tab 6.1	
0.425	CF	p144			12,524	GJ per MWcap		
EE	**1.5MW**	p168, Fig 7.3			GJ/MWcap			
Constr		0.74			9,267.62			
Oper		0.23			2,880.48			
Transm & Distr		0.01			125.24			
Decommission		0.02			250.48			
SUM		1			12,523.81			
EE	**1.5MW**							
Components								
NOT PROVIDED???								
GWP	**1.5MW**	p181, Fig 7.11			t CO2 Eq/MW Cap			
Construction		0.7357	0.74148		582.59	165,000	t CO2 Eq / Farm	
Operation		0.2203	0.22203		174.45			210
Transm & Distr		0.0062	0.00625		4.91			MW cap
Decommissioning		0.03	0.03024		23.76			
SUM		0.9922	1		785.71			
ERROR		0.0078						
Renormalize?								
GWP	**1.5MW**	p169, Fig 7.4			t CO2 Eq/MW Cap		**SUTPP**	
Tower		0.266	0.28358		165.21		0	None
Blades		0.125	0.13326		77.64		153.81	Est'd
Foundations		0.152	0.16205		94.41		0	None
Generator		0.155	0.16525		96.27		96.27	
Grid Conn & Cntl Mech		0.114	0.12154		70.81		70.81	
Nacelle		0.126	0.13433		78.26		78.26	
SUM		0.938	1		582.59		399.15	
ERROR		0.062						
Renormalize?								

Key:

123	Entered Values
123	Calculated Values
123	Concerns

APPENDIX F (continued)

TABLE F.2

TURBOGENERATOR IMPACTS (OFFSHORE GWP)

Offshore								
				EE	14,500,000	GJ	p170	
25	yr life	p153			1,001	MW	p156, Tab 6.13	
0.359	CF 3.6MW	p155, Tab 6.12			14,486	GJ per MWcap		
0.4685	CF 5MW	p155, Tab 6.12						
GWP	**Farm**	p182, Fig 7.13			t CO2 Eq/MW Cap at			CF
Construction		0.9033	0.90339		773.43			
Operation		0.0531	0.05311		45.47			
Transm & Distr		0.0047	0.0047		4.02			
Decommissioning		0.0388	0.0388		33.22			
SUM		0.9999	1		856.14	857,000	t CO2 Eq per Farm	
ERROR		1E-04						1001
Rounding - Renormalize								MW cap
GWP	**3.6MW**	p182, Fig 7.14			t CO2 Eq/MW Cap		**SUTPP**	
Foundations		0.3872	0.38724		299.50		0	None
Blades		0.1039	0.10391		80.37		58.56	Est'd
Nacelle		0.0664	0.06641		51.36		51.36	
Tower		0.2223	0.22232		171.95		0.00	None
Generator		0.0232	0.0232		17.95		17.95	
Offshore Grid Conn		0.01	0.01		7.74		7.74	Sim to
Onshore Grid Conn		0.0718	0.07181		55.54		55.54	Onshore
Mfg & Assy		0.1018	0.10181		78.74		78.74	
Transp Truck		0.0058	0.0058		4.49		4.49	
Transp Barge		0.0075	0.0075		5.80		5.80	US or ?
SUM		0.9999	1		773.43		280.174	
ERROR		1E-04			Assumed 3.6 & 5.0 Same			
Rounding - Renormalize								
GWP	**5MW**	p183, Fig 7.15			t CO2 Eq/MW Cap		**SUTPP**	
Foundations		0.2997	0.37472		289.82		0	
Tower		0.1719	0.21493		166.23		0	
Nacelle		0.1545	0.19317		149.41		149.41	
LACKS:	Generator		0		0.00		0.00	
Blades		0.0657	0.08215		63.53		40.81	Est'd
Onshore Grid Conn		0.0556	0.06952		53.77		53.77	
Offshore Grid Conn		0.0078	0.00975		7.54		7.54	
Mfg & Assy		0.0246	0.03076		23.79		23.79	
Transp Truck		0.0052	0.0065		5.03		5.03	
Transp Barge		0.0147	0.01838		14.22		14.22	US or ?
Diesel (Burned in Bldg Machine)		0.0001	0.00013		0.10		0.10	
SUM		0.7998	1		773.43		294.65	
ERROR		0.2002			Assumed 3.6 & 5.0 Same			
Renormalize?								

APPENDIX F (continued)

TABLE F.3

TURBOGENERATOR IMPACTS (OFFSHORE EE)

Offshore									
			MW @	qty	MW	CF	Product		
	Offshore		3.6	185	666	0.359	239.094		
	p156, Tab 6.13		5	67	335	0.4685	156.9475		
					1001		396.0415	MW	
							1001	Cap	
EE	**Farm**	p170, Fig 7.5			GJ/MWcap		0.395646	CF Farm	
Construction		0.921	0.92192		13,354.51		0.788584	Missing Facgtor?	
Operation		0.06	0.06006		870.00		0.312	CF Farm Claim	
Transm & Distr		0.004	0.004		58.00				
Decommission		0.014	0.01401		203.00				
SUM		0.999	1		14,485.51				
ERROR		0.001							
Rounding - Renormalize									
EE	**3.6 MW**	p171, Fig 7.6			GJ/MWcap		**SUTPP**		
Foundatinos		0.362	0.36236		4,839.17		0.00	None	
Blades		0.11	0.11011		1,470.47		1,071.52	Est'd	
Nacelle		0.067	0.06707		895.65		895.65		
Tower		0.222	0.22222		2,967.67		0.00	None	
Generator		0.022	0.02202		294.09		294.09		
Offshore Grid Conn		0.01	0.01001		133.68		133.68	Sim to	
Onshore Grid Conn		0.076	0.07608		1,015.96		1,015.96	Onshore	
Mfg & Assy		0.118	0.11812		1,577.41		1,577.41		
Transp Truck		0.006	0.00601		80.21		80.21		
Transp Barge		0.006	0.00601		80.21		80.21	US or ?	
SUM		0.999	1		13,354.51		5,148.73		
ERROR		0.001			Assumed 3.6 & 5.0 Same				
Rounding - Renormalize									
EE	**5 MW**	p171, Fig 7.7			GJ/MWcap		**SUTPP**		
Foundatinos		0.354	0.35365		4,722.77		0		
Tower		0.217	0.21678		2,895.03		0		
Nacelle		0.195	0.19481		2,601.53		2,601.53		
LACKS:	Generator		0		0.00		0.00		
Blades		0.088	0.08791		1,174.02		754.07	Est'd	
Onshore Grid Conn		0.074	0.07393		987.25		987.25		
Offshore Grid Conn		0.01	0.00999		133.41		133.41		
Mfg & Assy		0.041	0.04096		546.99		546.99		
Transp Truck		0.007	0.00699		93.39		93.39		
Transp Barge		0.015	0.01499		200.12		200.12	US or ?	
SUM		1.001	1		13,354.51		5,316.76		
ERROR		-0.001			Assumed 3.6 & 5.0 Same				
Rounding - Renormalize									

APPENDIX F (continued)

TABLE F.4

TURBOGENERATOR IMPACTS (SUMMARY PER MW CAPACITY)

Summary					
Blade Masses					
MW	Mass (t)				
1.5	5.384	p300, Tab C.1			
3.6	14.638	p303, Tab C.4			
5	16.607	p305, Tab C.5			
3	Blades p139 (1.5), rest assume 3				
Convert all to		2	t blades, qty 16		
	wind	SUTPP			
	mass (t)	mass (t)	Multiple		
1.5	16.152	32	1.98118		
3.6	43.914	32	0.7287		
5	49.821	32	0.6423		
SUTPP Construction					
Summary of Windfarm --> SUTPP Conversions					
MW	GWP	EE			
1.5	399.15		Throw out 1.5 GWP		
3.6	280.17	5,148.73	Avg'd 3.6 & 5.0 MW		
5	294.65	5,316.76	Use for SUTPP		
	287.41	5,232.74	in 2.5-5.5MW range		
	Therefore, for Construct SUTPP				
	287.41 t CO2 Eq/MW Cap				
	5232.7 GJ/MWcap				
SUTPP Operation					
Convert Oper Impact to per 100% CF and per Year					
	(Oper GWP/MW cap) / (CF*25yr life)				
	(Oper GJ/MW cap) / (CF*25yr life)				
	MW	GWP	EE		
	1.5	16.42	271.10	Not use, diff MWs	
	3.6 & 5	5.07	96.94	Use, Similar MWs	
Then Mult by CF of each SUTPP Config					
Gives same Maint / Pwr Out					
			Per MWCap		
		CF	GWP	EE	
BSUTPP		0.2791	**1.414**	**27.05**	
BSUTPP-1/2DG		0.2995	**1.517**	**29.03**	
BSUTPP-DG		0.31212	**1.581**	**30.26**	
VSUTPP		0.43751	**2.216**	**42.41**	
ASUTPP		0.54547	**2.763**	**52.88**	
ASUTPP-DG		0.63601	**3.222**	**61.65**	
SUTPP Decommision:					
Use Offshore Farm Decom w/o Tower & Foundation Share					
12.97 GWP/MW cap			**107.2 EE/MW Cap**		

The original values were all taken from Papadopoulos [136], and included data for 1.5 MW onshore turbines at Whitelee Scotland wind farm, and 3.6 and 5.0 MW offshore wind turbine installations in the London Array in the outer region of the Thames Estuary. The total GJ of energy produced per lifetime by each was divided by MW capacity to obtain GJ/MWcap. The percentage of Global Warming Potential (GWP) and Embodied Energy (EE) in each of the life phases was used to determine the GJ/MWcap for each phase.

The GJ/MWcap for Construction was then multiplied by the percentage for each of the major components (such as the tower or blades.) Yellow cells call attention to some of the percentage values that did not add up to 100%, so the data was renormalized to 100% as needed. The tower and foundation were then eliminated, and the turbines were all changed to 16 blades of 2 t each, to obtain the GJ/MWcap for the major subassemblies of a 1.5, 3.6 and 5 MWcap system representative of what may be used in a SUTPP. The 1.5 MWcap case was then dropped as the numbers obtained were different enough from the offshore numbers, which were for MWcap sizes much closer to the 2.33 to 5.65 MWcap sizes for the SUTPPs in this thesis (Reference Table E.10), and the 3.6 and 5 MW GWP and EE values were averaged to obtain 287 t CO2 Eq/MWcap and 5233 GJ/MWcap.

The GWP and EE for Operation were divided by the product of the wind turbine capacity factor and # yrs operation, then multiplied by the SUTPP generator capacity factor, to obtain the turbo-generator lifetime GWP and EE per MWcap.

These values were then transferred to the top of Table F.5 where they were multiplied by the MWcap for each SUTPP configuration. The equivalent to the 25 year service life was found for each SUTPP configuration taking into account the ratio of capacity factors, and the anticipated service life was increased 30% to roughly account for a longer service life due to the much more steady airflow velocity expected inside the SUTPP (vs. the gusty winds experienced by a wind turbine), and this increased life was then determined to be ½, 1/3 or ¼ of an estimated 80 year life of the SUTPP, thus implying the turbo-generators will be changed out 2, 3 or 4 times during the life of the SUTPP. Operating impacts per MWh produced where assumed to be the same as for a wind farm (no savings due to the more steady airflow) to conservatively account for the possibility any savings due to more steady airflow will be cancelled out by other factors associated with a new and different installation and operating environment. Thus this thesis assumes the turbo-generators produce 30%v more MWh but not experience any savings in GWP or EE per MWh produced vs. a conventional wind farm. The final values obtained at the bottom of Table F.5 are repeated in Table 5.5.

Table F.5

SUTPP TURBOGENERATOR IMPACTS

All per MW Cap		BSUTPP	B-1/2DG	B-DG	WSUTPP	ASUTPP	ASUTPP-DG			
Constr	GWP	287.41	287.41	287.41	287.41	287.41	287.41	t CO2 Eq/MW Cap		
	EE	5,232.74	5,232.74	5,232.74	5,232.74	5,232.74	5,232.74	GJ/MWcap		
Oper	GWP/yr	1.41	1.52	1.58	2.22	2.76	3.22	t CO2 Eq/MW Cap		
	EE/Yr	27.05	29.03	30.26	42.41	52.88	61.65	GJ/MWcap		
Decom	GWP	12.97	12.97	12.97	12.97	12.97	12.97	t CO2 Eq/MW Cap		
	EE	107.18	107.18	107.18	107.18	107.18	107.18	GJ/MWcap		
Mult by Cap		137.43	161.53	169.56	85.32	69.25	65.1	MW		
Constr	GWP	39,499	46,426	48,734	24,522	19,903	18,711	t CO2 Eq		
	EE	719,136	845,245	887,264	446,458	362,367	340,652	GJ		
Oper	GWP/yr	194	245	268	189	191	210	t CO2 Eq		
	EE/Yr	3,718	4,690	5,130	3,619	3,662	4,014	GJ		
Decom	GWP	1,783	2,096	2,200	1,107	898	845	t CO2 Eq		
	EE	14,730	17,313	18,174	9,145	7,422	6,978	GJ		
CF		0.279	0.300	0.312	0.438	0.545	0.636	vs	0.395646	W Farm
Equiv Life	25	35.44	33.03	31.69	22.61	18.13	15.55	Years		
Life Multiplier		46.07	42.93	41.20	29.39	23.57	20.22	Years	1.3	Life Mult
# lives/SUTPP life		2	2	2	3	4	4			
Life Assumed		40	40	40	26.66667	20	20	Years	80	SUTPP yrs
Oper	GWP/Turb	7,772	9,803	10,724	5,043	3,827	4,195	t CO2 Eq		
	EE/Turb	148,724	187,587	205,203	96,493	73,233	80,271	GJ		
Totals for Entire SUTPP Life										
		BSUTPP	B-1/2DG	B-DG	WSUTPP	ASUTPP	ASUTPP-DG			
Constr	**GWP**	**78,999**	**92,852**	**97,468**	**73,566**	**79,614**	**74,843**	**t CO2 Eq**		
	EE	**1,438,271**	**1,690,490**	**1,774,527**	**1,339,373**	**1,449,470**	**1,362,606**	**GJ**		
Oper	**GWP**	**15,544**	**19,606**	**21,448**	**15,128**	**15,309**	**16,780**	**t CO2 Eq**		
	EE	**297,448**	**375,173**	**410,407**	**289,480**	**292,933**	**321,084**	**GJ**		
Decom	**GWP**	**3,566**	**4,191**	**4,399**	**3,321**	**3,594**	**3,378**	**t CO2 Eq**		
	EE	**29,461**	**34,627**	**36,348**	**27,435**	**29,690**	**27,911**	**GJ**		
Total	**GWP**	**98,109**	**116,649**	**123,315**	**92,015**	**98,516**	**95,000**	**t CO2 Eq**		
	EE	**1,765,180**	**2,100,290**	**2,221,283**	**1,656,288**	**1,772,092**	**1,711,601**	**GJ**		

F.4 Other Infrastructure

As stated in Section 4.9, this thesis assumes other infrastructure, at a minimum includes the items in Table 4.17.

APPENDIX F (continued)

<u>baselines:</u>

Two research papers on Life Cycle Assessments of University Buildings were located during the literature search and used to derive a rough baseline to evaluate the buildings in Table 4.17. A summary of each is presented below, along with calculations of values to be used to derive a baseline:

1. "Life Cycle Energy and Environmental Performance of a New University Building: Modeling Challenges and Design Implications" by Scheuer et al. [104].

   7300 m^2 6 story 75 year life, 3 floors classes & offices, 3 floors hotel rooms, University of Michigan Campus (Need Heat and Air Conditioning)

   Embodied Energy:
   316 GJ/ m^2 per 75 year life, together with percentages below imply can calculate #s at right:

2.2% Construction	6.95 GJ/ m^2
96.6% Operation	4.07 GJ/(m^2*year)
0.2% Decommission	0.632 GJ/ m^2

   The 96.6% consists of 94.4% HVAC/Electric, and 3.3% Water

   GWP 100:
   135,000 t CO_2 Equiv / 7300m^2 = 18.493 t CO_2 Eq/m^2
   A 75 year life, with percentages below imply the #s at right:

3% Construction	0.555 t CO_2 Eq/m^2
96.5% Operation	0.238 t CO_2 Eq/(m^2*year)
0.5% Decommission	0.0925 t CO_2 Eq/m^2

2. "LCA and Carbon Footprint of Multi-Storey Timber Buildings Compared with Steel and Concrete Buildings" (2012) by A Buchanan, S John, S Love [105].

   1980m^2 3 storey 60 year life, New Zealand, (Moderate temperature climate)

   Embodied Energy:

Construction:	6,700 GJ/1980 m^2
Operation:	50,000 GJ Lifetime Total – 6,700 GJ Constr = 43,300 GJ Operation.
Decommission:	-4,900 GJ (due to recycling building materials.)

   Given 1980 m^2 floor area and 60 life this gives:

Construction:	3.38 GJ/m^2
Operation:	0.292 GJ/(m^2*year)
Decommission:	-2.48 GJ/m^2

GWP 100:
2793 t CO_2 Equiv per lifetime / 1,980 m^2 = 1.41 t CO_2 Eq/m^2
Construction: (382 t CO_2 Eq Materials) + (27 t CO_2 Eq Transportation) = (409 t CO_2 Eq)
1980m^2 0.207 t CO_2 Eq/m^2
Operation: (2,376 t CO_2 Eq Operation) + (77 t CO_2 Eq Maintenance) = (2,453 t CO_2 Eq)
For 60 yr, 1980m^2 0.0206 t CO_2 Eq/(m^2*year)
Decommission: -69 t CO_2 Eq (due to recycling building materials.)
For 1980m^2 -0.000626 t CO_2 Eq/m^2

Embodied Energy:
Construction: Avg (6.95, 3.38) =5.17 GJ/m^2
Operation: Consider (4.07, 0.292) GJ/(m^2*year)→
Use 4.07 GJ/(m^2*year) for control bldg that uses HVAC, houses running computers or where cooking (cafeteria, break room) may occur.
Decommission Avg (0.632, -2.48) = -0.924 GJ/m^2
Assume average of conventional and recycling cases

GWP (100):
Construction: Avg (0.555, 0.207) = 0.381 t CO_2 Eq/m^2
Operation: Consider (0.238, 0.0206) t CO_2 Eq/(m^2*year)→
Use 0.238 t CO_2 Eq/(m^2*year)
for same reason used 4.07 GJ/(m^2*year)
Decommission Avg (0.0925, -0.000626) = 0.0919 t CO_2 Eq/m^2
Not sure which to use but impact too small to matter.

These coefficients are summarized in Table F.6.

TABLE F.6

BASELINE BUILDING ENVIRONMENTAL IMPACTS PER FLOOR AREA

	Construction	Operation	Decommission
Embodied Energy	5.17 GJ/m^2	4.07 GJ/(m^2*year)	0.924 GJ/m^2
GWP (100)	0.381 t CO_2 Eq/m^2	0.238 t CO_2 Eq/(m^2*year)	0.0919 t CO_2 Eq/m^2

Impact Estimation:

Control Building and Visitor's Center:

The control building and visitor's center are assumed to be conventional relatively energy intensive buildings. While it may be appropriate to maximize the use of green methods of construction and temperature control, it may also be the case the special requirements for one or both of these buildings negate the benefits due to higher energy demands for operational needs. If these buildings of lesser environmental impact then these conventional assumptions will result in conservative estimates that overestimates the impact, bust this thesis considers such estimates to be reasonable for preliminary analysis. Therefore the impacts of these buildings was estimated by multiplied by 100% of the embodied energy and GWP coefficients derived above, at shown in Table 5.6.

Other Buildings:

The workshop is assumed to have only limited environmental control, and may be unused at times, thus it is assumed to require half the energy use per floor area, and its "Fraction" value is set to .5 for the use phase for both embodied energy and GWP.

The minimal storage is assumed to be infrequently accessed and without environmental control, except for a small corner office. Lights can be turned out in unused areas. Thus its operation phase "Fractions" are set to 0.1 to account for lights, power for stock moving equipment and the small office area.

The Maximum storage is assumed to be mostly a large stock or transparency material in a naturally ventilated area that seldom requires power, with a smaller area used much like the minimal storage option. Therefore its "Fraction" for the operation phase is set to 0.03.

Road:

According to "Embodied Energy and Carbon in Construction Materials" by Hammond and Jones [137] road and pavement is assumed to be 1.24 GJ/m^3 and 0.128 t CO_2 Eq/ m^3, as shown in Table 5.2. It is assumed the road will need to be replaced once during its lifetime as a basis for "operation" impacts, thus its fraction is set to 1/(years of operation). Road decommissioning is not included in the LCA.

F.5 LCA Analysis Spreadsheet

The "LCA Calc" spreadsheet shown in Table F.7 was constructed in Microsoft Excel to estimate the Global Warming Potential (GWP) and embodied Energy (EE) impacts of each aspect of the SUTPP system modeled. The spreadsheet is a summation of products of quantities such as mass, km transported or MWh of electricity used times coefficients that convert those quantities into GWP or EE impacts (in rows) that are summed up (in columns) by subsystem area (such as tower or collector) then the subsystems are summed up at the top for each life cycle phase (Construction, Operation and Decommissioning). Each Life cycle has a range of columns between bold vertical lines that consists of GWP columns first (one for the material or energy flow, the next few for distance transported and transport GWP impact), followed by the same pattern of columns for EE. Black Bold numbers above each subsystem are the sums of the GWP and EE impacts, each with the transportation term broken out separately. The red bold numbers above that are the GWP and EE with transportation included. At the top of each life cycle area, on row 14, the Black bold numbers are the sums of all the subsystem GWP and EE numbers with transportation still broken out, and on row 10, the red bold numbers add transportation in. Starting in the Operation Lifecycle area, Row 8 gives cumulative sums of GWP and EE of this and prior life cycle phases, which together with the GWh/y and # years of operation are used to compute the bold boxed quantities: (t CO_2 Eq/GWh) and EROEI. Gray boxes indicate this contribution is not needed or appropriate. Blue font indicates the cell value was set equal to that value on another worksheet that calculated that value. Green font indicates the cell value is set equal to a cell on the "LCA" worksheet discussed in the paragraph below. Pink boxes were spreadsheet features that were not utilized.

To simplify input/output (I/O), a more compact "LCA" spreadsheet worksheet was created as shown in Table F.8. Inputs may be made by adjusting the values in the non-bold single cell boxes, while the relevant outputs are shown in a more compact form.

To avoid entry errors, and permit accurate records of input and output to be made and kept, this "LCA" spreadsheet for I/O was copied to a template worksheet which was further simplified to the :"Input" form shown in Table F.9, which includes only "Input" information. Copies of this "Input" form were made and edited to reflect all cases for which LCA values were calculated. To run the LCA on an input case, the "input" file was entered into the "LCA" spreadsheet by using "Copy" and "Paste Special > Values, Skip Blanks".

After Pasting in inputs, the resulting "LCA" spreadsheet was copied and pasted as values into a "Output" file to preserve all the numeric inputs and outputs.

Key results from the "LCA" spreadsheet are summarized in a compact "Summary" worksheet form in the "Output" file shown in Table F.10.

Table F.7, Table F.8 and Table F.9 illustrate the BSUTPP "Configuration" with the "Case 1" (Light) structure. The LCA spreadsheet file also contained the tables imported into this thesis to permit results of supporting calculations, such as tons of glass required or embedded energy in a turbo-generator system to be directly fed into the "LCA Calc" spreadsheet to assure values are propagated through all the calculations.

TABLE F.7

“LCA CALC” ANALYSIS SPREADSHEET

Row	E	F	G	H	I	J	L	N	O	Q	R	S
3	**Contributing Items**											
10	Group	Item and Qty					GWP	Energy		Transportation		
11	Qty										GWP	Energy
12	Coef	Item	Params		Qty	(Units)	Coef	Coef	Effic	How	Coef	Coef
16	1	Structure Case										
17	Collector											
18	1	Glass			195,093	(t)	1.27	23.5	1	Truck	0.00007882	
19	0	ETFE			6,825	(t)	3	26.5	1	Truck	0.00007882	
20	1	Steel Struct			104,976	(t)	1.78	25.4	1	Truck	0.00007882	
21	1				104,976	(t)			1	Ship	0.00001314	
22	1	Steel Rebar			979	(t)	1.71	24.6	1	Truck	0.00007882	
23	1				979	(t)			1	Ship	0.00001314	
24	1	Post Concrete C70/85			0	(t)	0.212	1.41	1	Truck	0.00007882	
25	1	Footing Concr			34,003	(t)	0.159	1.11	1	Truck	0.00007882	
28	Water Mgmt											
29	0	WSUTPP- ETFE			5,121	(t)	3	26.5	1	Truck	0.00007882	
30	0	WSUTPP-Plastic			15,497	(t)	3	100	1	Truck	0.00007882	
31	0	WSUTPP-Fiberglass Tanks			719	(t)	8.1	100	1	Truck	0.00007882	
33	1	Others - Fiberglass Tanks			1,438	(t)	8.1	100	1	Truck	0.00007882	
35	0	Fill WSUTPP			2,929,394	(t)	0	0	1	Truck	0.00007882	
36	1	Fill Other Tanks			20,000	(t)	0	0	1	Truck	0.00007882	
38	0	HERO WSUTPP Tanks			13,113	(MWh)	0.69	3.6	1			
39	1	HERO Other Tanks			90	(MWh)	0.69	3.6	1			
41	1	Electricity			0	(MWh)	0.69	3.6	1			
42	1	Machines										
43					GWP	EE		GWP	EE		GWP	EE
44					Constr			Use			Decom	
45	Tower & Foundation											
46	1	Tower Concrete C50/60			682,738	(t)	0.212	1.41	1	Truck	0.00007882	
47	1	Tower Steel			21,831	(t)	1.78	25.4	1	Truck	0.00007882	
48	1				21,831	(t)			1	Ship	0.00001314	
49	1	Foundation Concrete C25/30			181,432	(t)	0.128	0.95	1	Truck	0.00007882	
50	1	Foundation Steel			4,470	(t)	1.78	25.4	1	Truck	0.00007882	
51	1				4,470	(t)			1	Ship	0.00001314	
52	0	Forms			0	(t)	0	0	1	Truck	0.00007882	
54					Constr			Use			Decom	
55	Turb/Gen/Electrical Package				GWP	EE		GWP	EE		GWP	EE
56	1	BSUTPP			78,999	1,438,271		15,544	297,448		3,566	29,461
57	0	BSUTPP-1/2DG			92,852	1,690,490		19,606	375,173		4,191	34,627
58	0	BSUTPP-DG			97,468	1,774,527		21,448	410,407		4,399	36,348
59	0	WSUTPP			73,566	1,339,373		15,128	289,480		3,321	27,435
60	0	ASUTPP			79,614	1,449,470		15,309	292,933		3,594	29,690
61	0	ASUTPP-DG			74,843	1,362,606		16,780	321,084		3,378	27,911
64			Constr		(t)	Operate	per year	Decommission		Transportation		
65	Other Infrastructure		GWP	Energy		GWP	Energy	GWP	Energy	How	GWP	Energy
66	1	Control Bldg	229	3,102		143	2,442	55	554			
67	1	Visitor's Center	229	3,102		143	2,442	55	554			
68	1	Workshop	476	6,463		149	2,544	115	1,155			
69	1	Storage (Minimum)	381	5,170		30	509	92	924			
70	0	Storage (Maximum)	20,604	279,594		483	8,254	4,970	49,970			
71	1	Roads	2,079	20,138	16,240	26	252	0	0	Truck	7.882E-05	

APPENDIX F (continued)

TABLE F.7 (Continued)

	V	X	Z	AA	AD	AF	AI	AK	AM	AN	AQ	AS
1												
2												
3	**Construction**						**Operation**		125	MW	(GWh/y)	336
4									Rated Capacity		(years)	80
5											(GJ)	96,768,000
6								GWP Constr + Operation				
7								34	($t\ CO_2$ Eq/GWh)		EROEI	7.51
8								Cum GWP ($t\ CO_2$ Eq)		917,136	Cum Enrg (GJ)	12,886,580
9												
10		GWP	($t\ CO_2$ Eq)	786,971	Energy (GJ)	10,736,336		GWP	($t\ CO_2$ Eq)	130,165	Energy (GJ)	2,150,244
11	Qty	Material	Transportation		Material	Transp	Qty	Material	Transportation		Material	Transp
12	Coef	GWP	Dist	GWP	Energy	Energy	Coef	GWP	Dist	GWP	Energy	Energy
13		($t\ CO_2$ Eq)	(km)	($t\ CO_2$ Eq)	(GJ)	(GJ)		($t\ CO_2$ Eq)	(km)	($t\ CO_2$ Eq)	(GJ)	(GJ)
14		750,587		36,384	10,736,336	0		126,577		3,588	2,150,244	0
15												
16		466,671			7,312,903			65,402			1,146,171	
17		441,706		24,965	7,312,903	0		61,942		3,460	1,146,171	0
18	1	247,768	900	13,839	4,584,686	0	0.25	61,942	900	3,460	1,146,171	0
19	1	0	3,000	0	0	0	0.00	0	3,000	0	0	0
20	1	186,857	900	7,447	2,666,390	0	0	0	900	0	0	0
21	1	0	2,400	3,310	0	0	0	0	2,400	0	0	0
22	1	1,674	900	69	24,083	0	0	0	900	0	0	0
23	1	0	2,400	31	0	0	0	0	2,400	0	0	0
24	1	0	125	0	0	0	0	0	125	0	0	0
25	1	5,406	100	268	37,743	0	0	0	100	0	0	0
26												
27		11,792			144,122			9,884			51,568	
28		11,710		83	144,122	0		9,884		0	51,568	0
29	1	0	3,000	0	0	0	3.0	0	3,000	0	0	0
30	1	0	1,000	0	0	0	3.0	0	1,000	0	0	0
31	1	0	450	0	0	0	0	0	450	0	0	0
32												
33	1	11,648	450	51	143,800	0	0	0	450	0	0	0
34												
35	1	0	20	0	0	0	0	0	20	0	0	0
36	1	0	20	32	0	0	0	0	20	0	0	0
37												
38	1	0			0		3	0			0	
39	1	62			322		160	9,884			51,568	
40												
41	0	0			0		0	0			0	
42	1	0			0		0	0			0	
43												
44		225,989			1,803,066			0			0	
45		214,779		11,209	1,803,066	0		0		0	0	0
46	1	144,740	125	6,727	962,660	0	0	0	125	0	0	0
47	1	38,859	900	1,549	554,507	0	0	0	900	0	0	0
48	1	0	2,400	688	0	0	0	0	2,400	0	0	0
49	1	23,223	125	1,788	172,360	0	0	0	125	0	0	0
50	1	7,957	900	317	113,538	0	0	0	900	0	0	0
51	1	0	2,400	141	0	0	0	0	2,400	0	0	0
52	1	0	100	0	0	0	0	0	100	0	0	0
53												
54		78,999			1,438,271			15,544			297,448	
55		78,999		0	1,438,271	0		15,544		0	297,448	0
56	1	78,999			1,438,271		1	15,544			297,448	
57	1	0			0		1	0			0	
58	1	0			0		1	0			0	
59	1	0			0		1	0			0	
60	1	0			0		1	0			0	
61	1	0			0		1	0			0	
62												
63												
64		3,521			37,974			39,335			655,058	
65		3,393		128	37,974	0		39,207		128	655,058	0
66	1	229			3,102		1	11,424			195,360	
67	1	229			3,102		1	11,424			195,360	
68	1	476			6,463		1	11,900			203,500	
69	1	381			5,170		1	2,380			40,700	
70	1	0			0		1	0			0	
71	1	2,079	100	128	20,138	0	1	2,079	100	128	20,138	0

APPENDIX F (continued)

TABLE F.7 (Continued)

	AV	AX	AZ	BA	BD	BF
1						
2						
3	**Decommision**					
4						
5						
6		**GWP Constr + Operation**				
7		34	(t CO_2 Eq/GWh)		EROEI	7.49
8		Cum GWP (t CO_2 Eq)		921,147	Cum Enrg (GJ)	12,919,229
9						
10		GWP (t CO_2 Eq)		4,011	Energy (GJ)	32,648
11	Qty	Material	Transportation		Material	Transp
12	Coef	GWP	Dist	GWP	Energy	Energy
13		(t CO_2 Eq)	(km)	(t CO_2 Eq)	(GJ)	(GJ)
14		3,883		128	32,648	0
15						
16		0			0	
17		0		0	0	0
18	0	0		0	0	0
19	0	0		0	0	0
20	0	0		0	0	0
21	0	0		0	0	0
22	0	0		0	0	0
23	0	0		0	0	0
24	0	0		0	0	0
25	0	0		0	0	0
26						
27		0			0	
28		0		0	0	0
29	0	0		0	0	0
30	0	0		0	0	0
31	0	0		0	0	0
32						
33	0	0		0	0	0
34						
35	0	0		0	0	0
36	0	0		0	0	0
37						
38	0	0			0	
39	0	0			0	
40						
41	0	0			0	
42	0	0			0	
43						
44		0			0	
45		0		0	0	0
46	0	0		0	0	0
47	0	0		0	0	0
48	0	0		0	0	0
49	0	0		0	0	0
50	0	0		0	0	0
51	0	0		0	0	0
52	0	0		0	0	0
53						
54		3,566			29,461	
55		3,566		0	29,461	0
56	1	3,566			29,461	
57	1	0			0	
58	1	0			0	
59	1	0			0	
60	1	0			0	
61	1	0			0	
62						
63						
64		445			3,188	
65		317		128	3,188	0
66	1	55			554	
67	1	55			554	
68	1	115			1,155	
69	1	92			924	
70	1	0			0	
71	1	0	100	128	0	0

APPENDIX F (continued)

TABLE F.8

“LCA” INPUT/OUTPUT SPREADSHEET

Row	C	D	E	I	J	K	L
2	**Contributing Items**			CONFG:	BSUTPP		
3						336.0	(GWh/y)
4	Trransportation					80	(years)
5	Glass	Truck	900			96,768,000	(GJ)
6	ETFE	Truck	3000			137.4	MWcap
7	Plastic	Truck	1000				
8	Steel	Truck	900				
9		Ship	2400		Structure Case	1	
10	LS Conc	Truck	100	Collector			
11	Roads	Truck	100	1	Glass	195,093	(t)
12	HS Conc	Truck	125	0	ETFE	6,825	(t)
13	Fiberglass	Truck	450	1	Steel Struct	104,976	(t)
14	Water	Truck	20	1			
15	Forms	Truck	100	1	Steel Rebar	979	(t)
16				1			
17	Rough Values			1	Post Concrete C70/85	0	(t)
18		GWP	EE	1	Footing Concr	34,003	(t)
19	ETFE	3					
20	ETFE	3					
21	Plastic	3	100	Water Mgmt			
22	Plastic (t)	15,497		0	WSUTPP- ETFE		
23				0	WSUTPP-Plastic		
24	Wash Machines			0	WSUTPP-Fiberglass Tanks		
25		GWP	EE	1	Others - Fiberglass Tanks		
26	Constr	0	0	0	Fill WSUTPP		
27	Use	0	0	1	Fill Other Tanks		
28	Decom	0	0	0	HERO WSUTPP Tanks		
29	(MWh)	0		1	HERO Other Tanks		
30				1	Electricity		
31	Forms			1	Machines		
32	Mass (t)	0					
33	GWP	0					
34	EE	0		Tower & Foundation			
35				0	Forms		
36	1	BSUTPP					
37	0	BSUTPP-1/2DG					
38	0	BSUTPP-DG		Turb/Gen/Electrical Package			
39	0	WSUTPP					
40	0	ASUTPP				Min Storage	1
41	0	ASUTPP-DG		Other Infrastructure		Max Storage	0

Row	O	Q	S	V	X
2	**Construction**				
4		GWP		Energy	
5		786,971	(t CO2 Eq)	10,736,336	(GJ)
6	Qty	Material	Transp	Material	Transp
7	Coef	750,587	36,384	10,736,336	0
9		466,671		7,312,903	
10		441,706	24,965	7,312,903	0
11		247,768	13,839	4,584,686	0
12		0	0	0	0
13		186,857	7,447	2,666,390	0
14		0	3,310	0	0
15		1,674	69	24,083	0
16		0	31	0	0
17		0	0	0	0
18		5,406	268	37,743	0
20		11,792		144,122	
21		11,710	83	144,122	0
22		0	0	0	0
23		0	0	0	0
24		0	0	0	0
25		11,648	51	143,800	0
26		0	0	0	0
27		0	32	0	0
28	1	0	0	0	0
29	1	62	0	322	0
30		0	0	0	0
31		0	0	0	0
33		225,989		1,803,066	
34		214,779	11,209	1,803,066	0
35		0	0	0	0
37		78,999		1,438,271	
38		78,999	0	1,438,271	0
40		3,521		37,974	
41		3,393	128	37,974	0

Row	AA	AC	AE	AH	AJ
2	**Operation**				
3	GWP	34	(t CO2 Eq/GWh)	Energy	7.51
4	Cum	917,136	(t CO2 Eq)	12,886,580	(GJ)
5	Op	130,165	(t CO2 Eq)	2,150,244	(GJ)
6	Qty	Material	Transp	Material	Transp
7	Coef	126,577	3,588	2,150,244	0
9		65,402		1,146,171	
10		61,942	3,460	1,146,171	0
11	0.25	61,942	3,460	1,146,171	0
12	0.00	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	0	0
17	0	0	0	0	0
18	0	0	0	0	0
20		9,884		51,568	
21		9,884	0	51,568	0
22	3.0	0	0	0	0
23	3.0	0	0	0	0
24	0	0	0	0	0
25	0	0	0	0	0
26	0	0	0	0	0
27	0	0	0	0	0
28	3	0	0	0	0
29	160	9,884	0	51,568	0
30	0	0	0	0	0
31	0	0	0	0	0
33		0		0	
34		0	0	0	0
37		15,544		297,448	
38		15,544	0	297,448	0
40		39,335		655,058	
41		39,207	128	655,058	0

Row	AM	AO	AQ	AT	AV	AY	AZ
2	**Decommision**						
3	GWP	34	(t CO2 Eq/GWh)	Energy	7.49	27	#Turbs
4	Cum	921,147	(t CO2 Eq)	12,919,229	(GJ)	5.09	MW cap/turb
5	Op	4,011	(t CO2 Eq)	32,648	(GJ)	0.279	CF
6	Qty	Material	Transp	Material	Transp		
7	Coef	3,883	128	32,648	0		
9		0		0			
10		0	0	0	0		
11		0	0	0	0		
12		0	0	0	0		
13		0	0	0	0		
14		0	0	0	0		
15		0	0	0	0		
16		0	0	0	0		
17		0	0	0	0		
18		0	0	0	0		
20		0		0			
21		0	0	0	0		
22		0	0	0	0		
23		0	0	0	0		
24		0	0	0	0		
25		0	0	0	0		
26		0	0	0	0		
27		0	0	0	0		
28		0	0	0	0		
29		0	0	0	0		
30		0	0	0	0		
31		0	0	0	0		
33		0		0			
34		0	0	0	0		
37		3,566		29,461			
38		3,566	0	29,461	0		
40		445		3,188			
41		317	128	3,188	0		

APPENDIX F (continued)

TABLE F.9

“LCA INPUT” SPREADSHEET (PASTED IN)

	C	D	E	I	J	K	L	O	AA	AY	AZ
2	**Contributing Items**			CONFG:	BSUTPP						
3					336.0	(GWh/y)				27	#Turbs
4	Trransportation				80	(years)				5.09	MW cap/turb
5	Glass	Truck	900							0.279	CF
6	ETFE	Truck	3000		137.4	MWcap					
7	Plastic	Truck	1000								
8	Steel	Truck	900								
9		Ship	2400		**Structure Case**	1					
10	LS Conc	Truck	100	**Collector**							
11	Roads	Truck	100	1	Glass	195,093	(t)		0.25		
12	HS Conc	Truck	125	0	ETFE	6,825	(t)		0.00		
13	Fiberglass	Truck	450	1	Steel Struct	104,976	(t)		0		
14	Water	Truck		1					0		
15	Forms	Truck	100	1	Steel Rebar	979	(t)		0		
16				1					0		
17	Rough Values			1	Post Concrete C70/85	0	(t)		0		
18		GWP	EE	1	Footing Concr	34,003	(t)		0		
19	ETFE										
20	ETFE										
21	Plastic			**Water Mgmt**							
22	Plastic (t)			0	WSUTPP- ETFE				3.0		
23				0	WSUTPP-Plastic				3.0		
24	Wash Machines			0	WSUTPP-Fiberglass Tanks				0		
25		GWP	EE	1	Others - Fiberglass Tanks				0		
26	Constr			0	Fill WSUTPP				0		
27	Use			1	Fill Other Tanks				0		
28	Decom			0	HERO WSUTPP Tanks			1	3		
29	(MWh)			1	HERO Other Tanks			1	160		
30				1	Electricity				0		
31	Forms			1	Machines				0		
32	Mass (t)										
33	GWP										
34	EE			**Tower & Foundation**							
35				0	Forms						
36	1	BSUTPP									
37	0	BSUTPP-1/2DG									
38	0	BSUTPP-DG		**Turb/Gen/Electrical Package**							
39	0	WSUTPP									
40	0	ASUTPP				Min Storage	1				
41	0	ASUTPP-DG		**Other Infrastructure**		Max Storage	0				

APPENDIX F (continued)

TABLE F.10

"SUMMARY" SPREADSHEET (LISTS MULTIPLE OUTPUTS)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1			St Case	Configuration										
2								Cum Tot	Phase Tot	Collector	Water Sys	Tower	Turb/Gen	Other
3		#	Stats		GWP	Phase	(t CO2 Eq/GWh)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)
4					EE	Phase	EROEI	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)
6			1	BSUTPP										
7		1	336	GWh/y	GWP	Constr		786,971	786,971	466,671	11,792	225,989	78,999	3,521
8			80	yrs		Oper	34.12	917,136	130,165	65,402	9,884	0	15,544	39,335
9			137.4	MW cap		Decom	34.27	921,147	4,011	0	0	0	3,566	445
10			27	# Turbs	EE	Constr		10,736,336	10,736,336	7,312,903	144,122	1,803,066	1,438,271	37,974
11			5.09	MW cap/turb		Oper	7.51	12,886,580	2,150,244	1,146,171	51,568	0	297,448	655,058
12			0.279	CF		Decom	7.49	12,919,229	32,648	0	0	0	29,461	3,188
14			1	BSUTPP-1/2DG										
15		2	423.8	GWh/y	GWP	Constr		951,390	951,390	617,237	11,792	225,989	92,852	3,521
16			80	yrs		Oper	32.50	1,101,966	150,576	81,751	9,884	0	19,606	39,335
17			161.5	MW cap		Decom	32.64	1,106,602	4,636	0	0	0	4,191	445
18			29	# Turbs	EE	Constr		13,547,549	13,547,549	9,871,897	144,122	1,803,066	1,690,490	37,974
19			5.57	MW cap/turb		Oper	7.60	16,062,038	2,514,490	1,432,691	51,568	0	375,173	655,058
20			0.300	CF		Decom	7.58	16,099,853	37,815	0	0	0	34,627	3,188
22			1	BSUTPP-DG										
23		3	463.6	GWh/y	GWP	Constr		1,106,572	1,106,572	767,802	11,792	225,989	97,468	3,521
24			80	yrs		Oper	34.39	1,275,341	168,769	98,103	9,884	0	21,448	39,335
25			169.6	MW cap		Decom	34.52	1,280,185	4,844	0	0	0	4,399	445
26			30	# Turbs	EE	Constr		16,190,576	16,190,576	12,430,887	144,122	1,803,066	1,774,527	37,974
27			5.65	MW cap/turb		Oper	7.02	19,026,865	2,836,289	1,719,257	51,568	0	410,407	655,058
28			0.312	CF		Decom	7.00	19,066,401	39,536	0	0	0	36,348	3,188
30			1	WSUTPP										
31		4	327	GWh/y	GWP	Constr		853,548	853,548	466,671	83,801	225,989	73,566	3,521
32			80	yrs		Oper	45.62	1,193,413	339,866	65,402	220,001	0	15,128	39,335
33			85.3	MW cap		Decom	45.76	1,197,179	3,766	0	0	0	3,321	445
34			25	# Turbs	EE	Constr		12,297,792	12,297,792	7,312,903	1,804,477	1,803,066	1,339,373	37,974
35			3.41	MW cap/turb		Oper	4.81	19,586,231	7,288,439	1,146,171	5,197,730	0	289,480	655,058
36			0.438	CF		Decom	4.80	19,616,854	30,623	0	0	0	27,435	3,188
38			1	ASUTPP										
39		5	330.9	GWh/y	GWP	Constr		1,148,003	1,148,003	827,087	11,792	225,989	79,614	3,521
40			80	yrs		Oper	49.45	1,309,034	161,031	91,563	14,826	0	15,309	39,335
41			69.3	MW cap		Decom	49.60	1,313,073	4,039	0	0	0	3,594	445
42			25	# Turbs	EE	Constr		16,665,440	16,665,440	13,230,809	144,122	1,803,066	1,449,470	37,974
43			2.77	MW cap/turb		Oper	4.94	19,295,422	2,629,982	1,604,640	77,351	0	292,933	655,058
44			0.545	CF		Decom	4.93	19,328,300	32,878	0	0	0	29,690	3,188
46			1	ASUTPP-DG										
47		6	362.7	GWh/y	GWP	Constr		1,464,123	1,464,123	1,147,979	11,792	225,989	74,843	3,521
48			80	yrs		Oper	56.51	1,639,704	175,580	104,640	14,826	0	16,780	39,335
49			65.1	MW cap		Decom	56.64	1,643,527	3,823	0	0	0	3,378	445
50			28	# Turbs	EE	Constr		21,963,185	21,963,185	18,615,416	144,122	1,803,066	1,362,606	37,974
51			2.33	MW cap/turb		Oper	4.20	24,850,506	2,887,321	1,833,828	77,351	0	321,084	655,058
52			0.636	CF		Decom	4.20	24,881,604	31,099	0	0	0	27,911	3,188

Preparing and entering the correct values for all required LCA inputs was found to be somewhat complicated. Therefore Table F.11 was developed to document the input entries required to be consistent with the entirety of material presented in this thesis and its appendices.

APPENDIX F (continued)

TABLE F.11

REQUIRED INPUTS

Input Values:	Gray Items where NOT changed for any of the LCA evlauations.		
LCA Cell	Name or Purpose	Logic or Value (with supporting calculations)	
C5 - E34	"Contributing Items"	Nothing in Cell range C5 to E 34 was changed.	
I13	Steel Struct	1	Always
I14		1	Always
I15	Steel Rebar	1	Always
I16		1	Always
I17	Post Concrete C70/85	1	Always
I18	Footing Concr	1	Always
I35	Forms	0	(Not used)
J4	(years)	80	Not Adjusted
K11	Glass (t)	195093	Always
K12	ETFE (t)	6825	Always
O28	HERO WSTUPP Tanks	1	Always
O29	HERO Other Tanks	1	Always
AA13	Steel Struct	0	Assumed Never Replace
AA14		0	
AA15	Steel Rebar	0	
AA16		0	
AA17	Post Concrete C70/85	0	
AA18	Footing Concr	0	
AA22	WSUTPP- ETFE	3	WSUTPP Tanks Replaced & Refilled every 20 years.
AA23	WSUTPP-Plastic	3	WSUTPP Tanks Replaced & Refilled every 20 years.
AA24	WSUTPP-Fiberglass Tanks	0	Assume Never Replace
AA25	Others - Fiberglass Tanks	0	Assume Never Replace
AA26	Fill WSUTPP	0	Not Applicable to Operations - HERO instead
AA27	Fill Other Tanks	0	Not Applicable to Operations - HERO instead
AA28	HERO WSUTPP Tanks	3	WSUTPP Tanks Replaced & Refilled every 20 years.
AA30	Electricity	0	Not Simulated
AA31	Machines	0	Not Simulated

Abbreviated Abbriviations:	
B	BSUTPP
B-1/2DG	BSUTPP-1/2DG
B-DG	BSUTPP-DG
W	WSUTPP
A	ASUTPP
A-DG	ASUTPP-DG

APPENDIX F (continued)

TABLE F.11 (Continued)

REQUIRED INPUTS (2 of 6 = Left Hand Side)

C36 - C41	Configurations	Set ONE = 1, the others = 0.					
J2	CONFG:	Fill in Config Name: ETFE or other variation detials					
	Water Mgmt	WSUTPP	All Others				
I22	WSUTPP- ETFE	1	0				
I23	WSUTPP-Plastic	1	0		Abbreviated Abbriviations:		
I24	WSUTPP-Fiberglass Tanks	1	0		B	BSUTPP	
I25	Others - Fiberglass Tanks	0	1		B-1/2DG	BSUTPP-1/2DG	
I26	Fill WSUTPP	1	0		B-DG	BSUTPP-DG	
I27	Fill Other Tanks	0	1		W	WSUTPP	
I28	HERO WSUTPP Tanks	1	0		A	ASUTPP	
I29	HERO Other Tanks	0	1		A-DG	ASUTPP-DG	
I30	Electricity	0	1				
I31	Machines	0	1				
		BSUTPP	B-1/2 DG	B-DG	W	A	A-DG
J3	(GWh/y)	336.0	423.8	463.6	327.0	330.9	362.7
J4	(years)	80	80	80	80	80	80
J6	Mwcap	137.4	161.5	169.6	85.3	69.3	65.1
K9	Structure Case	1, 2 or 3					
K13	Steel Struct	Config	Mtl	Case 1	Case 2	Case 3	
		B & W	Any	104,976		496,649	
		B-1/2DG	Any	115,474	507,147	546,314	
		B-DG	Glass	125,972	517,645	595,979	
			ETFE	104,976			
		A	Any	157,465	549,137	905,406	
		A-DG	Others	188,958	580,630	1,004,736	
			All ETFE	157,465			
		Case 1	Case 2,3				
K15	Steel Rebar (t)	979	4,734				
K17	Post Concrete C70/85 (t)	0	32,504				
K18	Footing Concr (t)	34,003	164,462				
L40	Min Storage	1	Default				
L41	Max Storage	0	Change it to this if want large one.				

APPENDIX F (continued)

TABLE F.11 (Continued)

REQUIRED INPUTS (3 of 6 = Right Hand Side)

			All but A, A-DG		A & A-DG		
			Glass	ETFE	Glass	ETFE	
AA29	HERO Other Tanks	Low	40	8	60	12	
		Med	160	24	240	36	
		High	480	80	720	120	
			5 yr Cleaning Rates (From other Worksheet)				
					Glass	ETFE	
			Low	Top	2.5	0.5	
				Both	3.75	0.75	
			Med	Top	10	1.5	
				Both	15	2.25	
			High	Top	30	5	
				Both	45	7.5	
			80	Life			
			5	Life in Table Above			
			16	Multiplier			
		BSUTPP	B-1/2 DG	B-DG	W	A	A-DG
AY3	#Turb	27	29	30	25	25	28
AY4	MW Cap/turb	5.09	5.57	5.65	3.41	2.77	2.33
AY5	CF	0.279	0.300	0.312	0.438	0.545	0.636

APPENDIX F (continued)

TABLE F.11 (Continued)

REQUIRED INPUTS (4 of 6 = Low Cleaning Rate)

I11	Glass	# of 19.5 km^2 layers of glass
AA11	Glass Replacement Rate	
I12	EFTE	# of 19.5 km^2 layers of EFTE
AA12	ETFE Replacement Rate	

Table Below gives values for these four cells:

Cells Addresses		Cell Contents	
I11	AA11	# Lay Gl	Repl G
I12	AA12	# Lay ET	Repl E

MEDIUM REPLACEMENT RATES:

Calculations:

Repl has to be (Lay/Life) / Lay as it will be multipled by #Lay again in LCA Spread

Repl Rate = SUM(4 column entries to the right)

Confg	row/mtl	# Lay	Repl	Repl Rate (Lay/Life)	Primary Top	Primary Under	Secondary Top	Secondary Under
B & W	1 Glass	1	0.06	0.06	0.06			
	1 ETFE	0	0	0				
	2 Glass	0	0	0				
	2 ETFE	1	1.2	1.2	1.2			
B-1/2DG	1 Glass	1.5	0.048	0.072	0.06	0.012		
	1 ETFE	0	0	0				
	2 Glass	1	0.06	0.06	0.06			
	2 ETFE	0.5	0.25	0.125		0.125		
B-DG	1 Glass	2	0.042	0.084	0.06	0.024		
	1 ETFE	0	0	0				
	2 Glass	0	0	0				
	2 ETFE	2	1.2	2.4	2.4			
A	1 Glass	2	0.04	0.08	0.06		0.02	
	1 ETFE	0	0	0				
	2 Glass	1	0.06	0.06	0.06			
	2 ETFE	1	0.5	0.5			0.5	
	3 Glass	0	0	0				
	3 ETFE	2	0.85	1.7	1.2		0.5	
A-DG	1 Glass	3	0.02933	0.088	0.06		0.02	0.008
	1 ETFE	0	0	0				
	2 Glass	2	0.04	0.08	0.06		0.02	
	2 ETFE	1	0.25	0.25				0.25
	3 Glass	1	0.06	0.06	0.06			
	3 ETFE	2	0.5	1			1	
	4 Glass	0	0	0				
	4 ETFE	3	0.73333	2.2	1.2		1	

LOW Probability Coefs from Replacement Rate Definition:

Glasss		ETFE Single Membrane	
0.06	Pri Top	1.2	Pri Top
0.02	Sec Top	0.5	Sec Top
0.024	DG Pri Bot	0.25	DG Under Top Glass
0.008	DG Sec Bot	0.25	DG Under Bot Glass
		Pillows	
		2.4	Pri Top
		1	Sec Top

= /2 because 50% of area

Abbreviated Abbriviations:	
B	BSUTPP
B-1/2DG	BSUTPP-1/2DG
B-DG	BSUTPP-DG
W	WSUTPP
A	ASUTPP
A-DG	ASUTPP-DG

APPENDIX F (continued)

TABLE F.11

REQUIRED INPUTS (5 of 6 = Medium Cleaning Rate)

								Table Below gives values for these four cells:						
I11	Glass			# of 19.5 km^2 layers of glass				Cells Addresses			Cell Contents			
AA11	Glass Replacement Rate							I11	AA11		# Lay Gl	Repl G		
I12	EFTE			# of 19.5 km^2 layers of EFTE				I12	AA12		# Lay ET	Repl E		
AA12	ETFE Replacement Rate													
MEDIUM	**REPLACEMENT RATES:**			Calculations:		Repl has to be (Lay/Life) / Lay as it will be multipled by #Lay again in LCA Spread								
						Repl Rate = SUM(4 column entries to the right)								
				Repl Rate	Primary		Secondary							
Confg	row/mtl	# Lay	Repl	(Lay/Life)	Top	Under	Top	Under						
B & W	1 Glass	1	0.25	0.25	0.25									
	1 ETFE	0	0	0										
	2 Glass	0	0	0					MEDIUM	Probability Coefs from Replacement Rate Definition:				
	2 ETFE	1	3	3	3							ETFE		
B-1/2DG	1 Glass	1.5	0.20833	0.3125	0.25	0.0625			Glasss			Single Membrane		
	1 ETFE	0	0	0					0.25	Pri Top		3	Pri Top	
	2 Glass	1	0.25	0.25	0.25				0.1	Sec Top		1.5	Sec Top	
	2 ETFE	0.5	0.75	0.375		0.375			0.125	DG Pri Bot		0.75	DG Under Top Glass	
B-DG	1 Glass	2	0.1875	0.375	0.25	0.125			0.05	DG Sec Bot		0.5	DG Under Bot Glass	
	1 ETFE	0	0	0								Pillows		
	2 Glass	0	0	0								6	Pri Top	
	2 ETFE	2	3	6	6							3	Sec Top	
A	1 Glass	2	0.175	0.35	0.25		0.1							
	1 ETFE	0	0	0							= /2 because 50% of area			
	2 Glass	1	0.25	0.25	0.25									
	2 ETFE	1	1.5	1.5			1.5							
	3 Glass	0	0	0						Abbreviated Abbriviations:				
	3 ETFE	2	2.25	4.5	3		1.5			B	BSUTPP			
A-DG	1 Glass	3	0.13333	0.4	0.25		0.1	0.05		B-1/2DG	BSUTPP-1/2DG			
	1 ETFE	0	0	0						B-DG	BSUTPP-DG			
	2 Glass	2	0.175	0.35	0.25		0.1			W	WSUTPP			
	2 ETFE	1	0.5	0.5				0.5		A	ASUTPP			
	3 Glass	1	0.25	0.25	0.25					A-DG	ASUTPP-DG			
	3 ETFE	2	1.5	3			3							
	4 Glass	0	0	0										
	4 ETFE	3	2	6	3		3							

APPENDIX F (continued)

TABLE F.11

REQUIRED INPUTS (6 of 6 = High Cleaning Rate)

I11	Glass	# of 19.5 km^2 layers of glass
AA11	Glass Replacement Rate	
I12	EFTE	# of 19.5 km^2 layers of EFTE
AA12	ETFE Replacement Rate	

Table Below gives values for these four cells:

Cells Addresses		Cell Contents	
I11	AA11	#Lay Gl	Repl G
I12	AA12	#Lay ET	Repl E

MEDIUM REPLACEMENT RATES: Calculations:

Repl has to be (Lay/Life) / Lay as it will be multipled by #Lay again in LCA Spread

Repl Rate = SUM(4 column entries to the right)

Confg	row/mtl	#Lay	Repl	Repl Rate (Lay/Life)	Primary Top	Primary Under	Secondary Top	Secondary Under
B & W	1 Glass	1	1	1	1			
	1 ETFE	0	0	0				
	2 Glass	0	0	0				
	2 ETFE	1	8	8	8			
B-1/2DG	1 Glass	1.5	0.83333	1.25	1	0.25		
	1 ETFE	0	0	0				
	2 Glass	1	1	1	1			
	2 ETFE	0.5	3	1.5		1.5		
B-DG	1 Glass	2	0.75	1.5	1	0.5		
	1 ETFE	0	0	0				
	2 Glass	0	0	0				
	2 ETFE	2	8	16	16			
A	1 Glass	2	0.75	1.5	1		0.5	
	1 ETFE	0	0	0				
	2 Glass	1	1	1	1			
	2 ETFE	1	4	4			4	
	3 Glass	0	0	0				
	3 ETFE	2	6	12	8		4	
A-DG	1 Glass	3	0.58333	1.75	1		0.5	0.25
	1 ETFE	0	0	0				
	2 Glass	2	0.75	1.5	1		0.5	
	2 ETFE	1	2	2				2
	3 Glass	1	1	1	1			
	3 ETFE	2	4	8			8	
	4 Glass	0	0	0				
	4 ETFE	3	5.33333	16	8		8	

HIGH Probability Coefs from Replacement Rate Definition:

Glasss		ETFE Single Membrane	
1	Pri Top	8	Pri Top
0.5	Sec Top	4	Sec Top
0.5	DG Pri Bot	3	DG Under Top Glass
0.25	DG Sec Bot	2	DG Under Bot Glass
		Pillows	
		16	Pri Top
		8	Sec Top

= /2 because 50% of area

Abbreviated Abbriviations:	
B	BSUTPP
B-1/2DG	BSUTPP-1/2DG
B-DG	BSUTPP-DG
W	WSUTPP
A	ASUTPP
A-DG	ASUTPP-DG

APPENDIX G

LCA WORK AND CALCULATIONS

This appendix includes calculations and results of interest left out of the thesis for brevity.

G.1 Additional Results for Chapter 6.

TABLE G.1

CASE 2 STRUCTURE RESULTS WITH GLASS

	St Case	Configuration										
						Cum Tot	Phase Tot	Collector	Water Sys	Tower	Turb/Gen	Other
#	Stats		GWP	Phase	(t CO2 Eq/GWh)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)
			EE	Phase	EROEI	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)
	2	BSUTPP										
1	336	GWh/y	GWP	Constr		1,560,072	1,560,072	1,239,772	11,792	225,989	78,999	3,521
	80	yrs		Oper	62.88	1,690,237	130,165	65,402	9,884	0	15,544	39,335
	137.4	MW cap		Decom	63.03	1,694,248	4,011	0	0	0	3,566	445
	27	# Turbs	EE	Constr		20,967,843	20,967,843	17,544,410	144,122	1,803,066	1,438,271	37,974
	5.09	MW cap/turb		Oper	4.19	23,118,088	2,150,244	1,146,171	51,568	0	297,448	655,058
	0.279	CF		Decom	4.18	23,150,736	32,648	0	0	0	29,461	3,188
	2	BSUTPP-1/2DG										
2	423.8	GWh/y	GWP	Constr		1,724,491	1,724,491	1,390,338	11,792	225,989	92,852	3,521
	80	yrs		Oper	55.31	1,875,067	150,576	81,751	9,884	0	19,606	39,335
	161.5	MW cap		Decom	55.44	1,879,703	4,636	0	0	0	4,191	445
	29	# Turbs	EE	Constr		23,779,054	23,779,054	20,103,402	144,122	1,803,066	1,690,490	37,974
	5.57	MW cap/turb		Oper	4.64	26,293,543	2,514,490	1,432,691	51,568	0	375,173	655,058
	0.300	CF		Decom	4.64	26,331,358	37,815	0	0	0	34,627	3,188
	2	BSUTPP-DG										
3	463.6	GWh/y	GWP	Constr		1,879,673	1,879,673	1,540,904	11,792	225,989	97,468	3,521
	80	yrs		Oper	55.23	2,048,442	168,769	98,103	9,884	0	21,448	39,335
	169.6	MW cap		Decom	55.36	2,053,287	4,844	0	0	0	4,399	445
	30	# Turbs	EE	Constr		26,422,083	26,422,083	22,662,394	144,122	1,803,066	1,774,527	37,974
	5.65	MW cap/turb		Oper	4.56	29,258,372	2,836,289	1,719,257	51,568	0	410,407	655,058
	0.312	CF		Decom	4.56	29,297,908	39,536	0	0	0	36,348	3,188
	2	WSUTPP										
4	327	GWh/y	GWP	Constr		1,626,649	1,626,649	1,239,772	83,801	225,989	73,566	3,521
	80	yrs		Oper	75.17	1,966,514	339,866	65,402	220,001	0	15,128	39,335
	85.3	MW cap		Decom	75.32	1,970,280	3,766	0	0	0	3,321	445
	25	# Turbs	EE	Constr		22,529,299	22,529,299	17,544,410	1,804,477	1,803,066	1,339,373	37,974
	3.41	MW cap/turb		Oper	3.16	29,817,738	7,288,439	1,146,171	5,197,730	0	289,480	655,058
	0.438	CF		Decom	3.16	29,848,361	30,623	0	0	0	27,435	3,188
	2	ASUTPP										
5	330.9	GWh/y	GWP	Constr		1,921,102	1,921,102	1,600,186	11,792	225,989	79,614	3,521
	80	yrs		Oper	78.65	2,082,133	161,031	91,563	14,826	0	15,309	39,335
	69.3	MW cap		Decom	78.81	2,086,172	4,039	0	0	0	3,594	445
	25	# Turbs	EE	Constr		26,896,922	26,896,922	23,462,291	144,122	1,803,066	1,449,470	37,974
	2.77	MW cap/turb		Oper	3.23	29,526,904	2,629,982	1,604,640	77,351	0	292,933	655,058
	0.545	CF		Decom	3.22	29,559,782	32,878	0	0	0	29,690	3,188
	2	ASUTPP-DG										
6	362.7	GWh/y	GWP	Constr		2,237,223	2,237,223	1,921,078	11,792	225,989	74,843	3,521
	80	yrs		Oper	83.15	2,412,803	175,580	104,640	14,826	0	16,780	39,335
	65.1	MW cap		Decom	83.29	2,416,626	3,823	0	0	0	3,378	445
	28	# Turbs	EE	Constr		32,194,666	32,194,666	28,846,898	144,122	1,803,066	1,362,606	37,974
	2.33	MW cap/turb		Oper	2.98	35,081,988	2,887,321	1,833,828	77,351	0	321,084	655,058
	0.636	CF		Decom	2.97	35,113,086	31,099	0	0	0	27,911	3,188

APPENDIX G (continued)

TABLE G.2

CASE 3 STRUCTURE RESULTS WITH GLASS

	St Case	Configuration										
						Cum Tot	Phase Tot	Collector	Water Sys	Tower	Turb/Gen	Other
#	Stats		GWP	Phase	(t CO2 Eq/GWh)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)
			EE	Phase	EROEI	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)
	3	BSUTPP										
1	336	GWh/y	GWP	Constr		1,560,072	1,560,072	1,239,772	11,792	225,989	78,999	3,521
	80	yrs		Oper	62.88	1,690,237	130,165	65,402	9,884	0	15,544	39,335
	137.4	MW cap		Decom	63.03	1,694,248	4,011	0	0	0	3,566	445
	27	# Turbs	EE	Constr		20,967,843	20,967,843	17,544,410	144,122	1,803,066	1,438,271	37,974
	5.09	MW cap/turb		Oper	4.19	23,118,088	2,150,244	1,146,171	51,568	0	297,448	655,058
	0.279	CF		Decom	4.18	23,150,736	32,648	0	0	0	29,461	3,188
	3	BSUTPP-1/2DG										
2	423.8	GWh/y	GWP	Constr		1,798,222	1,798,222	1,464,068	11,792	225,989	92,852	3,521
	80	yrs		Oper	57.48	1,948,798	150,576	81,751	9,884	0	19,606	39,335
	161.5	MW cap		Decom	57.62	1,953,434	4,636	0	0	0	4,191	445
	29	# Turbs	EE	Constr		24,773,895	24,773,895	21,098,244	144,122	1,803,066	1,690,490	37,974
	5.57	MW cap/turb		Oper	4.47	27,288,385	2,514,490	1,432,691	51,568	0	375,173	655,058
	0.300	CF		Decom	4.47	27,326,200	37,815	0	0	0	34,627	3,188
	3	BSUTPP-DG										
3	463.6	GWh/y	GWP	Constr		2,027,135	2,027,135	1,688,365	11,792	225,989	97,468	3,521
	80	yrs		Oper	59.21	2,195,904	168,769	98,103	9,884	0	21,448	39,335
	169.6	MW cap		Decom	59.34	2,200,748	4,844	0	0	0	4,399	445
	30	# Turbs	EE	Constr		28,411,767	28,411,767	24,652,077	144,122	1,803,066	1,774,527	37,974
	5.65	MW cap/turb		Oper	4.27	31,248,056	2,836,289	1,719,257	51,568	0	410,407	655,058
	0.312	CF		Decom	4.27	31,287,592	39,536	0	0	0	36,348	3,188
	3	WSUTPP										
4	327	GWh/y	GWP	Constr		1,626,649	1,626,649	1,239,772	83,801	225,989	73,566	3,521
	80	yrs		Oper	75.17	1,966,514	339,866	65,402	220,001	0	15,128	39,335
	85.3	MW cap		Decom	75.32	1,970,280	3,766	0	0	0	3,321	445
	25	# Turbs	EE	Constr		22,529,299	22,529,299	17,544,410	1,804,477	1,803,066	1,339,373	37,974
	3.41	MW cap/turb		Oper	3.16	29,817,738	7,288,439	1,146,171	5,197,730	0	289,480	655,058
	0.438	CF		Decom	3.16	29,848,361	30,623	0	0	0	27,435	3,188
	3	ASUTPP										
5	330.9	GWh/y	GWP	Constr		2,591,768	2,591,768	2,270,852	11,792	225,989	79,614	3,521
	80	yrs		Oper	103.99	2,752,799	161,031	91,563	14,826	0	15,309	39,335
	69.3	MW cap		Decom	104.14	2,756,838	4,039	0	0	0	3,594	445
	25	# Turbs	EE	Constr		35,946,155	35,946,155	32,511,523	144,122	1,803,066	1,449,470	37,974
	2.77	MW cap/turb		Oper	2.47	38,576,136	2,629,982	1,604,640	77,351	0	292,933	655,058
	0.545	CF		Decom	2.47	38,609,014	32,878	0	0	0	29,690	3,188
	3	ASUTPP-DG										
6	362.7	GWh/y	GWP	Constr		3,035,590	3,035,590	2,719,446	11,792	225,989	74,843	3,521
	80	yrs		Oper	110.67	3,211,170	175,580	104,640	14,826	0	16,780	39,335
	65.1	MW cap		Decom	110.80	3,214,994	3,823	0	0	0	3,378	445
	28	# Turbs	EE	Constr		42,966,959	42,966,959	39,619,191	144,122	1,803,066	1,362,606	37,974
	2.33	MW cap/turb		Oper	2.28	45,854,280	2,887,321	1,833,828	77,351	0	321,084	655,058
	0.636	CF		Decom	2.28	45,885,379	31,099	0	0	0	27,911	3,188

APPENDIX G (continued)

TABLE G.3

BSUTPP-½DG (GLASS) UNCERTAINTIES AND CORRECTED RESULTS

	BSUTPP-1/2DG									
	0.300	Capacity Factor				**GWP**	(t CO2 Eq/GWh)	**EROEI**		
	122,054,400	GJ Produced/Lifetime				Corrected	± Uncertainty	Corrected	± Uncertainty	
	7.60	EROEI				**37.46**	**2.52**	**6.72**	**0.44**	
	32.50	(t CO2 Eq/GWh)				90% Conf Interval		90% Conf Interval		Delta
						34.95	Min	6.31	Min	-0.41
	GWP	EE				39.98	Max	7.18	Max	0.46
	1,101,966	16,062,038							Avg	0.44
	(t CO2 Eq)	(GJ)								
	% GWP	**% EE**	Min	Max	Range	**Mean**	**90% Intv**	**Mean**	**90% Intv**	
Glass	43.03%	51.74%	0%	15%	15%	46.26%	3.23%	55.62%	3.88%	
Steel Collector Struct	19.73%	18.26%	0%	25%	25%	22.19%	2.47%	20.54%	2.28%	
Tower & Foundation	20.51%	11.23%	-15%	15%	30%	20.51%	3.08%	11.23%	1.68%	
Turb/Gen/Electrical Package	10.21%	12.86%	-25%	33%	58%	10.61%	2.96%	13.37%	3.73%	
Other Infrastructure	3.89%	4.31%	-30%	100%	130%	5.25%	2.53%	5.82%	2.80%	
Fiberglass Tanks & Water Syst's	1.06%	0.90%	100%	700%	600%	5.31%	3.18%	4.48%	2.69%	
Footing Concrete	0.51%	0.23%	-50%	100%	150%	0.64%	0.39%	0.29%	0.18%	
Steel Rebar	0.16%	0.15%	-50%	100%	150%	0.20%	0.12%	0.19%	0.11%	
Purify Wash Water (HERO)	0.90%	0.32%	50%	700%	650%	4.29%	2.93%	1.53%	1.05%	
Transport Water	0.003%	0.000%	0%	0%	0%	0.003%	0.00%	0.000%	0.00%	
	Sum	Sum				Sum	RSS	Sum	RSS	
	100.00%	100.00%				115.26%	7.75%	113.08%	7.30%	
						GWP/GWh (t CO2 Eq/GWh)			EE (GJ)	
						37.46	2.52	18,162,329	1,171,934	
						Corrected	90% Intv	Corrected	90% Intv	

TABLE G.4

BSUTPP (ETFE) UNCERTAINTIES AND CORRECTED RESULTS

	BSUTPP: All ETFE									
	0.279	Capacity Factor				**GWP**	(t CO2 Eq/GWh)	**EROEI**		
	96,768,000	GJ Produced/Lifetime				Corrected	± Uncertainty	Corrected	± Uncertainty	
	12.35	EROEI				**26.49**	**3.69**	**11.55**	**1.87**	
	24.93	(t CO2 Eq/GWh)				90% Conf Interval		90% Conf Interval		Delta
						22.80	Min	9.97	Min	-1.57
	GWP	EE				30.18	Max	13.71	Max	2.16
	670,081	7,835,341							Avg	1.87
	(t CO2 Eq)	(GJ)								
	% GWP	**% EE**	Min	Max	Range	**Mean**	**90% Intv**	**Mean**	**90% Intv**	
Glass	13.19%	9.23%	-30%	15%	45%	12.20%	2.97%	8.54%	2.08%	
Steel Collector Struct	29.49%	34.03%	-50%	25%	75%	25.80%	11.06%	29.78%	12.76%	
Tower & Foundation	33.73%	23.01%	-15%	15%	30%	33.73%	5.06%	23.01%	3.45%	
Turb/Gen/Electrical Package	14.11%	22.15%	-25%	33%	58%	14.67%	4.09%	23.04%	6.42%	
Other Infrastructure	6.40%	8.84%	-30%	100%	130%	8.63%	4.16%	11.94%	5.75%	
Fiberglass Tanks & Water Syst's	1.75%	1.84%	100%	700%	600%	8.73%	5.24%	9.18%	5.51%	
Footing Concrete	0.85%	0.48%	-50%	100%	150%	1.06%	0.64%	0.60%	0.36%	
Steel Rebar	0.26%	0.31%	-50%	100%	150%	0.33%	0.20%	0.38%	0.23%	
Purify Wash Water (HERO)	0.23%	0.10%	50%	700%	650%	1.09%	0.75%	0.49%	0.33%	
Transport Water	0.005%	0.000%	0%	0%	0%	0.005%	0.00%	0.000%	0.00%	
	Sum	Sum				Sum	RSS	Sum	RSS	
	100.00%	100.00%				106.25%	14.80%	106.96%	16.85%	
						GWP/GWh (t CO2 Eq/GWh)			EE (GJ)	
						26.49	3.69	8,380,645	1,320,474	
						Corrected	90% Intv	Corrected	90% Intv	

APPENDIX G (continued)

TABLE G.5

BSUTPP-DG (ETFE) UNCERTAINTIES AND CORRECTED RESULTS

	BSUTPP-DG: All ETFE									
	0.312	Capacity Factor				GWP	(t CO2 Eq/GWh)	EROEI		
	133,516,800	GJ Produced/Lifetime				Corrected	± Uncertainty	Corrected	± Uncertainty	
	14.82	EROEI				**22.08**	**2.89**	**14.03**	**2.12**	
	21.11	(t CO2 Eq/GWh)				90% Conf Interval		90% Conf Interval		Delta
						19.20	Min	12.23	Min	-1.80
	GWP	EE				24.97	Max	16.46	Max	2.43
	782,808	9,008,006							Avg	2.12
	(t CO2 Eq)	(GJ)								
	% GWP	% EE	Min	Max	Range	Mean	90% Intv	Mean	90% Intv	
Glass	22.57%	16.06%	-30%	15%	45%	20.88%	5.08%	14.86%	3.61%	
Steel Collector Struct	25.24%	29.60%	-50%	25%	75%	22.09%	9.47%	25.90%	11.10%	
Tower & Foundation	28.87%	20.02%	-15%	15%	30%	28.87%	4.33%	20.02%	3.00%	
Turb/Gen/Electrical Package	15.19%	24.26%	-25%	33%	58%	15.80%	4.41%	25.23%	7.03%	
Other Infrastructure	5.47%	7.69%	-30%	100%	130%	7.39%	3.56%	10.39%	5.00%	
Fiberglass Tanks & Water Syst's	1.49%	1.60%	100%	700%	600%	7.47%	4.48%	7.98%	4.79%	
Footing Concrete	0.72%	0.42%	-50%	100%	150%	0.91%	0.54%	0.52%	0.31%	
Steel Rebar	0.23%	0.27%	-50%	100%	150%	0.28%	0.17%	0.33%	0.20%	
Purify Wash Water (HERO)	0.20%	0.09%	50%	700%	650%	0.94%	0.64%	0.42%	0.29%	
Transport Water	0.004%	0.000%	0%	0%	0%	0.004%	0.00%	0.000%	0.00%	
	Sum	Sum				Sum	RSS	Sum	RSS	
	100.00%	100.00%				104.63%	13.68%	105.65%	15.59%	
						GWP/GWh (t CO2 Eq/GWh)			EE (GJ)	
						22.08	2.89	9,517,020	1,404,015	
						Corrected	90% Intv	Corrected	90% Intv	

TABLE G.6

ASUTPP (ETFE) UNCERTAINTIES AND CORRECTED RESULTS

	ASUTPP: All ETFE									
	0.545	Capacity Factor				GWP	(t CO2 Eq/GWh)	EROEI		
	95,299,200	GJ Produced/Lifetime				Corrected	± Uncertainty	Corrected	± Uncertainty	
	10.54	EROEI				**29.73**	**4.87**	**10.09**	**1.91**	
	28.46	(t CO2 Eq/GWh)				90% Conf Interval		90% Conf Interval		Delta
						24.86	Min	8.53	Min	-1.56
	GWP	EE				34.60	Max	12.35	Max	2.26
	753,443	9,043,465							Avg	1.91
	(t CO2 Eq)	(GJ)								
	% GWP	% EE	Min	Max	Range	Mean	90% Intv	Mean	90% Intv	
Glass	9.53%	6.50%	-30%	15%	45%	8.81%	2.14%	6.01%	1.46%	
Steel Collector Struct	39.34%	44.23%	-50%	25%	75%	34.42%	14.75%	38.70%	16.58%	
Tower & Foundation	29.99%	19.94%	-15%	15%	30%	29.99%	4.50%	19.94%	2.99%	
Turb/Gen/Electrical Package	12.60%	19.27%	-25%	33%	58%	13.10%	3.65%	20.04%	5.59%	
Other Infrastructure	5.69%	7.66%	-30%	100%	130%	7.68%	3.70%	10.35%	4.98%	
Fiberglass Tanks & Water Syst's	1.55%	1.59%	100%	700%	600%	7.76%	4.66%	7.95%	4.77%	
Footing Concrete	0.75%	0.42%	-50%	100%	150%	0.94%	0.56%	0.52%	0.31%	
Steel Rebar	0.24%	0.27%	-50%	100%	150%	0.29%	0.18%	0.33%	0.20%	
Purify Wash Water (HERO)	0.30%	0.13%	50%	700%	650%	1.44%	0.99%	0.63%	0.43%	
Transport Water	0.004%	0.000%	0%	0%	0%	0.004%	0.00%	0.000%	0.00%	
	Sum	Sum				Sum	RSS	Sum	RSS	
	100.00%	100.00%				104.46%	17.10%	104.46%	19.11%	
						GWP/GWh (t CO2 Eq/GWh)			EE (GJ)	
						29.73	4.87	9,447,061	1,728,348	
						Corrected	90% Intv	Corrected	90% Intv	

APPENDIX G (continued)

TABLE G.7

ASUTPP-DG (ETFE) UNCERTAINTIES AND CORRECTED RESULTS

	ASUTPP-DG: ETFE Primary & Secondary										
	0.636	Capacity Factor				GWP	(t CO2 Eq/GWh)		EROEI		
	104,457,600	GJ Produced/Lifetime				Corrected	± Uncertainty		Corrected	± Uncertainty	
	10.42	EROEI				**31.05**	**4.66**		**10.09**	**1.76**	
	30.23	(t CO2 Eq/GWh)				90% Conf Interval			90% Conf Interval		Delta
						26.39	Min		8.63	Min	-1.47
	GWP	**EE**				35.72	Max		12.16	Max	2.06
	877,154	10,024,713								Avg	1.76
	(t CO2 Eq)	(GJ)									
	% GWP	**% EE**	Min	Max	Range	**Mean**	**90% Intv**		**Mean**	**90% Intv**	
Glass	22.66%	16.24%	-30%	15%	45%	20.96%	5.10%		15.02%	3.65%	
Steel Collector Struct	33.79%	39.90%	-50%	25%	75%	29.57%	12.67%		34.91%	14.96%	
Tower & Foundation	25.76%	17.99%	-15%	15%	30%	25.76%	3.86%		17.99%	2.70%	
Turb/Gen/Electrical Package	10.45%	16.80%	-25%	33%	58%	10.86%	3.03%		17.47%	4.87%	
Other Infrastructure	4.89%	6.91%	-30%	100%	130%	6.60%	3.18%		9.33%	4.49%	
Fiberglass Tanks & Water Syst's	1.33%	1.43%	100%	700%	600%	6.67%	4.00%		7.17%	4.30%	
Footing Concrete	0.65%	0.38%	-50%	100%	150%	0.81%	0.49%		0.47%	0.28%	
Steel Rebar	0.20%	0.24%	-50%	100%	150%	0.25%	0.15%		0.30%	0.18%	
Purify Wash Water (HERO)	0.26%	0.12%	50%	700%	650%	1.24%	0.85%		0.57%	0.39%	
Transport Water	0.004%	0.000%	0%	0%	0%	0.004%	0.00%		0.000%	0.00%	
	Sum	Sum				Sum	RSS		Sum	RSS	
	100.00%	100.00%				102.73%	15.42%		103.22%	17.53%	
						GWP/GWh (t CO2 Eq/GWh)				EE (GJ)	
						31.05	4.66		10,347,963	1,756,962	
						Corrected	90% Intv		Corrected	90% Intv	

G.2 Supplemental Calculations for Chapter 7.

The GWP and EROEI for the glass BSUTPP were rescaled to a 30 year life by using only 3/8 of the operation contributions for an 80 year life as shown in Table G.8. Similarly, the GWP and EROEI for 3 SUTPPs were rescaled for a 120 year life in Table G.9, then the GWP and EROEI were computed again (in red on the right side of table) using only the GWP and EE contributions from construction to compare to Niemann's published value of 10 t CO_2 Eq/GWh.

APPENDIX G (continued)

TABLE G.8

BSUTPP OVER 30 YEAR LIFE

St Case	Configuration										
					Cum Tot	Phase Tot	Collector	Water Sys	Tower	Turb/Gen	Other
Stats		GWP	Phase	(t CO2 Eq/GWh)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)
		EE	Phase	EROEI	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)
1	BSUTPP										
336	GWh/y	GWP	Constr		786,971	786,971	466,671	11,792	225,989	78,999	3,521
80	yrs		Oper	34.12	917,136	130,165	65,402	9,884	0	15,544	39,335
137.4	MW cap		Decom	34.27	921,147	4,011	0	0	0	3,566	445
27	# Turbs	EE	Constr		10,736,336	10,736,336	7,312,903	144,122	1,803,066	1,438,271	37,974
5.09	MW cap/turb		Oper	7.51	12,886,580	2,150,244	1,146,171	51,568	0	297,448	655,058
0.279	CF		Decom	7.49	12,919,229	32,648	0	0	0	29,461	3,188
	30 yrs			**GWP**			**EE & EROEI**				
	336	GWh/y		130,165	80 yrs		2,150,244	80 yrs			
	30	**yrs**		0.375			0.375				
	10,080	**GWh**		48,812	30 yrs		806,342	30 yrs			
	3,600	GJ/GWh		786,971	Constr		10,736,336	Constr			
	36,288,000	**GJ**		**835,783**	**30yr tot**		**11,542,678**	**30yr tot**			
				82.91	**t CO_2 Eq/GWh**		**3.14**	**EROEI**			

APPENDIX G (continued)

TABLE G.9

BSUTPP OVER 120 YEAR LIFE

St Case	Configuration										
					Cum Tot	Phase Tot	Collector	Water Sys	Tower	Turb/Gen	Other
Stats		GWP	Phase	(t CO2 Eq/GWh)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)	(t CO2 Eq)
		EE	Phase	EROEI	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)	(GJ)
1	BSUTPP										
336	GWh/y	GWP	Constr		786,971	786,971	466,671	11,792	225,989	78,999	3,521
80	yrs		Oper	34.12	917,136	130,165	65,402	9,884	0	15,544	39,335
137.4	MW cap		Decom	34.27	921,147	4,011	0	0	0	3,566	445
27	# Turbs	EE	Constr		10,736,336	10,736,336	7,312,903	144,122	1,803,066	1,438,271	37,974
5.09	MW cap/turb		Oper	7.51	12,886,580	2,150,244	1,146,171	51,568	0	297,448	655,058
0.279	CF		Decom	7.49	12,919,229	32,648	0	0	0	29,461	3,188
	120 yrs			**GWP**			**EE & EROEI**				
	336	GWh/y		130,165	80 yrs		2,150,244	80 yrs		**786,971**	**GWP Const**
	120	**yrs**		1.500			1.5			**19.52**	**t CO_2 Eq/GWh**
	40,320	**GWh**		195,247	120 yrs		3,225,366	120 yrs			
	3,600	GJ/GWh		786,971	Constr		10,736,336	Constr		**10,736,336**	**EE Const**
	145,152,000	**GJ**		**982,218**	**30yr tot**		**13,961,702**	**30yr tot**		**13.52**	**EROEI**
				24.36	**t CO_2 Eq/GWh**		**10.40**	**EROEI**			
1	BSUTPP-1/2DG										
423.8	GWh/y	GWP	Constr		951,390	951,390	617,237	11,792	225,989	92,852	3,521
80	yrs		Oper	32.50	1,101,966	150,576	81,751	9,884	0	19,606	39,335
161.5	MW cap		Decom	32.64	1,106,602	4,636	0	0	0	4,191	445
29	# Turbs	EE	Constr		13,547,549	13,547,549	9,871,897	144,122	1,803,066	1,690,490	37,974
5.57	MW cap/turb		Oper	7.60	16,062,038	2,514,490	1,432,691	51,568	0	375,173	655,058
0.300	CF		Decom	7.58	16,099,853	37,815	0	0	0	34,627	3,188
	120 yrs			**GWP**			**EE & EROEI**				
	423.8	GWh/y		150,576	80 yrs		2,514,490	80 yrs		**951,390**	**GWP Const**
	120	**yrs**		1.500			1.5			**18.71**	**t CO_2 Eq/GWh**
	50,856	**GWh**		225,864	120 yrs		3,771,735	120 yrs			
	3,600	GJ/GWh		951,390	Constr		13,547,549	Constr		**13,547,549**	**EE Const**
	183,081,600	**GJ**		**1,177,254**	**30yr tot**		**17,319,283**	**30yr tot**		**13.51**	**EROEI**
				23.15	**t CO_2 Eq/GWh**		**10.57**	**EROEI**			
1	BSUTPP-DG: All ETFE										
463.6	GWh/y	GWP	Constr		588,010	588,010	249,241	11,792	225,989	97,468	3,521
80	yrs		Oper	21.11	782,808	194,798	132,533	1,483	0	21,448	39,335
169.6	MW cap		Decom	21.24	787,653	4,844	0	0	0	4,399	445
30	# Turbs	EE	Constr		6,849,632	6,849,632	3,089,942	144,122	1,803,066	1,774,527	37,974
5.65	MW cap/turb		Oper	14.82	9,008,006	2,158,375	1,085,175	7,735	0	410,407	655,058
0.312	CF		Decom	14.76	9,047,542	39,536	0	0	0	36,348	3,188
	120 yrs			**GWP**			**EE & EROEI**				
	463.6	GWh/y		194,798	80 yrs		2,158,375	80 yrs		**588,010**	**GWP Const**
	120	**yrs**		1.500			1.5			**10.57**	**t CO_2 Eq/GWh**
	55,632	**GWh**		292,197	120 yrs		3,237,562	120 yrs			
	3,600	GJ/GWh		588,010	Constr		6,849,632	Constr		**6,849,632**	**EE Const**
	200,275,200	**GJ**		**880,207**	**30yr tot**		**10,087,193**	**30yr tot**		**29.24**	**EROEI**
				15.82	**t CO_2 Eq/GWh**		**19.85**	**EROEI**			

APPENDIX H

ISO STANDARDS

Those desiring more detail are strongly encouraged to read the original document, or the ISO standards listed in Appendix H.

ISO 14001:2004 Environmental management systems -- Requirements with guidance for use
ISO 14001:2004/Cor 1:2009
ISO 14006:2011 Environmental management systems -- Guidelines for incorporating ecodesign
ISO 14004:2004 Environmental management systems -- General guidelines on principles, systems and support techniques
ISO/TS 14033:2012 Environmental management -- Quantitative environmental information -- Guidelines and examples
ISO 14040:2006 Environmental management -- Life cycle assessment -- Principles and framework
ISO 14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines
ISO/TR 14047:2012 Environmental management -- Life cycle assessment -- Illustrative examples on how to apply ISO 14044 to impact assessment situations
ISO/TS 14048:2002 Environmental management -- Life cycle assessment -- Data documentation format
ISO/TR 14049:2012 Environmental management -- Life cycle assessment -- Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis
ISO 14050:2009 Environmental management -- Vocabulary
ISO 14051:2011 Environmental management -- Material flow cost accounting -- General framework
ISO 14064-1:2006 Greenhouse gases -- Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals
ISO 14064-2:2006 Greenhouse gases -- Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements
ISO 14064-3:2006 Greenhouse gases -- Part 3: Specification with guidance for the validation and verification of greenhouse gas assertions
ISO 14065:2007 Greenhouse gases -- Requirements for greenhouse gas validation and verification bodies for use in accreditation or other forms of recognition
ISO 14066:2011 Greenhouse gases -- Competence requirements for greenhouse gas validation teams and verification teams