QUANTITATIVE SUSTAINABILITY MODELING AND ASSESSMENT OF
US TRANSPORTATION ENERGY SYSTEMS, INCLUDING CASE
STUDIES OF ALTERNATE BIOFUEL PRODUCTION
AND ORBITAL TRANSPORTATION SYSTEMS

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Civil and Environmental Engineering).

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ABSTRACT

This research identified and assessed the sustainability risks of existing and emerging US transportation energy systems using quantitative sustainability engineering methodologies including life cycle assessment (LCA) and growth curve modeling. A macro-level analysis of US energy and transportation system dynamics was performed to identify system level sustainability impacts and risks. Two case studies were explored with the aim of identifying where policy and technological solutions could improve sustainability: alternative biofuel production and orbital transportation systems. The findings demonstrated that logistic growth curve modeling fixed condition forecasts can be used to evaluate macro US energy and biofuel production systems. The macro-level assessment suggested the need for significant efforts to ensure the sustainable development of US energy and fuel production through 2040 with appropriate policy support employing such sustainability methodologies. Findings regarding alternate biofuel production demonstrated that biofuels cultivated on marginal lands could noticeably contribute to increased sustainable fuel production in the US. The environmental impact assessment results for biofuel cultivation on abandoned mine land showed the modeled land amelioration and biofuel production process produced significantly less environmental impact than other commonly employed reclamation processes. US biofuel policy would benefit from including such biofuel production on marginal lands in production goals. Furthermore, this research included the first LCA of orbital transportation systems including a proposed space elevator with comparison to existing terrestrial megaprojects. Results showed that the space elevator has the potential to be an environmentally- and cost-effective means for payload delivery to Earth’s orbits, and that reusable rocket launch infrastructure such as with the Falcon Heavy significantly reduced environmental and cost impacts. These quantitative sustainability models, assessment, and case studies revealed them to be a robust and versatile set of tools and that sustainable engineering can shed light on potential paths to a more sustainable future.
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<td>Life Cycle Assessment</td>
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<td>LCI</td>
<td>Life Cycle Inventory</td>
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<tr>
<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
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<tr>
<td>FU</td>
<td>Functional Unit</td>
</tr>
<tr>
<td>EROI</td>
<td>Energy Return on Investment</td>
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<tr>
<td>AML</td>
<td>Abandoned Mine Land</td>
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<tr>
<td>AMD</td>
<td>Acid Mine Drainage</td>
</tr>
<tr>
<td>PFD</td>
<td>Product Flow Diagram</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information Systems</td>
</tr>
<tr>
<td>EIO-LCA</td>
<td>Economic Input-Output Life Cycle Assessment</td>
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<tr>
<td>TRACI</td>
<td>Tool for Reduction &amp; Assessment of Chemical &amp; Environmental Impacts</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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<tr>
<td>eq.</td>
<td>Equivalent</td>
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<tr>
<td>NAICS</td>
<td>North American Industry Classification System</td>
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<tr>
<td>HDI</td>
<td>Human Development Index</td>
</tr>
<tr>
<td>US (USA)</td>
<td>United States (of America)</td>
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<tr>
<td>DOE</td>
<td>US Department of Energy</td>
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<td>USDA</td>
<td>US Department of Agriculture</td>
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<td>NSF</td>
<td>US National Science Foundation</td>
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<td>EIA</td>
<td>US DOE Energy Information Administration</td>
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<td>EPA</td>
<td>US Environmental Protection Agency</td>
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<td>EISA</td>
<td>US Energy Independence and Security Act of 2010</td>
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<td>RFS</td>
<td>US EPA Renewable Fuel Standard</td>
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<td>RFS1</td>
<td>US EPA 2007 Renewable Fuel Standard</td>
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<td>RFS2</td>
<td>US EPA 2010 Renewable Fuel Standard</td>
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<tr>
<td>NASA</td>
<td>US National Aeronautics and Space Administration</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>JAXA</td>
<td>Japan Aerospace Exploration Agency</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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<td>IEA</td>
<td>International Energy Agency</td>
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</table>
FAA  Federal Aviation Administration
UN   United Nations
LEO  Low Earth Orbit
GEO  Geosynchronous Earth Orbit
GTO  Geosynchronous Transfer Orbit
HEO  High Earth Orbit
ISS  International Space Station
SSP  Space Solar Power
LOX  Liquid Oxygen (Compressed)
RP-1 Rocket Grade Kerosene Fuel
EML1 Earth-Moon LaGrange Point 1
EML5 Earth-Moon LaGrange Point 1
CNF (CNT) Carbon Nanofibers (Carbon Nanotubes)
GPS  Global Positioning System
i.e.  id est: “in other words…”
e.g.  exempli gratia: “for example…”
&c  et cetera: “and so forth”
et al.  et alia: “and others”
H2S  Sulfuric Acid
HCl  Hydrochloric Acid
CO2  Carbon Dioxide
g, kg, t  grams, kilograms, metric tons
yr  year
m, km  meters, kilometers
BTU  British Thermal Unit
m3  Cubic Meters
m2  Square Meters,
ha  Hectare
$USD  US Dollar
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As greater than 25% of total US energy consumption and 27% of US greenhouse gas emissions (GHG) results from the transportation sector, considerable effort should be placed on ensuring the sustainability of US transportation fuel and energy systems (DOE EIA 2015). Alternative transportation fuels and systems – such as biofuels, electrically propelled vehicles, and potentially fuels derived from space resources – present an opportunity to improve the sustainable development of the US transportation sector. However, in 2015 biofuels accounted for less than 10% of total US transportation fuel use despite considerable policy efforts to increase production (EPA 2010, EIA 2016). Furthermore, biofuels and space resource utilization, like many other exciting advanced technologies, are often pursued without fully assessing the life-cycle sustainability implications and unintended consequences (Miller, Landis et al. 2007). And while space-derived fuels and resources are on the horizon, the sustainability risks and rewards have not been rigorously evaluated for either the existing space industry (i.e. orbital transportation system) or proposed space resource utilization technologies. To help ensure the long-term sustainability of transportation systems, it is vital to identify, quantify, evaluate, and mitigate the sustainability impacts and risks at the macro-level (e.g. modeling and assessing the increased impact from the scale-up of a suite of sustainable fuels). Once the emerging transportation technologies and systems with the greatest potential to improve overall sustainable development are identified, sustainability engineering case studies can be used to improve and encourage such development.

The purpose of this research was to determine, evaluate, and assess the environmental impacts and sustainability risks of existing and emerging US transportation sector energy systems using quantitative sustainability engineering methodologies such as life cycle assessment (LCA) and logistic growth curve modeling. Three specific research goals were defined with headings Macro Energy System Dynamics Modeling, Biofuel Cultivation on Abandoned Mine Land Case Study, and Orbital Transportation Systems Case Study were completed through five chapters of focused research and findings. An introduction, background, and extensive literature review for each research goal has been provided in this introduction chapter.
The three research goals were:

**Research Goal 1: Macro Energy System Modeling and Assessment**
- Determine, evaluate, and assess the sustainability impacts and risks of the US transportation energy system – via macro analysis of US energy production, consumption, and policy data – and to provide impact and risk mitigation recommendations

**Research Goal 2: Biofuel Cultivation on Abandoned Mine Land Case Study**
- Determine the extent to which producing biofuel using marginal lands in Appalachia – particularly biofuel cultivation on abandoned coal mine refuse piles ameliorated with bauxite residue – can reclaim and repurpose abandoned mine lands while sustainability increasing biofuel production in the US

**Research Goal 3: Orbital Transportation System Case Study**
- Determine, evaluate, and assess the sustainability impacts and risks of established and proposed space elevator orbital transportation system, and lunar mining of rocket propellant

Presented herein are series of published, peer-reviewed journal articles, and manuscripts not yet submitted. Table 1.1 summarizes the organization of this thesis. Multiple articles/manuscripts contribute to each research goal. Some papers are published, and the full references have been provided in Other papers have not yet been published, though still presented within each chapter as a journal article manuscript. The status of the not-yet-published manuscripts are also provided in Table 1.1.

Table 1.1. Overview of Research Goals, Chapters, and Publications. RG = Research Goal.

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<th>Research Goal Title</th>
<th>Covered In</th>
<th>Related Manuscript/Publication</th>
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<td>Tyler M. Harris, Vikas Khanna, Amy E. Landis, “Logistic Growth Curve Modeling of US Biofuel Production” Not Yet Submitted</td>
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<td>RG3</td>
<td>Orbital Transportation Systems Case Study</td>
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<td>Tyler M. Harris, Pragnya L. Eranki, Amy E. Landis, “Life Cycle Assessment of Proposed Space Elevator Designs” Not Yet Submitted</td>
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<td>Chapter 7</td>
<td>Tyler M. Harris, Pragnya L. Eranki, Amy E. Landis, “Environmental and Cost Life Cycle Assessment of Orbital Transportation Systems including Megaproject Infrastructure Comparisons” Not Yet Submitted</td>
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US total energy production in 2015 was within 10% of total US consumption for the first time since 1982, primarily resulting from unprecedented production growth in petroleum and natural gas since 2010 and because of steady increases in renewables since 2000. However, past trends have been short lived and total production could begin to decrease again in the future. For RG1: Macro Energy System Dynamics Analysis, I demonstrated that logistic growth curve modeling could be used to evaluate energy production trends (Chapter 2). I also investigated using logistic modeling to establish quantitative, measurable, practical, sustainable, and scientifically justified future US biofuel policy production targets using five-parameter multi-cycle growth curve modeling, LCA, and economic impact analysis (Chapter 3). Macro level analysis of US energy dynamics can help identify, assess, and mitigate sustainability risks in the US transportation sector’s energy system.

For RG2: Biofuel Production Case Studies, I used LCA and economic impact analysis for evaluating biofuel production techniques utilizing industrial symbiosis. An overwhelming consensus of biofuel LCAs in the early 2000s indicated that first generation biofuels produced
from corn and soybean in the US were not as environmentally benign as originally thought (Landis, Miller et al. 2007, Yang, Bae et al. 2012). Significant research and development of advanced biofuel production (which often utilizes LCA in the development process) has since occurred (Naik, Goud et al. 2010, Davis, Kucharik et al. 2013, Menten, Chèze et al. 2013, Zaimes, Soratana et al. 2015, Harris, Hottle et al. 2016). This increase focus on biofuel sustainability was reflected in the EISA/RFS2 energy policy, which required first generation biofuel production to plateau, advanced biofuel production to rapidly increase, and all biofuel production to achieve greenhouse gas reduction thresholds below a 2005 petroleum fuel baseline (Skone and Gerdes 2008, EPA 2010). First generation US biofuel production has in-fact plateaued as of 2014, however, advanced biofuel production has not increased in any notable amount since that time. Thus, my research identifies the sustainability implications of novel production pathways for biofuels, such as using waste products and marginal lands to cultivate biofuels (Chapters 4 and 5).

Space-derived fuels and resources are soon to be a reality. However, the sustainability risks and rewards have not been investigated. To guide the long-term sustainable development of space transportation systems, it is vital to quantify the sustainability impacts. For RG3: Orbital Transportation Systems Case Studies, I used hybrid LCA to compare established and proposed orbital transportation systems. The systems of study included a space elevator (Chapter 6), traditional ‘rockets’ and other earth-based mega-infrastructure projects such as a seaport or airport (Chapter 7).

1.1. Broader Impacts and Intellectual Merit

Broader Impacts: The ability to provide biofuel policy with estimates of realistic biofuel production capability and the resultant impacts of such policy on economics, jobs, and environmental impacts could transform how policy targets are set. Successful biofuel policy has the potential to improve the well-being of society through reduced environmental impact, improved economic conditions, and greater social acceptance and perception of biofuels. Successful biofuel policy also has the potential to improve national security through reduced dependence on foreign sources of transportation fuel and reduced environmental impact such as climate change. Increased economic competitiveness of the US through increased sustainable renewable energy technological development and production would be another potential benefit,
including the development of a globally competitive STEM workforce through an increase in domestic renewable energy jobs, which span across agricultural and industrial sectors. This research also has the potential to develop increased and ongoing working relationships and partnerships between academia and policy makers. Once the integrated Life-cycle, Logistic, and Economic Modeling approach is developed and validated, this approach could be used to evaluate and set other renewable or energy policy.

Intellectual Merit: This research evaluates the sustainability risks and environmental impact potentials of the US transportation system’s fuel and energy production and consumption. The scope of this research extends from macro system dynamics of US energy production, consumption, and policy (breadth), to sustainability case studies of biofuel production on coal refuse piles and proposed rocket propellant production on the lunar surface (depth). Novel steady-state forecasting and sustainability risk assessment methodologies of US transportation energy systems will be conducted using our innovative growth curve modeling techniques. Growth curve models have never been applied to biofuel production, nor have they been applied to each primary energy source to provide an overall view of the energy production consumption landscape. My development and use of growth curve equations to model energy production and consumption trends presents a novel transformation and application of this flexible and prolific modeling tool.

I present biofuel production LCA case studies that are the first to assess the feasibility and sustainability of cultivating biofuel feedstocks on coal refuse piles through industrial symbiosis. I develop novel solutions for setting and achieving socially, economically, and environmentally sustainable US biofuel policy targets and goals including cultivation on marginal lands. I present novel combinations of growth curve modeling and LCAs to scale environmental impacts with production growth. I also am integrating economic impact analysis with LCA which allows for novel analysis of economic and social impact potentials, such as jobs created and total economic output, alongside traditional environmental impact potentials. And my LCA case studies on orbital transportation systems and sustainability benefits of utilizing space resources are the first of their kind.
1.2. **Research Background and Literature Review**

The following sections are the extended background and literature review related to the research questions and chapters. There may be similarities in the text between the chapter 1 literature review and the introduction sections of the individual chapters. Extra background text created in development of the research chapters had been removed and placed in the lit review section. However, in some cases a sentence within the larger section of text remains the same in both locations. However, this background literature review goes into greater detail in all cases.

1.2.1. **Sustainability Engineering**

To many, sustainability is synonymous with environmental sustainability, therefore it is not surprising to find that, for example, a policy with the aim of sustainability often only applies to the environmental pillar, and either only addresses the economic and social pillars loosely or not at all (Soratana, Harden et al. 2014). The same applies to tools, methods, and research studies. However, there are many policies and tools that focus exclusively on economic or social sustainability issues, though not explicitly referring to sustainability in their respective pillars. To truly achieve sustainability, all three pillars from a life-cycle approach must be considered in policy development, even if the specific objective of the policy, tool or analysis, focuses on only one aspect.

Too often, new products and technologies are developed around a single sustainability assumption, such as “products made from biomass are inherently green because they’re derived from natural materials”; in fact many products made from biomass have been shown to be unsustainable when rigorous sustainability analyses are applied (Miller, Landis et al. 2007, Tabone, Cregg et al. 2010, Zaimes, Vora et al. 2015). In addition, a major criticism of sustainability research is that it is applied to evaluate technologies and products after they are already on the market (Hottle, Bilec et al. 2013, Chong, Chang et al. 2015, Walker, Bosso et al. 2015). Though sustainability life-cycle research can be applied to all three pillars, it primarily focuses on the environmental aspects in the form of life cycle assessment (LCA). Furthermore, policies and LCA that have an environmental sustainability focus often cover only aspects of climate change and greenhouse gas emissions.
Since the industrial revolution humankind has been mastering the ability to manipulate energy (mainly from fossil fuels) to suit its growing demands. Now, international electric grids and fuel transportation networks cross continents and seas to deliver safe, cheap, and dependable energy to the far reaches of the world. There is no physical reason for any problems related to energy access or equity in the modern world. Unfortunately, global energy access and equity for all people has not been achieved. To look only at the overall energy consumption fails to show the vast regional inequality in the supply of a minimum amount of energy.

The average human on earth over the last 30 years has consumed about 2100 watts, while North American inhabitants have maintained about a 10,000-watt average and African inhabitants about 500 watts average (Mandil 2003). While the average North American inhabitant consumes 20 times the power than the average African inhabitant, the African continent holds twice the number of people and has twice the rate of population growth. It is important to consider social aspects of energy sustainability for the entire world population.

A nation’s overall human development has been quantified by the United Nations’ Human Development Index (HDI) with health, education and wealth as the determining factors (Kelley 1991). The HDI value ranges between 0 (low) and 1 (high) is determined by measuring and weighting quantifiable values attributed to a given population: the life expectancy at birth (1/3 weight), the educational adult literacy (2/9 weight), educational enrollment ratio (1/9 weight), and per capita gross domestic product (1/3 weight). A strong logarithmic correlation was found between a nation’s HDI and its per capita power consumption. That is to say nations with greater per capita power consumption are more likely to have significantly higher levels of human development, and no nation with low per capita power consumption is highly developed (i.e. HDI>0.8) (Bala, 1998).

However, the increased energy production needed to develop the entire Earth’s population must be sustainably engineered, produced, and utilized to avoid environmental consequences. As demonstrated by the ozone hole created in the 20th Century, global anthropogenic forcing can and does affect the global climate and atmosphere. However, the ozone depletion problem and its source, aerosols and CFC’s, were quickly identified and a global solution was implemented by the Montréal Protocol in 1987. The scientific consensus of today is that the corrective actions taken by the world over the last twenty years have significantly reduced the depletion of this
protective atmospheric layer. Humankind does have a global footprint, but we have proven that we can tread lightly as well as even cover some of our tracks.

Now the world faces another test in foresight with the continually increasing atmospheric CO$_2$ content. There is no contention in the scientific community on carbon dioxide’s place as an atmospheric greenhouse gas. It is observed in the lab that CO$_2$ molecule absorbs infrared radiation (heat emitted from the earth) and reemit that thermal energy in a random direction (half being sent back to earth). In fact, the base unit of the scale used by scientists to measure the amount of greenhouse warming potential (GWP) a chemical contains is benchmarked by CO$_2$ (i.e. GWP$_{CO2} = 1.0$). Though there are greenhouse gases (GHG) that have far greater GWP than CO$_2$, it is the rapidly increasing load of CO$_2$ deposited in the atmosphere that is the primary driver of the problem.

No one has yet critically evaluated what sustainability means for space applications. To date, there is no literature on the implications of sustainability and space beyond those of near earth activities other than international law having a general ban against space contamination and pollution (Christol 1982). Life cycle assessments (LCAs) of space operations have been very limited, one of which includes an LCA by members of this research group of the space elevator concept (Hayami, Nakamura et al. 2005, Harris 2016)

1.2.1.1. Discussion on Modeling

As this research is computational in nature, it is important to understand and clarify the types, uses, and limitations of computational models. The following summary of modeling approaches was taking from a biosystems engineering microbial food safety textbook (Guevara-Gonzalez and Torres-Pacheco 2014).

Mathematical models are simplified analytical abstractions of real world observations, representing an approximation of behaviors. All mathematical models require quantification and measurement of phenomena. By their nature, abstractions (i.e. models) attempt to simplify the phenomena into only critical details and discard irrelevant ones. Models should have retrodiction (be consistent with observed behavior) and prediction (be consistent with future or perturbed behavior).
There are three main categories of models with a wide variety of names:

- **White box modeling** – referred to as mechanistic or systems analytic models, also referred to as realistic or intrinsic models
  - Describes physical, chemical, or biological behaviors of a system through analytical causal relationships and mechanisms

- **Black box modeling** – referred to as empirical, extrinsic, statistical, or phenomenological models, also referred to descriptive or identification models
  - Describes phenomena mathematically without deeper explanation or mechanistic relevance

- **Gray box modeling** – referred to as hybrid models
  - Describes behaviors and phenomena through a combination of both mechanistic white box and statistical black box modeling methodologies

White box modeling is considered deterministic or explanatory – such models attempt to explain the important elements of the system and how they relate. These models can be conceptual in nature but are represented through mathematical means. They assume the state of a system is quantifiable, and any changes in the system can be modeled mathematically. Parameters of mechanistic models all should have physical, chemical, or biological relevance. Parameters should also demonstrate structural connectivity and describe functional mechanisms of the phenomena.

White box models can be static (i.e. steady state) or dynamic (change in states). Steady state models will produce the same output given the same starting condition or initial state and consider no randomness. That is, the system is fixed, the only change in output comes from changes in the system inputs. Elements of a steady state models which form a set of state-space equations include state variables, differential equations, parameters, and inputs. Dynamic models represent systems that change over time. The same inputs can produce different outputs at different times depending on a changing system condition or state.

Black box models are interested only in the providing a mathematical construct which produces an output that describes the event or effect itself (i.e. descriptive statistics). These models do not attempt to identify, model, or understand the underlying causes. These modeling systems only require a sound mathematical system with any number of useful parameters. Phenomenological models include regression (linear, multiple-linear, and non-linear) and other
statistical methods. It has been suggested that such black box models should not be used for
extrapolative purposes (Rescigno and Thakur 2012).

The logistic growth curve models used in this research are hybrid models. The logistic
equation itself is an empirical or black box model, however, the specific parameterization of the
growth curve model was using white box modeling. LCA is also a hybrid modeling technique.
Black box models are used to transfer vital life cycle inventory data and descriptive statistics
from primary data sources to the system inventory. The primary data itself used in the LCI may
have been collected and calculated by either white box, black box, or hybrid methods. However,
the LCIA impact characterization methodologies employed are often white box in nature.

1.2.2. Life Cycle Assessment (LCA)

This research employs life cycle assessment as the fundamental methodology within several
chapters. Traditional life cycle assessment methodology only quantifies impacts in the
environmental pillar of sustainability. Life cycle assessment (LCA), first employed by Coca Cola
to determine the environmental impacts of switching from glass to plastic bottles, is a
quantitative tool used to help make decisions with environmental implications (Hunt, Franklin et
al. 1996). LCA has been used to evaluate the environmental sustainability of products, processes,
and activities throughout their life cycle to ascertain and interpret the environmental impacts and
tradeoffs. LCAs are often used to either compare products (e.g. compare biofuels to fossil fuels)
or to evaluate a system with the goal of making improvements (e.g. how can we improve the
design and use of a space system).

1.2.2.1. ISO Process-LCA Methodology

LCA is used to evaluate environmental performance of products, services and processes,
provide quantitative and aggregated information to decision makers, select environmental
indicators and measurement techniques, and in some cases to help market products as
environmentally sound. As the name suggests, LCA analyzes environmental impacts throughout
the entire life-cycle of a system including all inputs and output, including from cradle-to-grave.

LCA methodological standards have been developed and vetted that are widely used today.
The International Organization for Standardization (ISO) have published to pertinent reports on
of and LCA: 1) Goal and Scope Definition, 2) Life Cycle Inventory (LCI) Collection and Analysis, 3) Life Cycle Impact Assessment (LCIA), and 4) Interpretation of Results. Each step requires multiple iterations of previous stages, often requiring updates and improvements as more information and analysis is completed.

The ISO 14040 series clearly defines each of the four steps required in LCA (ISO 2006):

1. The goal and scope "states the intended application, the reasons for carrying out the study, the intended audience… [and] should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient… [and] includes …the functional unit; the system boundary; [and] allocation procedures."

2. LCI is the “phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle”.

3. LCIA is the “phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.”

4. Interpretation is the “phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.”

Important features of the goal and scope step are the system boundary and functional unit definition. The system boundary defines what lies within (and without) the scope of the study. The functional unit is a standard quantitative reference that best represents a particular unit of good or service that impacts can be assigned. Careful selection and revision of the boundary and functional unit is vital to the success of the study. The inventory phase consists of collecting quantitative data on flows into and out of each process or step required in producing one unit of product. LCIA is the portion of an LCA which calculates and compares impacts through a common functional unit utilizing established impact categories and methods (e.g. US EPA TRACI). Impact categories often include global warming potential, resource depletion, ecotoxicity, acidification, and eutrophication. The elements to LCA interpretation include a completeness check, i.e., ensuring relevant information and data are available and complete, a sensitivity check, i.e., assess reliability by determining how results are affected by uncertainties in data, assumptions, and methodologies, and scenario analysis.
“Sensitivity analysis is a procedure to determine how changes in data and methodological choices affect the results of the LCIA” (ISO 14044). Scenario analysis is a tool used for evaluating a prospective or proposed system that assigns input parameters to represent sets of system configurations or assumption criteria. “Uncertainty analysis is a procedure to determine how uncertainties in data and assumptions progress in the calculations and how they affect the reliability of the results of the LCIA” (ISO 14044). “Gravity analysis (e.g. Pareto analysis) is a statistical procedure that identifies those data having the greatest contribution to the indicator result. These items may then be investigated with increased priority to ensure that sound decisions are made” (ISO 14044). The consistency check determines whether assumptions, methods, and data are consistent with stated goal and scope. And the data quality check is to “address both quantitative and qualitative aspects of time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, sources of data, and uncertainty. Data from specific sites or representative averages should be used. Treatment of missing data and data gaps should result in a "non-zero" data value that is explained, a "zero" data value if explained, or a calculated value based on the reported values from unit processes employing similar technology” (ISO 14044).

There are common terms that refer to the scope of an LCA. Cradle-to-gate: a life-cycle scope which includes all upstream activities until a designated upstream point in time before end-of-life, often ending at the output “gate” of the product’s factory floor. Cradle-to-use: a life-cycle scope which extends the cradle-to-gate scope to include the use of the product or system but does not include end-of-life assessment. Cradle-to-grave: a life-cycle scope which includes all upstream and downstream activities from materials extraction through end-of-life waste disposal. Cradle-to-cradle: a life-cycle scope similar to cradle-to-grave but attempts to include recycling, reuse, coproduct management, and other ideas related to industrial ecology and circular economies.

1.2.2.2. EIO-LCA and Hybrid LCA

There are two primary methods for performing LCAs: process LCA and EIO-LCA. A third approach takes a hybrid of the two methods. Process LCA is a valuable tool used to quantify the environmental impacts of a product or process for a period of or over its entire life-cycle and is defined by the ISO 14040 series (ISO 2006, ISO 2006). Process LCAs are attributional in nature,
and quantify and assess environmental impacts from each activity, product, or method (i.e. unit and system processes) included in the system boundary. Process-LCAs utilize and tally large datasets including emissions, flows, and resource usage for each process in the system. The more specific the data to the processes modeled, the more precise and accurate the results. However, as such specific and extensive datasets are not available for new and emerging technologies, economic input-output LCA (EIO-LCA) can be used to provide more generalized results.

EIO-LCA was first developed by researchers at Carnegie Mellon University and is available for use at “eiolca.net”. EIO-LCA estimates environmental emissions resulting from economic activities (i.e. purchases) in the major sectors of the economy using input-output tables derived from the bureau of labor statistics (Matthews and Small 2000). EIO-LCA results are often not representative of a specific product since they rely on sector-level averages. A hybrid LCA combines elements of process-LCA and EIO-LCA methods. Hybrid LCAs utilize both methods in various combinations; often a process LCA model is built first and missing process data is supplemented with EIO-LCA data.

LCA continues to develop as a quantitative sustainability engineering tool and industry. There is still development in the specific details as it applies to different subjects, such as biophysical and biogeochemical feedbacks and other land use issues (Versteeg 2016). There are also other quantitative sustainability assessment methodologies in practice and development that make efforts to integrate triple-bottom-line sustainability (society, economy, and environment) such as life cycle sustainability assessment (LCSA), life cycle costing (LCC) consequential and prospective LCA, and integration of various other quantitative methodologies such as material flow analysis (MFA) and green chemistry. However, this research did not focus on such development related to LCA and other quantitative sustainability assessments.

1.2.3. Logistic Growth Curve Modeling

The logistic equation is well known and included in most college level mathematics textbooks. Sigmoid or s-shaped growth curves are found throughout biology, from microbe to human populations, and from plant growth to global human energy production. Yet there has been little work in determining the common factors driving this seemingly universal biological trend, or the underlying reasons for why an empirical population model is effective for energy production modeling. The s-shaped growth curve tends to only represent the trends of renewable
(and nuclear) energy production (as well as all forms of energy consumption), while the derivative of the s-shaped curve tends to represent the bell-shaped (or normal) trends of fossil fuel production. However, there has not yet been a complete academic exploration of its different forms, history, and uses.

Biology and calculus textbooks tend to use the logistic differential equation for population growth similar in form to that given by Equation 1.1 (Raven, Johnson et al. 2007):

\[
\frac{dN}{dt} = rN \left( \frac{K-N}{K} \right)
\]

where \( \frac{dN}{dt} \) is the population growth rate, \( N \) is the number of individuals (population) at time \( t \), \( r \) is the intrinsic growth rate, and \( K \) is the maximum number of individuals the environment can support or carrying capacity.

The rate of population growth at a given time is calculated by multiplying the intrinsic population increase \( (rN) \) with the fraction of remaining capacity \( (K-N/K) \). This helps explain the sigmoid shape of the logistic equation, when the population \( (N) \) is small, the fraction of remaining capacity is near one, and the intrinsic (exponential) population increase dominates. As the population increases, the fraction of remaining capacity decreases, thereby slowing the rate of growth. Finally, as the population nears the remaining capacity, the fraction of remaining capacity approaches zero, thus the growth rate approaches zero, and the population plateaus.

The solution to the standardized logistic differential equation is given by Equation 1.2 (Raven, Johnson et al. 2007):

\[
N(t) = \frac{K}{1+\left(\frac{K-N_0}{N_0}\right)e^{-rt}}
\]

where \( N_0 \) is the number of individuals at \( t=0 \).

It was later shown that the logistic equation has an alternate equivalence that utilizes the hyperbolic tangent function and takes the form of Equation 1.3 (Bradley 2007):

\[
N(t) = \frac{1}{2}K \left( 1 + \tanh \left( \frac{1}{2}r \left( t - \frac{1}{r} \log \left( \frac{K-N_0}{N_0} \right) \right) \right) \right)
\]

with the input for the hyperbolic tangent in radians.
1.2.3.1. Development and Early History of the Logistic Equation

The logistic equation was first developed by Pierre François Verhulst in 1838 when exploring the modeling of population in Paris (Verhulst 1838). His essay explored a population model expanding upon the concepts discussed in 1798 by Thomas Malthus in the well-known *An Essay on the Principle of Population* (Malthus 1798). The concept of exponential growth was first explored by Thomas Malthus through this research. Malthus postulated that human population growth was exponential, and when this growth passed a resource limit, a point of crisis would ensue. However, it wasn’t until 1838 that Pierre Francois Verhulst formalized the exponential growth curve equation, “en progression géométrique,” in *Law of Increasing Population*, i.e. the differential equation (Equation 1.4) (Verhulst 1838):

\[
\frac{dp}{dt} = rp
\]  

(1.4)

where \( p \) is population, \( r \) is the empirically derived growth rate factor, \( dp \) is infinitesimally small change in population over the infinitesimally short period time \( dt \). Though not discussed by Verhulst or Malthus, the solution to this differential equation is the familiar formula for exponential increase (or continuously compounded interest), and is shown in Equation 1.5 (Stewart 1995):

\[
A(t) = A_0 \cdot e^{rt}
\]  

(1.5)

where \( e \) is the mathematical constant, also known as Euler’s number (an irrational number, approx. 2.7828), and also the base to the natural logarithm, \( A(t) \) is the population (or accumulated debt) at time \( t \), \( A_0 = A(0) \) or initial population (or initial debt), and \( r \) is the growth (or interest) rate.

With this exponential or Malthusian model for population growth, the population increases indefinitely, without bounds. It was in an effort to correct Malthus’s suppositions of unbridled population growth until collapse which Verhulst suggested another approach (Verhulst 1838, Schtickzelle 1981). Verhulst argued that Malthus’s fear of population growth until a point of crisis was not justified. Verhulst proposed instead that environmental conditions created a “carrying capacity,” or limit to population growth, which slows growth as it is approached. The rate of growth continues to diminish until a stable population is maintained near its carrying
capacity. Conversely, when a population is far below its carrying capacity, \( c \), population growth would be near exponential. This so called “logistic growth” produces an elongated, symmetrical, \( s \)-shaped (or sigmoid) curve. Verhulst demonstrated the use of this model through tabular logistic fits to population data in France (Verhulst 1838).

Without formally naming it, Verhulst first described logistic equation roughly as the population growth retarded by that same population growth Equation 1.6 (Verhulst 1838):

\[
\frac{dp}{dt} = rp - \varphi(p)
\]

(1.6)

where function \( \varphi(p) \) is Equation 1.7:

\[
\varphi(p) = np^\mu
\]

(1.7)

and arbitrary constant parameters \( \mu \) and \( n \), with Verhulst speculating a value \( \mu =2 \) and \( n \) empirically derived, giving us the original logistic differential equation of population growth Equation 1.8 (Verhulst 1838):

\[
\frac{dp}{dt} = rp - np^2
\]

(1.8)

and with a solution for the original logistic equation calculating population at a given time \( p(t) \) slightly simplified from what was originally published by Verhulst as Equation 1.9 (Verhulst 1838):

\[
p(t) = \frac{p_\infty}{1 + \left(\frac{p_\infty}{p_0}\right)e^{-rt}}
\]

(1.9)

where, \( p_\infty \) is the immediate limit of the population, also known as the carrying capacity (later defined herein as the high plateau), \( p_0 = p(t_0) \) or initial population at start time \( t_0 \) (later defined herein as the low plateau), and Equation 1.10:

\[
p_\infty = \frac{r}{n}
\]

(1.10)

Verhulst described the logistic equation as exponential growth retarded by another function of the population (Equation 1.11):
\[ \frac{dp}{dt} = rp - \phi(p) \]  

where function \( \phi(p) \) is Equation 1.12:

\[ \phi(p) = \frac{r}{c}p^n \]

with \( c \), the carrying capacity. Verhulst speculated a value \( n = 2 \), giving us the differential logistic growth equation (Equation 1.13) (Verhulst 1838):

\[ \frac{dp}{dt} = rp - \frac{r}{c}p^2 = rp \left( 1 - \frac{p}{c} \right) \]

with the solution to the differential equations, providing a time function for growth, given by Equation 1.14:

\[ p(t) = \frac{c}{1 + \left( \frac{c}{p_0} - 1 \right)e^{-rt}} \]

However, it wasn’t until Pearl and Reed derived the same logistic solution for modeling US population did its use become more academically relevant. In 1920, Pearl and Reed independently derived the logistic equation in *On the Rate of Growth of the Population of the United States* (Pearl and Reed 1920). They were unsatisfied by population modeling efforts at the time that were modifications of the Malthusian theory of growth. (An example of modeling efforts of the time included the phenomenological model \( p(t) = a_1 + a_2t + a_3t^2 + a_4\log_{10}t \), which fit the US population data well, however, showed uninhibited future growth). Unaware of Verhulst’s work, they argued that as a population approaches its subsistence level for a limited area (i.e. carrying capacity), an inflection point must occur in the growth, and the rate of increase reduces to zero as the subsistence population is reached.

Since they were unaware of any mechanistic biological growth models, they approached the problem phenomenologically, defining a set of conditions that must be fulfilled by the mathematical expression representing the “growth of a population in an area of fixed limits.” These conditions were based upon the hypothesis that the rate of population increase in a limited area at a given time is proportional to the population at that time, and proportional to the area’s population support potential. The conditions are that the:
1. growth curve is asymptotic to the carrying capacity as time approaches infinity
2. growth curve is asymptotic to zero when time approaches negative infinity
3. growth curve has one point of inflection at some point $t_{\text{Inflection}}$
4. growth curve is concave upwards when $t < t_{\text{Inflection}}$, and concave downwards when $t > t_{\text{Inflection}}$
5. growth curve is only stable (horizontal slope) as time approaches infinity and negative infinity
6. growth curve varies continuously from zero to carrying capacity

Pearl and Reed proposed the following equation to fulfil those requirements (Equation 1.15):

$$p(t) = \frac{\alpha_2}{\alpha_3 - e^{-\alpha_1 t}}$$  \hspace{1cm} (1.15)

where $\alpha_1$, $\alpha_2$, and $\alpha_3$ are empirically derived positive values. Expressed as a differential growth expression with Equation 1.16:

$$\frac{dp}{dt} = \frac{\alpha_1 p(\alpha_2 - \alpha_3 p)}{\alpha_2}$$  \hspace{1cm} (1.16)

and with Equation 1.17 and Equation 1.18:

$$M = t_{\text{Inflection}} = \log_{10}\left(\frac{\alpha_3^{-\alpha_1^{-1}}}{\alpha_2}\right)$$  \hspace{1cm} (1.17)

$$c = \frac{\alpha_2}{\alpha_3}$$  \hspace{1cm} (1.18)

where $t_{\text{Inflection}}$ is the time of inflection when $dy/dt=0$, or when increase is at maximum. Pearl and Reed quickly realized that this was the same logistic equation proposed by Verhulst, slightly reparametrized. They did argue however, that the symmetrical shape or skewness of the curve should be another aspect needing parameterization but provided no model.

Pearl and Reed continued applying and testing this more parameterized logistic equation with biological population growth beyond humans including fruit flies and yeast (Pearl and Reed 1920, Pearl 1926, Pearl 1927). This appears to be the first application of sigmoid growth curve modeling to microbiological growth Yeast culture growth under various conditions was also
modeled using the logistic equation, demonstrating that growth rates and carrying capacity can be altered greatly while the growth trends still follow the logistic trend (Richards 1928).

Multi-cycles of growth were discussed in human populations by Pearl and Reed as well (Pearl and Reed 1920, Pearl 1926, Pearl 1927). They suggested using piecewise functions as a method for modeling separate growth cycles with Equation 1.19:

\[
p(t) = \begin{cases} 
  p_0 + \frac{\alpha_2}{\alpha_3 - e^{-\alpha_1 t}} & \text{if } t \leq t_\Delta \\
  \frac{\alpha_2}{\alpha_3} + \frac{\alpha_2}{\alpha_3} - e^{-\alpha_2 t} & \text{if } t > t_\Delta
\end{cases}
\]

(1.19)

where \( t_\Delta \) is the time at which the significant change in trend occur, where the tangents of the two curves meet. This can also be represented without a piecewise function in Equation 1.20 as such:

\[
p(t) = p_0 + \frac{\alpha_2}{\alpha_3 + e^{-\alpha_1 t + \alpha_2 t^2 + \alpha_3 t^3 + \ldots + \alpha_n t^n}}
\]

(1.20)

The name logistic equation itself was based on it using the base of the natural logarithm and coined by Pearl (Pearl and Reed 1920, Pearl 1926, Pearl 1927).

1.2.3.2. Other Growth Curves

Verhulst was the first to formalize both exponential growth and symmetrical sigmoid (i.e. logistic) growth in formal differential equations, as well as introduction of the then novel concept of carrying capacity. However, Verhulst’s logistic equation was not the first s-shaped curve developed. In 1825, Benjamin Gompertz empirically developed an equation using mortuary tables to calculate the cumulative distribution of human mortality by age (Gompertz 1825). This produced a skewed sigmoid curve, where the initial increase in growth is at a greater rate than the final decrease in growth before plateau. This suggested that though the extremely young and old ages are more likely to produce mortality, the older are slightly more resilient. Like the logistic equation, the Gompertz equation is also a constraint condition put on exponential growth dictated by the natural log of the ratio of population to carrying capacity.

The Gompertz equation has since been used to model biological growth in many applications, and using the same parameters as above is given by Equation 1.21 (Gompertz 1825):
\[
\frac{dp}{dt} = rp \ln\frac{c}{p}
\]

(1.21)

with the solution as Equation 1.22:

\[
p(t) = c \left(\frac{p_0}{c}\right)^{e^{-rt}}
\]

(1.22)

Like the logistic equation, the Gompertz equation is also a constraint condition put on exponential growth dictated by the natural log of the ratio of population to carrying capacity.

The development of probability distribution functions (PDF) or curves was also applicable to logistic growth. Work by countless mathematicians and astronomers including de Moivre, Laplace, Gauss, and Maxwell are credited with the formalization of the “normal distribution”, though the name “Gaussian distribution” still remains synonymous (Jackson 2012). The normal PDF produces a symmetrical bell-shaped curve, or “bell curve”. The integral of the normal (or most any) PDF creates a s-shaped curve known as a cumulative distribution function. Logistic, Gompertz, and other such biological growth curves are simply PDFs, and “logistic regression” is a standard modeling technique used in statistical applications. There is minimal difference between the shapes of normal and logistic curves.

In 1908, an autocatalytic monomolecular modeling process for the growth of an organism’s mass was proposed as Equation 1.23 (Robertson 1908):

\[
\frac{dp}{dt} = Rp(c - p)
\]

(1.23)

with the solution (base 10 log was chosen as the constant modulus) as Equation 1.24:

\[
\log_{10} \frac{p}{c-p} = cR(t - t_{Inflection})
\]

(1.24)

and another form as Equation 1.25:

\[
\log_{10} \frac{p}{c-p} = r(t - t_{Inflection})
\]

(1.25)

or as Equation 1.26:

\[
p(t) = \frac{c}{1+10^{-r(t-t_{Inflection})}}
\]

(1.26)
For rat species, this appeared to adequately model growth, however, human growth demonstrates two cycles of growth. (Apparently, rats and humans both demonstrate three growth cycles, where humans have one in utero, and rats two (Robertson 1908). For multiple growth cycles a type of piecewise modeling system was applied with Equation 1.27:

\[ p(t) = p'(t) + p''(t) \]  \hspace{1cm} (1.27)

In 1949, Jacques Monod proclaimed, “growth of bacterial cultures… is the basic method of microbiology” (Monod 1949). Monod defined the primary population unit to be measured in microbiological growth as cell concentration (cells/volume) which differs from, but can be proportional to, microbe density (mass/volume). Monod also connected the growth rate to the “mean cell division rate” given by Equation 1.28:

\[ r = \frac{\log_2 p_2 - \log_2 p_1}{t_2 - t_1} \]  \hspace{1cm} (1.28)

Monod pointed out for such microbiological growth modeling, there are the assumptions that most all cells are viable, or capable of division, and of a homogeneous (i.e. one species) population. However, this equation does not consider death rates, only cell reproduction rates.

Monod defined 4 growth phases (Monod in fact defined 6 stages, however, Monod’s original stages 2 & 3, and 4 & 5 have been subsequently combined into 4 stages) with differing growth rates, the lag, growth, stationary, and death phases (Monod 1949). The carrying capacity, or high-plateau of the stationary phase is limited by the metabolic activity of the culture in conjunction with the culture medium. Limiting factors can include exhaustion of nutrient, accumulation of toxic metabolic products, and changes in ion equilibrium (e.g. pH). Any limit to the 4 required materials to sustain life – water, electron donor, electron receptor, and carbon source – would factor in the carrying capacity. Thus, growth experiments on such limiting factors to carrying capacity should be certain to only limit one while providing excess of the others. Monod found that the growth yield, k, is proportional to the population and inversely proportional to the amount of limiting nutrient use and are linear and reproducible for given strains in given conditions.

Growth rates in the exponential phase depend on the concentrations of the reactants/metabolites and catalysts/enzymes and is considered constant (or in a stead state of
balance) during the linear portion of the growth phase. However, Monod warned against attempting to model the growth rate on a single limiting slowest/master reaction in the chain, as many stages are reversible, removing the likelihood of a weak link in the chain. Monod suggested distinguishing which limiting factors independently effect the growth rate and carrying capacity. Monod also theorized that under the right conditions, growth could occur linearly indefinitely.

Monod also proposed a model for calculating lag time (Monod 1949). Lag time is the gradual buildup of a steady state system of growth, or time between initial and steady states. This lag time is affected by catalyst/enzyme activation/formation rates and/or reactants/metabolites availability. This phase can be affected by the slowest/master reactions, which can be used to model lag times if properly performed. Enzymatic adaptations required because of a change in environment (e.g. substrate, medium) also affect the lag time. For example, experiments showed no lag time of E. coli growth with glucose, and a lag time of 2.5 hours for E. coli growth in xylose, but with the same ultimate growth rates and carrying capacities. Monod pointed out the implication that enzyme systems in microbial cells are adaptive and go through a sort of natural selection when cultures are placed in a new environment. Furthermore, Monod suggested that other, non-catalyst/reactant factors affecting lag time should be studied.

Monod also explored the concept of multiple growth cycles, likely caused by a change in the medium or substrate composition (Monod 1949). Interestingly, Monod associates these separate growth cycles with changes in the growth rate, as opposed to changes in the carrying capacity. This changing growth rate can come from environmental forcing or exclusive utilization of different nutrients exhausted as different times.

Monod also stressed the importance of correlation between regular turbidity or optical density measurements, and the checks against direct density or concentration measurements (Monod 1949). Much research on the differences between turbidity and actual cell counts has subsequently occurred. Other indirect methods for estimating microbe density include chemical methods for measuring nutrient or oxygen consumption or waste production. It is interesting to note, that Monod refers to the linear trend in growth as the exponential phase, rather than the gradually yet constantly increasing growth curve we defined as exponential growth.

Monod’s equation of growth rate via an environmental microbiology textbook is given by Equation 1.29 and Equation 1.30 (Maier, Pepper et al. 2009):
\[ r = \frac{r_{max} S}{K + S} \]  
(1.29)

\[ \frac{dp}{dt} = \frac{r_{max} S p}{K + S} \]  
(1.30)

where \( K \) is the half-saturation constant (mass/volume) and \( S \) is the substrate concentration.

In 1951, von Bertalanffy in *Theoretical Models in Biology and Psychology*, discussed the comparison between theoretical models and empirical models (Bertalanffy 1951). Theoretical models are those of “laws of nature”, with meaningful parameters and mathematical proofs. These theoretical models represent macro-level behavior, so they are laws explaining the average natural behavior. Where empirical models are mathematically derived from collected data, and parameters do not necessarily have definable meaning. Then in 1957 von Bertalanffy generalized growth equations for the mass of an organism, for simplification this equation will be referred to as the generalized logistic equation (Equation 1.31) (Von Bertalanffy 1957):

\[ \frac{dp}{dt} = r_1 p^m - r_2 p^n = r_1 p^m \left( 1 - \left( \frac{p}{r_1^{1/(n-m)}} \right)^{n-m} \right) \]  
(1.31)

with \( r_2 \) defined as the inverse growth rate in Equation 1.32:

\[ r_2 = \frac{r_1}{e^{n-m}} \]  
(1.32)

There is no simple solution to this equation, however, if \( n=1 \), then it becomes the generalized logistic equation. \( M \) is the dependence of anabolism on body mass which is determined empirically, and metabolic rate are measured as oxygen consumption.

Bertalanffy proposed \( m \) is the dependence of anabolism on body mass which is determined empirically, with metabolic rates measured as oxygen consumption (Von Bertalanffy 1957). Bertalanffy discusses three types of metabolic systems which shape growth curves when \( n = 1 \) because of insensitivity: 1) where respiration is proportional to \( 2/3s \) power of mass given the surface rule \( (m = 2/3) \), as found with most animals, particularly fish; 2) where respiration is proportional to mass \( (m \approx 1) \), and not respiration (the more massive the organism, the faster the growth), found with insect larva, until becoming linear after reaching carrying capacity defined by metamorphosis; and 3) where respiration is intermediately proportion to mass surface rule \( (2/3 < m < 1) \), found with pond snails. Bertalanffy also suggested the inverse growth rate \( (r_2) \) is
determined by the protein turnover rate. Additionally, some mammals have a decrease in growth rate at the time of reproductive maturation, such as rats. And in humans, there is an initial growth spurt before a traditional curve appears.

The generalized logistic equation was developed by Richards in 1959 in *A Flexible Growth Function for Empirical Use* for modeling plant growth (Richards 1959). This was an extension to von Bertalanffy’s work. The Richards equation adds another parameter, skewness, \( z \), to the logistic equation, which under specific conditions produces both the standard logistic equation, as well as the Gompertz equation.

Richards puts into equation von Bertalanffy’s observations into a generic differential growth rate equation given by Equation 1.33 and Equation 1.34 (Richards 1959):

\[
\frac{dp}{dt} = r_1 p^m - r_2 p = r_1 p^m \left(1 - \left(\frac{p}{\frac{r_1}{r_2}}\right)^{1-m}\right)
\]

(1.33)

\[
\frac{dp}{dt} = r p \left(\frac{(c/p)^{1-m} - 1}{1-m}\right)
\]

(1.34)

with \( r_1 \) the anabolism rate, \( r_2 \) the catabolism rate, and \( m \) the slope of the allometric line, and its solution Equation 1.35:

\[
p(t) = \left(\frac{r_1}{r_2}\right)^{\frac{1}{1-m}} \frac{1}{e^{-r_2 t(1-m)}}
\]

(1.35)

with the carrying capacity, \( c \), given by Equation 1.36:

\[
c = \left(\frac{r_1}{r_2}\right)^{\frac{1}{1-m}}
\]

(1.36)

The differential equation becomes Equation 1.37:

\[
\frac{dp}{dt} = r_1 p^m \left(1 - \left(\frac{p}{c}\right)^{1-m}\right)
\]

(1.37)

and when \( m=0 \) it produces a monomolecular/unimolecular curve, \( m=2 \) the autocatalytic/logistic curve, and \( m \) near 1 the Gompertz curve.
Another form of sigmoid curves which have many names (often referred to as the Richards equation, however, it was developed by Bertalanffy years earlier) were developed by Bertalanffy, Richards, and others in the 1930s-60s (Von Bertalanffy 1938, Richards 1959). For simplification this equation will be referred to as the generalized logistic equation. Though there are many variations in parameterization, the generalized logistic equation can be summarized by the following modification function in Equation 1.38:

$$\beta_{\text{Gen}}(p) = p^{m-1} \left(1 - \left(\frac{p}{c}\right)^{n-m}\right)$$  \hspace{1cm} (1.38)

where \(m\) and \(n\) are skewing parameters with \(n-m \neq 0\) (the Richards equation is when \(n = 1\), \(m\) is the slope of the allometric line, \(r\) the anabolism rate, and \(r_2\) the catabolism rate). This is referred to as the generalized logistic equation because when \(m=1\) and \(n=2\), it produces the logistic equation, when \(m=1\) and \(n\) approaches 1 (i.e. the limit of \(\beta_{\text{Gen}}\) as \(n\) approaches 1 and \(m=1\)) it produces the Gompertz equation, and when \(m=1\) and \(n\) approaches negative infinity (i.e. the limit of \(\beta_{\text{Gen}}\) as \(n\) approaches \(-\infty\) and \(m=1\)), it produces the exponential equation. The full differential equation for the generalized logistic model becomes Equation 1.39:

$$\frac{dp}{dt} = rp^m - \frac{r}{c^{n-m}} p^n$$ \hspace{1cm} (1.39)

with \(r_2\) defined as the inverse growth rate in Equation 1.40:

$$r_2 = \frac{r}{c^{n-m}}$$ \hspace{1cm} (1.40)

Fisher and Pry in 1971 also independently derived the logistic equation to model the diffusion of a technology in *A Simple Substitution Model of Technological Change* (Fisher and Pry 1971). This research explored substitution of products over time including various fiber types (e.g. natural fiber vs synthetic fiber), agricultural products (e.g. butter vs margarine), and material types (e.g. metal vs plastic). The logistic equation derived for technological diffusion is given by Equation 1.41, Equation 1.42, and Equation 1.43:

$$p(t) = \frac{1}{2} \left(1 + \tanh r(t - t_0)\right)$$ \hspace{1cm} (1.41)

$$\frac{dp}{dt} = rp^2(1 - p)$$ \hspace{1cm} (1.42)
\[
\frac{p}{1-p} = e^{2r(t-t_o)}
\]  

(1.43)

This application shows sigmoid growth curves fit growth of railroads and highways to smartphone sales and active Pandora listeners.

A review paper in 1990 statistically compared the three-parameter logistic and Gompertz model with the four-parameter generalized logistic/Richards equation for bacterial growth (Zwietering, Jongenburger et al. 1990). The study found the generalized logistic and Gompertz models were statistically better than the logistic model, and in only 2 of 40 cases, the four-parameter generalized logistic was better than the three-parameter Gompertz. It provided meaningful parameterized solutions to the logistic, generalized logistic and Gompertz differential equations (Equation 1.44, Equation 1.45, and Equation 1.46):

\[
p(t) = \frac{m}{1+e^{2+\frac{r}{m}(g-t)}}
\]

(1.44)

\[
p(t) = m \left( 1 + ze^{1+ze^{r}} e^{m(r+\frac{1}{z})(g-t)} \right)^{1-\frac{1}{z}}
\]

(1.45)

\[
p(t) = me^{-e^{1+\frac{r}{m}(g-t)}}
\]

(1.46)

where \( m \) is the asymptotical value, and \( g \) is the lag time. However, the differential equations were not provided in the study.

Various equations for shifting the three-parameter Gompertz equation, with \( m \), asymptote, \( r \), specific growth rate, and \( g \), lag time are given by Equation 1.47, Equation 1.48, and Equation 1.49 (Zwietering, Jongenburger et al. 1990, Zwietering, Cuppers et al. 1994):

\[
m = a \frac{(T-T_{min})(T-T_{max})}{(T-b)(T-c)}
\]

(1.47)

\[
r = \left( b(T-T_{min}) \left( 1 - e^{c(T-T_{max})} \right) \right)^2
\]

(1.48)

\[
g = e^{-2ln(b(T-T_{min})e^{c(T-T_{max})})}
\]

(1.49)

1.2.3.3. Hubbert’s Peak and the Logistic Modeling of Energy Resources

Growth curve modeling using the logistic equation has been regularly used for fossil fuel production modeling (Tao and Li 2007, Höök, Zittel et al. 2010, Nashawi, Malallah et al. 2010, Maggio and Cacciola 2012), as well as for energy consumption (Siemek, Nagy et al. 2003,

\[
\frac{p(t)}{c} - 1 = be^{-rt}
\]

(1.50)

where \(b\) is an empirically derived parameter. Hubbert also suggested that the s-shaped logistic curve would likely be suitable for nuclear and hydroelectric energy production, however, data was not yet available at the time for verification.

In 1962 Hubbert published the linearized form of equation used to model US petroleum production (Equation 1.51) (Hubbert 1962):

\[
\frac{Q_t}{Q_\infty} - 1 = a_h e^{-b_h t}
\]

(1.51)

where \(Q_t\) is the cumulative production at time \(t\), \(Q_\infty\) is the ultimate cumulative production, and \(a_h\) and \(b_h\) are empirically derived parameters. A flaw in Hubbert’s technique was in utilizing proved reserve values for determining the ultimate cumulative production \((Q_\infty)\).

Work by Kenneth Deffeyes since developed a method for determining the ultimate cumulative production \((Q_\infty)\) by linearizing the stable correlation between annual percent of cumulative growth (production over a given period of time \((P_t)\) divided by the cumulative production at that time \((Q_t)\)) versus the cumulative production at that time \((Q_t)\), or \(P_t / Q_t\) v. \(Q_t\) and determine the x-intercept which determines the approximated ultimate cumulative production \((Q_\infty)\) (Deffeyes 2006, Deffeyes 2008). Deffeyes used the following forms of the logistic equation (Equation 1.52, Equation 1.53, and Equation 1.54):
\[ Q_t = \frac{Q_0}{1 + e^{a(t_0-t)}} \]  
\[ P_t = \frac{dQ_t}{dt} = \frac{Q_0ae^{a(t_0-t)}}{(1+e^{a(t_0-t)})^2} \]  
\[ \frac{P_t}{Q_t} = a - \left( \frac{a}{Q_0} \right) Q_t \]

It was not Hubbert’s intent to predict the exact timing of peak US crude oil production but rather demonstrate the general bell-shaped production trend of an exhaustible resource (Deffeyes 2008) US crude oil production did in fact peak in 1970 (EIA 2016) This unintended yet accurate peak forecast sparked great interest in, use of, and debate over energy production modeling using the logistic equation, as well as the establishment of the phrase “Hubbert’s peak”. Until around 2010 logistic modeling of crude oil production had been frequently explored academically, and many researchers published results which modeled global conventional crude oil production peaking in the late 2000s (Campbell and Laherrère 1998, Bakhtiari 2004, Hirsch, Bezdek et al. 2005, Simmons 2006, Hart and Skrebowski 2007, Bardi 2009). Unfortunately, some researchers and many activists misinterpreted these results to mean that there was an impending peak in total global crude oil production, sparking the somewhat frenzied and apocalyptic “peak oil” movement (Bardi 2009).

In the 1990s, researchers began applying logistic modeling to global crude oil production, with many models showing conventional production peaking before 2010. Because of Hubbert’s accidental 1970 US “peak oil” prediction, many interpreted these global production results as a sign of an impending global energy crisis. However, the distinction between conventional and unconventional oil production was overlooked, and total global oil production continued to rise from the rapid scale-up of unconventional production – likely resulting in part from the conventional oil modeling results. Though global conventional crude oil production likely peaked before 2010, the perceived failure of logistic modeling has decreased its popularity (as evidenced by the number of academic citations of Hubbert’s 1956 paper peaking in 2013 at 128 and declining to 75 in 2016 – also producing a statistically significant fit with the logistic equation) and made the method somewhat taboo in academic research.

However, the technological development of hydraulic fracturing (fracking) and unconventional crude oil production (e.g. oil shales and tar sands) were deployed extensively over the last decade to great impact (Sieminski 2014) (in part due to the logistic modeling...
research) total global crude oil production continued to rise (while conventional global oil production began to decline) (Murphy and Hall 2011, Hallock, Wu et al. 2014). Furthermore, total US crude oil production ended its steady decline and began to increase again in 2009, reaching nearly the same amount in 2015 as the first peak in 1970 because of this boom in fracking (EIA 2016). Similarly, US natural gas production was at an all-time high in 2015 (EIA 2016) because of unconventional production techniques. Meanwhile, US renewable energy production has been progressively increasing since the 1960s (though still only 10.9% of total US energy production in 2015) and US nuclear energy production has remained relatively stable since 2000 (9.5% of total production in 2015), leaving the majority of US energy production to come from fossil fuels (79.6% in 2015) (EIA 2016). Total US energy consumption has been relatively stable since 1996, remaining within 4% of its 97.3 quadrillion “quad” BTU (British thermal unit) average (EIA 2016), despite continued US population growth. With the combination of growth in both renewable and fossil fuel energy production and the plateau in consumption, total US energy production in 2015 is within 10% of total US energy consumption for the first time since 1971 (EIA 2016).

Despite this dramatic shift in the US energy production/consumption landscape, only one example of logistic growth curve modeling of US energy production has been found in academic literature since 2009 (Daim, Harell et al. 2012). This lack of utilizing logistic modeling for energy production is likely because of the misunderstood results of global conventional crude oil production logistic modeling and because of arguments regarding logistic modeling’s lack of complexity, particularly that it does not explicitly accounting for reserve estimate and market conditions (Kaufmann and Cleveland 2001, Brandt 2010).

1.2.4. US Energy & Biofuels Policy

US energy policy supports the increased production of biofuels to reduce the dependence on foreign sources of petroleum and reduce the environmental impact of transportation fuels (Congress 2007). The Energy Independence and Security Act of 2007 (EISA) set forth specific annual production requirements and greenhouse gas emission reduction thresholds for various categories of biofuel production out to 2022, and was implemented with the Environmental Protection Agency’s (EPA) Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule in 2010 (RFS2) which established the rules and methods to carry
out the policy (EPA 2010). Since then, biofuel production growth in the US has stalled (EIA 2016), forcing the EPA to alter the production requirements out to 2017 (EPA 2016), and as a result a market condition evolved which discourages the use of higher ethanol blended fuel (e.g. E85) (Verleger 2013). Previous US biofuel policies also set annual production volume targets for US biofuel production, namely the US Energy Policy Act of 2005 and accompanying 2007 US Renewable Fuel Standard (RFS1). The effectiveness of the RFS1 policy was also questionable, as it was immediately replaced by congress the same year of implementation.

The RFS2 classified the total renewable fuel requirement into four individual categories: renewable fuel, advanced biofuel, biomass-based diesel, and cellulosic biofuel. However, all four categories are not mutually exclusive, that is, the advanced biofuel category contains both biomass-based diesel and cellulosic biofuel. Therefore, all four RFS2 individual biofuel categories do not sum to make the total renewable fuel requirement, only the renewable fuel and advanced biofuel categories. The renewable fuel category volumes themselves were not mandated, as the policy expects these first-generation biofuels to plateau and remain indefinitely at 15 billion gallons per year starting in 2015, with advanced biofuels expected to provide all the required biofuel production growth. Only the total renewable fuel, advanced biofuel, biomass-based diesel, and cellulosic biofuel categories of the RFS2 have specific production requirements, thus, the renewable fuel category values can be obtained by subtracting the advanced biofuel requirements from the total renewable fuel requirements. Because there are no historical datasets available for production of biomass-based diesel, cellulosic biofuel or advanced biofuel, and they cannot be easily combined or split to match the EIA reported biofuel production categories, only the RFS2 total renewable fuel requirement can be directly compared with the total US biofuel production data and logistic models.

The US Energy Policy Act of 2005 & RFS1 and EISA & RFS2 US biofuel policy targets (established by volumetric production and emission reduction mandates) were arguably not rooted in science nor sustainability engineering, nor were they highly effective. In neither the first nor second US renewable fuel standards (RFS1 & RFS2) is there any explanation for the methods used for setting the biofuel volumetric production mandates, nor is there any explanation for the GHG reduction requirement values. Investigations revealed an absence of published sources giving any scientific explanation or justification for the policies’ requirements and regulations. Neither the RFS2 biofuel production requirements nor total greenhouse gas
(GHG) emission reduction goals have been met since 2012. And though these policies attempt to reduce the global warming potential (GWP) of biofuel production through GHG-LCA documentation, they have not been informed by comprehensive triple-bottom-line, life-cycle sustainability science.

Though sustainability life-cycle research can be applied to all three of the pillars, similar to policy, engineering research often focuses exclusively on the environmental aspects resulting from LCAs. Similarly, policies that have an environmental sustainability focus often only cover aspects of climate change and greenhouse gas emissions. This lack of inclusion of sustainable life-cycle metrics, approaches and environmental impacts in US biofuel policy means that our biofuels policies risk overlooking important environmental consequences and tradeoffs as the US biofuel industry continues to develop.

However, the application of sustainability and life-cycle concepts to US biofuel policy has been limited (Soratana, Harden et al. 2014). Results showed that of the 1368 state and federal documents found in a US DOE database of biofuel-related policies through 2013 (including Statutes, Codes, House Bills, and Administrative Rules); less than 32% of biofuel policies had some sort of reference to a sustainable approach (i.e. contained references to sustainability, environmental impact, and/or LCA), and less than 5% directly referenced LCA. And in most of those cases, those sustainability policies only focused on life-cycle greenhouse gas emissions, and not the multitude of other important environmental impact categories that one should consider when promoting biofuels (such as eutrophication, land and water use, and air quality).

To determine if biofuels are indeed more environmentally sustainable than petroleum derived transportation fuels, LCA is used to quantify the environmental impacts of both fuel types over their entire life-cycles (from extraction/cultivation, through refining/conversion, to combustion and emissions). These transportation fuel LCAs ascertain the environmental benefits, consequences, and tradeoffs of biofuel production and use. Results from the majority of biofuel LCAs revealed first generation biofuels produced from corn and soybean in the US were not as environmentally benign as originally thought (Landis, Miller et al. 2007, Yang, Bae et al. 2012). Significant research and development of advanced biofuel production (which often utilizes LCA in the development process) has since occurred (Naik, Goud et al. 2010, Davis, Kucharik et al. 2013, Menten, Chèze et al. 2013, Zaimes, Soratana et al. 2015, Harris, Hottle et al. 2016).
These sustainability insights gained from biofuel LCAs were in fact reflected in the RFS2 which set regulations to influence first generation biofuel production growth to halt and plateau while promoting the rapid increase of advanced biofuel production. The RFS2 also required all biofuel production to achieve greenhouse gas reduction thresholds below 2005 petroleum fuel baseline set by an LCA conducted by the National Energy Technology Laboratory (NETL) (Skone and Gerdes 2008, EPA 2010). First generation US biofuel production has in-fact plateaued as seen in the data, however, advanced biofuel production has not increased in any notable amount.

Other recent US biofuel policy research often covers economic effects of policy including US transportation fuel prices and volatility (McPhail and Babcock 2012), agricultural market shifts (Babcock 2012), world transportation fuel and food grain markets (Drabik 2011), and a combination of local and global economic and environmental consequences (primarily greenhouse gas emissions) (Thompson, Whistance et al. 2011, Oladosu 2012). US biofuel policy research has also covered topics including examining the methods of implementation and enforcement (McPhail, Westcott et al. 2011), effects on public and policy maker perception of the policy itself (Mondou, Skogstad et al. 2014), and social impacts (De Gorter and Just 2010). US biofuel policy analysis that focus on environmental aspects most often explore land use change and resulting greenhouse gas emissions (Keeney and Hertel 2009, Oladosu and Kline 2010, Kline, Oladosu et al. 2011, Broch, Hoekman et al. 2013, Mosnier, Havlík et al. 2013). Very few specific US biofuel policy studies were found that covered environmental impacts beyond greenhouse gas emissions, including a master’s thesis completed by one of the PI’s students (Harden 2014) and a review paper that discussed water quality and use concerns (Adusumilli and Leidner 2014). All these studies often provide recommendations for future policy related to the specific effect under analysis, though usually inexplicit and requiring substantial research and effort by the policy makers themselves.

Research on developing more comprehensive best practices for biofuel policy has also been limited, including recommendations of relying more on “good science” (Hecht, Shaw et al. 2009), not having multiple equally important objectives (Jaeger and Egelkraut 2011), combining mandates with economic incentives (Wiesenthal, Leduc et al. 2009, Lapan and Moschini 2012), not combining mandates with economic incentives (de Gorter and Just 2010, Ziolkowska, Meyers et al. 2011), developing an international framework (Lima and Gupta 2013), and creating
carbon taxes, technological investment, and food crisis funds (Sexton, Rajagopal et al. 2009). There is significant need for developing effective policy goals and targets that are environmentally, economically, and socially sustainable.

Published academic research was also found that stated the three most common renewable energy policy support mechanisms were feed in tariffs, tax credits (or certificates), and grants (Falconett and Nagasaka 2010). Feed in tariffs were most effective for developing technologies, renewable energy certificates were most effective for established technologies, and governmental grants (as well as carbon credit mechanisms and markets) were secondary support mechanisms. Another study found that the most successful energy policies encourage a sizable, stable market and provide incentives for technology/fuel to be manufactured locally (Lewis and Wiser 2007). Public knowledge and support of sustainable energy development and policy is also instrumental in its establishment and ultimate success (Cudmore 2011). The knowledge and support for biofuel in the US has been mixed (Sengers, Raven et al. 2010, Selfa, Kulcsar et al. 2011, Wright and Reid 2011, Vogelpohl 2012, Lee, Loveridge et al. 2015) and the growth of biofuel production in the US has stagnated as of 2015 (EIA 2016).

Other US energy policy related to a specific energy type has been nuclear regulation and protection. In the late 1970s, US nuclear energy production was approaching a plateau because of disconcerted nuclear energy policies (Session 2013) and because of increasing public skepticism from the Three Mile Island accident in 1979 (Dohrenwend, Dohrenwend et al. 1981). However, because of a combination of the Power Plant and Industrial Fuel Use Act of 1978 and the second US oil crisis in 1979 the nuclear energy production trend began to steadily increase in 1981 for nearly the next 20 years (through the Chernobyl disaster in 1986) before approaching another plateau in the 2000s. Growth curve modeling offers an elegant and computationally efficient method to estimating volumetric production compared to time-consuming and computationally cumbersome methods involving GIS and uncertain estimates of individual farm-scale production potential.

1.2.4.1. **Biofuels on Marginal Lands and Abandoned Mine Land (AML)**

AML and associated refuse piles, also known as legacy mine land occupy over 600,000 sites and 3 million hectares in the United States (BLM, 2013; Mining, 2002; Worrall et al., 2009). Acid and toxic mine drainage results in severe ecosystem deterioration and plagues local
ecosystems and watersheds (Worrall et al., 2009). Acid mine drainage (AMD) creates acidic runoff in the range of 2.2-3.5 pH that greatly disturbs local ecosystems and hinders regional economic development (Sheoran et al., 2010).

The EPA regulated mine closures and associated refuse piles since the Surface Mining Control and Reclamation Act of 1977 (SMCRA) and Clean Water Act of 1972 (CWA). These policies require mining companies to follow “standards to minimize damage to the environment and to productivity of the soil and to protect the health and safety of the public” (Interior, 2012). Despite those regulatory changes, many “legacy mine land” locations from decades and even centuries past are still in need of reclamation, remediation, or other value creating activity (Ditsele and Awuah-Offei, 2012; Powell, 1988; Wei et al., 2011). Many of these AML sites are abandoned coal mine refuse piles in the eastern mining district located in the 13 Appalachian states.

AML have the potential for economic, recreational and esthetic use, by recognizing the unique potential of the marginal land by using sustainable technologies and measures for transformation (Cao, 2007). The EPA has been successfully experimenting with producing biofuels on AMLs in “sustainable energy parks” (Butler et al., 2013). Studies in Appalachia have shown that apt reclamation practices improved water quality in nearby watersheds over time (Wei et al., 2011). Phytostabilization has been proposed as a low-cost method for reducing the mobility of heavy metals in marginal lands by strategic plant growth (Conesa and Faz, 2011). It has also been proposed that the industrial ecology methodology, including the integrated biotechnological approach, can enhance the restoration of AMLs by using waste streams from other industries to treat the soil (Chen et al., 2013; Deng, 2013; Juwarkar et al., 2010; Mercuri et al., 2005).

AML acidic infertile soils can be neutralized and ameliorated using concepts of industrial symbiosis and byproduct synergies. Bauxite residue is an alkaline, high pH, clay substance generated as a byproduct from bauxite mining and the aluminum processing industry. Bauxite is an aluminum ore used to produce commercial aluminum. Alcoa Inc. demonstrated that high pH value (10-12) and alkalinity of bauxite residue can neutralize the acidity (pH < 3.5) of the coal mine refuse by mixing the two co-products. This process showed promise for allowing resilient plants to germinate and develop successfully at an AML site near Mather, PA (Alcoa, 2010; MSDS, 2007). However, the Alcoa study only used typical reclamation plants (such as Lygeum...
spartum, Piptatherum miliaceum and Helichrysum decumbens), not evaluating the feasibility of biofuel feedstock cultivation on AML (Conesa and Faz, 2011).

The EPA also sponsored several projects under their Superfund Redevelopment Initiative and the RE-Powering America's Land Initiative, which focuses on biofuel and renewable energy on contaminated lands (EPA, 2011). Research has shown that bioenergy crops cultivated on Brownfields do not have significantly different yields than on other agricultural lands (Smith et al., 2013). As of 2015, there were no publications on the subject of biofuel cultivation on AML.

1.2.5. **Sustainability Through Space Resources**

The ability of humans to tap the vast resources beyond the edge of Earth’s atmosphere has been merely an academic issue since the 1960s. For example, a 1976 NASA publication entitled *Space Settlements: A Design Study* provided the design for a 100,000-person space colony in orbit between the Moon and Earth’s surface. This large torus-shaped space colony was to be built mostly from materials mined from the moon. The space colony’s primary mission was to manufacture solar power satellites with materials also from the moon. These solar power satellites were then to orbit the Earth delivering clean power directly to the grid through natural microwave band radiation window in the atmosphere (Johnson and Holbrow 1977). This NASA design study concluded that with a green light from congress, the colony would be up and running in 30 years and this space-based manufacturing colony would produce its first solar power satellite in 2006. The project was ultimately not funded because of a change in presidential administrations.

However, with solar flux in Earth’s orbit approximately 8 times larger than on the Earth’s surface, it only made sense for NASA to draw up designs for such space-based solar energy production. This NASA *Space Settlements* publication presented detailed plans for mass production of 263 solar power satellites (SPS) over 45 years (NASA, 1976). At 5 GW per SPS, this would have been over of 1 TW of additional power by 2050. An advantage to this plan besides the higher solar flux in orbit is the utilization of resources on the lunar surface for the majority of satellite production and space colony manufacturing facility. In effect, this allows for offsetting the environmental impacts of energy production off the surface of Earth, and many social impacts as well, while still gaining the vast economic benefits of a new untapped space resource base.
Another proposed space solar energy and resource utilization plan has the same basic concept but removes several steps in the process. Instead of building an orbiting manufacturing facility to produce solar power satellites to beam power to earth, this proposal suggests manufacturing and placing the solar power plants directly on the lunar surface. Then the energy would be beamed to any location on the Earth via several microwave redirecting satellites. It has been reasonably demonstrated that 1 TW of electric power on Earth can be produced within 15 years of program start and over 20 TW in 45 years (Criswell). Both of these systems transmit the energy through a natural microwave window in the atmosphere that allows for almost no interference with power transmission. The intensity (230 W/m\(^2\)) and wavelengths (10 cm) of microwaves beamed to the Earth engineered properly pose no threat to human or animal health greater than any other microwave source or receiver such as microwaves and cell phones. Rectennas, or microwave receiving antennas that are principally wire mesh, will be built on the surface land or oceans of Earth at sizes 0.2 km\(^2\) or greater and with average electric outputs of 180 W/m\(^2\).

There has been extremely limited direct exploration of the various ways which sustainable development on Earth can be improved and enhanced through space exploration and resource development (Chow 2012). However, as previously discussed there has been research and exploration on how specific aspects Earth sustainability could be addressed by space exploration and development. These include space solar power (SSP), geoengineering, in-space manufacturing, and asteroid mining (Wittenberg, Santarius et al. 1986, Keith 2000, Lior 2001, Ross 2001, Hoffert, Caldeira et al. 2002, Criswell 2003, Yamagiwa 2004, Swan and Swan 2006, Zidanšek, Ambrožič et al. 2011, Sanchez and McInnes 2012, Clinton 2014). To a limited extent, there has been some discussion a long-term view of sustainability and suggests that space colonization will ultimately be a requirement for the sustainability (i.e. survivability) of humankind itself (Baum 2010).

Other discussions somewhat related to sustainability and space revolve around political and economic considerations of the US space program and mission objectives (Ross, Hastings et al. 2004, Broniatowski and Weigel 2008, Broniatowski and Weigel 2008, Vedda 2008). Other concerns regarding sustainability and space involve the growing problem of space debris including the creation of an ISO standard in 2013 (Grego 2010, Jakhu 2011, Brachet 2012, Williamson 2012, Kato, Lazare et al. 2013). Social consideration of sustainability and space explore issues of commercial efforts, property rights, international law and cooperation, and

Quantitative sustainability assessments of products extracted, manufactured, or utilized in space must account for both the impacts of production on earth as well as those in space. Traditionally, sustainability assessments consider metrics in the three pillars of sustainability: environment, economy and society. For activities on earth we will use Life Cycle Assessment (LCA), Techno-economic analysis (TEA), and social LCA to quantify sustainability impacts in each pillar, respectively. For activities that occur in space, we need a unique set of metrics and tools that integrate theoretical and philosophical implications of space exploration and colonization. Biomanufacturing in space environments would have additional complications from those on earth, for instance the common practice of using of heavy stainless-steel equipment and single-use apparatus would be increasingly complex and have significant material burdens. In other ways the space environment could make some practices easier, such as maintaining cleanrooms, operating equipment, and sterilization techniques that use characteristics of space such as the vacuum and reactions at near-zero kelvin temperatures.

1.2.5.1. Space Elevator

According to NASA, the average cost to transport mass from the earth’s surface to its orbit (cost-to-orbit) is $10,000 per pound (NASA, 2018). This high cost results in part from the disposable and complex nature of rocket spacecraft, and the vibration resistant structures required for violent ascension to orbit. Approximately 100 tons of satellite mass was launched into space in 2013 for a commercial profit of $1.9 billion (FAA, 2014). If the cost-to-orbit and structural requirements were significantly reduced, humans would have greater access to the vast and valuable resources of space. A potential solution is the space elevator concept. Estimates on
the cost-to-orbit using a space elevator range from $100 to $1000 per pound (Swan, Raitt et al. 2013).

The space elevator is a large space-tether which connects a large counterbalance in far orbit to the earth’s surface. The orbiting counterbalance provides tension to the carbon nanofiber cable through centripetal force (Swan, Raitt et al. 2013). Vessels then climb and descend the taunt cable tether at will delivering payloads to and from various earth orbits.

The first concept of a space elevator was proposed in 1895 by a Russian scientist, Konstantin Tsiolkovsky, whose idea was to construct a giant Eiffel Tower-like structure to reach and obtain geosynchronous orbit (GEO) (Tsiolkovski 1895). Great for the science fiction writers of the 20\textsuperscript{th} Century, it wasn’t until 1959 when another Russian scientist, Yuri N. Artsutanov, proposed the more technically feasible space-tether concept that applies opposing centripetal and tensile forces to hold the elevator in place, rather than that of a traditional compression structure like the Eiffel Tower (Artsutanov 1960). While remaining fuel for science fiction authors, the scientific community began taking the space elevator concept more seriously as the development of graphene and carbon nanofibers in the 1990s and 2000s made the space-tether elevator concept technically feasible (Raitt 2017).

As of 2016, there were over 2,000 academic publications on the topic “space elevator,” with over 550 published between 2012 and 2016. Seminal papers on the subject include: Jerome Pearson’s “The orbital tower: a spacecraft launcher using the Earth’s rotational energy,” which in 1974 quantitatively demonstrated the feasibility of the concept; Bradley Edwards’ “Design and deployment of a space elevator,” which in 2000 further explored feasibility with emerging technologies such as carbon nanotubes; David Raitt’s “The Space Elevator: Economics and Applications,” which in 2004 budgets the concept at $6.2 billion and Earth-to-GEO-orbit costs at $100/kg; and Cathy and Peter Swan’s “Why we need a space elevator,” which in 2006 argues the merits of constructing a space elevator (Pearson 1975, Edwards 2000, Raitt and Edwards 2004, Swan and Swan 2006). In 2017, there were at least two for-profit companies with active plans to construct a space elevator. LiftPort Group is a privately-owned US company with plans to build a lunar space elevator, breaking ground on the moon in 2020 (lunarelevator.com/liftport-home). Obayashi Corporation is a public Japanese company with plans to complete a terrestrial space elevator by 2050 (obayashi.co.jp). However, there are no life cycle assessments (LCA) for any proposed space elevator technologies.
The space elevator concept, though sophisticated, is based on simple physics, and all indications point to technology having advanced beyond the point required to successfully deploy and operate a space-tether elevator. The general lack of knowledge and understanding regarding the feasibility and benefits of a space elevator (and subsequent lack of funding and interest) appear to be the primary barriers to space elevator implementation than technological issues.

The space elevator idea has existed in various forms since 1895 when Konstantin Tsiolkovsky envisioned an enlarged Eiffel Tower which reached into space, which is what people often think of when first hearing the term “space elevator” (Tsiolkovski 1895). A more accurate description would be a planetary space-tether used for intra-orbital transport, or more simply a space-tether elevator. The basic physics of this concept is simple and intuitive, as almost all humans have spun a string with a weight on the end making the system “defy gravity,” which is the basic concept of the space elevator. In essence, a counterweight in orbit is connected to the equator via a tether or ribbon. Hence the counteracting tension and centripetal forces keep the tether in place, allowing climbers (or lifters) to ascend and descend at will.

Bradley Edwards completed feasibility research on space elevator designs for NASA in 2003. This design uses an old oil rig at the equator as the anchor, a carbon nanofiber weave for the ribbon, and laser beaming for powering the climbers, and was deemed feasible at the 2003 technology level (Edwards and Westling 2003). Unfortunately, the public and investment community still believe the SEC to be science fiction rather than realistic possibility. One cost estimate by Edwards for building a space elevator is $6.2 billion (Raitt and Edwards 2004), which is arguably reasonable when viewed against the $15 billion just cut from Shell’s budget (“Shell resumes Arctic drilling but cuts $15bn from global investment” http://www.bbc.com/news/business-31034870) because of lower gas prices.

The literature on the space elevator, estimating the cost per kilogram to geosynchronous orbit (GEO) and return on investment, assumes that the demand for delivering mass to and from orbit would increase directly with capacity. The 2013 delivery of satellite mass to GEO was 100 tons at an average cost around $25,000/kg to orbit [REFS], while the space elevator, under Dr. Edwards’ plan to reach the near $100/kg to GEO cost, would be capable of delivering 1500 tons per year. Even though the significantly lower cost to orbit would help inspire increased demand, it might be naïve to think that in one-years’ time extremely complex and expensive industries could
increase production by fifteen times to create enough demand for exploiting the increased capacity. It would also be naïve to think that the investors in the space elevator with the intent of making a significant return on investment wouldn’t insist on charging far more than just the cost and mark up the cost for as much profit as possible.

Looking at ribbon failure, because the proposed ribbon design options are inherently designed to be robust (i.e. withstand tension, compression, static and dynamic deformation, and oscillatory forces, as well as micrometeors, space debris, and satellites, electrical induction, radiation, oxidation, lightening, wind, and storms), most likely ribbon failure would come from some other unknown, unconsidered event/force, and because of this, resiliency must be considered, however beyond the current scope of this study. Thus, ribbon failure must be considered no matter how much it is designed against. The worst case scenario would most likely be a complete failure (i.e. detachment) at GEO, as any segment above the break would float into space with the possibility of recovery, while the segment below the break would fall to earth (Aslanov, Ledkov et al. 2013). Though relatively minimal, the damage and possible casualties resulting from the segment returning to earth is great enough to design cataclysmic fail-safes (or safe-fails) into the system. One such failsafe could be if the active monitoring system detects an eminent ribbon failure, the bottom segment of the ribbon would be detached, while emergency rockets on the counterweight activate, causing the entire ribbon to float into space.

Though the current earth-to-orbit technology would certainly not disappear or be unnecessary, as the trip up the elevator will take between 5-10 days, there will be times and situations when a faster trip up or down to/from orbit is required. The industry would be changed comprehensively and permanently.

The current earth-to-orbit infrastructure is presumably somewhat locked in, in that it is a multi-billion-dollar industry built upon advanced science and engineering and employing hundreds of thousands of people worldwide with well-established traditions, associations, and “way of doing things.” As the space elevator technology is almost completely independent from the current earth-to-orbit technologies, a natural rejection and defense against this new technology can be anticipated. Ideally, the current earth-to-orbit industry would recognize the value in a space elevator.

Therefore, the space elevator would likely be a disruptive technology (i.e. a technology which displaces and nearly replaces a previous technology). If the estimates are correct on the cost to
orbit via the space elevator, major economic and technological shifts and changes are bound to occur. The cheaper orbital delivery cost, increased payload capacity, less restrictive cargo requirements, and improved reliability could allow for the satellite and space exploration industries to scale up demand to meet the new supply. If so, this could create huge increases in economic activity, technological and scientific advancement, and continued significant demand for rocket delivery to space. Conversely, another hypothetical scenario could be that after deploying the space elevator, it turns out that the demand for earth-to-orbit transport was not limited by the technological and cost limitations of the current industry and there is only limited use of the space elevator before it falls into disrepair and discarded into space as an economic failure and regarded as an example of technological excess. However, substantial economic feasibility research on the space elevator has been completed and results point to an ultimate demand of several space elevators worth of payload delivery to orbit [ref].

To minimize the possible negative effects or outcomes of the space elevator, first it must be evaluated and designed for optimal functionality in terms of society, culture, environment, and economy. Sociocultural considerations, while discussed elsewhere, are most likely the most complex of them all, from which governments and organizations design, construct and operate the space elevator, and under what mandates, to philosophical, theological, or metaphysical objections to its very existence. Sociocultural studies are in development to further explore this complex issue.

Life cycle assessments and sustainability experiments should be continued throughout the process of development to understand, deal with, and minimize environmental impacts and maximize beneficial environmental functionality.

The immediate utility or goal of the space elevator is to deliver objects to and from orbit in a safe, reliable, smooth, and relatively inexpensive way. Plainly speaking, a space elevator’s primary mission is to make travel to and from orbit a mundane everyday thing.

Secondary duties a space elevator could eventually play a direct role in include research to better understanding climatology and environmental science, or establishing a US Space Corps base and supply chain. Other examples are enhanced satellite and telecommunication capabilities, expansion of the space tourism industry, rapid development of space power, mining and manufacturing industries, and tendency to replicate. Some more concerning examples are enhanced espionage and military capabilities, and possible commercial exploitation.
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CHAPTER TWO
LOGISTIC GROWTH CURVE MODELING OF US ENERGY PRODUCTION AND CONSUMPTION

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Abstract

This research used four-parameter multi-cycle logistic growth curve models on US Energy Information Agency annual data from 1949 to 2015 to produce fixed condition forecasts of US energy production and consumption to 2040. These models and forecasts were used to assess the ability of US energy production sources to meet demand, to anticipate production and technology challenges, and to make general policy recommendations. The logistic fixed condition forecasts indicated the ongoing increases in total US energy production dominated by crude oil and natural gas production will likely peak in 2017 (at 95.0 quadrillion “quad” BTU) then rapidly decrease through 2040 (at 36.2 quad BTU), while total US energy consumption indicated an ongoing plateau (at 98.1 quad BTU). New growth cycles not evident in the 2015 data will certainly occur, mitigating the decline in energy production before 2040. However, without adequate foresight and preemptive action, it is possible that new production growth would not be adequate to reverse the decline given historical growth trends. Therefore, in addition to continued increases in energy efficiency, reductions in use, and implementation of carbon management technologies, direct effort towards the sustainable development of substantial new growth cycles in all energy

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production sources (through adequate investment of resources) should be a priority of the US energy industry, policy makers, and the public alike.

Keywords: Logistic Equation, Logistic Growth Curve Modeling, Growth Cycle, Energy Production and Consumption Modeling, Fixed Condition Forecast

Highlights

- S-shaped growth curves (with plateaus) fit renewable and nuclear energy production.
- Bell-shaped growth curves (with peaks/declines) fit fossil fuel energy production.
- The total US energy production model indicated a 95 quadrillion BTU peak in 2017.
- The total US energy consumption model indicated an ongoing 98 quad BTU plateau.
- To meet projected demand, new growth cycles are needed for US energy production.

Figure 2.1. Growth Curve Graphical Abstract.

2.1. Introduction

Modeling and forecasting of a nation or region’s energy system and dynamics is important for evaluating ongoing trends and possible demands on future resources. Such modeling allows the energy industry, academics, policy makers, and community to anticipate prospective outcomes and consequences (Robinson 1982, Angelis-Dimakis, Biberacher et al. 2011, Gilbert and Sovacool 2016). However, the most commonly used models are complex, based on economic theory, and require dedicated software with heavy reliance on user input assumptions (Loulou,
Goldstein et al. 2004). The reparametrized logistic equation and straightforward methodology provided herein establish a novel technique for empirical modeling of a region’s energy system (Maggio and Cacciola 2012). For validation and as a case study, logistic growth curve modeling was applied to the US energy system landscape. Each primary US energy production source was modeled individually and then aggregated and compared to a total US energy consumption model for a unique perspective on the US energy outlook.

The logistic equation produces a trend commonly referred to as a “growth curve” (Höök, Li et al. 2011). The logistic growth curve has been used to model various forms of biological production (including population (Pearl and Reed 1920, Kingsland 1995), physical measurements (Hubbert 1956, Bardi and Lavacchi 2009), and technological diffusion (Fisher and Pry 1971, Grübler 1996)) since it was originally established by Pierre Verhulst in 1838 (Verhulst 1838). The logistic equation was first used to model US crude oil production and other US energy sources by M. King Hubbert in 1956 (Hubbert 1956). This research lead to the definitive demonstration of the distinctive bell-shaped production trend of crude oil and fossil fuel production over time, i.e. increase, peak, and decline in production. However, with the rapid deployment of hydraulic fracturing (i.e. fracking) and increase in unconventional crude oil production (e.g. oil shales and tar sands) since the early 2000s, new unconventional fossil fuel production growth curves had put US crude oil and natural gas production at an all-time high in 2015 (EIA 2016).

Meanwhile, US renewable energy production has been progressively increasing and US nuclear energy production has remained relatively stable (9.5% of total production in 2015), leaving the majority of US energy production to come from fossil fuels (79.6% in 2015) (EIA 2016). On the other hand, total US energy consumption has been relatively stable remaining within 4% of its 97.3 quadrillion British thermal unit (quad BTU) average (EIA 2016) despite continued US population growth.

Despite this dramatic shift in the US energy production/consumption landscape, only one example of logistic growth curve modeling of US energy production has been found in academic literature since 2009 (Daim, Harell et al. 2012). More complex tools often used for energy production are economic optimization models, including top-down general equilibrium models that are based on macroeconomic factors, or bottom-up technology explicit partial equilibrium or agent simulation models which focus on energy sector details (Loulou, Goldstein et al. 2004).
These models (e.g., IEA’s MARKAL and DOE’s NEMS) are based on economic theory and require dedicated software, large calibration datasets, and a multitude of equations, variables, inputs, and assumptions. Further discussion and analysis of other energy production models can be found in the Supplementary Materials.

The novel and straightforward logistic growth curve modeling technique developed in this study only requires historical data and spreadsheet software with solver capabilities; it can be used to produce fixed condition forecasts for a wide variety of biological phenomena including energy production and consumption. Though historically used on individual energy production and consumption sources, the logistic equation has not yet been used to produce a comprehensive aggregate model for analysis of a nation’s energy landscape. This is the first study to use this new four-parameter multi-cycle logistic growth curve modeling methodology to assess the ability of US energy production sources to meet estimated demand, to anticipate environmental and technological challenges, and to make policy recommendations.

2.1.1. Logistic Growth Curve Modeling

The logistic equation was first used to model population in France as a response to concerns regarding uninhibited growth of populations (Malthus 1798, Verhulst 1838, Verhulst 1846). Then about 80 years later the logistic equation was empirically derived using US population data (Pearl and Reed 1920), and was subsequently adapted to fit multiple cycles of logistic growth (Pearl 1926, Pearl 1927). Finally, the logistic equation was proposed as a suitable modeling tool for both fossil fuel and non-fossil fuel national energy production, forecasting the original 1970 peak in US crude oil production (Hubbert 1956, Hubbert 1962, Hubbert 1982). The logistic equation has since been used to model coal and natural gas production (Tao and Li 2007, Höök and Aleklett 2009, Höök and Aleklett 2010, Höök, Zittel et al. 2010, Maggio and Cacciola 2012) in addition to crude oil (Tao and Li 2007) for various regions around the world. The logistic equation has also been established as a valid model for rates of technological change (Fisher and Pry 1971), and to illustrate the connection between technological progress, energy production, and logistic trends (Marchetti and Nakicenovic 1979, Grübler, Nakićenović et al. 1999). Logistic modeling of non-fossil fuel energy production has included modeling of US nuclear energy production (Meyer 1994, Rao and Kishore 2010, Höök, Li et al. 2011), wind energy projections in India and China (Mabel and Fernandez 2008, Changliang and Zhanfeng 2009), hydroelectric
energy production in China (Yiming and Xifan 2010), and US renewable energy production (Daim, Harell et al. 2012). It has also been shown to adequately model energy demand and consumption (Mohamed and Bodger 2003, Siemek, Nagy et al. 2003, Mohamed and Bodger 2005, Forouzanfar, Doustmohammadi et al. 2010, Sugan thi and Samuel 2012). Most recently, there has been research on s-shaped logistic model fits to European hydro and solar, and global nuclear energy production (Hansen, Narbel et al. 2017).

The \textit{s-shaped logistic equation} produces a sigmoid shape similar to an elongated “S” commonly seen in biology for population modeling (Kingsland 1995) and can be used as a cumulative distribution function (CDF). The s-shaped curve starts from a low production plateau (zero in cases where the production source was completely new, and greater than zero if the production source had undergone a previous growth cycle), undergoes a near exponential increase until flattening out into near linear growth through the cycle’s midpoint, then follows a near exponential decrease in growth until reaching a high production plateau (known as the carrying capacity when modeling population). Renewable energy sources tend to produce an s-shaped production trend as the source of energy is not depleted once utilized, but rather is renewed on a periodic basis.

The historical cumulative production trend of a depleting finite resource tends to follow an s-shaped trend over time. The time derivative of the cumulative production curve of a finite resource gives the production rate of that resource, thereby producing a bell-shaped trend. This bell-shaped logistic equation provides an appropriate model for the production rate of a finite resource. Though nuclear energy production is not considered renewable (as it relies on a finite fuel source), the abundance of nuclear fuel has not yet limited the amount of nuclear energy produced annually. Therefore, nuclear energy production trend evolves similar to renewable energy sources and is modeled here with the s-shaped logistic equation.

Limitations to logistic modeling include its inability to anticipate new cycles of growth (e.g. US production of crude oil showed minimal indications of a new growth cycle prior to 2009 (EIA 2016)), and the unlikeliness of predicting the exact timing and magnitudes of curve features such as peaks and plateaus. We acknowledge that no modeling technique can confidently predict future events and emphasize this model is not an oracle of knowledge. Another complication can be the many options for parameterization and the various fitting and evaluation techniques of the logistic equation (Hubbert 1956). This study developed a straightforward parameterization and
fitting methodology to reduce such complications. Criticisms of using the logistic equation for modeling energy systems include concerns of long-range projections (Smil 2000) and the descriptive nature of logistic modeling not explicitly including economic or market input parameters (Tsoularis and Wallace 2002, Brandt 2010). The logistic modeling results presented herein are defined as fixed condition forecasts, or forecasts based on an assumption that the conditions (or state) of the system remains unchanged throughout the forecast period. These fixed condition forecasts are not intended to predict the future, as the state of this dynamic system is constantly in flux. Rather, they reveal the trends of the current state for greater insight into the energy landscape and augment or evaluate other modeling techniques.

2.1.2. Environmental Implications

Fossil fuel production in the US is at an all-time high (EIA 2016) despite increasing concerns over greenhouse gas emissions and global warming (Chu and Majumdar 2012), as well as other environmental impacts such as eutrophication, water and land use, and ecotoxicity (Hertwich, Gibon et al. 2015) from energy production and consumption. Furthermore, the unconventional fossil fuel extraction techniques now frequently employed cause greater environmental impact while producing lower energy return on investment than traditional extraction techniques (Murphy 2014, Nduagu and Gates 2015). Additionally, US renewable energy development has yet to significantly reduce the need for fossil fuel use despite recent increases. However, renewable energy sources have their own environmental impacts of concern (Hill, Nelson et al. 2006, Turconi, Boldrin et al. 2013).

The logistic growth curve modeling methodology explored herein could be applied to forecast environmental impacts and tradeoffs from different energy production scenarios and technological developments. Logistic modeling could also be used to create impact category values which change over time because of cleaner or more efficient technology development. It can also be used to create estimated atmospheric carbon reduction models from policy change or negative carbon emission deployment scenarios. In a related study we used logistic growth curve modeling to create fixed condition forecasts of atmospheric carbon reduction from Federal policy mandates including the 2010 EPA Renewable Fuel Standard (RFS2) (Harris 2016). Our study found that the RFS2 biofuel volumetric production and emission reduction requirements would
have been better served by using the logistic growth curve modeling methodology described herein for establishing policy goals and targets.

There has been no published research that combines logistic growth curve modeling of individual fossil fuel, nuclear, and renewable energy production data, along with total energy consumption modeling, to explore the broad perspective of a nation’s energy landscape. With this original logistic growth curve modeling methodology, the logistic equation has been applied as a case study to model all primary energy sources in the US. To demonstrate the utility of this methodology and perform preliminary validation, logistic fixed condition forecasts of historical data were developed from each primary US energy production source (as defined and provided by the US Energy Information Administration), as well as from US total energy consumption. An aggregated total energy production and consumption fixed condition forecast to 2040 was then evaluated for a novel examination of the future US energy landscape. The logistic fixed condition forecasts and methodology can be used by anyone interested in another tool to help guide future energy system actions and decisions.

2.2. Material and Methods

Each primary US energy production source reported by the US DOE EIA – Coal, Natural Gas (Dry), Crude Oil, Natural Gas Plant Liquids, Nuclear Electric Power, Hydroelectric Power, Geothermal Energy, Solar/PV Energy, Wind Energy, and Biomass Energy (EIA 2016) – was modeled individually using a four-parameter logistic equation with multi-cycle growth, then aggregated to produce a US total energy production model. The US total energy consumption data from the EIA was also modeled with multi-cycle logistic modeling and compared to the US total energy production aggregate model. Renewable and nuclear energy production, as well as energy consumption, were modeled with the s-shaped logistic curve. Fossil fuel energy production was modeled with the bell-shaped logistic curve. Multi-cycle logistic growth modeling was required for all energy sources other than hydroelectric.

2.2.1. US Energy Production and Consumption Data

US energy production and consumption data from 1949 to 2015 was exclusively obtained from the EIA Annual Energy Review (AER) (EIA 2016, EIA 2016). All data and models used the energy unit of quadrillion ($10^{15}$, “quad”) BTU (equivalent to 1.055 exajoules) per year. The
EIA primary energy production categories Coal, Natural Gas (Dry), Crude Oil, and Natural Gas Plant Liquids were modeled using the bell-shaped logistic equation, while the Nuclear Electric Power, Hydroelectric Power, Geothermal Energy, Solar/PV Energy, Wind Energy, and Biomass Energy production, as well as the EIA Total Primary Energy Consumption category, were modeled using the s-shaped logistic equation. As discussed in the introduction, nuclear energy production was modeled with the s-shaped logistic equation as its production data follows an s-shaped trend because the number of nuclear energy production sites limits the production rate, rather than the rate of nuclear fuel production. The EIA energy production sub-category of Biofuels Energy, which is included in the Biomass Energy data, was also modeled independently using the s-shaped logistic equation for reference and discussion only, but was not used for the aggregate production model. For simplicity and consistency, the Natural Gas (Dry), Natural Gas Plant Liquids, Nuclear Electric Power, Hydroelectric Power, and Solar/PV Energy production categories were referred to henceforth as Dry Natural Gas, Natural Gas Liquids, Nuclear Energy, Hydroelectric Energy, and Solar Energy production respectively.

All the bell-shaped fossil fuel logistic models were summed to produce a US total fossil fuel aggregate model and the s-shaped hydroelectric, geothermal, solar, wind, and biomass energy logistic models were summed to produce a US total renewable energy aggregate model. These two aggregate models were then added to the s-shaped nuclear energy logistic model to produce a total US energy production aggregate model. This US total energy production model was then compared to the s-shaped US total energy consumption logistic model for analysis.

The fixed condition forecasts were reported to 2040 for a sufficient perspective of the US energy landscape. 2040 was also the forecast range of the 2016 NEMS model. Logistic fixed condition forecasts could be projected forward indefinitely, however, the further forward the forecasts, the greater the uncertainty (Smil 2000). By their nature, these fixed condition forecasts do not account for any subsequent changes in the state of the system, but only represent the system as if it were coasting forward. That is to say, this forecasting to 2040 does not imply future production will precisely follow these fixed condition forecast trends for the entire period. Rather, reporting these models for this period was intended only as a general trend analysis to allow the energy industry, policy makers, and general public to anticipate likely paths of current trends and make appropriate adjustments in their decisions and actions.
2.2.2. Logistic Growth Curve

The logistic equation has two primary forms when it comes to production modeling, an s-shaped (sigmoid) curve and a bell-shaped curve. The base form of the logistic equation (producing the s-shaped curve) is given in two equivalent formulas (Bradley 2007) as Equation 2.1:

\[
y = \frac{1}{1+e^{-x}} = \frac{1}{2} \left( 1 + \text{tanh} \left( \frac{x}{2} \right) \right) \quad (2.1)
\]

where \( x \) and \( y \) are standard independent and dependent variables, \( e \) is the mathematical constant known as Euler’s number (approximately \( 2.71828 \)) and \( \text{tanh} \) is the hyperbolic tangent function. This logistic equation was then modified into a more flexible four-parameter logistic equation and included multi-cycle growth modeling as needed for this research.

2.2.2.1. S-Shaped Logistic Equation

The s-shaped four-parameter logistic equation (adapted from Minitab) used herein is given as Equation 2.2:

\[
P(t) = H + \frac{L-H}{1+e^{\left(\frac{t-M}{W}\right)}} \quad (2.2)
\]

where \( P \) is the annual production rate, \( L \) is the low-plateau (or starting annual production rate), and \( H \) is the high-plateau (or ending annual production rate) all in quad BTU per year; \( t \) is the production year, \( M \) is the midpoint of growth, and \( W \) is the width (or inverse growth factor) of the curve all in years.

As there is no traditional growth rate parameter for this four-parameter s-shaped logistic equation, the equation obtained by taking the time derivative of the four-parameter s-shaped logistic equation at the midpoint (\( M \)) was used to describe the growth of the s-shaped logistic trend, given as Equation 2.3:

\[
G_{@M} = \frac{(H-L)}{4W} \quad (2.3)
\]

where \( G_{@M} \) is the instantaneous increase in production at the midpoint (\( M \)), or growth at midpoint, in quad BTU, and \( H, L, \) and \( W \) are the same parameters as above.
2.2.2.2. Bell-Shaped Logistic Equation

The four-parameter bell-shaped logistic equation used herein (obtained by taking the time derivative of Equation 2.2) is given as Equation 2.4:

\[ P(t) = \frac{(H_Q - L_Q)e^{\frac{t-M}{W}}}{W(1+e^{\frac{t-M}{W}})^2} \]  

(2.4)

where \( P \) is the annual production rate in quad BTU per year; \( L_Q \) is the low-plateau of cumulative production and \( H_Q \) is the high-plateau of cumulative production both in quad BTU; \( t \) is the production year, \( M \) is the midpoint of growth, and \( W \) is the width factor all in years; and \( e \) is Euler’s number. Note that the low- and high-plateau parameters for the bell-shaped logistic equation (\( L_Q \) and \( H_Q \) respectively) are not rates, but rather cumulative production values as denoted by the \( Q \) subscripts, and the \( L_Q \) is a set at zero because only the difference between \( L_Q \) and \( H_Q \) is relevant. Because the s-shaped logistic curve represents cumulative production for finite resources, when the time derivative of the s-shaped equation is taken, the width factor (in units of time) appears in the denominator resulting in \( P \) having the correct unit of production rate.

The equation obtained by the time derivative of Equation 2.4 evaluated at the root of its second time derivative (i.e. \( M' = W \ln(2 - \sqrt{3}) + M \)) was used to describe the growth of the s-shaped logistic trend, given as Equation 2.5:

\[ G_{@M'} = \frac{\left(L_Q - H_Q\right)\left(e^{\left(M' - M\right)/W} - 1\right)e^{\left(M' - M\right)/W}}{W^2\left(1+e^{\left(M' - M\right)/W}\right)^2} \]  

(2.5)

where \( G_{@M'} \) is the instantaneous increase in production at the time of greatest increase in growth, or growth at prime, in quad BTU per year, and \( H_Q \), \( L_Q \), \( M \), and \( W \) are the same parameters as above.

2.2.3. Multi-Cycle Logistic Growth Modeling

Multiple growth cycles occur because of the dynamic nature of energy systems, resulting from changes in the system conditions including demand, technology, policy, and resource
availability. Growth cycles can occur in discrete series after the previous cycles of growth have completed, observed more often in s-shaped production trends (Figure 2.1), or in overlapping series at any point during the previous cycles of growth, observed more often in bell-shaped production trends (Figure 2.2). For discrete multi-cycle growth, a piecewise logistic function was used, with the previous cycle’s high-plateau production rate \( H \) set as the new cycle’s low-plateau production rate \( L \). For overlapping multi-cycle growth, the sum (of the multiple independent, overlapping logistic models) was used (similar to Maggio et al. 2009 for world crude oil and natural gas production modeling). Multiple cycles of growth often occur because of technological development leading to new sources of energy, new techniques to utilize sources of energy, or both.

Figure 2.2. Discrete S-Shaped Multi-Cycle Growth Example. Parameters were set to illustrate distinct cycles with different width parameters.
The more logistic growth cycles added to a bell-shaped energy production model, the more precise a fit the model becomes to the dataset, however, this increase in precision comes with a loss of the model’s usefulness in terms of analysis of ongoing growth cycles. That is, the many-cycle model becomes a tool only for discovering historical, more regional cycles and provides little insight into possible outcomes of ongoing trends because it finds the smallest cycles to produce the closest fit, and thus tends to show the ongoing cycle’s midpoint ($M$) immediately following the last data point. Therefore, the least number of cycles required to produce a sufficient fit was used for fossil fuel production modeling. Discussion of parameter fitting, descriptive statistics, and validation can be found in Appendix A.
2.3. Results and Discussion

The logistic growth curve modeling methodology developed through this research was found to be a valid and useful tool in the toolbox for assessing and forecasting complex energy production and consumption systems. Using this innovative and straightforward multi-cycle four-parameter logistic equation and fixed condition forecasting methodology a thorough case study and analysis of the US energy landscape was completed. Fixed condition forecasts of US energy production and consumption data to 2015 and validated with 2016-17 data, were constructed, aggregated, and evaluated to 2040. The descriptive statistics for all models were R-squared >0.93 (aside from hydroelectric, see 3.2) and P-value <0.00001. The percent error (100% * |actual value – forecasted value|/actual value) for validation years 2016 and 2017 ranged from 0.4% to 31% error, with the 2017 aggregate total US energy production fixed condition forecast at 7.8% error and total US energy consumption fixed condition forecast at 0.35% error. Please refer to Appendix A for more details on the modeling parameters, descriptive statistics, and validation.

Data showed US crude oil, natural gas, and wind and solar energy production increasing between 2010 and 2015, pushing total US energy production to within 10% of total energy consumption. The logistic growth curve modeling fixed condition forecasts indicate the trend of increased production from ongoing growth cycles may be short lived and substantial effort towards increased and improved production from all energy sources is likely needed. New growth cycles will commence or may have already started; however, they often need time to grow to produce substantial effect, or the growth cycles will be short lived. Of note is the abstract observation that s-shaped production plateaus (representing renewables and nuclear via Equation 2.2) are more desirable than the bell-shaped production peaks and declines (representing fossil fuels via Equation 2.4) when it comes to long term energy trends.

2.3.1. Individual US Fossil Fuel Production Source Models

The recent boom in hydraulic fracking and unconventional oil production over the last decade caused a dramatic shift cycle in US crude oil production (Inderwildi and King 2016). The new growth cycle in crude oil production from these new resource bases changed a long-term gradual decline in total production to a period of rapid increase starting in 2009. This shift in the
production trend required a two-phase multi-cycle logistic model to fit the data (Figure 2.3). Though the newest logistic growth cycle revealed a cumulative high-plateau ($H_Q$) over 8 times lower than that of the previous cycle, the growth at prime ($G@M'$) of the newest cycle was over 6 times larger than that of the previous cycle. The majority of the increase in crude oil production since 2009 occurred in Texas (53%) and North Dakota (23%), followed by Offshore – Gulf of Mexico (8%), Oklahoma (6%), New Mexico (5%), and Wyoming (2%) (EIA 2016).

Though the actual production peak for the first cycle occurred in 1970, the logistic model indicated a midpoint ($M$) of the cycle of 1975.6. This acts as a reminder that logistic modeling is not a predictive tool, but rather a descriptive tool for analysis of historical and ongoing production trends. Thus, the midpoint ($M$), of 2017.3 for the most recent cycle, is not intended to predict the exact timing of the peak for the ongoing cycle, but rather to serve as an indication of the production trend behavior given the most recent data available.

The growth at prime ($G@M'$) for the most recent crude oil production cycle from fracking revealed the largest growth of all the US energy sources at 2.47 quad BTU at 2014. This growth demonstrated by the ongoing crude oil production cycle is extraordinary, however, because fossil fuel production tends to follow a symmetrical bell-shaped trend, the decline in production following the peak will tend to be as rapid. This points directly to an inherent weakness of finite resource production, the faster it is extracted and used, the faster that resource base is exhausted. Therefore, renewable technology development because of its tendency to plateau as opposed to peak, should be the long-term priority for energy sustainability in all senses of the word.

The area under the logistic curve was summed and converted to barrels (given the EIA crude oil energy content value of 5.800 million BTU per barrel (EIA 2014)), showing a cumulative crude oil production in the US between 2016 and 2040 of 35.4 billion barrels. This is within 3% of the most recent EIA proved reserve estimate of 36.4 billion barrels in 2014 (EIA 2015), but over 6 times smaller than the 2009 EIA technically recoverable US crude oil resource estimate of 220.2 billion barrels (EIA 2012), and over 7 times smaller than a 2016 study by Rystad Energy suggesting 264 billion barrels of technically recoverable US crude oil given the “most likely estimate for existing fields, discoveries and yet undiscovered fields” (Nysveen 2016). These estimates by EIA and Rystad Energy suggest that less than half of the crude oil available in the US has been extracted since oil production began in 1860 (cumulative US crude oil production in 2015 was approximately 215.5 billion barrels (EIA 2016)).
This high recoverable US crude oil reserve estimate also suggests new growth cycles in US crude oil production will occur prior to 2040. However, the remaining US crude oil resource base is primarily unconventional, which causes greater environmental impact and lower energy return on investment, and increased production is likely to continue being actively explored. Therefore, it is highly recommended that substantial technological development leading to reductions in environmental impacts from unconventional crude oil extraction, increases in vehicle gas mileage, and pursuit of alternate fuel options be aggressively pursued and possibly mandated, regardless of production modeling results.

US dry and liquid natural gas production also required multi-cycle logistic modeling, however, three phases were required in both cases (Figure 2.4 and Figure 2.5). For both dry and liquid natural gas, there were smaller production cycles between the new and original cycles, with the original cycles having larger cumulative high-plateaus ($H$) but the new cycles having larger growth at primes ($G_{@M'}$). The trend of increasing growth in natural gas production began in 2006, with the majority of the growth occurring in Pennsylvania (45%) and Texas (30%), followed by West Virginia (9%), Oklahoma (7%), Ohio (5%), and North Dakota (3%) (EIA 2016).

The midpoint ($M$) for the new dry natural gas cycle was 2020.2 and was 2018.7 for natural gas plant liquids. The growth at prime ($G_{@M'}$) for the most recent dry natural gas cycle was the second largest for all US energy sources at 1.68 quad BTU in 2011.2.

The area under both dry and liquids natural gas logistic curves was summed and converted to cubic feet (given the EIA natural gas energy content value of 1,035 BTU per cubic foot (EIA 2014)), showing a modeled cumulative total natural gas production in the US between 2016 and 2040 of 543.5 trillion cubic feet. This is 1.4 times larger than the most recent EIA proved reserve estimate of 388.8 trillion cubic feet in 2014 (EIA 2015), but 4.1 times smaller than the 2009 EIA technically recoverable US natural gas resource estimate of 2,203.3 trillion cubic feet (EIA 2012). Since natural gas extraction and combustion generally creates less environmental impact than crude oil and coal, and estimates show a large recoverable resource base, natural gas would be the preferred fossil fuel option. However, environmental impacts from natural gas extraction and combustion are not negligible and should be reduced through technological development.
US coal production data from 1949 to 2015 indicated a two-phase growth trend, however, unlike crude oil and natural gas there was no evidence of a recent growth cycle, but rather an unexpected decline in production (Figure 2.6). The majority of the first visible growth phase occurred prior to the start of the dataset in 1949, with production declining up to 1961. Coal production began increasing again in 1962, and continued a general trend of growth until a peak in production in 1998, followed by a period of relative stable production to 2008 then a general decline in growth to 2015. After several modeling attempts it was determined to confirm an adequate logistic fit of the most recent production cycle, US coal production data prior to 1949 was required. Historical US coal consumption data back to 1850 from the 2011 EIA Annual Energy Review (AER) (EIA 2012), and as annual US coal imports were below 0.01 quad BTU in 1949 (EIA 2016) it was assumed the pre-1949 coal consumption data would serve as an adequate stand in for US coal production. Pre-1949 data revealed two previous overlapping growth phases which multi-cycle logistic modeling showed both diminished to below 1 quad BTU by 1963.

Production data between 2012 and 2015 appeared to be trending down below the model and monthly EIA coal production data through June 2016 also showed a rapid decline below the logistic model trend. The EIA reports this decline in coal production was a result of the combination of environmental regulations, reduced growth in overall electricity demand, competition with increasingly cheaper natural gas, and a warmer than average 2015-2016 winter (EIA 2016). However, it is unclear if this greater-than-expected production decline is perpetual.

The area under coal logistic curve was summed and converted to short tons (given the EIA coal energy content value of 24.800 million BTU per short ton (EIA 2014)), showing a modeled cumulative coal production in the US between 2016 and 2040 of 14.6 billion short tons. This is 32.7 times smaller than the most recent EIA demonstrated reserve base estimate of 478 billion short tons in 2014 (EIA 2016). Therefore, the observed decline in US coal production since 2013 was likely not driven by a limit on recoverable resources. If a new significant growth cycle in US coal production from the vast demonstrated resource base is pursued, it is highly recommended that substantial reductions in environmental impacts from coal extraction and combustion also be aggressively pursued and possibly mandated.
Figure 2.4 Multi-Cycle Logistic Model of US Crude Oil Production. US crude oil production in 2015 was just shy of the previous peak in 1970. The logistic fixed condition forecast revealed a peak in the second cycle in 2017.
Figure 2. 5. Multi-Cycle Logistic Model of US Dry Natural Gas Production. US dry natural gas production in 2015 was the largest in the historical record with the logistic model showing a peak in the third cycle in 2020.
Figure 2. 6. Multi-Cycle Logistic Model of US Natural Gas Liquids Production. US natural gas liquids production in 2015 was also the largest in the historical record with the logistic model showing a peak in the third cycle in 2018.
Figure 2.7. Multi-Cycle Logistic Model of US Coal Production. Three overlapping cycles of growth were required to produce a suitable logistic fit using historical data not shown here, with the majority of the first two cycles peaking before 1949, and the third cycle peaking in 2000.
2.3.1.1. Individual US Renewable Energy Production Source Models

The US biomass energy logistic model (which includes biofuels energy) demonstrated two discrete growth phases, the first between 1974 and 1983, and the second between 2004 and 2013 (Figure 2.7). The data trend revealed the second biomass energy growth phase (primarily from biofuels energy production modeled independently in Figure 2.7) had reached its logistic high-plateau \( (H = 4.72 \text{ quad BTU}) \) as of 2015. The US biofuels energy (biomass sub-category) logistic model had three discrete growth phases, the first two 1982-1986 and 1991-1994, and the third biofuels growth phase 2002-2014 reaching its high-plateau \( (H = 2.14 \text{ quad BTU}) \) as of 2015. Though the logistic model revealed biomass energy production at a plateau, US energy policy actively promotes growth in advanced biofuel production (EPA 2010) so a new growth cycle occurring before 2040 is possible.

According to the 2011 EIA Annual Energy Review of 1635-1945 estimated energy consumption data, the decline in biomass energy production data prior to 1960 was the result of a declining cycle of wood biomass energy production. Because this data had little effect on the overall 1949-2015 logistic fixed condition trend, the pre-1949 data was not considered in the modeling process.

The US hydroelectric energy logistic model revealed one growth cycle between 1955 and 1973, followed by large production fluctuations about the logistic high-plateau \( (H = 2.89 \text{ quad BTU}) \) (Figure 2.8), with pre-1949 energy consumption data from the 2011 EIA AER showing two previous periods of growth between 1890 and 1920 and between 1935 and 1945 (EIA 2012). After 2000 hydroelectric energy production appeared to be trending downward, however, production values were within the range of error resulting from annual fluctuations so the possibility of a generally decreasing production trend remains. After reviewing the monthly EIA production data through June 2016 and attempting a declining second cycle fit, it remained unclear whether hydroelectric energy production was on a declining growth cycle. Regardless of the current trend, a new increasing hydroelectric energy growth cycle occurring before 2040 is possible. According to the DOE an additional 0.77 quad BTU per year hydroelectric energy production capacity (not including hydrokinetic technologies) could be added by 2030, and 1.44 quad BTU by 2050, depending on future US energy policy and technological development (DOE 2016).
The lower R-squared for hydroelectric is a result of greater annual fluctuation in production because of weather variations (Kao, Sale et al. 2015) and the tendency for chaotic behavior to emerge after an s-shaped logistic trend reaches the high-plateau \( (H) \) (as found when calculating the iterates of the logistic difference equation (Wu and Baleanu 2014)). When the R-squared was calculated for the hydroelectric logistic model from 1949 to 1980 (before the fluctuations but after reaching the high-plateau) the R-squared value became 0.952. With the first and third quartiles of the R-squares for energy production sources being 0.965 and 0.995 respectively, the 0.806 R-squared for the hydroelectric model was determined to be an outlier (i.e. outside 1.5 times the interquartile range below the first or above the third quartile), and the pre-fluctuation R-squared of 0.952 adequate to deem the model a suitable fit to the data.

The US wind energy logistic model exhibited two discrete growth phases, with the first small and short lived between 1988 and 1990, and the second starting around 2000 and still ongoing (Figure 2.9). Wind energy production growth diminished in 2014 and 2015 pointing to the production cycle approaching its high-plateau \( (H = 2.06 \text{ quad BTU}) \) before 2020, though it is possible these years were anomalous, and this cycle could continue to grow beyond the indicated plateau. A new wind energy growth cycle occurring before 2040 is also possible. According to the DOE depending on future US energy policy and technological development, an additional 0.66 quad BTU per year of offshore wind energy production capacity could be added by 2030, and 2.57 quad BTU by 2050 (DOI 2016).

Despite the solid fit of the annual data, analysis of monthly wind energy production data through June 2016 suggested the 2014 and 2015 reduced growth may have been an anomaly, and growth in the future may continue at pre-2014 rates and continue to grow. Because of seasonal wind cycles, the monthly data for the first half of 2016 could provide an inappropriate estimate for the annual production trend (thus, monthly not included in the figure).

Like wind energy, the US solar energy logistic model showed two discrete growth phases, with the first small and short lived between 1988 and 1990, and the second starting around 2005 and still ongoing (Figure 2.10). The best-fit logistic model showed solar energy just beyond the midpoint of its ongoing growth cycle in 2015, with the model reaching its high-plateau \( (H = 0.66 \text{ quad BTU}) \) in the early 2020s. However, other non-best-fit logistic parameters could also produce reasonable fits with high-plateaus between 0.5 and 2.0 quad BTU (see Appendix A). With a study by the DOE proposing the possibility of total US solar energy production reaching
2.19 quad BTU by 2030, and 4.94 quad BTU by 2050 (DOE 2012), the ongoing growth cycle could continue and/or a new growth cycle may begin before 2040.

As the best-fit showed the solar energy growth curve only just beyond the midpoint ($M = 2014.40$) of the second cycle in 2015, it is possible that the ongoing growth curve will not plateau at 0.66 quad BTU and continue to grow. This serves as another reminder that logistic modeling does not predict the future, but rather only reveals ongoing trends from available data. Regardless, as US solar energy production was less than 0.5% of total US production, even if it increased 1000%, it wouldn’t play a significant role in counteracting the modeled decline in fossil fuel production.

The US geothermal energy logistic model indicated three discrete growth phases, with the first between 1972 and 1976, the second between 1979 and 1990, and the third between 2005 and 2011, and in 2015 was near its high-plateau ($H = 0.22$ quad BTU) (Figure 2. 11). It is possible new cycles of geothermal energy production growth will occur, but the DOE has not yet completed its study with possible 2030 and 2050 capacity increases.

There was a noticeable increase in 2015 production above the 2014 production value, which may be indication of the beginning of a new growth cycle or just the typical fluctuations observed in an s-shaped trend after reaching a plateau. After reviewing monthly EIA data through June 2016, the behavior of the trend did not yet indicate the beginning of a new growth cycle. It is unknown why the size and shape from one geothermal growth cycle to the next were much more erratic than other renewable multiple growth cycles. Similar behavior in the future growth of geothermal is possible and further investigation is warranted.

Data for biomass, hydroelectric, and geothermal energy as of 2015 showed production near their best-fit logistic high-plateaus ($H$), which suggests new growth cycles would have to begin for their production to steadily increase again. Wind and solar energy production growth, however, have not leveled off, and even though their best-fit logistic models point to production approaching plateaus in the near future, it is possible for new growth to begin while the current cycle continues.

2.3.1.2. Individual US Nuclear Energy Production Model

US nuclear energy production, though not a renewable energy source, tends to follow an s-shaped growth trend because the number of nuclear power plants limits the production value
rather than the rate of uranium production. However, nuclear energy production data demonstrated a behavior not observed with the renewable energy production trends. After what appeared to have been a completed initial growth cycle between 1967 and 1981, a second growth cycle picked up mid-stream between 1982 and 2002 (Figure 2.12). The second cycle followed close to what a single cycle logistic model of the entire nuclear energy production dataset after 1982 and produced a nearly identical logistic high-plateau ($H = 8.42$ Quad BTU for second multi-cycle and 8.43 for single-cycle). Since the multi-cycle model produced a better overall fit, it was used for the total US energy production aggregate model.

The mid-stream nuclear energy trend change in 1981 was counterintuitive, as between 1974 and 1985 numerous nuclear policy and regulation changes arose, further restricting nuclear energy production (Session 2013), and the Three Mile Island accident occurred in 1979 increasing the skepticism of nuclear power in the general public (Dohrenwend, Dohrenwend et al. 1981), however, shortly after that time nuclear energy production began to rapidly increase. What was a likely cause of this dramatic increase in nuclear energy production was the Power plant and Industrial Fuel Use Act of 1978 and the second US oil crisis in 1979, which encouraged a shift from petroleum electricity generation to nuclear and renewables (EIA 2002) (between 1978 and 1985 US electricity generation from petroleum decreased 73% (EIA 2016)).

2.3.1.3. **Individual Total US Energy Consumption Model**

The total US energy consumption logistic model showed two discrete growth phases, with the first between 1953 and 1980, and the second between 1985 and 2000, with total energy consumption fluctuating within 4% of the logistic high-plateau ($H = 98.07$ quad BTU) from 2000 to 2015 (Figure 2.13). As seen with other s-shaped logistic trends, periods of greater fluctuation were observed during periods of plateaued growth. This plateaued consumption trend occurred even though US population has continued to steadily increase (EIA 2016), and though this is a possible sign of sustainable development (because of technological advances or behavioral efficiency), it is unknown how long this plateau will last. However, since no evidence of a new growth cycle was found in the data, total US energy consumption modeled was at a stable plateau through 2040, though new growth is entirely possible.
Figure 2.8. Multi-Cycle Logistic Models of US Biomass Energy and Biofuels Energy Production. The biofuels production subcategory is also included in the biomass production category. The logistic models showed both biomass and biofuel production having reached high-plateaus by 2015.
Figure 2.9. Single-Cycle Logistic Model of US Hydroelectric Energy Production. Because of the variable weather patterns (Kao, Sale et al. 2015) and the tendency of s-shaped production data to behave chaotically after reaching a plateau (Wu and Baleanu 2014), hydroelectric energy production showed significant fluctuations since 1980.
Figure 2. 10. Multi-Cycle Logistic Model of US Wind Energy Production. Wind energy growth has slowed since 2013 and appears to be approaching a plateau, however, it is possible the cycle continues to a larger high-plateau.
Figure 2. 11. Multi-Cycle Logistic Model of US Solar Energy Production. The best-fit logistic model showed solar energy production approaching a high-plateau ($H$) of 0.66 quad BTU around 2022, however, the cycle’s high-plateau could be significantly larger.
Figure 2. 12. Multi-Cycle Logistic Model of US Geothermal Energy Production. Geothermal energy production data showed closely overlapping logistic cycles with peculiar behavior between 1987 and 1996.

<table>
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<th>Third</th>
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<tr>
<td>H</td>
<td>0.04</td>
<td>0.17</td>
<td>0.22</td>
</tr>
<tr>
<td>L</td>
<td>0.00</td>
<td>0.04</td>
<td>0.17</td>
</tr>
<tr>
<td>W</td>
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Figure 2. 13. Multi-Cycle and Single-Cycle Logistic Models of US Nuclear Energy Production. Both models suitably fit the data and produced similar logistic high-plateaus.

<table>
<thead>
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<th>Single</th>
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Figure 2.14. Multi-Cycle Logistic Model of Total US Energy Consumption. Despite continued growth in US population total energy consumption has remained relatively stable since 2000.
2.3.1.4. Aggregate US Energy Production Models

The sum of the individual bell-shaped US fossil fuel logistic models created a US total fossil fuel aggregate model which indicated a peak of 76.3 quad BTU in 2017 (Figure 2.14). The recent steady increase in US fossil fuel production started in 2010 and continued through to 2015, which surpassed the previous 1970 peak in US fossil fuel production in 2011, and in 2015 production was 15.5% larger than the peak in 1970. This growth was brought on by a boom in natural gas and crude oil production from unconventional sources and advanced extraction techniques, such as shale gas, tight oil, oil sands and oil shale, and hydraulic fracturing and horizontal drilling (Whitney, Behrens et al. 2009, Sieminski 2014). These techniques and sources had been available for some time (Hubbert and Willis 1972), but it was not until rising prices because of declining conventional production made their employment economically viable (Deffeyes 2006). This change in trend was most notable with crude oil production which had been declining (other than a slight increase in 1991) between 1986 and 1999. This unprecedented increase in domestic crude oil production was also encouraged US policy intended to lessen the dependence on foreign sources of oil (Congress 2007, Greene and Liu 2015).

With monthly coal production data indicating a more rapid decline than the model indicated after 2015, total fossil fuel production in the future could be lower than the model. On the other hand, with technically recoverable crude oil and natural gas estimates from the EIA showing significantly greater cumulative recovery potential, the peaks for crude oil and natural gas could be later and have a greater magnitude, or new growth cycles could begin.

The sum of individual s-shaped US renewable energy logistic models created a US total renewable energy aggregate model which indicated a plateau of 10.6 quad BTU being approached before 2020 (Figure 2.15). Given the trends up to 2015, logistic analysis indicated. It is likely that renewable energy production will begin new growth cycles prior to 2040, and wind and solar energy production may not reach a plateau as soon as the models suggest. However, logistic modeling of data up to 2015 suggested the recent period of renewable energy growth starting around 2005 is nearing its end, and less than 1 quad BTU growth between 2016 and 2040. Renewable energy technologies in development that could create sizeable new growth cycles (~2 quad BTU) before 2040 include biomass (including advanced biofuels) (EPA 2010), hydrokinetic energy, and offshore windfarms (DOE 2015).
The model values being consistently above the data between 2001 and 2015 (aside from 2011) is a result of hydroelectric energy production data below its logistic model high-plateau. The small increase seen in the aggregate model between 1988 and 1989 is not a plotting artifact, but a result of both wind and solar energy model’s first small growth cycles occurring at the same time during that period.

The sum of the US total fossil fuel aggregate model, US total renewable energy aggregate model, and US nuclear energy logistic model (i.e. the sum of all individual US energy logistic models) created a total US energy production aggregate model which indicated a peak of 95.0 quad BTU in 2017 (Figure 2.16). After the production peak in 2017, the model indicated a rapid decline in total energy production down to 36.2 quad BTU in 2040. Because the bell-shaped trends from fossil fuel production made up the majority of US energy production and the renewable energy logistic models did not indicate substantial ongoing growth, the total US energy production model was dominated by the shape of the aggregated fossil fuel production model to beyond 2040.

Though the model fits well with the data, this logistic analysis of US energy production does not suggest that no new growth cycles will occur before 2040, only that historical production data to 2015 revealed trends which followed this path of production. However, because both s-shaped and bell-shaped production trends grow slowly at the beginning of a cycle, it may be that in 2015 new growth cycles have already begun but not yet generated notable increases in production. This behavior of preliminary slow growth also means that to counteract the modeled rapid decline in production, new production cycles must begin sooner rather than later.

If total US energy production does in fact follow these logistic trends and rapidly decline after 2017 it is reasonable to speculate that significant government support will ensue to produce new cycles of growth from both renewables and fossil fuels, and possibly nuclear. However, as it becomes more difficult, costly, and environmentally harmful to discover and extract new sources of fossil fuel, there may be less support for or increased resistance to new US fossil fuel production despite a decline in production. Therefore, there may be a greater push to increase renewable and possibly nuclear energy production to mitigate or reverse the decline. Regardless, reduced environmental impact should be aggressively pursued and possibly mandated for all energy production sources and uses.
Figure 2.15. Each US Fossil Fuel Production Source Logistic Model and Total US Fossil Fuel Production Aggregate Model. The aggregate model for total fossil fuel production revealed a fixed condition forecast peak in 2017.
Figure 2. 16. Each US Renewable Energy Production Source Logistic Model and Total US Renewable Energy Production Aggregate Model. All renewable energy production source models were approaching or already at high-plateaus in 2015, thus, the total renewable energy production aggregate model showed limited growth beyond 2020.
2.3.1.5. Total US Energy Production Aggregate and Total Consumption Models

The total US energy production aggregate model comes within 3.2 quad BTU of the total US energy consumption logistic model at its peak of 95.05 quad BTU in 2017, the closest US energy production has been to energy consumption since 1967, then declines to 61.9 quad BTU below the consumption model in 2040 (Figure 2.17). If US energy consumption begins a new growth cycle and rises above its logistic high-plateau (H), this modeled energy deficit would become even larger. Conversely, if consumption declines, the energy deficit would be less, however, it is unlikely that consumption would decline at a rate like that of the production model without some sort of massive national disaster or inability to import fossil fuel at the rate required.

In 2015, total renewable energy production accounted for 9.8% of total US energy consumption and modeling only indicated growth of renewables’ share of energy to 10.7% in 2040. Non-fossil fuel (i.e. renewable and nuclear) energy production accounted for 18.4% of US energy consumption in 2015 and the modeling similarly indicated growth of its share of consumed energy to 19.3% in 2040. To compensate for the modeled decline in fossil fuel production, total renewable energy production would have to grow over 546% by 2040, increasing its share of consumed energy to over 63%. Or for non-fossil fuel energy production to compensate for the modeled decline it would have to grow over 245% by 2040.

Total US energy production increased 18.5 quad BTU between 2005 and 2015, with renewable energy accounting for 3.4 quad BTU of the increase, and fossil fuel 15.0 quad BTU (with nuclear accounting for the remaining 0.1 quad BTU). Without hypothetical modeling of new logistic growth cycles it is difficult to speculate on if growth necessary to completely compensate for the modeled decline after 2017 is likely given past growth trends. There certainly will be new growth cycles and actual energy production will not perfectly follow the fixed condition forecast. However, if such a decline in the ongoing US fossil fuel production growth cycles does occur (a 53.9 quad BTU decrease by 2040), to compensate, new production growth cycles equivalent to 2.9 times the total energy production increases between 2005 and 2015 would need to occur. If that rate of growth occurred for the 23 years between 2017 and 2040 for an increase of 42.6 quad BTU, it would still be over 11 quad BTU shy of compensating for the modeled decline. Furthermore, if this new growth was to be produced by renewable sources alone, this would require growth of over 15.8 times the renewable energy production increases between 2005 and 2015, or 7.9 times the increase of the same growth rate over 23 years.
Figure 2. 17. Total US Fossil Fuel Production Aggregate Model, Total US Renewable Energy Production Aggregate Model, US Nuclear Energy Logistic Model, and Total US Energy Production Aggregate Model. Because fossil fuel production was the bulk of total energy production, the total energy production aggregate model fixed condition forecast followed the total fossil fuel aggregate model trend, with a production peak in 2017.
Figure 2. 18. Total US Energy Production Aggregate Model and Total US Energy Consumption Logistic Model. The models showed total energy production in 2017 would be the closest to total energy consumption since 1967.
It must be noted that individual US energy source consumption demands were not modeled, therefore the specific demand for heat energy, electricity, and transportation fuel requiring specific renewable energy sources cannot be directly compared to the production models. But as a quick reference, total US biofuels energy production increased from nothing in 1980 to 2.16 quad BTU in 2015 (EIA 2016), while the US crude oil logistic model showed a decrease of 17.7 quad BTU by 2040 from crude oil production in 2015. Thus, an increase of over 817% in biofuel production would be required to compensate for the modeled decrease in crude oil production. Though the increase alone appears overwhelming, it appears even less likely to occur considering that US biofuel energy production has only increased 0.13 quad BTU between 2011 and 2015 despite US energy policy requiring significant annual increases in biofuel production during that period (EIA 2016, Harris 2016). Regardless of past trends, sustainably increasing US biofuel production should continue to be a priority of US energy policy, and new, more effective policy mechanisms using quantitative modeling methodologies such as this logistic growth curve modeling methodology should be researched and implemented.

Given the capability of logistic growth curve modeling to represent US energy production and consumption trends, future production scenarios can be created to plan and optimize investment in energy resources and technologies. Furthermore, the energy production trends can be quantitatively associated with their environmental or other impacts. Moreover, this modeling technique is simple and accessible to most all researchers.

2.4. Conclusions

Logistic growth curve modeling is a valuable tool for empirical modeling of US energy production and consumption. The logistic growth curve modeling methodology developed through this research was found to be a valid tool for assessing and forecasting complex energy production and consumption systems such as the US energy production and consumption landscape. This straightforward multi-cycle four-parameter logistic equation and fixed condition forecasting methodology was used to perform a case study US energy production and consumption to 2040.

This research shows that US energy production is unlikely to meet demand even with consumption maintaining a plateau to 2040. Thus, US energy production systems need to initiate significant new growth cycles in all forms of energy production – from renewable, nuclear, and
unconventional sources – to meet the anticipated demand, as well as to managing consumption as much as reasonable. Furthermore, these results further illustrate the long-term benefits of renewable energy development over non-renewables. That is, while finite (i.e. bell-shaped) production trends inevitably peak and immediately decline, renewable (i.e. s-shaped) resource production trends tend to maintain a long-term plateau before decline. This suggests that greater effort be put towards developing sustainable s-shaped energy sources than towards developing finite bell-shaped energy sources. Even a sevenfold increase in the 2015 total annual renewable energy production rate, the fixed condition forecast deficit in 2040 would not be eliminated. Therefore, effort should be put towards sustainably increasing all energy sources for the immediate future.

New production growth will certainly occur before 2040 despite new growth cycles not being evident in the modeled data. However, the prohibitively large size of the new production growth cycles required to compensate for the fixed condition forecast decline appear unlikely given historical growth trends. (The only proposed energy production sources that theoretically could compensate for the modeled energy deficit are fusion and space resource technologies, and those arguably remain far from implementation (Hoffert, Caldeira et al. 2002).) Therefore, it appears energy imports (including crude oil) will continue to be necessary through 2040, and significant effort to develop new growth cycles in fossil fuel production in the US and elsewhere will be needed despite increasing environmental and sustainability concerns. Thus, aggressive effort in improving the sustainability of fossil fuel production and use to reduce resulting environmental, social, and economic consequences, as well as the possible deployment of atmospheric carbon management technologies to prevent climate change, would also be required.

Overall, this research suggests the need for immediate substantial investment and effort towards developing new, large cycles of growth in all energy production sources, particularly renewables for the long term and fossil fuels for the interim. While at the same time, greater energy efficiency, reduced energy use, improved sustainability in energy production, and the deployment of negative carbon emission technologies should be parallel priorities. All these efforts should be aggressively pursued and perhaps mandated. Substantial innovation, research, and development is required to ensure a sustainable future in which the US continually and cleanly produces the majority of the energy it consumes.
Supplementary Material

Supplementary material and data associated with this article can be found in Appendix A.

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2.5. References


EIA. (2016g). Crude Oil Production. from EIA


CHAPTER THREE

LOGISTIC GROWTH CURVE MODELING OF
US BIOFUEL PRODUCTION

Modified from a paper to be submitted to
Renewable & Sustainable Energy Reviews

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Abstract

A logistic growth curve model was fit to US biofuel production for the purpose of analyzing production trends, while evaluating and improving US biofuel policy. This s-shaped four-parameter logistic model was fit to US Department of Energy (DOE) historical biofuel production data from 1995 to 2015. The best fit logistic model exhibited a production plateau of 15.8 billion gallon per year, 29\% short of the Environmental Protection Agency (EPA) 2010 Renewable Fuel Standard (RFS2) requirement of 22.25 billion gallons of total renewable fuel in 2016. These results indicated future production of biofuel in the US is unlikely to meet the original RFS2 biofuel production requirements and that policy mandated production volumes are unlikely to yield the desired results. Additional analysis of the first Renewable Fuel Standard (RFS1) from 2007 and the individual RFS2 biofuel categories was conducted, suggesting needed improvements in future policy development.

Keywords: Logistic Equation, Logistic Growth Curve Modeling, Energy Production Modeling, Biofuel Production, Biofuel Policy, Renewable Fuel Standards

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Highlights

- US biofuel production was modeled using the logistic equation for policy analysis
- The total biofuel production model indicated a 15.8 billion gallon per year plateau
- The 2010 renewable fuel standard has not effectively increased biofuel production
- Total US biofuel production is unlikely to reach original RFS2 policy requirements
- Future biofuel policy would benefit by learning from such analysis of past policy

3.1. Introduction

US energy policy is most successful when based upon a solid understanding of energy production dynamics, to include energy production trend modeling (Robinson, 1982). A commonly used empirical energy production modeling tool, the logistic growth curve model, was derived from the logistic equation and has primarily been used to model finite resources such as crude oil (Deffeyes, 2006; Hubbert, 1956). However, logistic growth curve modeling can also be used to model renewable resources as demonstrated by recent research (Changliang and Zhanfeng, 2009; Mabel and Fernandez, 2008; Yiming and Xifan, 2010), though, it has yet to be used for modeling biofuel production, or biofuel policy analysis and development. This research applies a simple and robust logistic growth curve modeling technique to analyze biofuel production trends, and evaluates the feasibility of current US biofuel policy, such as the Renewable Fuel Standard (Congress, 2007; Schnepf and Yacobucci, 2013).

3.1.1. Logistic Modeling Background

The relationship between policy and environmental issues and logistic modeling dates back to the origin of the logistic equation in the mid-1800s. In response to concerns of boundless and possibly catastrophic population growth – expressed most famously by English scholar and cleric Thomas Malthus in 1798 (Malthus, 1798) – the French mathematician Pierre Verhulst first published the logistic equation in 1838 (Verhulst, 1838) which bounds a region’s population growth with an upper plateau or carrying capacity. The logistic equation in its original population modeling form produces an s-shaped (sigmoid) curve which grows near exponentially at first, slows and flattens out through the midpoint, and then decreases near exponentially as it reaches the upper plateau.
In the mid-twentieth century an American geophysicist, M. King Hubbert, explored the concept of modeling energy production with the logistic equation (Hubbert, 1956). Hubbert modeled US crude oil production with an alternate form of the logistic equation (a symmetrical bell-shaped logistic equation, the derivative of the s-shaped equation) knowing that a finite resource would increase to a peak production value then decrease at a similar rate rather than reach a production plateau (see Supplementary Material). Less explored has been the suggestion by Hubbert that nuclear and renewable energy production (specifically hydroelectric) would likely follow an s-shaped logistic trend (Hubbert, 1956). However, logistic growth curve modeling of renewable energy production has begun to be explored more recently in academic literature (Changliang and Zhanfeng, 2009; Mabel and Fernandez, 2008; Yiming and Xifan, 2010).

Modeling of the diffusion of a technology using an independently derived version of the logistic equation (though in an equivalent hyperbolic tangent form (Bradley, 2007)) was done by Fisher and Pry in the early 1970s (Fisher and Pry, 1971). The connection between technology and the logistic equation has led to successful logistic growth curve modeling of varied other technologies such as miles of canals and train track (Grübler, 1996), the number of active internet users and servers (Devezas et al., 2005), and telecommunications (Vanston and Hodges, 2004). The technological diffusion approach to logistic modeling has also been successfully applied to energy production trends including nuclear and renewables (Grübler et al., 1999). This connection between the logistic equation and technological diffusion arguably adds support to the foundation that the logistic equation is a suitable model for biofuel production, as a significant portion of biofuel development is technologically driven (Rao and Kishore, 2010) (in addition to the agricultural, land use, and economically driven aspects, which are also inherently included in the empirically based logistic modeling technique).

A common misconception about logistic modeling is that it is a tool that can be used to predict exact dates and magnitudes of future energy production peaks and plateaus, however, this is not often the case. One prime example was the “Peak Oil” movement in the 2000s where many researchers produced logistic growth curve models that indicated global conventional crude oil production would likely peak before 2010 (Aleklett and Campbell, 2003; Campbell and Laherrère, 1998; Deffeyes, 2008). However, new growth cycles in production from the boom in hydraulic fracturing and unconventional crude oil production allowed total global crude oil
production to rise through 2015 (EIA, 2016b). Though it has been argued that global conventional crude oil production has already peaked (Hallock et al., 2014; Murphy and Hall, 2011), the conventional/unconventional production nuance has been generally overlooked, and many have dismissed the logistic growth curve modeling technique as a result. Regardless, as energy production is dynamic and complex, pinpointing exact future peaks and plateaus is unlikely. However, the inability to act as a crystal ball by no means renders the logistic equation useless when it comes to energy production modeling. As applied in this research, logistic modeling can be successfully employed as a tool to analyze ongoing production trends, make general forecasts, and inform policy.

3.1.2. US Renewable Fuel Standards

Biofuel production in the United States had been driven by policy for many years starting with the Clean Air Act (via the Energy Policy Act of 2005) (Congress, 2005), which culminated in the first Environmental Protection Agency (EPA) Regulation of Fuels and Fuel Additives: Renewable Fuel Standard Program; Final Rule in 2007 (RFS1) (EPA, 2007). Subsequently, the Energy Independence and Security Act of 2007 (EISA) became the driving force “to increase the production of clean renewable fuels” (Congress, 2007) which resulted in the second EPA Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule in 2010 (RFS2) (EPA, 2010). Regardless, both of the EPA renewable fuel standards set annual production volume requirements for US biofuel production in billion gallons per year (RFS1 from 2006 to 2012, and RFS2 from 2008 to 2022). In an effort to make production more sustainable, the RFS2 restricted feedstocks, production techniques, and types of land that could be used to produce biofuel that qualifies as clean renewable fuel. The final mandated biofuel production value of the RFS2 for total biofuel is 36 billion gallons in the year 2022. Neither the rational nor any modeling techniques is discussed in either of the renewable fuel standard programs (RFS1 or RFS2), or the EISA, nor has the approach for setting the mandated production targets been made known elsewhere.

Therefore, this research establishes an s-shaped four-parameter logistic equation and novel, simple fitting technique to model biofuel production for trend and policy analysis, and for use in future policy development. The empirically driven logistic growth curve modeling technique when applied to biofuel production does not explicitly take the availability of land and biomass,
technological readiness, market conditions, or economic incentives into consideration, but rather takes historical US biofuel production data and solves for the best fit logistic growth curve model parameters. By using this logistic growth curve modeling technique, energy policy makers can become aware of the general trend of renewable energy production to set more attainable future production targets, as well as evaluate the ways in which policy has influenced production trends. It can also provide insight into how renewable energy production generally evolves (e.g. shape and size of growth trends), and what trends might be expected from new and developing energy technologies. Furthermore, it is simple enough that anyone with a renewable energy dataset and spreadsheet program with solver capability can perform their own energy production analysis and forecasts.

3.2. Methodology and Data

Energy production data was collected from the US Department of Energy (DOE) Energy Information Agency (EIA) Annual and Monthly Energy Reviews (AER and MER) (EIA, 2016a, c). The EIA publishes a variety of renewable energy data including various biofuel categories and units of measure, however, there is no direct comparison between any of the EIA biofuel production categories/units and the renewable fuel standards’ categories/units. The renewable fuel standards are in billions of gallons of biofuel while the EIA reports total biofuels production in trillion British thermal units (BTU), and the energy-volume conversion of biofuels depends on multiple factors (i.e. density and energy content). The EIA does report individual US fuel ethanol production and US biodiesel production data in millions of gallons, therefore the EIA fuel ethanol and biodiesel (which includes other diesel biofuel liquids such as green diesel) categories were summed to create a total US biofuel production category in billions of gallons per year that could then be compared with the various RFS biofuel production categories.

The RFS2 classified the total renewable fuel requirement into four individual categories: renewable fuel, advanced biofuel, biomass-based diesel, and cellulosic biofuel. However, all four categories are not mutually exclusive, that is, the advanced biofuel category contains both biomass-based diesel and cellulosic biofuel. Therefore, all four RFS2 individual biofuel categories do not sum to make the total renewable fuel requirement, only the renewable fuel and advanced biofuel categories. The renewable fuel category volumes themselves were not mandated as the policy expects these first-generation biofuels to plateau and remain indefinitely
at 15 billion gallons per year starting in 2015, with advanced biofuels expected to provide all the required biofuel production growth. Only the total renewable fuel, advanced biofuel, biomass-based diesel, and cellulosic biofuel categories of the RFS2 have specific production requirements, thus, the renewable fuel category values were obtained by subtracting the advanced biofuel requirements from the total renewable fuel requirements. Because no historical datasets were available for production of biomass-based diesel, cellulosic biofuel or advanced biofuel, and those RFS2 categories could not be matched to the EIA reported categories. Only the RFS2 total renewable fuel requirement could be directly compared with the total US biofuel production data and logistic models.

The s-shaped curve of the logistic equation can be produced by numerous mathematical representations. In its most simple form it is an altered exponential function (or modified hyperbolic tangent function) and is given in Equation 3.1 with standard x and y dependent and independent variables:

\[ y = \frac{1}{1 + e^{-x}} = \frac{1}{2} \left(1 + \tanh \left(\frac{x}{2}\right)\right) \] (3.1)

where \( e \) is the mathematical constant known as Euler’s number (approximately 2.71828) and \( \tanh \) is the hyperbolic tangent function, with the proof of the two forms being equivalent given by David M. Bradley in 2007 (Bradley, 2007).

A four-parameter s-shaped logistic equation was obtained from the non-linear regression fitting tools in the Minitab statistical software package (Minitab, 2015), and its conversion from the above form to the form used in this research is done through basic function shifting and scaling, and variable substitution (see Supplementary Material). The logistic equation used herein is the four-parameter logistic model given as Equation 3.2:

\[ P = H + \frac{L-H}{1+e^{(L-M)/W}} = H + \left(\frac{L-H}{2}\right) \left(1 + \tanh \left(\frac{M-t}{2W}\right)\right) \] (3.2)

where \( P \) is the production rate at time \( t \), \( L \) is the initial production rate plateau or “low-plateau”, \( H \) is the production rate plateau resulting from the logistic growth cycle or “high-plateau”, \( M \) is the time of greatest instantaneous change in production rate or the s-shaped curve “midpoint”, and \( W \) is the “width factor”. The units of \( P \), \( H \), and \( L \) are in billion gallons per period, and \( t \), \( M \), and \( W \) are in years. Though both forms of the equation produce identical results, the first form
using Euler’s number was used in this research because it is the standard form and slightly easier to enter in programming syntax.

Since this four-parameter logistic equation does not have a traditional growth rate parameter, an additional equation can be used to describe the growth of the logistic trend which is simply the time derivative of the four-parameter logistic equation taken at the midpoint (M) (see Supplementary Material) given as Equation 3.3:

\[ G_{@M} = \frac{(H-L)}{4W} \]  

where \( G_{@M} \) is the instantaneous increase in production at \( M \) or the “growth at midpoint” in billion gallons per period, and \( H, L, \) and \( W \) are the same parameters as above.

Parameter fitting was conducted using the Microsoft (MS) Excel Analysis Add-in Solver tool using the Generalized Reduced Gradient (GRG) Nonlinear solver method, with default settings and 0.000001 constraint precision and 0.0001 convergence (Microsoft, 2013). The method of least squares was used by squaring the difference between the model’s production value and the actual production value for each period, summing them together, and then minimizing them by varying the \( H, L, M, \) and \( W \) parameters with the Solver tool. Descriptive statistics for the model’s quality of fit were obtained by using the MS Excel Data Analysis Add-in Regression Tool using the default settings with a 95% confidence interval (Microsoft, 2013). Both \( R^2 \) squared, which reports values between 0 and 1, with values closer to 1 representing better fits, and P-value, which reports the calculated probability of data falling outside the confidence interval from the model value (the smaller the better), were determined and presented to represent each model’s quality of fit. With a 95% confidence interval the model was considered significant if the P-value was less than 0.05.

### 3.3. Results and Discussion

Logistic growth curve modeling of US biofuel production confirms that the RFS2 has not yet significantly increase advanced biofuel production, as shown in Figure 3. 1. Logistic modeling also indicates that total US biofuel production consisting mainly of first generation biofuels has stagnated at a production plateau of around 15.8 billion gallons per year as of 2015. The models were created using EIA’s US fuel ethanol production data, US biodiesel production data, and
their sum, the total US biofuel production category, as well as for each of the RFS1 and RFS2 requirements to serve as a general trend reference (Figure 3.2 and Table 3.1). The US fuel ethanol logistic model and US biodiesel logistic model were also summed and compared to the total US biofuel logistic model, and only a minimal difference was observed. Because the total US biofuel logistic model and the summed US fuel ethanol and biodiesel logistic model produced similar results the total US biofuel logistic model was generally used for analysis and discussion. All models had an R-squared greater than 0.900 and P-value <0.00001 and were therefore considered significant fits.

Figure 3.1. Total Annual US Biofuel Production, RFS 1 & 2 Total Renewable Mandates, and Logistic Growth Curve Model. The logistic model for total US biofuel production created from EIA data revealed a production high-plateau (H) of 15.8 billion gallons per year, however, new growth should be expected.
Figure 3. 2. Annual US Biofuel Production, All RFS Mandates, and Logistic Growth Curve Models. *US fuel ethanol production* and *US biodiesel production* are raw datasets from the US DOE Energy Information Administration (EIA), while *total US biofuel production* is the sum of the ethanol and biodiesel annual data. Similarly, the *US fuel ethanol logistic model*, *US biodiesel logistic model*, and *total US biofuel logistic model* are logistic models fit to the data, while the *summed fuel ethanol and biodiesel logistic model* is the sum of the *US fuel ethanol logistic model* and *US biodiesel logistic model*. The two EPA renewable fuel standards (RFS) were released in 2007 (RFS1) and 2010 (RFS2).
Table 3. 1. Logistic Growth Curve Model Parameters and Descriptive Statistics for Annual US Biofuel Production Datasets.

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<td>H (billion gallons per year)</td>
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<td>L (billion gallons per year)</td>
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<td>G@M (billion gallons)</td>
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<td>R Squared</td>
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<td>Statistic Observations</td>
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The logistic models for US biofuel production created from the EIA data showed production high-plateaus ($H$) between 15.8 and 16.4 billion gallons per year, over 26% below the 2016 RFS2 requirement of 22.25 billion gallons per year and over 45% below the final RFS2 requirement of 36 billion gallons per year in 2022. This is not to imply additional growth will not occur in total US biofuel production prior to 2022 – on the contrary, future growth is expected with two new biofuel production facilities being constructed and one facility being significantly expanded in 2016 according to the Renewable Fuels Association (Dinneen, 2016) – this is only showing that production trends up to 2015 show US biofuel production presently in a period of stagnated growth regardless of the increasing annual RFS2 requirements.

As the RFS2 renewable fuel category (including mainly first-generation biofuel) maintains an annual production value of 15 billion gallons per year after 2014, the remainder of RFS2 biofuel production growth is expected from the RFS2 advanced biofuel requirement (which contains both the RFS2 cellulosic biofuel requirement and RFS2 biomass-based diesel requirement). Though it is not possible to determine the amount of advanced biofuel that is represented in the EIA biofuel production data (as the EIA does not publish energy production data in categories that align with RFS2), assuming 15 billion gallons of the 2015 total US biofuel production value of 16.1 billion gallons is from the RFS2 renewable fuel category, only 1.1 billion gallons would be from advanced biofuel production, far short of the 5.5 billion gallons required by the RFS2 in 2015.
By comparing the growth indicators of logistic models fit to the RFS2 mandated production values themselves to the growth of actual US biofuel production, further insight into the magnitude of growth required by the RFS2 can be gained. The logistic growth at midpoint \( (G@M) \) of the RFS2 cellulosic and advanced biofuel requirement logistic models (2.38 billion gallons in 2020 and 2.52 billion gallons in 2019 respectively) were both greater than that of the total US biofuel logistic model (2.16 billion gallons in 2007). Furthermore, the logistic high-plateaus \((H)\) of 25.2 billion gallons for cellulosic, 30.5 billion gallons for advanced were 37% and 48% larger respectively than the current high-plateau \((H)\) of 15.8 billion gallons for total US biofuel production. Even without the logistic analysis, the RFS2 advanced biofuel requirement growth from 0 to 21 billion gallons over 14 years is over 28% larger than the significant growth of 15.1 billion gallons actual US biofuel production made over the last 14 years. This means the RFS2 requires new biofuel production to out-perform the original US biofuel growth cycle, which itself grew faster and larger than the RFS1 anticipated. However, the continued RFS2 requirement of 1.0 billion gallons of biomass-based diesel per year after 2012 (with a \(G@M\) of 0.22 billion gallons) appears reasonable when compared to the US biodiesel logistic model (with a \(G@M\) of 0.17 billion gallons and \(H\) of 1.9 billion gallons per year).

Factors that could have negatively influenced the development of new biofuel production since 2010 include the boom in crude oil production from hydraulic fracturing and unconventional oil production, and the subsequent resulting reduction in the price of both crude oil and gasoline (Kilian, 2016). This was likely unanticipated when the RFS2 requirements were developed and could account for the recent inability of total US biofuel production to reach the RFS2 requirements. However, it is standard practice to mix 10% fuel ethanol (as an oxygenate) with gasoline for both engine performance (preventing engine knock) and emission reduction (Ceviz and Yüksel, 2005), thus the more conventional fuel produced should generally lead to more biofuel production despite the blend wall. So the influence of increased US crude oil production likely only negatively affected higher blend ethanol fuel (e.g. E85: 85% ethanol, 15% gasoline) and 100% biofuel consumption. An environmental factor that demonstrably had a negative effect on biofuel production values after the RFS2 release was a major drought that occurred in the US in 2012 (Boyer et al., 2013). There was a dip in biofuel production in 2012 and 2013 (more evident in the monthly production data), however, production growth had
already begun to diminish prior to the drought, and once the drought was over production quickly picked back up to the production values before the drought.

Another factor that may have chilled the growth in US biofuel production since 2010 was the complex and significant restrictions placed on biofuel production by the RFS2 itself, while necessitating significant technological development requiring significant government support (Bracmort, 2013; Economic and Production, 2011). The RFS2 added three new biofuel production categories that further restricted feedstocks, conversion technologies, and land use, as well as requiring significant (50% and 60%) reduction in greenhouse gas (GHG) emissions from these new categories. This may have been premature with the yet emerging cellulosic biofuel technology taking the brunt of the responsibility in production growth (Huttner, 2013). The RFS2 also enforced a blend wall, limiting the amount of ethanol blended into conventional gasoline at 10%, which restricted the biofuel volume that could be sold in the traditional transportation fuel market (Tyner, 2013). The blend wall in combination with the ability of obligated transportation fuel producers to trade biofuel volume requirements has created a market situation which discourages flex fuel vehicle owners from purchasing higher ethanol blend fuels (e.g. E85) (Verleger, 2013).

These additional regulations and restrictions placed on the US biofuel industry by the RFS2 were likely in response to concerns over unintended and unforeseen environmental impact tradeoffs and consequences. As life cycle assessments (LCA) of the biofuel industry over the past 15 years have shown, first generation biofuel production (e.g. corn ethanol and soybean biodiesel which comprise most of the RFS1 and RFS2 renewable fuel category) are not as sustainable and environmentally benign as once thought because of land use change and unintended environmental consequences (Fargione et al., 2008; Landis et al., 2007; Melillo et al., 2009; Searchinger et al., 2008). Research shows that biofuel production and use can produce greenhouse gas emissions similar to those of fossil fuels because of land use change, as well as producing significant environmental impacts such as eutrophication and increased water use (Domínguez-Faus et al., 2009; Miller et al., 2007; Yang et al., 2012). Though the RFS2 intended to improve the overall sustainability of the biofuel industry, this in itself likely had the unintended consequences of stifling the growth of the biofuel industry, further delaying the increase in sustainability and independence of US transportation fuels.
It is vital to advance sustainability in all forms of production, however, the RFS2 may have pushed too hard, too soon, chilling the growth of a vital US industry. While the less-restrictive RFS1 (with requirements that undershot production) may have boosted production growth, the more-restrictive RFS2 (with requirements that eventually overshot production) may have discouraged production growth. This is an indication that RFS production requirements themselves had little effect on production, but rather the type and complexity of the regulations had more significant effects.

3.3.1. Abridged Logistic Models

To assess the RFS requirement values given the data available at the time of their releases, two abridged logistic models of biofuel production values were also produced. The 2007 abridged total US biofuel logistic model, representing the RFS1 released on May 1, 2007, was created using annual EIA data from 1995 to 2006, and the 2010 abridged total US biofuel logistic model, representing the RFS2 released on March 26, 2010, was created using annual EIA data from 1995 to 2009 (Figure 3.3). It must be noted the required production volumes in the RFS2 were actually set forth in the EISA of 2007 (Congress, 2007). However, as the EISA allows the policy administrator (i.e. the EPA) to modify the requirements based on “existing technologies [and] … the feasibility of achieving requirements,” the required production volumes of the 2010 RFS2 could have been adjusted from those in the EISA. This is evident from the 2013 revised RFS2 which essentially adjusted the 2013 volume requirements to match the anticipated 2013 production volumes and speculated future volume requirements would need to be adjusted (EPA, 2013). But as no concrete volume requirements were set beyond 2013 in the 2013 RFS2, it was not included in this analysis.

Table 3.2. Logistic Growth Curve Model Parameters and Descriptive Statistics for Annual US Biofuel Production Abridged Datasets.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Period (months)</td>
<td>1995-2009</td>
<td>1995-2006</td>
</tr>
<tr>
<td>H (billion gal/year)</td>
<td>21.27</td>
<td>9.95</td>
</tr>
<tr>
<td>L (billion gal/year)</td>
<td>1.24</td>
<td>1.14</td>
</tr>
<tr>
<td>M (year)</td>
<td>2008.82</td>
<td>2006.48</td>
</tr>
<tr>
<td>W (years)</td>
<td>2.17</td>
<td>2.25</td>
</tr>
<tr>
<td>G@M (billion gal)</td>
<td>2.31</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Table 3.2. Continued.

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>R Squared</td>
<td>0.937</td>
<td>0.155</td>
</tr>
<tr>
<td>P-value</td>
<td>&lt;0.00001</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td>Observations</td>
<td>15</td>
<td>12</td>
</tr>
</tbody>
</table>

The abridged 2007 logistic model, with a high-plateau \((H)\) of 10.0 billion gallons per year, points to RFS1 having had undershot the logistic trend, while the abridged 2010 logistic model, with a high-plateau \((H)\) of 21.3 billion gallons per year, points to RFS2 having had at first undershot, then after 2014 overshot, the logistic trend. The abridged logistic models themselves, however, were also off the mark in anticipating the settling point of the high-plateau \((H)\) of the first growth cycle of US biofuel production. Actual biofuel production growth was greater than the abridged 2007 logistic model and less than the abridged 2010 logistic model, with biofuel production data settling in-between the two abridged models, pointing to the renewable fuel standards influencing the production trends.

![Figure 3.3](image)

Figure 3.3. Annual Total US Biofuel Production, RFS Mandates, and Abridged Logistic Growth Curve Models. The 2007 abridged total US biofuel logistic model was created using production data available at the time of RFS1 (1995-2006), and the 2010 abridged total US biofuel logistic model was created with production data available at the time of RFS2 (1995-2009).
3.4. Conclusions and Policy Implications

The RFS1 mandated production values were increasingly lower than the actual production values with its final 2012 requirement of 7.5 billion gallons being nearly doubled by the actual production in 2012 of 14.2 billion gallons. If policy makers intended production at least maintain its growth rate, a production target should have been set no lower than the 2007 logistic trend had indicated, somewhere around 8.5 billion gallons in 2010 rather than the RFS1 requirement of 6.8 billion gallons in 2010. However, all things being equal, this requirement would have still been below 2010 production by over 5 billion gallons. Because the RFS1 requirements were far below the actual biofuel production values, the production requirements themselves likely had little promoting effect on US biofuel production, however, the minimal regulation of the RFS1 might have been what pushed the growth in production beyond what the 2007 logistic trend had shown (Yacobucci and Capehart, 2008).

The RFS2 total renewable fuel requirement was reached by actual annual production until 2012, but was lower than the 2010 abridged logistic trend until 2015. However, the trend of the RFS2 total renewable fuel requirement shows fairly constant growth (with an average annual increase of over 1.8 billion gallons) through to the final requirement of 36 billion gallons in 2022. After 2015 the RFS2 total renewable fuel requirement continues growing further above the 2010 abridged logistic model, even with the abridged logistic model having also overshot actual production values.

Based on the production data available at the time of RFS2 release, a target for total US biofuel production might have been set just above the 2010 logistic model high-plateau ($H$) at around 21.5 billion gallons per year in 2022. Aside from the logistic modeling, the average annual growth of total US biofuel production since 2010 was 5.3%, while the RFS2 total renewable fuel requirement requires an average annual growth of 9.4%. It is evident that since 2013 the RFS2 has failed to encourage US biofuel production growth irrespective of the mandate and 2010 logistic trend.

For greater data resolution and to explore any possible changes in production trends for the beginning of 2016, logistic models were produced with the most updated monthly EIA biofuel production data at the time of submission (through September 2016) and compared with the logistic models produced from the annual data (see Supplementary Material). The monthly data analysis revealed logistic modeling of annual data is adequate for general trend analysis as the
high-plateau \((H)\) for the monthly total US biofuel logistic model fell within 3\% of the annual total US biofuel logistic model and summed US fuel ethanol and biodiesel logistic model at 16.1 billion gallons per year. However, it was found the earlier in the growth cycle a logistic model is fit to data – with more data points and flexibility in choosing datasets – the more significant the difference between monthly and annual logistic model parameters. Furthermore, some growth in total biofuel production was observed within the available 2016 monthly data (an average 3.6\% increase from the previous year), which is a positive sign. However, it is too early to attribute this increase to a new growth cycle.

Regarding the intended reduction in GHG emissions, because the required production volumes set forth in the RFS2 have not been achieved since 2011, the corresponding reduction in GHG emissions has therefore not occurred. And with the greater GHG reductions required from advanced biofuels which have not yet increased significantly, the intended reduction in environmental impact by the RFS2 has been delayed even further. Though it is vital to continue developing sustainable biofuels, the stagnated growth suggests that biofuel production is a longer term solution to the growing problem of climate change, and that developing other technologies such as negative carbon emissions and continued efforts to increase transportation efficiency are required for more immediate results.

This analysis of the renewable fuel standards using logistic growth curve modeling suggests that requiring specific annual production volumes does little in influencing production trends. The nature of the regulations themselves can have a greater influence, as illustrated by production increasing more than expected after the less regulated RFS1 release and production stagnating after the more regulated RFS2 release which had higher mandated production values. More effective energy policy would set adjustable production targets based off of estimates of production capability rather than arbitrarily set mandated values. Logistic models provide a simple and robust method to establish more realistic energy policies and set realistic production goals. Furthermore, when setting production targets for extremely nascent technologies (with little to no production history as with advanced biofuels) policy makers might set production targets based on the previous year’s production, such as encouraging a 5\% increase from the prior year’s production value (or an increase commiserate with annually adjusted logistic models), rather than requiring indiscriminately large and continuous production increases.
As demonstrated here, the logistic equation is a valuable model tool for biofuel energy production trends, revealing US biofuel production is currently in a period of stagnated growth around 16 billion gallons per year and shortcomings in previous renewable fuel standard releases. Production of biofuel in the US will likely begin another growth cycle and increase again when advanced biofuel production technology becomes more mature, maybe even with greater growth than the original cycle. However, logistic and historical trends indicate that biofuel production is unlikely to reach the original RFS2 requirements in the future.

Acknowledgements

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3.5. References


EIA. (2016g). Crude Oil Production. from EIA


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CHAPTER FOUR

LIFE CYCLE ASSESSMENT OF SUNFLOWER CULTIVATION ON ABANDONED MINE LAND FOR BIODIESEL PRODUCTION

Modified from a paper published in the Journal of Cleaner Production

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Abstract

Producing biofuel feedstock on marginal lands is a viable way to offset fossil fuel production, global warming, and other adverse environmental impacts, while at the same time performing positive ecosystem services by reclaiming unused areas with value producing activities. This research study explored low-input production of sunflower biodiesel feedstock on abandoned mine land (AML) from coal mining refuse treated with bauxite residue (alkaline clay) through the lens of Life Cycle Assessment (LCA).

An attributional LCA was conducted from the gate of an aluminum production facility (which produces the bauxite residue), through AML amelioration and low-input agricultural activities, to the gate of a biodiesel production facility. A 26-hectare (ha) coal mine refuse pile located in Mather, PA, (91 km south of Pittsburgh), was used as an example location. Analysis of published agricultural data and greenhouse research led to a conservative sunflower oilseed yield of 500 kg/ha estimate, with a subsequent biodiesel yield of 190 kg/ha (217 l/ha).

Results show substantial impact from the initial soil amendment process, however, when compared to complete restoration of the AML and other similar fuel production activities, overall

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environmental impacts over a twenty-year production cycle are sensible. An alternative allocation of the bauxite residue transport (i.e. associating transport impacts to aluminum industry) and addition of other fuel conversion pathways would show an improved energy return and better environmental outlook from biofuel production on AML.

4.1. Introduction

Environmental impacts of modern human activity continue to grow at rates incompatible with sustainable development. Among the most complex impacts are global climate change, ecosystem deterioration, and resource depletion. Abandoned mine lands (AML) and associated refuse piles contribute to local ecosystems deterioration, while expanded use of fossil fuels depletes petroleum resources while simultaneously adding to greenhouse gas emissions (Worrall et al., 2009). A body of literature on the capability of biofuels cultivated using traditional agricultural techniques to reduce greenhouse gas emissions and offset fossil fuel use exists – more recently on second and third generation biofuel feedstocks, including cellulosic biomass and algae (Singh and Singh, 2010). However, as of 2015, there were no publications on the subject of biofuel cultivation on AML.

AML and associated refuse piles, also known as legacy mine land (collectively AML for the purposes of this paper, but not to include slurry containment areas) occupy over 600,000 sites and 3 million hectares in the United States (BLM, 2013; Mining, 2002; Worrall et al., 2009). Acid and toxic mine drainage, resulting in severe ecosystem deterioration, is one of the major consequences of AML which plagues ecosystems and watersheds (Worrall et al., 2009). Acid mine drainage (AMD) creates acidic runoff in the range of 2.2-3.5 pH that completely destroys local ecosystems and hinders regional economic development (Sheoran et al., 2010). Current regulations by the EPA – including the Surface Mining Control and Reclamation Act of 1977 (SMCRA) and Clean Water Act of 1972 (CWA) – require mining companies to follow “standards to minimize damage to the environment and to productivity of the soil and to protect the health and safety of the public” (Interior, 2012). Despite these regulatory changes in the ‘70s, many locations from decades and even centuries past, most in the eastern mining district in the Appalachian states, are still in need of reclamation, remediation, or other value creating activity (Ditsele and AwuahOffei, 2012; Powell, 1988; Wei et al., 2011).
AML have the potential for economic, recreational and esthetic use, by recognizing the unique potential of the marginal land by using sustainable technologies and measures for transformation (Cao, 2007). The EPA has been successfully experimenting with producing biofuels on AMLs in “sustainable energy parks” (Butler et al., 2013). Studies in Appalachia have shown that apt reclamation practices improved water quality in nearby watersheds over time (Wei et al., 2011). Phytostabilization has been proposed as a low-cost method for reducing the mobility of heavy metals in marginal lands by strategic plant growth (Conesa and Faz, 2011). It has also been proposed that the industrial ecology methodology, including the integrated biotechnological approach, can enhance the restoration of AMLs by using waste streams from other industries to treat the soil (Chen et al., 2013; Deng, 2013; Juwarkar et al., 2010; Mercuri et al., 2005).

The methods for treatment of AML and acid mine drainage (AMD) include both active and passive methods (Sheoran et al., 2010). The most common method is to cover the polluted area with a layer of soil and passively allow the local biota to reclaim the land. Composts, manure, biochar and other organic materials have also been proposed as passive soil amendments to increase the productivity of AML and other marginal lands (Beesley et al., 2011; Fellet et al., 2011). The typical active acidic soil neutralization technique used by the agricultural industry, liming the soil, is known to have negative environmental impacts including metallic sludge runoff and continuing treatment requirements (Johnson and Hallberg, 2005).

Another method of neutralizing AML acidic soil – using concepts of industrial symbiosis and byproduct synergies – is to utilize alkaline wastes from other industries to mix with and amend the soil. Bauxite residue is an alkaline, high pH, clay substance generated as a byproduct from bauxite mining and the aluminum industry. Bauxite is an aluminum ore used to produce commercial aluminum. Alcoa Inc. demonstrated that high pH value (10-12) and alkalinity of bauxite residue can neutralize the acidity (pH < 5.5) of the coal mine refuse by mixing the two co-products, allowing resilient plants to germinate and develop successfully at an AML site near Mather, PA (Alcoa, 2010; MSDS, 2007). However, the Alcoa study only used typical reclamation plants (such as Lygeum spartum, Piptatherum miliaecum and Helichrysum decumbens), not evaluating the feasibility of biofuel feedstock cultivation on AML (Conesa and Faz, 2011). Conversely, the EPA sponsored several projects under their Superfund Redevelopment Initiative and the RE-Powering America's Land Initiative, which focuses on
biofuel and renewable energy on contaminated lands (EPA, 2011). Research has shown that bioenergy crops cultivated on brownfields do not have significantly different yields than on other agricultural lands (Smith et al., 2013). This study brings the two concepts together.

A refuse pile occupying approximately 26 ha of land near the small town of Mather in southwest Pennsylvania was produced from a coal mine closed in 1965 (Alcoa, 2010; GoogleEarthPro, 2014). The Mather coal mine refuse pile is also known for its severe AMD and ecosystem deterioration, resulting in rivers colored red as seen in Figure 4.1, since the mine closure and abandonment in the 1960s (Deng, 2013; McCaa and Howarth, 1928). The refuse pile has gone through several phases of reprocessing (dismantling onsite buildings, covering of a creosote plume, railroad tie removal, and grading) and agricultural experimentation with limited reclamation success (Alcoa, 2010; Matesic, 2013).

![Figure 4.1. Mather coal mine refuse pile in 2013. After minor reclamation; map showing location of Mather, PA, 91 km south of Pittsburgh; Mather Coal Mine Refuse Pile in 2006 with acid mine drainage (AMD) visible as brown pool of water.](image)

A greenhouse experiment was conducted at University of Pittsburgh, PA (Pitt) and was focused on biofuel feedstock phytotransmission of metal contaminants found in the coal mine refuse; while a greenhouse experiment at Arizona State University, AZ (ASU) was to test the growth of several biofuel feedstock plant species on a soil treatment with 10% by volume bauxite residue (aka alkaline clay) mixed with coal mine refuse collected from the Mather site, compared to respective growth in commercial topsoil. The aim of the ASU greenhouse study was to determine if feedstock growth was possible in the treated soil. As seen in Figure 4.2, four biofuel plant species showed adequate growth on the AML refuse treated with bauxite residue: sunflower, sorghum, canola, and camelina, while the control showed none.
Figure 4. 2. Growth of biofuel feedstock on bauxite residue treated coal mine refuse. Photos from the informal ASU greenhouse experiment of pure Mather coal mine refuse with no growth compared to biofuel feedstock grown in 1:9 bauxite residue treated coal mine refuse. Feedstocks sown from commercial seed were sunflower, sorghum, canola, and camelina.

There has been a surge in research on biofuel feedstock cultivation on marginal lands because of the “food, energy and environment trilemma” (Ajanovic, 2011; Butterbach-Bahl and Kiese, 2013). By producing biofuel on marginal lands, food production will not be offset by biofuel feedstock production, fossil fuel depletion may be reduced, global warming may be mitigated, and other environmental impacts removed. However, to gain these benefits, several constraints must be employed: energy consumption through agricultural production must be minimized, local biofuel production facilities must be available, and appropriate feedstock must be produced (Gelfand et al., 2013; Iglesias et al., 2012; Johnson et al., 2013). The proper choice of feedstock is one of the most important factors for the viability and sustainability of biofuel cultivation on AML. Some considerations are yield, low agricultural input demands, tolerance to unfavorable conditions, plant root penetration, soil carbon sequestration potential, and beneficial ecosystem services (Braimoh and Vlek, 2008; Cherubini et al., 2009; Yusuf et al., 2011).

Sunflower (Helianthus annuus L.) was a valid selection and has proved successful for biofuel feedstock production on marginal lands (Niblick et al., 2013; Olson and Fletcher, 2000; Zhao et al., 2014). One study has even shown that on mine polluted lands, oil content of sunflower seeds is greater than that of sunflower grown in nearby non-polluted areas, and measured levels of toxic elements in the plant matter were below those harmful to plants, animals, and humans (Madejon et al., 2003 ). The sunflower plant is extremely resilient with relatively high tolerance to drought, salinity, trace element contamination, and other agricultural stresses (NSA, 2010).
The goal of this study was to explore one possible novel, sustainable, and valuable use of abandoned mine lands (AML), particularly the cultivation of sunflower as a biodiesel feedstock on bauxite residue treated coal AML, via Life Cycle Assessment (LCA) methodologies. A legacy coal mine refuse pile located near Mather, PA, was used as a reference site to determine the feasibility of treating the acidic abandoned coal mine lands with industrial coproducts, namely bauxite residue from aluminum production, to neutralize the soil and safely enable biofuel feedstock cultivation.

LCA is a quantitative tool used to evaluate environmental performance of products, services and processes, provide quantitative and aggregated information to decision makers, select environmental indicators and measurement techniques, and in some cases to help market products as environmentally sound (Hunt et al., 1996; ISO, 2006a,b). LCA is the ideal tool for evaluating the feasibility of cultivating biofuel feedstocks on AML because of its ability to foresee unintended environmental impacts, allow decision makers to choose the best course of action and minimize negative consequences and tradeoffs (Cherubini et al., 2009; Sanz Requena et al., 2011). LCAs demonstrated environmental impacts from first generation biofuels (i.e. corn ethanol and soybean biodiesel) were arguably just as bad, or worse, than petroleum production itself, inspiring the US Environmental Protection Agency's (EPA) push away from generation one biofuels in the 2010 Renewable Fuel Standard (RFS2) (Davis et al., 2013; Landis et al., 2007).

Additionally, in order to fully evaluate the feasibility of this process it is vital to review the various environmental health and safety (EHS) regulations that may apply and examine potential impacts. As such, Section 3.7 Regulatory Review is a standard regulatory review and due diligence of the regulations that would likely apply. And though the EPA RFS2 does not credit biofuel crops grown on AML as “renewable biomass” (due to the requirement that land be “agricultural land cleared prior to December 19, 2007 and actively managed or fallow on that date”), the cultivation of feedstock on AML or other marginal lands is lawful and could contribute to increased renewable fuels in the US, furthermore, EPA policy should be adjusted to credit biofuel feedstock cultivation on marginal lands (EPA, 2010; Morrison, 2011).
4.2. Material and methods

This LCA was conducted to determine if cultivating and processing biodiesel from oilseed sunflower feedstock using sustainable or low-input dryland agricultural practices on abandoned coal mine refuse, mixed with 10% bauxite residue, is beneficial from a life cycle perspective. Using the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), this LCA evaluated environmental impacts resulting from the entire sunflower cultivation and biodiesel production cycle, and also developed an energy outlook. This use of AML was then compared to traditional restoration of the site, complete removal of all the coal mine refuse, and to other biodiesel production methods.

A legacy coal mine refuse pile located in Mather, PA served as a reference to conduct a gate-to-gate, process-based, attributional LCA examining sunflower biodiesel feedstock cultivation on treated AML and subsequent biodiesel production. An allocation approach was taken while conducting the LCA; that is, quantitative inputs and outputs for each unit process within the system boundary (Figure 4.3) were determined and environmental impacts were attributed to the respective processes and materials.

The functional unit for the LCA was biodiesel production per unit area of AML in kilograms (and liters) of fuel per hectare (kg/ha and l/ha). Biodiesel production per unit area was chosen rather than per quantity of fuel because the use of the land was the primary element of investigation. This study used two timeframes for analysis, reviewing the cumulative first year and twentieth year impacts, both including the initial land amelioration and bauxite residue transport. Kilograms, or mass, of biodiesel was chosen for ease in modeling but liters, or volume, of biodiesel was also calculated per literature standard.

The system boundary began at the tailpipe of an aluminum processing facility (which produces the bauxite residue used as a soil amendment) and the tailpipe of a coal mining operation (which produced the coal mine refuse pile), and ended at the gate of the biodiesel production facility (Figure 4.3). This study did not include use of the fuel. The main system boundary included five system processes: land amelioration, seed preparation, pest control, agricultural production, and biofuel production. Land preparation included two unit (or subsystem) processes: transportation of alkaline clay and the mixing of the alkaline clay with the mine tailings. Agricultural preparation included four unit processes: seed manufacture, seed transportation, pre-planting irrigation, and seed sowing. Pest control included three unit
processes: pest control substance manufacture, pest control substance transportation, and pest control substance application. Agricultural production included three unit processes: harvesting, drying, and storage. Biofuel production included three unit processes: transportation, oil extraction and biofuel processing. The alternate scenario of complete removal of the coal mine refuse from the site included two unit processes: refuse extraction and refuse transportation to landfill.

Life Cycle Impact Assessment (LCIA) was completed using the TRACI 2.1 V1.01 impact characterization and evaluation method (Bare, 2011). Ten primary TRACI impacts (ozone depletion, global warming, smog, acidification, eutrophication, carcinogens, non carcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion) were calculated and analyzed for this study. However, there were several impact characterization and evaluation methods available in
addition to TRACI, thus a sensitivity analysis was completed using several other LCIA methods including ReCiPe Midpoint V1.08, and BEES þ V4.03. Results of the analysis showed minimal variation between the LCIA methods.

Major assumptions of the LCA included:

- Because results from the Pitt greenhouse study on metal uptake into above ground plant matter showed that phytotransmission of pollutants was negligible per harvest and would not cause any health hazards to humans or animals, no additional impact from phytotransmission was considered.
- There would be a 40% yield reduction of sunflower oilseed grown on bauxite residue treated coal mine refuse as determined by the ASU greenhouse experiment.
- The nearest biodiesel processing facility to Mather was located in Pittsburgh, PA. This facility could incorporate the additional feedstock produced from the AML without any major expansion to the facility.
- There are many forms of transportation possible, for simplification a >32 ton lorry (flatbed truck) was used for modeling impacts from bauxite residue transport, and a 16e32 ton lorry was used for all other transport modeling. A sensitivity analysis was conducted on several other transport processes available in the ecoinvent 3 database and can be seen in 4.1 Transportation Analysis.
- Labor (including training and personal protective equipment) only causes negligible impact, and thus left outside the system boundary per literature standard.

It was assumed that no special agricultural practices would be required for growing biofuel on AML other than the preliminary soil amelioration, that is, no further amelioration would be necessary beyond the initial treatment with 10% bauxite residue to permanently neutralize the soil. Additionally, there are no specific regulations (e.g. Toxic Substances Control Act, Resource Conservation and Recovery Act, and Comprehensive Environmental Response, Compensation, and Liability Act) regarding the handling, transporting, or working near either coal mine refuse or bauxite residue, as both materials are relatively inert, provide minimal health hazards, and can be disposed of as non-hazardous solid waste (MSDS, 2006, 2007). A complete regulatory review was conducted to determine which regulations would impact the results of this study (see 4.3.7 Regulatory Review).
This study did not take into consideration direct or indirect land use change. Since AMLs are not being used for any productive activity, biological activity is at a minimum, and soil organic carbon levels are negligible, there would be minimal direct land use change, and if there were, it would most likely result in positive environmental impact (Vazquez-Rowe et al., 2013). For indirect land use change, any impact would also be minor and likely positive (Aoun et al., 2013).

Sensitivity analyses were conducted on several aspects of this study which demonstrated the greatest possible variation in results; these included sunflower feedstock yield, biodiesel energy content, and transportation processes selected from the ecoinvent database. As detailed in 4.3 Life Cycle Inventory (LCI), a conservative yield estimate was chosen for the LCA, however, to understand the range of potential outcomes resulting from changes in yield, high and low estimates were also evaluated to determine the sensitivity of the results to the yield. There was also a wide range of biodiesel energy-content data. The lowest of the lower heating values was used in the model while the highest of the lower heating values was used for sensitivity analysis. And because transportation caused some of the largest environmental impacts (as seen in 4.4 Results and Discussion), comparisons were made for several possible transportation processes from the ecoinvent 3 database, including different size trucks using different fuel types.

### 4.3. Life Cycle Inventory (LCI)

Data was collected mainly through peer reviewed publications, governmental agricultural data, and LCI databases (e.g. ecoinvent 3). Inventory data collection is described in subsequent sections, following the process flow diagram in Figure 4.3 from upstream data collection through soil amendment, agricultural practices, harvesting, and biofuel conversion processes. Table 4.1 summarizes the inventory.

<table>
<thead>
<tr>
<th>Data description</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area Functional Unit</td>
<td>1</td>
<td>Hectare</td>
<td></td>
</tr>
<tr>
<td>Bauxite Residue to Coal Mine Refuse Ratio</td>
<td>1:9</td>
<td>Ratio by Volume</td>
<td>ASU Greenhouse Experiment</td>
</tr>
<tr>
<td>Deep Plough Depth</td>
<td>0.43</td>
<td>Meters</td>
<td>(Botta et al., 2006)</td>
</tr>
<tr>
<td>Area per Hectare</td>
<td>10,000</td>
<td>Square Meters per Hectare</td>
<td>Google Unit Converter</td>
</tr>
<tr>
<td>Bauxite Residue Volume per Hectare</td>
<td>4300</td>
<td>Cubic Meters per Hectare</td>
<td>(MSDS, 2007)</td>
</tr>
<tr>
<td>Bauxite Residue Density</td>
<td>860</td>
<td>Kilograms per Cubic Meter</td>
<td>(Husted, 1994; Malgeryd and Wetterberg, 1996)</td>
</tr>
<tr>
<td>Bauxite Residue Mass per Hectare</td>
<td>371</td>
<td>Metric Tons</td>
<td></td>
</tr>
<tr>
<td>Ravenswood, WV to Mather, PA</td>
<td>266</td>
<td>Kilometers</td>
<td>Google Earth</td>
</tr>
<tr>
<td>Average Solid Manure Density</td>
<td>675e715</td>
<td>Kilograms per Cubic Meter</td>
<td>(Husted, 1994; Malgeryd and Wetterberg, 1996)</td>
</tr>
</tbody>
</table>
Table 4.1. Continued.

<table>
<thead>
<tr>
<th>Data description</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunflower Plant Density</td>
<td>25,000</td>
<td>Plants per Hectare</td>
<td>(Alessi et al., 1977; Jones, 1978, 1984; Villalobos et al., 1994)</td>
</tr>
<tr>
<td>Sunflower Seeds for Sowing per Hectare</td>
<td>50,000</td>
<td>Seeds per Hectare</td>
<td>(Alessi et al., 1977)</td>
</tr>
<tr>
<td>Sunflower Seed Mass</td>
<td>0.06</td>
<td>Grams</td>
<td>(Goksoy et al., 2004; Gupta and Das, 1997; Karam et al., 2007)</td>
</tr>
<tr>
<td>Mass of Sunflower Seeds for Sowing per Hectare</td>
<td>3</td>
<td>Kilograms per Hectare</td>
<td></td>
</tr>
<tr>
<td>North Dakota Center to Mather, PA</td>
<td>2235</td>
<td>Kilometers</td>
<td>Google Earth</td>
</tr>
<tr>
<td>Wayne, NJ to Mather, PA</td>
<td>601</td>
<td>Kilometers</td>
<td>Google Earth</td>
</tr>
<tr>
<td>Reduced Yield Estimate</td>
<td>40</td>
<td>Percent</td>
<td>ASU Greenhouse Experiment</td>
</tr>
<tr>
<td>US Average Dryland Sunflower Oilseed Yield</td>
<td>1354</td>
<td>Kilograms per Hectare</td>
<td>See 3.4 Agricultural Production</td>
</tr>
<tr>
<td>High Sunflower on AML Yield Estimate (60% US Dryland)</td>
<td>812</td>
<td>Kilograms per Hectare</td>
<td></td>
</tr>
<tr>
<td>Sunflower on AML Yield Estimate</td>
<td>500</td>
<td>Kilograms per Hectare</td>
<td></td>
</tr>
<tr>
<td>Low Sunflower on AML Yield Estimate</td>
<td>56</td>
<td>Kilograms per Hectare</td>
<td>(Niblick et al., 2013)</td>
</tr>
<tr>
<td>US Average Sunflower Oilseed Oil Content</td>
<td>42.2</td>
<td>Percent</td>
<td>NSA, 2013</td>
</tr>
<tr>
<td>Sunflower Oil Density</td>
<td>0.92</td>
<td>Kilograms per Liter</td>
<td>(Singh and Singh, 2010)</td>
</tr>
<tr>
<td>Sunflower Biodiesel Density</td>
<td>0.86</td>
<td>Kilograms per Liter</td>
<td>(Singh and Singh, 2010)</td>
</tr>
<tr>
<td>Sunflower Oilsed Density (at 20% Moisture Content)</td>
<td>765</td>
<td>Kilograms per Cubic Meter</td>
<td>(Gupta and Das, 1997)</td>
</tr>
<tr>
<td>Pittsburgh, PA to Mather, PA</td>
<td>91</td>
<td>Kilometers</td>
<td>Google Earth</td>
</tr>
<tr>
<td>Sunflower Oil Yield per Hectare</td>
<td>211</td>
<td>Kilograms per Hectare</td>
<td></td>
</tr>
<tr>
<td>Sunflower Oil to Biodiesel Transeseification Efficiency</td>
<td>90</td>
<td>Percent</td>
<td>(Singh and Singh, 2010)</td>
</tr>
<tr>
<td>Sunflower Biodiesel Yield per Hectare</td>
<td>190</td>
<td>Kilograms per Hectare</td>
<td></td>
</tr>
<tr>
<td>Sunflower Biodiesel Yield per Hectare</td>
<td>231</td>
<td>Liters</td>
<td>(Singh and Singh, 2010)</td>
</tr>
<tr>
<td>Biodiesel Lower Heating Value</td>
<td>32.6</td>
<td>Megajoules per Liter</td>
<td>(Singh and Singh, 2010)</td>
</tr>
<tr>
<td>Biodiesel Higher Heating Value</td>
<td>47.4</td>
<td>Megajoules per Liter</td>
<td>(EIA, 2014)</td>
</tr>
<tr>
<td>Mather Coal Mine Refuse Volume</td>
<td>2.3</td>
<td>Million Cubic Meters</td>
<td>(Alcoa, 2010)</td>
</tr>
<tr>
<td>Area of Mather Coal Mine Refuse Pile</td>
<td>26</td>
<td>Hectares</td>
<td>Google Earth Pro</td>
</tr>
<tr>
<td>Mather Coal Mine Refuse Volume per Hectare</td>
<td>99,567</td>
<td>Cubic Meters per Hectare</td>
<td></td>
</tr>
<tr>
<td>Coal Mine Refuse Density</td>
<td>2630</td>
<td>Kilograms per Cubic Meter</td>
<td>(MSDS, 2006)</td>
</tr>
<tr>
<td>Mather Coal Mine Refuse Mass per Hectare</td>
<td>262</td>
<td>Million Kilograms per Hectare</td>
<td></td>
</tr>
<tr>
<td>Mather, PA to Chestnut Valley Landfill, PA</td>
<td>27</td>
<td>Kilometers</td>
<td>Google Earth</td>
</tr>
</tbody>
</table>

4.3.1. Land amelioration

Mixing of the bauxite residue with the coal mine refuse was at a ratio of 1:9 by volume (3.4 Agricultural Production) and at a deep plough depth of 0.43 m (1700). For one hectare of area (10,000 m²), the amount needed to reach a bauxite residue volume of 10% is 4300 cubic meters (m³). With a density of 860 kg/m³ (0.86 g/cm³ 10⁶ cm³/m³ 0.001 kg/g) the mass of bauxite clay required is 371,348 kg (MSDS, 2007). The nearest aluminum processing facility to the Mather mine is 266 km (165 mi) away in Ravenswood, WV, resulting in a shipping value of 98,608 tkm/ha (metric tonkilometers per hectare).

The process selected for the spreading of bauxite residue in the ecoinvent 3 database was loading and spreading of solid manure. One study reported solid manure densities ranging from 550 to 800 kg/m³ (0.55e0.8 kg/l to 1000 l/m³) depending on the animal source with an average of 675 kg/m³ (Husted, 1994). Another study showed a wider range of densities between 400 and 1030 kg/m³ with an average of 715 kg/m³ (Malgerdy and Wetterberg, 1996). These values are similar to the density of alkaline clay (860 kg/m³), thus the loading and spreading of solid
manure processes could adequately represent spreading the bauxite residue amendment (and wear on the machinery from alkaline clay would produce negligible additional impact). In order to produce sufficient mixing of the materials, two individual deep plow runs were required (Velykis and Satkus, 2010). As one hectare is 10,000 m², two plow runs per hectare covers an area of 20,000 m².

4.3.2. Seed preparation

Many studies of optimal sunflower plant density have been conducted with a general consensus that 25,000 plants per hectare is appropriate (Alessi et al., 1977; Jones, 1978, 1984; Villalobos et al., 1994). Using hybrid seeds for optimal growth, seeds for sowing must be purchased on an annual basis per standard agricultural practice. For a density of 25,000 plants per hectare, approximately 50,000 seeds must be sown per hectare assuming a conservative germination rate (Alessi et al., 1977). With a seed mass of 0.06 g (3.5 Biodiesel Production), each hectare required 3 kg of seeds to be purchased and sown annually per hectare. Since the majority of sunflower production is done in North Dakota, the seeds for sowing were modeled to be transported from there. The distance from the center of North Dakota to Mather, PA is 2235.4 km (1389 mi) thus the shipping value was 6.7 tkm/ha. Seed sowing over one hectare requires 10,000 m² of sowing.

4.3.3. Excluded agricultural processes

Typical intensive agricultural practices focus solely on high yield output by tilling between crop cycles, adding nitrogen, phosphorus and potassium (N, P, & K) fertilizers before and during crop cycles, irrigating prior to planting and during crop cycles, and applying multiple pesticides before and during crop cycles (Tilman et al., 2002). Because this study chose to minimize environmental impacts by using low-input agricultural practices, these techniques were evaluated to determine which, if any, were vital in providing adequate yield.

Sunflower production is often conducted under dryland conditions worldwide; that is, grown without any irrigation besides rainfall (Cox and Jolliff, 1986; Goksoy et al., 2004; Jones, 1984; Karam et al., 2007; Monotti, 2003; Unger, 1980). In the Midwestern region, there is regular rainfall and irrigation is often not needed (USDA, 2008). Therefore, this study considered
irrigation unnecessary for sunflower growth in Mather, PA, as irrigation would also cause additional environmental impact (Goglio et al., 2012).

Studies conducted on dryland tillage systems showed little sunflower yield response to increased tillage practices (Bonciarelli, 2001; Martínez-Mena et al., 2013; Monotti, 2003). It has also been shown that no-till practices can sequester 1.22 metric tons of CO$_2$ equivalent per hectare per year (Post et al., 2012). Therefore this study used non-till cultivation procedures beyond the initial mixing of bauxite residue.

Studies conducted on sunflower fertilization revealed little response to both nitrogen and phosphorus, and even reduced oil yield of higher nitrogen levels (Geleta et al., 1997; Lewis et al., 1991; Zubriski and Zimmerman, 1974). Additionally, the ASU greenhouse experiment showed no additional growth of the sunflower plants in the bauxite residue/mine refuse with added fertilizer. Therefore this study did not include the addition of any fertilizer as its use would cause additional environmental impact (Geleta et al., 1997; Goglio et al., 2012; Sanz Requena et al., 2011).

4.3.4. Pest control

Like any crop, there are diseases and pests that can negatively affect the sunflower plant. These ailments are typically managed with pesticides (i.e. insecticides and herbicides). Two of the most common problems are the sunflower moth that then results in sclerotinia/rhizopus head rot (Jones, 1984; Meyer, 1999; Unger, 1980). The most common insecticide used for moth control was methyl parathion at a rate of 0.6 kg/ha. Another commonly used pesticide for sunflower production was linuron, but because of the high impacts and side effects associated with this product it was not considered for this study (Iriarte et al., 2010; Sanz Requena et al., 2011). The nearest production facility which manufactures methyl parathion was located in Wayne, NJ, 601 km (373 mi) away from Mather, PA (MSDS, 2005). The shipping value was then 0.36 tkm/ha. There was no ecoinvent data for the manufacture of methyl parathion in the database. However, there was generic pesticide production data in the ecoinvent 3 database which was used for the model. Commonly used herbicides applied to sunflower fields included Eptam, trifluralin and profluralin (Alessi et al., 1977; Jones, 1978; Meyer, 1999; Unger, 1980). Because weeds were less likely to grow on marginal lands such as AML and herbicide
manufacture and use would add environmental impact, weed control was not considered necessary for this study. Pest control over one hectare requires 10,000 m\(^2\) of application.

4.3.5. Agricultural production

Combine harvesting includes cutting, threshing, separating, cleaning, and collecting of the sunflower seeds (Tiwari and Singh, 2012). Studies have shown that the use of a combine harvester was significantly more efficient than traditional or manual harvesting (Hassena et al., 2000; Stan et al., 2013). Therefore the combine harvester within the ecoinvent 3 database was used in the model. Cultivation over one hectare requires 10,000 m\(^2\) of harvesting. For grain storage procedures, studies have demonstrated that hermetically sealed silos provide adequate pest control without the use of pesticides, significantly reducing grain loss (Gitonga et al., 2013; Tefera et al., 2011). Therefore the no ventilation storage of grain process found in the ecoinvent 3 database was used.

Most sunflower farming in the US was done in the Great Plains region due to the draught tolerant nature of the sunflower plant and most literature on the yield and production details of sunflower cultivation in the United States came from that region (NSA, 2010). The US dryland average yield was determined to be 1354 kg/ha (Alessi et al., 1977; Cox and Jolliff, 1986; Frickel et al., 2002; Jones, 1978, 1984; NSA, 2010). Results from the informal ASU greenhouse experiment cultivating sunflowers in a Mather coal mine refuse/bauxite residue mix showed an approximate 40% reduction in seed yield when compared to the sunflower grown in commercial soil. Using the reduced growth factor with the US dryland average, the seed yield on dryland bauxite residue treated coal mine refuse would reasonably be 812 kg/ha.

Dryland seed yield data from sunflower grown on marginal lands in the Pittsburgh, PA, area was drastically lower at 56 kg/ha (Niblick et al., 2013). However, optimizing yield was not of primary concern to the study at the time (Troy Hottle, one of this paper's coauthors, was a project manager who worked directly on these research sites). Thus, an average seed yield of 500 kg/ha was chosen as a conservative estimate for oilseed sunflower cultivation on bauxite residue treated abandoned coal mine refuse in Mather, Pennsylvania. For sensitivity analysis, given the data discussed above an upper yield limit of 812 kg/ha and lower yield limit of 56 kg/ha were chosen.
4.3.6. Biodiesel production

Oil content of the oilseed sunflower seed generally ranges from 39 to 49% by mass (Putnam et al., 1990). The average US sunflower oilseed oil content over the last 6 years was 42.2% (NSA, 2013). The density of sunflower oil is 0.916 kg/l while the density of biodiesel produced from sunflower oil through transesterification is 0.860 kg/l (Singh and Singh, 2010). Sunflower seed density at 20% moisture content is 765 kg/m³ and at 4% moisture content is 706 kg/m³ (Gupta and Das, 1997). Thus 500 kg of sunflower seeds at the harvesting moisture content of 20% will occupy a volume of 0.65 m³. The mass of an individual seed depends on many variables (hybrid type, moisture content, location of seed on plant flower head, etc.) but ranges between 0.05 and 0.08 g with a mean of 0.06 g (Goksoy et al., 2004; Gupta and Das, 1997; Karam et al., 2007).

Prior to transesterification, the oil must be separated from the solid parts of the seed, known as the meal. There was no ecoinvent data specifically for sunflower oil extraction, however, there was data for soybean oil extraction and for biodiesel production processes through transesterification of soybean oil. Since soybean and soybean oil are similar in size and properties to sunflower seed and oil, respectively, soybean oil extraction and biodiesel production processes were used to estimate the impacts for sunflower seed processing and conversion to biodiesel (Singh and Singh, 2010).

The nearest biofuel production facility to Mather is in Pittsburgh, 91 km away. With a yield of 500 kg the shipping value used in the model was 45.5 tkm/ha. At an oil content of 42.2%, 500 kg of seeds would produce approximately 211 kg of vegetable oil. Though there are several different processes for converting sunflower seed oil into biodiesel, the most common method, enzymatic transesterification using methanol generally has a conversion efficiency around 90% (Singh and Singh, 2010). At a 90% conversion efficiency, 211 kg of oil would produce approximately 189.9 kg of biodiesel.

Depending on the data source, there was a wide range in values of the energy content of biodiesel. One study reported a lower heating value of 32.6 MJ/l (117,093 BTU/gal) for biodiesel produced from sunflower oil (Singh and Singh, 2010). Another study reported the higher heating value between 33.7 and 34.9 MJ/l (39.2-40.6 MJ/kg) (Yusuf et al., 2011). While the US Energy Information Administration (EIA) reported two biodiesel energy content values: 34.5 and 47.4 MJ/L depending on units reported (5.359 MBTU/barrel and 17,253 BTU/lb) (EIA, 2014). The
lowest of the values, 32.6 MJ/L, was used in the model, while the higher value of 47.4 MJ/l was used for sensitivity analysis.

### 4.3.6.1. Sunflower and biodiesel coproducts

Coproducts resulting from the entire system processes included cellulosic biomass, press cake (meal), soap, and glycerol (Iglesias et al., 2012; Sanz Requena et al., 2011). Even though studies show negligible phytotransmission of hazardous materials, the positive offsets from the use of these coproducts were not considered in this study. Per agricultural best practices, sunflower stover (stalks) were left on the field for soil health, but any related carbon or nutrient benefits and offsets resulting in greenhouse gas reduction and feedstock yield increases were not included either.

### 4.3.7. Refuse excavation and transportation (alternate scenario)

Alcoa reported the volume of coal refuse at the Mather site to be 2.3 million m$^3$ (Alcoa, 2010). With a coal mine slag density of 2630 kg/m$^3$, the mass of the Mather coal mine slag pile is 6 million metric tons (MSDS, 2006). The average volume and mass per hectare was 88,462 m$^3$ and 232,654 metric tons, respectively. The nearest landfill to Mather is in Chestnut Valley Landfill, PA, 27.4 km (18 miles) away, thus the shipping value of mine slag removal was 6,739,563 tkm/ha. Table 4.2 summarizes the life cycle inventory reference flows and ecoinvent 3 processes.

Table 4.2. Life cycle inventory reference flow data with ecoinvent 3 processes used for modeling scenarios and normalization. Abbreviations include: RoW - rest of world data (outside Europe); US - United States data; GLO - global data; Alloc Def, U - allocation default unit process (opposed to consequential and system processes). Values in table are bold in 3 Calculations (Life Cycle Inventory (LCI)).

<table>
<thead>
<tr>
<th>Land amelioration</th>
<th>Reference flow</th>
<th>Unit</th>
<th>ecoinvent 3 process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport of Alkaline Clay</td>
<td>98,608</td>
<td>tkm</td>
<td>Transport, freight, lorry &gt;32 metric ton, EURO5 (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Spreading of Alkaline Clay</td>
<td>371,348</td>
<td>kg</td>
<td>Solid manure loading and spreading, by hydraulic loader and spreader (RoW)</td>
</tr>
<tr>
<td>Mixing of Alkaline Clay</td>
<td>20,000</td>
<td>m$^2$</td>
<td>Tillage, ploughing (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Seed preparation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed Manufacturing</td>
<td>3</td>
<td>kg</td>
<td>Sunflower seed, for sowing (GLO) Alloc Def, U</td>
</tr>
<tr>
<td>Seed Transport</td>
<td>6.7</td>
<td>tkm</td>
<td>Transport, freight, lorry 16x32 metric ton, EURO5 (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Seed Sowing</td>
<td>10,000</td>
<td>m$^2$</td>
<td>Sowing (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Pest control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pest Control Manufacturing</td>
<td>0.6</td>
<td>kg</td>
<td>Pesticide, unspecified (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Pest Control Transportation</td>
<td>0.36</td>
<td>tkm</td>
<td>Transport, freight, lorry 16x32 metric ton, EURO5 (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Pest Control Application</td>
<td>10,000</td>
<td>m$^2$</td>
<td>Application of plant protection product, by field sprayer (RoW) Alloc Def, U</td>
</tr>
</tbody>
</table>
Table 4.2. Continued.

<table>
<thead>
<tr>
<th>Land amelioration</th>
<th>Reference flow</th>
<th>Unit</th>
<th>ecoinvent 3 process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural production</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harvesting</td>
<td>10,000</td>
<td>m$^2$</td>
<td>Combine harvesting (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Drying</td>
<td>0.65</td>
<td>m$^3$</td>
<td>Drying of bread grain, seed and legumes (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Storage</td>
<td>500</td>
<td>kg</td>
<td>Operation, dried roughage store, non ventilated (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Biofuel production</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feedstock Transportation</td>
<td>45.5</td>
<td>tkm</td>
<td>Transport, freight, lorry 16/32 metric ton, EURO5 (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Oil Extraction</td>
<td>211</td>
<td>kg</td>
<td>Soybean oil, crude (US) soybean meal and crude oil production, Alloc Def, U</td>
</tr>
<tr>
<td>Transesterification</td>
<td>189.9</td>
<td>kg</td>
<td>Vegetable oil methyl ester (US) esterification of soybean oil, Alloc Def, U</td>
</tr>
<tr>
<td>Alternate scenario</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refuse Extraction</td>
<td>88,462</td>
<td></td>
<td>Excavation, hydraulic digger (RoW) processing j Alloc Def, U</td>
</tr>
<tr>
<td>Refuse Transport</td>
<td>6,739,563</td>
<td>m$^3$tkm</td>
<td>Transport, freight, lorry &gt;32 metric ton, EURO5 (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Normalization processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean Biodiesel Production</td>
<td>189.9</td>
<td>kg</td>
<td>Vegetable oil methyl ester (US) esterification of soybean oil, Alloc Def, U</td>
</tr>
<tr>
<td>Petroleum Diesel Production</td>
<td>189.9</td>
<td>kg</td>
<td>Diesel, low-sulfur (RoW) production, Alloc Def, U</td>
</tr>
</tbody>
</table>

4.3.8. **Regulatory review**

A thorough regulatory review and due diligence of regulations that apply to the use of coal mine refuse and bauxite residue was conducted with co-author and EHS professional Jonathan Klane (M.S.Ed., CIH, CSP, CHMM, CET). Both general and specific environmental health and safety (EHS) regulations were reviewed and examined across the spectrum of regulating bodies, regulations, and general practices. Table 4.3 summarizes the findings of this regulatory review. The overall finding of the regulatory review and due diligence is that negligible change in LCIA, if any, would result from compliance of expected applicable EHS regulations and requirements.

Table 4.3. Regulatory review and due diligence for environmental health and safety.
4.4. Results and discussion

This LCA determined if producing sunflower oilseed on bauxite residue treated abandoned coal mine refuse for the purpose of biodiesel production was feasible. Furthermore it assessed whether this specific strategy would be beneficial from an environmental perspective, and to foresee any environmental tradeoffs or unintended consequences. The results show notable environmental impacts from the land amelioration and agricultural production processes over a twenty year production cycle, though the impacts are minimal when put into perspective and compared to traditional land reclamation. The impacts are also similar to those of other comparable fuel production methods. Additionally, the twenty-year cumulative environmental
impacts are 2.8-16.7 times less than those projected for the soil-covering reclamation process being conducted at the Mather site at the time of this study (4.4.5 Mather Coal Mine Refuse Pile Reclamation Activities).

The LCIA showed environmental impacts from the AML initial soil amelioration as the largest contributor for the first year of production, with transportation of the bauxite residue from the aluminum processing facility to the coal mine refuse site contributing the most in every TRACI category, seen in Figure 4. Unlike land amelioration, agricultural production impacts - including those from harvesting, drying and storing the sunflower feedstock - would occur on an annual basis for each year the feedstock is produced. Thus the cumulative impacts from twenty years of production was dominated by agricultural production, with seed drying contributing the most in all impact categories other than ozone depletion and fossil fuel depletion (where transportation of the bauxite residue still dominated). The other continually accruing system processes (namely seed preparation, pest control, and biofuel processing) did not produce significant impacts even after twenty years of cumulative production.

Transportation of the bauxite residue for the initial soil amelioration caused some of the greatest environmental impacts as seen outlined in Figure 4. Therefore, care must be taken when choosing to apply the techniques discussed in this study to Appalachian AML sites. There are similar abandoned coal mine refuse piles located throughout the Eastern Mining District for which this same technique could be utilized. Because most aluminum processing facilities in the US are located near the Mississippi River, the further east the AML site is located, the greater the impacts from bauxite residue transportation. Conversely, the closer the coal mine refuse site is to an aluminum processing plant, the greater the benefits from growing biofuel feedstock on AML.

4.4.1. Transportation analysis

A sensitivity analysis was conducted for the transportation process because of the significant environmental impacts associated with the bauxite residue transport process. Table 4. 4 shows the ecoinvent 3 processes reasonable for transporting the soil amendment. Of the six transport methods selected for comparison, the one selected for bauxite residue transport in this study (Transport, freight, lorry >32 metric ton, EURO5) had the lowest environmental impacts in all cases except one (the process which used biodiesel fuel showed fossil fuel depletion impact lower by 22%). The biodiesel transportation process has relatively large eutrophication and non
carcinogenic human health impacts resulting from the traditional agricultural practices used for biodiesel production. The agricultural tractor and trailer has particularly high impact across the spectrum, most likely because of the different methods of calculating impacts by different studies (e.g. the agricultural tractor and trailer dataset specifically included impacts from the tire abrasion with the road which may explain the near 50 times greater non carcinogens impact). The modeled transport process impacts were lower in general likely because the process was specifically selected for its efficiency in shipping large masses and volumes of material.

Table 4.4. Transportation Process Environmental Impact Sensitivity Analysis. TRACI impacts for six transportation methods compared for sensitivity analysis, normalized to the >32 lorry (tractor trailer) chosen for this study and highlighted in grey. The only transport method with lower impact category highlighted in green. Transport methods with impacts larger than ten times the impact of the method chosen in this study highlighted in blue.

<table>
<thead>
<tr>
<th>TRACI Impact Category</th>
<th>Transport, freight, lorry &gt;32 metric ton, EUROS</th>
<th>Transport, freight, lorry &gt;32 metric ton, EURO3</th>
<th>Transport, freight, lorry 16-32 metric ton, EUROS</th>
<th>Transport, freight, lorry 28 metric ton, vegetable oil methyl ester</th>
<th>Transport, freight, lorry, unspecified</th>
<th>Transport, tractor and trailer, agricultural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone depletion</td>
<td>100%</td>
<td>111%</td>
<td>149%</td>
<td>102%</td>
<td>145%</td>
<td>243%</td>
</tr>
<tr>
<td>Global warming</td>
<td>100%</td>
<td>112%</td>
<td>155%</td>
<td>112%</td>
<td>148%</td>
<td>350%</td>
</tr>
<tr>
<td>Smog</td>
<td>100%</td>
<td>218%</td>
<td>148%</td>
<td>407%</td>
<td>284%</td>
<td>577%</td>
</tr>
<tr>
<td>Acidification</td>
<td>100%</td>
<td>179%</td>
<td>147%</td>
<td>477%</td>
<td>231%</td>
<td>655%</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>100%</td>
<td>122%</td>
<td>139%</td>
<td>1408%</td>
<td>158%</td>
<td>961%</td>
</tr>
<tr>
<td>Carcinogens</td>
<td>100%</td>
<td>101%</td>
<td>135%</td>
<td>249%</td>
<td>130%</td>
<td>866%</td>
</tr>
<tr>
<td>Non carcinogens</td>
<td>100%</td>
<td>101%</td>
<td>138%</td>
<td>1235%</td>
<td>132%</td>
<td>4898%</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>100%</td>
<td>133%</td>
<td>141%</td>
<td>304%</td>
<td>164%</td>
<td>1040%</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>100%</td>
<td>101%</td>
<td>127%</td>
<td>226%</td>
<td>124%</td>
<td>532%</td>
</tr>
<tr>
<td>Fossil fuel depletion</td>
<td>100%</td>
<td>112%</td>
<td>151%</td>
<td>78%</td>
<td>145%</td>
<td>217%</td>
</tr>
</tbody>
</table>
Figure 4. Environmental Impacts from Sunflower Biodiesel Production on Abandoned Mine Land. Results normalized to first year cumulative impact for each TRACI impact category. Xaxis abbreviations: Cum. Y1 ¼ Cumulative environmental impacts for all processes from the first year of production, bauxite residue transportation for initial land amelioration completed in the first year of production outlined in black; Cum. Y20 ¼ Cumulative environmental impacts for all processes from the twenty years of production. TRACI impact abbreviations: kg ¼ kilograms; CFC ¼ chlorofluorocarbons; eq ¼ equivalent; CO₂ ¼ carbon dioxide; O₃ ¼ ozone; SO₂ ¼ sulfur dioxide; N ¼ nitrogen; CTUh ¼ comparative toxic units for humans; PM2.5 ¼ particulate matter less than 2.5 mm diameter; CTUe ¼ comparative toxic units for aquatic life; MJ ¼ megajoules.
4.4.2. Impact normalization and comparison

As biodiesel is the primary tangible output from feedstock grown on AML, it may seem that the most reasonable comparison for the results of this study is that of other biofuels and petroleum diesel. However, the general effort of this study was to reclaim lands otherwise unusable and even creating environmental impact in their current states. Therefore, the primary comparison for this study is with alternative reclamation activities. One such reclamation activity is to wholly restore the area to its original state by completely removing the coal mine refuse and disposing it in a nearby landfill.

As shown in Figure 4.5, the complete removal of the Mather coal mine refuse pile significantly outweighs all impacts, at a minimum of 8 times, from the biofuel produced from the sunflower feedstock grown on the AML (note the scale of the y-axes was set at 15% for ease of viewing, while all impacts were normalized to complete removal impacts at 100%). The complete removal of the mine refuse also far outweighs impacts from biodiesel production with soybean feedstock (including cultivation) and production of petroleum diesel (including extraction). In general, the production of petroleum diesel causes the least environmental impact, except for ozone depletion and fossil fuel depletion. However, this study does not include the use system process (including transportation, marketing and combustion) of the fuel, and also does not include the capture (or negative emissions) of carbon dioxide from the atmosphere by sunflower photosynthesis, both of which reduce the impacts from biodiesel production on AML, making it even more appealing when compared to other fuel sources.

Because additional land amelioration must be completed in order for anything to grow on AML, it was not surprising the traditional production of soybean biodiesel did not result in as much environmental impact, as was the case in nine out of the ten impact categories. However, in one very important impact category, eutrophication, traditional soybean biodiesel production had greater impacts than the sunflower biodiesel feedstock cultivation on AML. The agricultural production considered for this study was that of low-input agricultural practices. Agricultural practices commonly used in the Corn Belt (e.g. irrigation, pesticide, and fertilizer use) which cause substantially more environmental impact, were not used in this model. Even with the additional land amelioration, this model's impacts are comparable to those from high-input agriculture processes like soybean biodiesel feedstock production.
Figure 4.5. Sunflower biodiesel production on abandoned mine land environmental impacts comparison. Results normalized to complete removal of Mather coal mine refuse pile by hectare; Y-axis value set to 6% to allow viewing of other data. Complete removal of mine refuse in orange includes excavation and transportation to nearest landfill. Sunflower biodiesel production from this study in yellow includes the impacts from twenty years of cumulative production per area functional unit. Soybean biodiesel production in green is a default process in the ecoinvent 3 database normalized to this study's functional unit. Petroleum diesel production in grey is a default process in the ecoinvent 3 database normalized to this study's functional unit. TRACI impact abbreviations: kg: kilograms; CFC: chlorofluorocarbons; eq: equivalent; CO\(_2\): carbon dioxide; O\(_3\): ozone; SO\(_2\): sulfur dioxide; N: nitrogen; CTUh: comparative toxic units for humans; PM2.5: particulate matter less than 2.5 mm diameter; CTUe: comparative toxic units for aquatic life; MJ: megajoules.
The ideal land use comparison to sunflower biodiesel feedstock cultivation as an AML reclamation strategy would be with the business as usual approach (i.e. doing nothing with AML until the refuse becomes a viable resource because of market driven factors, letting environmental impact continue unabated). This comparison was not included because there was no adequate way to calculate the environmental impacts of doing nothing, or determining when the refuse may change in value. However, this business as usual scenario would certainly result in continued AMD from the AML, and there is no TRACI impact category or ecoinvent process that would adequately model the impacts encompassing the severe local environmental harm caused by AMD.

4.4.3. Allocation of bauxite residue

Some portion of the environmental impact associated with the transportation of the bauxite residue waste stream could have been allocated to the aluminum processing facility e as the aluminum industry could be held responsible for coproduct delivery to market. This adjustment in allocation would significantly reduce the initial environmental impacts associated with the land amelioration. This LCA was conservative in all model development and calculations, and careful not to bias the results to favor sunflower biodiesel feedstock cultivation on AML. Therefore, all impacts from the bauxite residue transportation were included within the system boundary.

4.4.4. Energy outlook and yield sensitivity analysis

Because yield estimates were quite conservative, actual yields would likely be greater, with yields upwards of 1300 kg/ha feasible.

The greater the yield, the earlier the energy balance becomes positive. Although, environmental impacts would also increase along with the yield increase (because of increased drying of feedstock, extracting of oil and converting to biodiesel) these increases would be minor compared to the benefits. Additional energy may also be produced via fast pyrolysis of the sunflower stover, which should be explored in future studies. Figure 4.5 shows the energy outlook for this study with yield and heating value sensitivity analysis data.
Figure 4.6. Sunflower biodiesel production on abandoned mine land energy outlook. Energy used for production calculated from TRACI impact Fossil Fuel Depletion for all processes; Energy Production calculated from a yield of 500 kg/ha at the lower heating value estimate of 32.6 MJ/L; Yield error calculated using the high and low yield estimates of 812 kg/ha and 56 kg/ha at the lower heating value estimate; The light green dashed line represents the energy production using the higher heating value estimate of 47.4 MJ/L; All energy production values calculated using an oil content of 42.2% and biodiesel conversion efficiency of 90%.
4.4.5. Mather coal mine refuse pile reclamation activities

While completing this LCA, the Pennsylvania Department of Environmental Protection and Department of Conservation and Natural Resources broke ground on a new reclamation project for the Mather coal mine refuse pile which involves relocating soil from a nearby dry lakebed (Duke Lake Dam) and using it to top the coal mine refuse pile with a two feet layer of covering soil (Hess, 2014; Hopey, 2014; Layton, 2014; Niedbala, 2014). The dry lakebed is located in Ryerson Station State Park, PA, 44 km (27.3 mi) away from Mather, and requires 191 thousand m$^3$ (250 thousand yd$^3$) soil to be transported (Table 4. 5). At a conservative soil density of 1200 kg/m$^3$ the total soil mass needed to be transported and spread is 229 million metric tons, or 8.8 million metric tons per hectare, creating a shipping value of 388 thousand tkm/ha (Hipp, 1974).

Table 4. 5. Inventory data for ecoinvent 3 Processes for Soil-Covering Scenario.

<table>
<thead>
<tr>
<th>Soil-covering scenario</th>
<th>Value per FU</th>
<th>Unit</th>
<th>ecoinvent 3 process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Extraction</td>
<td>7351</td>
<td>m$^3$ tkm</td>
<td>Excavation, hydraulic digger (RoW) processing j Alloc Def, U</td>
</tr>
<tr>
<td>Soil Transport</td>
<td>387,586</td>
<td></td>
<td>Transport, freight, lorry &gt;32 metric ton, EURO5 (RoW) Alloc Def, U</td>
</tr>
<tr>
<td>Soil Spreading</td>
<td>8,821,787</td>
<td>kg</td>
<td>Solid manure loading and spreading, by hydraulic loader and spreader (RoW) Alloc Def, U</td>
</tr>
</tbody>
</table>

Figure 4. 7 demonstrates that all environmental impacts resulting from cultivating sunflower biodiesel feedstock from the bauxite residue treated coal mine refuse (for twenty cumulative years including all impacts from the initial soil amelioration) is a fraction of the impacts projected from the soil-covering reclamation activity being conducted at the Mather refuse AML site. At a minimum, the soil-covering reclamation activities would have over 19% greater environmental impact than the sunflower cultivation proposed in this study. Additionally, this projection does not include the environmental impact from treatment and disposal of the bauxite residue now not being used for the reclamation process, and it does not gain the benefits from alternate energy production and local economic stimulation. If these soil-covering reclamation activities were to be used at other sites, the transportation distances and the soil covering depths would need to be modified for proper comparison of reclamation activities.
Figure 4.7. Environmental impacts of sunflower biodiesel production on Mather abandoned mine land compared with soil-covering reclamation activities. All impacts are normalized to soil-covering reclamation activities in light brown. Sunflower biodiesel production on abandoned mine land impacts are in yellow with green outlines and percentages above.
4.5. Conclusion

Sunflower feedstock cultivated on AML for biodiesel production modeling shows this to be a reasonable remediation effort if undertaken for a period of at least twenty years. Though the benefit from reduced runoff and acid mine drainage were beyond the scope of this study, any changes in that respect are likely to be positive. Further research, experiments, and field tests are highly recommended for advancing this beneficial reclamation strategy for abandoned mine lands.

Acknowledgments

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4.6. References


Aoun, W.B., Gabrielle, B., Gagnepain, B., 2013. The importance of land use change in the environmental balance of biofuels. OCL 20, D505.


CHAPTER FIVE

SUNFLOWER CULTIVATION ON COAL MINE REFUSE PILES IN APPALACHIA FOR DIESEL BIOFUEL PRODUCTION FROM A LIFE-CYCLE PERSPECTIVE

Modified from a paper published in the

*Procedia Engineering*

Tyler M. Harris\(^1,2\), Gregory G. Zaimes\(^3,4\), Vikas Khanna\(^3,4\), Amy E. Landis\(^2,5\)

**Abstract**

As demand for alternatives to petroleum fuels increases to meet renewable fuel policy requirements (an attempt to address global climate change concerns) both agricultural production of biofuel feedstock and feedstock-to-fuel conversion pathways must be examined for both energy efficiency and sustainability. The overarching agricultural method evaluated in this research is that of cultivating low-input biofuel feedstock on marginal lands. With a growing body of literature on sunflower crops cultivated on marginal land, as well as previous work by these researchers, describing positive overall outcomes, this study extended the scope of that previous research conducted by this group, specifically, examining low-input sunflower feedstock production on abandoned mine lands in the Appalachia, and subsequent feedstock conversion to diesel fuel alternatives.

The previous life cycle assessment (LCA) demonstrated that growing sunflower feedstock on a specific abandoned coal mine refuse pile in Appalachia for production of biodiesel would be environmentally sound and net-energy positive if conducted with low input agricultural practices, and if production continues five years after initial soil amelioration. This LCA normalized the data and generalized the method in order to apply them to over 1000 coal mine

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\(^{4}\) Department of Civil and Environmental Engineering, University of Pittsburgh.

\(^{5}\) Research advisor; Professor.
refuse piles in three Appalachian states located through global information systems (GIS). Additionally, this study included two conversion pathways for diesel replacement biofuels, namely transesterification of sunflower oilseed for biodiesel production – included in the original LCA – and fast pyrolysis of sunflower silage for green diesel production – new to this study.

The results of this study indicate when cultivating sunflower feedstock for biodiesel production on the average coal refuse pile in the Appalachian region produce approximately 11.6 barrels of biodiesel, plus 18.5 barrels of green diesel, with a similar environmental impact landscape to that of the specific site explored in the original LCA. Including the additional biofuel pathway of fast pyrolysis does alter the energy return outlook for the average Appalachian site, depending on the transportation distances and yields, the energy return varies greatly between sites, however overall environmental impacts only increase nominally. Site by site evaluation should be conducted before implementation to ensure the benefits outweigh negative impacts and a positive energy return is achieved.

Because of the approximately 32 thousand barrels per year of renewable diesel biofuel which could be produced from 6642 ha of coal refuse piles in only three states, it is highly recommended that the US Environmental Protection Agency (EPA) consider expanding the Renewable Fuel Standard (RFS) to include biofuel production on marginal land for Renewable Identification Number (RIN) assignment.

5.1. Introduction

Using marginal lands to cultivate low-input biofuel feedstocks has the potential to improve US land and resource management while contributing to domestic energy production (Niblick, Monnell, Zhao, & Landis, 2013; Zhao, Monnell, Niblick, Rovensky, & Landis, 2014). Food crops and prime land are not diverted to fuel production, while minor ecosystems services and value producing activities are brought to otherwise unused and often environmentally degraded (i.e. marginal) lands. Life cycle assessment (LCA) is a method for quantifying the environmental impacts and unintended consequences of a product or service throughout its life-cycle. A previous LCA by two of this study’s authors demonstrated that cultivating sunflower feedstock on a 26 hectare (ha) abandoned coal mine refuse pile located in Mather, Pennsylvania, and subsequent production of biodiesel through transesterification, could be environmentally sound and net-energy positive if conducted with low input agricultural practices and production
continues for at least five years after initial soil amelioration (Harris, Hottle, Soratana, Klane, & Landis, 2016).

This study expands upon the previous LCA by applying the model to aggregated abandoned mine land (AML) data from three Appalachian states (Pennsylvania, Virginia, and West Virginia) using global information systems (GIS). Different land use strategies are compared, including removal of mine refuse to a landfill, covering the mine refuse with soil, and finally using the AML to generate biodiesel from sunflower oilseed and green diesel via fast pyrolysis of sunflower stover (plant residue remaining after oilseed harvest).

AML, including mine refuse piles, occupy over 600,000 sites and 3 million hectares in the United States resulting in acid and toxic mine drainage causing severe ecosystem deterioration [1,4]. The Environmental Protection Agency (EPA) has regulated mine closures and associated refuse piles since the Surface Mining Control and Reclamation Act of 1977 (SMCRA) and Clean Water Act of 1972 (CWA). However, there is much “legacy mine land” still remaining throughout the U.S., particularly in the Appalachians, still in need of reclamation or other value creating activities.

Cultivating sunflower biofuel feedstock on marginal lands, including coal mine refuse piles, has been experimented and is becoming a valid model for reclaiming coal mine refuse piles, while producing a notable amount of biofuel (Harris et al., 2016; Niblick & Landis, 2016; Zhao et al., 2014). Sunflower biomass can be converted into biofuel through various methods, including extracting the oil from the oilseed and performing transesterification to produce biodiesel, or collecting the sunflower stover (or refuse) after seed harvest for fast pyrolysis conversion into green diesel (Kalnes, Marker, Shonnard, & Koers, 2008; Zaimes, Soratana, Harden, Landis, & Khanna, 2015). Both biodiesel and green diesel are accepted petroleum diesel replacement fuels, each with its own merits and tradeoffs. For the scenario proposed in this study, both fuel conversion pathways will be included in the model.

5.2. Methods

This study uses an LCA framework to evaluate different land use strategies for AML. The LCA was conducted iteratively using four stages: 1. goal and scope definition, 2. inventory analysis, 3. impact assessment, and 4. interpretation. Inventory data was collected from
AspenONE models for fast pyrolysis of stover to green diesel, GIS data for AML area and transportation distances, and sunflower yield estimates from previous studies on the site.

5.2.1. **Goal, Scope, Functional Unit, and System Boundary**

The goal of this LCA was to expand the scope of a previous Life Cycle Assessment of Sunflower Cultivation on Abandoned Mine Land for Biodiesel Production that determined “if cultivating and processing biodiesel from oilseed sunflower feedstock using sustainable dryland agricultural practices on abandoned coal mine refuse mixed with 10% bauxite residue is beneficial from a life cycle perspective” to include additional Appalachian AML and biofuel conversion pathways (Harris et al., 2016). The scope of this study includes coal mine refuse pile sites from three Appalachian states (Pennsylvania, Virginia, and West Virginia) and process-based attributional gate-to-gate assessment of amelioration, cultivation, and conversion processes (Figure 5.1). Thus, this LCA evaluated environmental impacts resulting from the proposed biofuel production cycles and the energy return outlook. Impacts from sunflower-derived biofuel produced from treated AML were then compared to complete coal mine refuse pile land restoration (i.e. complete removal of all coal mine refuse) impacts, soil-covering reclamation, and also to other biodiesel production methods’ impacts.

![System Boundary Diagram](image-url)

Figure 5.1. System Boundary Diagram. Blue boxes represent system and unit processes; Light orange boxes represent products from the processes; Grey boxes represent inputs and outputs; Green box represent the functional unit; Arrows represent the flow of system. Items within and without the blue boxes are included and not included in the LCA model, respectively.
The functional unit remained the same as the previous LCA: biodiesel production per year per unit AML area in kilograms (and liters) of fuel per hectare (kg/ha and l/ha). Biodiesel production per unit area was chosen as the functional unit because the land choice (i.e. marginal land) was the primary element of investigation, and kilograms of biodiesel was chosen for modeling purposes, while liters of biodiesel was included for literature comparison (Harris et al., 2016).

5.2.2. Inventory, Impact Assessment, and Interpretation

Inventory data collection was conducted through an extensive literature review, an ecoinvent 3 database search, preliminary AspenONE (engineering optimization software) modeling, and governmental agricultural databases (ecoinvent, 2007). All efforts were made to ensure the reliability and suitability of the data input into the model.

Impact assessment was completed using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2.1 V1.01) and Cumulative Energy Demand (CED 1.8) impact characterization and evaluation methods. Three of the TRACI impacts (ozone depletion, global warming, and ecotoxicity) and one CED impact (cumulative energy demand PRé v1.02) were calculated and analyzed. (The previous LCA conducted a sensitivity analysis on several other impact characterization and evaluation methods including ReCiPe Midpoint V1.08 and BEES+ V4.03 with results of the analysis showing minimal variation between methods.)

The results of the LCA model were analyzed, evaluated, and interpreted as described in section 5.4. Sensitivity analysis was conducted on the minimum and maximum transportation distances between materials and processes sites, and normalization with other related system impacts was conducted.

5.3. Life Cycle Inventory (LCI)

Table 5.1 summarizes the land and dimensional data collected and calculated for this study. Table 5.2 summarizes the biomass and bioenergy data collected and calculated for this study. Table 5.3, Table 5.4, Table 5.5, and Table 5.6 summarize the reference flows and ecoinvent 3 processes used for this study.
Table 5. 1. Life Cycle Inventory: Land and Dimensional Data.

<table>
<thead>
<tr>
<th>Land and Dimensional Data Description</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area Functional Unit</td>
<td>1</td>
<td>Hectare (1 ha = 10000m²)</td>
<td>-</td>
</tr>
<tr>
<td>Time Function Unit</td>
<td>1</td>
<td>Annual Production Cycle</td>
<td>-</td>
</tr>
<tr>
<td>Bauxite Residue Mass per Hectare</td>
<td>371.35</td>
<td>Metric Tons per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>Average Bauxite Residue Transport Distance</td>
<td>250</td>
<td>Kilometers</td>
<td>[8,9,10,11], GIS Analysis</td>
</tr>
<tr>
<td>Sunflower Seeds for Sowing per Hectare</td>
<td>3</td>
<td>Kilograms per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>North Dakota Center to Appalachia Center</td>
<td>2500</td>
<td>Kilometers</td>
<td>Google Earth</td>
</tr>
<tr>
<td>Methyl Parathion Use per Hectare</td>
<td>0.6</td>
<td>Kilograms per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>Wayne, NJ to Appalachia Center</td>
<td>750</td>
<td>Kilometers</td>
<td>Google Earth</td>
</tr>
<tr>
<td>Average Feedstock Transport Distance</td>
<td>155</td>
<td>Kilometers</td>
<td>[8,9,10,11], GIS Analysis</td>
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<tr>
<td>Mather Coal Mine Refuse Pile Area</td>
<td>26</td>
<td>Hectares</td>
<td>[1]</td>
</tr>
<tr>
<td>- Refuse Volume per Hectare</td>
<td>88462</td>
<td>Cubic Meters per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>- Refuse Mass per Hectare</td>
<td>232654</td>
<td>Metric Tons per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>Mather, PA to Chestnut Valley Landfill, PA</td>
<td>27</td>
<td>Kilometers</td>
<td>[1]</td>
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<tr>
<td>Soil Covering for a Depth of Two Feet (Volume)</td>
<td>7352</td>
<td>Cubic Meters per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>- Soil Covering for a Depth of Two Feet (Mass)</td>
<td>8822</td>
<td>Metric Tons per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>Mather, PA to Ryerson Station State Park, PA</td>
<td>44</td>
<td>Kilometers</td>
<td>[1]</td>
</tr>
<tr>
<td>Total PA, VA, &amp; WV Coal Mine Refuse Pile Area</td>
<td>6643</td>
<td>Hectares</td>
<td>Calculation</td>
</tr>
<tr>
<td>- Total PA Coal Mine Refuse Pile Area</td>
<td>3281</td>
<td>Hectares</td>
<td>[8]</td>
</tr>
<tr>
<td>- Total VA Coal Mine Refuse Pile Area</td>
<td>393</td>
<td>Hectares</td>
<td>[9]</td>
</tr>
<tr>
<td>- Total WV Coal Mine Refuse Pile Area</td>
<td>2969</td>
<td>Hectares</td>
<td>[10]</td>
</tr>
<tr>
<td>- Total PA, VA, &amp; WV Coal Mine Refuse Pile Sites</td>
<td>1061</td>
<td>Coal Refuse Piles</td>
<td>[8,9,10]</td>
</tr>
<tr>
<td>Average PA, VA, &amp; WV Coal Mine Refuse Pile Area</td>
<td>6.26</td>
<td>Hectares</td>
<td>Calculation</td>
</tr>
</tbody>
</table>

Table 5. 2. Life Cycle Inventory: Biomass and Bioenergy data.

<table>
<thead>
<tr>
<th>Biomass and Bioenergy Data Description</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunflower Grain Yield Estimate</td>
<td>500</td>
<td>Kilograms per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>- Grain Yield Area Estimate</td>
<td>0.65</td>
<td>Cubic Meters per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>Sunflower Oil Yield Estimate</td>
<td>211</td>
<td>Kilograms per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>Sunflower Biodiesel Yield Estimate (Mass)</td>
<td>190</td>
<td>Kilograms per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>- Biodiesel Yield Estimate (Volume)</td>
<td>221</td>
<td>Liters per Hectare</td>
<td>[1]</td>
</tr>
<tr>
<td>Average Sunflower Stover:Grain Ratio</td>
<td>2.19</td>
<td>Ratio</td>
<td>[13,14,15,16], Calculation</td>
</tr>
<tr>
<td>Sunflower Stover Yield Estimate</td>
<td>1095</td>
<td>Kilograms per Hectare</td>
<td>Calculation</td>
</tr>
<tr>
<td>- Corn Stover Wet Density on Truck</td>
<td>127</td>
<td>Kilograms per Cubic Meters</td>
<td>[17]</td>
</tr>
<tr>
<td>- Sunflower Stover Yield Estimate (Area)</td>
<td>8.6</td>
<td>Cubic Meters per Hectare</td>
<td>Calculation</td>
</tr>
<tr>
<td>Sunflower Green Diesel Yield Estimate (Mass)</td>
<td>275</td>
<td>Kilograms per Hectare</td>
<td>AspenONE Estimate</td>
</tr>
<tr>
<td>- Green Diesel Density</td>
<td>0.78</td>
<td>Kilograms per Liter</td>
<td>[6]</td>
</tr>
<tr>
<td>- Sunflower Green Diesel Yield Estimate (Volume)</td>
<td>352</td>
<td>Liters per Hectare</td>
<td>Calculation</td>
</tr>
<tr>
<td>Sunflower Total Feedstock Yield Estimate</td>
<td>1595</td>
<td>Kilograms per Hectare</td>
<td>Calculation</td>
</tr>
<tr>
<td>- Sunflower Total Feedstock Yield Estimate (Area)</td>
<td>9.3</td>
<td>Cubic Meters per Hectare</td>
<td>Calculation</td>
</tr>
</tbody>
</table>
Table 5. 2. Continued.

<table>
<thead>
<tr>
<th>Biomass and Bioenergy Data Description</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunflower Diesel Biofuel Yield Estimate (Mass)</td>
<td>465</td>
<td>Kilograms per Hectare</td>
<td>Calculation</td>
</tr>
<tr>
<td>- Diesel Biofuel Yield Estimate (Volume)</td>
<td>573</td>
<td>Liters per Hectare</td>
<td>Calculation</td>
</tr>
<tr>
<td>- Diesel Biofuel Energy Yield Estimate</td>
<td>19</td>
<td>Gigajoules per Hectare</td>
<td>[1], AsperONE Estimate</td>
</tr>
<tr>
<td>Sunflower Diesel Biofuel Yield Estimate (Barrels)</td>
<td>31924</td>
<td>Barrels per Year</td>
<td>Calculation</td>
</tr>
<tr>
<td>- Total PA, VA, &amp; WV Coal Mine Refuse Pile</td>
<td>3.8x10^6</td>
<td>Liters per Year</td>
<td>Calculation</td>
</tr>
<tr>
<td>Sunflower Diesel Biofuel Yield Estimate (volume)</td>
<td>119.24</td>
<td>Liters per Barrel</td>
<td>Unit Conversion</td>
</tr>
<tr>
<td>Sunflower Diesel Biofuel Yield Estimate (Energy)</td>
<td>120</td>
<td>Terajoules per Year</td>
<td>Calculation</td>
</tr>
</tbody>
</table>

Table 5. 3. Land Amelioration Processes and Flows.

<table>
<thead>
<tr>
<th>Land Amelioration Process</th>
<th>Value per FU</th>
<th>Unit</th>
<th>ecoinvent 3 Process (Alloc Def, U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport of Alkaline Clay (Avg)</td>
<td>92837</td>
<td>tkm</td>
<td>Transport, freight, lorry &gt;32 metric ton, EURO5 (RoW)</td>
</tr>
<tr>
<td>- Transport of Alkaline Clay (Mather)</td>
<td>98607</td>
<td>tkm</td>
<td>Transport, freight, lorry &gt;32 metric ton, EURO5 (RoW)</td>
</tr>
<tr>
<td>Spreading of Alkaline Clay</td>
<td>371348</td>
<td>kg</td>
<td>Solid manure loading and spreading, hydraulic (RoW)</td>
</tr>
<tr>
<td>Mixing of Alkaline Clay (2 Runs)</td>
<td>20000</td>
<td>m2</td>
<td>Tillage, ploughing (RoW)</td>
</tr>
</tbody>
</table>

Table 5. 4. Seed Preparation Processes and Flows.

<table>
<thead>
<tr>
<th>Seed Preparation Processes</th>
<th>Value per FU</th>
<th>Unit</th>
<th>ecoinvent 3 Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed Manufacture</td>
<td>3</td>
<td>kg</td>
<td>Sunflower seed, for sowing (GLO)</td>
</tr>
<tr>
<td>Seed Transport</td>
<td>7.5</td>
<td>tkm</td>
<td>Transport, freight, lorry 16-32 metric ton, EURO5 (RoW)</td>
</tr>
<tr>
<td>Seed Sowing</td>
<td>10000</td>
<td>m2</td>
<td>Sowing (RoW)</td>
</tr>
</tbody>
</table>

Table 5. 5. Pest Control Processes and Flows.

<table>
<thead>
<tr>
<th>Pest Control Processes</th>
<th>Value per FU</th>
<th>Unit</th>
<th>ecoinvent 3 Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pest Control Manufacture</td>
<td>0.6</td>
<td>kg</td>
<td>Pesticide, unspecified (RoW)</td>
</tr>
<tr>
<td>Pest Control Transportation</td>
<td>0.45</td>
<td>tkm</td>
<td>Transport, freight, lorry 16-32 metric ton, EURO5 (RoW)</td>
</tr>
<tr>
<td>Pest Control Application</td>
<td>10000</td>
<td>m2</td>
<td>Application of plant protection product, field sprayer (RoW)</td>
</tr>
</tbody>
</table>

Table 5. 6. Agricultural Production Processes and Flows.

<table>
<thead>
<tr>
<th>Agricultural Production Processes</th>
<th>Value per FU</th>
<th>Unit</th>
<th>ecoinvent 3 Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvesting</td>
<td>10000</td>
<td>m2</td>
<td>Combine harvesting (RoW)</td>
</tr>
<tr>
<td>Drying</td>
<td>0.65</td>
<td>m3</td>
<td>Drying of bread grain, seed and legumes (RoW)</td>
</tr>
<tr>
<td>Storage</td>
<td>1595</td>
<td>kg</td>
<td>Operation, dried roughage store, non ventilated (RoW)</td>
</tr>
<tr>
<td>- Storage (Mather)</td>
<td>500</td>
<td>kg</td>
<td>Operation, dried roughage store, non ventilated (RoW)</td>
</tr>
</tbody>
</table>
The addition of three unit processes to the biofuel production system process were required to include the additional conversion pathway of fast pyrolysis to green diesel: Fast Pyrolysis Energy, Fast Pyrolysis Hydrogen, and Fast Pyrolysis Zeolite Powder (Table 5.7 and Table 5.8). Rough estimates were calculated for the inputs and outputs from fast pyrolysis of sunflower stover using AspenONE modeling. Data used for calculating the inputs and outputs is summarized in Table 5.9.

Table 5.7. Biofuel Production Processes and Flows.

<table>
<thead>
<tr>
<th>Biofuel Production Processes</th>
<th>Value per FU</th>
<th>Unit</th>
<th>ecoinvent 3 Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock Transportation (Avg)</td>
<td>247</td>
<td>tkm</td>
<td>Transport, freight, lorry 16-32 metric ton, EURO5 (RoW)</td>
</tr>
<tr>
<td>-Feedstock Transportation (Mother)</td>
<td>46</td>
<td>tkm</td>
<td>Transport, freight, lorry 16-32 metric ton, EURO5 (RoW)</td>
</tr>
<tr>
<td>Oil Extraction</td>
<td>211</td>
<td>kg</td>
<td>Soybean oil, soybean meal and crude oil production (US)</td>
</tr>
<tr>
<td>Transesterification</td>
<td>189.9</td>
<td>kg</td>
<td>Vegetable oil methyl ester, esterification of [mod.] oil (US)</td>
</tr>
<tr>
<td>Fast Pyrolysis Energy</td>
<td>299</td>
<td>MJ</td>
<td>Electricity, high voltage (RFC)</td>
</tr>
<tr>
<td>Fast Pyrolysis Hydrogen</td>
<td>50</td>
<td>kg</td>
<td>Hydrogen, liquid (GLO)</td>
</tr>
<tr>
<td>Fast Pyrolysis Zeolite Powder</td>
<td>12</td>
<td>kg</td>
<td>Zeolite, powder (GLO)</td>
</tr>
</tbody>
</table>

Table 5.8. Alternate and Normalization Processes and Flows.

<table>
<thead>
<tr>
<th>Alternate and Normalization Processes</th>
<th>Value per FU</th>
<th>Unit</th>
<th>ecoinvent 3 Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternate Scenario (Removal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refuse Extraction</td>
<td>88462</td>
<td>m³</td>
<td>Excavation, hydraulic digger (RoW)</td>
</tr>
<tr>
<td>Refuse Transport</td>
<td>6739563</td>
<td>tkm</td>
<td>Transport, freight, lorry &gt;32 metric ton, EURO5 (RoW)</td>
</tr>
<tr>
<td>Alternate Scenario (Covering)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Extraction</td>
<td>7352</td>
<td>m³</td>
<td>Excavation, hydraulic digger (RoW)</td>
</tr>
<tr>
<td>Soil Transport</td>
<td>387586</td>
<td>tkm</td>
<td>Transport, freight, lorry &gt;32 metric ton, EURO5 (RoW)</td>
</tr>
<tr>
<td>Soil Spreading</td>
<td>8821787</td>
<td>kg</td>
<td>Solid manure loading and spreading, hydraulic (RoW)</td>
</tr>
<tr>
<td>Normalization Processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean Biodiesel Production</td>
<td>465</td>
<td>kg</td>
<td>Vegetable oil methyl ester, esterification of soybean oil (US)</td>
</tr>
<tr>
<td>Petroleum Diesel Production</td>
<td>465</td>
<td>kg</td>
<td>Diesel, low-sulfur (RoW)</td>
</tr>
</tbody>
</table>

Table 5.9. Data for Fast Pyrolysis AspenONE Modeling.

<table>
<thead>
<tr>
<th>Data Description</th>
<th>Values</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Hemicellulose, Cellulose, Lignin</td>
<td>3.2, 31.5, 7.5</td>
<td>Percentage</td>
<td>[18]</td>
</tr>
<tr>
<td>% Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), and Sulfur (S); Dry</td>
<td>34.3, 5.7, 45.6, 1.0, 0.2</td>
<td>Percentage</td>
<td>[18]</td>
</tr>
<tr>
<td>% Moisture Content</td>
<td>72.5</td>
<td>Percentage</td>
<td>[18]</td>
</tr>
<tr>
<td>% C,H,O,N,S of Biochar</td>
<td>63.4, 0.7, 34.3, 1.6, 0.1</td>
<td>Percentage</td>
<td>[19]</td>
</tr>
<tr>
<td>Heating Value of Biochar</td>
<td>20.5</td>
<td>Megajoules per Kilogram</td>
<td>[19]</td>
</tr>
</tbody>
</table>
GIS software was used to locate data on abandoned coal mine refuse piles, bauxite processing facilities, and biofuel production facilities in or near the Appalachian region. Data from three states (Pennsylvania, Virginia, and West Virginia) was used for aggregating abandoned coal mine refuse pile information, data from the US Geological Survey (USGS) was used to locate the nearest bauxite processing plants, and data from the US Department of Agricultural (USDA) was used to locate the nearest biofuel production facilities. Figure 5.2 is a map of the region with all the data points identified (ArcGis, 2015).
5.4. Results and Discussion/Interpretation

This LCA determined that producing sunflower feedstock on abandoned coal mine refuse piles treated with bauxite residue for the purpose of biofuel production was feasible, assessing whether this strategy would be environmentally sound. The results showed notable environmental impacts from the land amelioration and agricultural production processes over a twenty-year production cycle, though the impacts are minimal when compared to complete traditional land reclamation.

Figure 5. 3. shows that the majority of first year impacts result from the transportation of the bauxite residue, while the agricultural and biofuel processing begin to take over as they continue to grow annually as seen in the cumulative twenty year impacts. Since these are impacts resulting from average transportation distances, the impacts could be reduced by locating feedstock cultivation near biofuel production facilities and aluminum processing facilities. Further analysis
will expand the impact categories considered and include stochastic modeling to include the
distribution of transportation distances considered.

Figure 5. 3. Environmental Impact Perspective. Normalized to first year of production; Black
enclosed blue area with percentage indicates amount of impact from transportation of bauxite
residue (conducted only once on the first year during land amelioration).

Figure 5. 4. revealed that environmental impacts from the new model are still significantly
lower than the alternate scenario models. Figure 5. 4 also revealed the impacts from other diesel
fuel options are similar over a twenty-year period to those proposed in this study. The impacts
resulting from the original site study are slightly lower (>1%) than that of the average
Appalachian site explored in this study. This resulted mainly from the addition of three fast
pyrolysis unit processes for the production of green diesel from sunflower stover in this study, as
the average transportation distances are similar to those considered for the Mather site. However,
the slight increase in impact from additional green diesel production resulted in an additional 382
liters per hectare of biofuel (159% increase), for a total diesel biofuel yield of 573 liters per hectare, or 19 gigajoules of energy per hectare.

Figure 5.4. Environmental Impact Normalization. Impacts normalized to complete removal of mine refuse impacts.

When this biofuel yield estimate was applied to the 1061 sites located in the three Appalachian states, the total of 6643 hectares of abandoned mine land should produce nearly 32 thousand barrels of diesel biofuel per year, or 120 terajoules per year. Because of this, it is highly recommended that the US Environmental Protection Agency (EPA) consider expanding the Renewable Fuel Standard (RFS) to include biofuel production on marginal land for Renewable Identification Number (RIN) assignment.
Acknowledgements

This research would not have been possible without funding provided by the National Science Foundation (NSF) Chemical, Bioengineering, Environmental, and Transport Systems (CBET) grant number 0933249/1254559 and the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture, Agriculture and Food Research Initiative Competitive Grant no. 2012-67009-19717; Any opinions, findings, conclusions, or recommendations expressed are those of the authors and do not necessarily reflect those of the NSF, CBET, USDA.

5.5. References

ArcGis. (2015). *ArcGis Online Data Search*.


CHAPTER SIX

LIFE CYCLE ASSESSMENT OF PROPOSED
SPACE ELEVATOR DESIGNS

Modified from a paper to be submitted to
Acta Astronautica

Tyler M. Harris¹,², Pragnya L. Eranki²,³, Amy E. Landis²,⁴

Abstract

The cost and design requirements required to transport satellites and payloads to space using existing orbital technology systems remain prohibitively high. Yet, quantitative sustainability assessments to evaluate system costs and impacts of existing and proposed orbital transportation systems are rare. Space elevators are intended to safely, gently, and inexpensively transport satellites and other payloads to and from space on a routine daily basis. This life cycle assessment (LCA) was completed to quantify, assess, compare, and suggest improvements to the environmental and financial performance of three proposed space elevator system designs, namely i) a One-Tether Initial Space Elevator (the base design) ii) a Two-Tether Initial Space Elevator iii) an Additional One-Tether Space Elevator. A sensitivity analysis to compare the impact of reduced utilization capacity of the one tether space elevator (i.e., base design) was additionally performed. Results indicated that the Additional One-Tether Space Elevator scenario has the lowest environmental impact, while the Two-Tether Initial Space Elevator scenario has the lowest production cost per unit mass delivered to orbit. This LCA identified system elements for targeted impact reduction, e.g. operational impacts could be significantly reduced by improving the sustainability of terrestrial transportation delivery systems to the space elevator port. Sensitivity analysis results showed producer cost to be the only impact category

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with a direct inversely correlated response to reduced capacity; all other impacts showed a less sensitive inverse correlation. Ultimately, the proposed space elevator design was found to be an environmentally and financially sustainable option for orbital transportation. Further application and refinement of such sustainable engineering and quantitative sustainability assessment methodologies to spacecraft, rocket, and other existing and proposed orbital transportation systems and industries is highly recommended.

Keywords: Quantitative Sustainability Assessments, Life Cycle Assessment (LCA), Orbital Transportation Systems, Geosynchronous Earth Orbit (GEO), Space Elevator, Carbon Nanofibers (CNF), Cislunar Economy

6.1. Introduction

The average cost to transport material from Earth’s surface to space has been roughly $20,000 per kilogram (Coopersmith, 2011) with the global space economy accounting for $323 billion of economic activity in 2015 (Hampson, 2017). However, other proposed and well-studied orbital transportation systems such as the space elevator could drastically reduce the cost and design requirements for payload delivery to orbit. The space elevator design presented by Swan et al. in 2013 has an estimated cost to geosynchronous earth orbit (GEO) of $500 per kilogram (P. A. Swan, Raitt, Swan, Penny, & Knapman, 2013). Yet quantitative sustainability assessment research of any existing or proposed orbital transportation systems is absent in the current literature.

Design and development of nascent technologies are improved by quantitative sustainability engineering methodologies such as life cycle assessment (LCA). LCA is a vetted and standardized engineering methodology that quantifies and assesses the environmental impact of a product, service, process, or activity throughout its life-cycle. The life cycle impact assessment (LCIA) portion of an LCA examines environmental impacts and anticipates impact tradeoffs and unintended consequences. This research performed an environmental LCA of a space elevator orbital transportation system to quantify, assess, and improve the environmental and cost performance of the proposed design.

Space elevators would deploy/collect satellites to/from any of Earth’s orbits, as well as deliver and receive payloads to/from cislunar or interplanetary space (Pugno, 2013). The Hubble Space
Telescope and International Space Station (ISS) are in low earth orbit (LEO) <1,000 km altitude, Global Positioning System (GPS) satellites are in a medium earth orbit (MEO) ~22,000 km altitude, and weather/communication satellites are commonly in GEO ~35,800 km – the minimum high earth orbit (HEO) that maintain their positions in orbit relative to a spot on the Earth’s surface. Payload to GEO accounts for less than 12% of the total mass at liftoff for existing rocket technologies. The space elevator payload to GEO was designed to account for 70% of the total space elevator climber departure mass (including its renewable power source). Because of the slow initial space elevator travel times, human travel to/from orbit will likely continue to utilize existing rocket orbital transportation technologies for the foreseeable future. The space elevator design includes a total of 7 tether climbers each operational space elevator tether for regular daily payload departures and arrivals. Estimates on the cost to deliver payloads to and from GEO from various space elevator concepts and designs ranged from $100 to $1000 per kilogram (D. Raitt, 2017).

The space elevator is an Earth-satellite tethered (space-tether) system connecting a counterbalance in far earth orbit (100,000 km altitude) to an offshore platform on the Equator by a large carbon nanofiber (CNF) ribbon or tether (Figure 6.1). The orbiting counterbalance satellite node provides tension to the CNF tether through centrifugal forces, while the surface anchor node (and tether system center of mass) holds the counterbalance satellite node in GEO via centripetal forces (P. A. Swan et al., 2013). Space vessels called tether climbers then traverse the taut CNF tether, delivering payloads to a GEO satellite node for final payload delivery to GEO and other desirable Earth orbits.

The development of graphene, carbon nanofibers, and nanotubes in the 2000s made the space-tether elevator concept technically feasible (D. I. Raitt, 2015). As of 2018, at least two for-profit companies (LiftPort Group and Obayashi Corp), as well as the Japanese Space Administration were actively developing a space elevator design for near-term deployment (Knapman & Swan, 2015; D. I. Raitt, 2015). A carbon nanotube LCA provided life cycle inventory (LCI) data, i.e. upstream and downstream energy and material flows, for each kilogram (kg) of carbon nanotube product produced (Khanna, Bakshi, & Lee, 2008). The remainder of the space elevator design parameters and LCI data required were collected from Swan et al. (2013).
Figure 6.1. Simple Map of Earth Orbits with Idealized Space Elevator System. The proposed space elevator design by Swan et al. (2013) is a 100,000-km carbon nanofiber tether [black line] in geosynchronous earth orbit (GEO) [green orbit] with a GEO Node [green] attached to an anchor node offshore platform near the equator held taunt through centrifugal force by an orbiting counterbalance node [purple] and traversed by solar powered tether climbers [blue] delivering payloads [red] to and from orbit and cislunar space. Centripetal and centrifugal forces hold the tether taunt and nodes in place.

This study quantifies the potential environmental impacts of the production, deployment, and use of a space elevator using LCA. This study is the first of its kind; at the time of completion there were no LCAs or sustainability assessments of any earth-to-orbit technologies including the space elevator. The use of this valuable quantitative sustainability assessment tool (i.e. life cycle assessment or LCA) and its applications in assessing the environmental sustainability of emerging space technologies is detailed and documented herein. Furthermore, as interest in the commercial research, development, and utilization of space resources continues to increase, humankind has a rare opportunity just prior to a period of rapid technological development to prevent possibly severe unintended consequences through application of quantitative sustainability assessments such as with this research.
6.2. Materials and methods

Life Cycle Assessment (LCA) is a method used to quantify the environmental impacts of a product or process throughout its entire lifetime, from raw materials extraction, including production, use and ultimately through end-of-life. The process-LCA methodology is defined by the ISO 14040 series, and includes four steps: 1. Goal and scope definition, 2. Life Cycle Inventory (LCI), 3. Life Cycle Impact Assessment (LCIA), and 4. Interpretation and improvement (ISO, 2006a, 2006b). LCAs start with an explicit statement of the goal, scope and system boundaries of the study. The second step, LCI, is the most data intensive part of an LCA, where all of the inputs and outputs for the product are quantified. The third step, LCIA, converts and presents the inventory data in meaningful terms, such as global warming potential, energy return on investment, and ecosystem impacts. The details of these steps are outlined in the materials and methods section below. Finally, in the interpretation step, covered in the results and discussion section, the findings of the LCA are evaluated in relation to the defined goal to develop conclusions and make recommendations.

Instead of only process-LCA, an attributional hybrid LCA was employed in this study, because of the nature of emerging technologies such as the space elevator. Attributional LCAs quantify and assess environmental impacts from each activity, product, or method (i.e. unit and system processes) included in the system boundary. Because research on the sustainability of orbital transportation systems and the space industry is rare, EIO-LCA methodology was used for all spacecraft production processes in the model. Economic input-output LCA (EIO-LCA) is an alternate method for performing LCA by determining the average environmental impact per dollar spent in a specified industrial classification. This EIO-LCA methodology was developed and maintained by researchers at Carnegie Mellon University (CMU), and utilizes linear algebra based on Leontief economic principles (Shrake, Bilec, & Landis, 2013; Simonen, 2014). It estimates environmental emissions resulting from economic activities (i.e. purchases) in the major sectors of the economy using input-output tables derived from the Bureau of Labor Statistics (CMU, 2002). Whereas process-LCA (described in the preceding paragraph) allocates impact potentials from extensive LCA databases containing all the system’s upstream material, energy flows and emissions, collecting and sharing such LCA databases is a resource intensive endeavor; furthermore, some products, processes, and services do not have such datasets.
available. In such cases, hybrid LCA methodologies can be used to establish a process-LCA model while filling any gaps in the LCA databases with EIO-LCA results.

In this study, scenario analysis was used to compare various configurations of the space elevator design and business plan, and corresponding transportation and utilization capacity use phase estimates (Table 6.1). Three space elevator design configurations/business plans were presented by Swan et al. (2013): One-Tether Initial Space Elevator, Two-Tether Initial Space Elevator, and Additional One-Tether Space Elevator; these configurations were evaluated in this study for both cradle-to-gate and cradle-to-use scopes. The One-Tether Initial Space Elevator scenario was the primary technical design configuration, or base design, while the Two-Tether Initial Space Elevator scenario represented the recommended business plan configuration. The Additional One-Tether Space Elevator scenario represents future space elevator systems deployed with a previous space elevator (without the need for initial rocket deployment).

Table 6.1. Space Elevator Design Scenario and Sensitivity Analyses Parameters and Use-Phase Transportation and Utilization Estimates.

<table>
<thead>
<tr>
<th>Scope</th>
<th>Scenario Name</th>
<th>Scenario Details</th>
<th># Ports</th>
<th># Tethers</th>
<th># Climbers</th>
<th># Anchors</th>
<th>Rocket Launch Mass (kg)</th>
<th>Design Capacity/Modeled Capacity (kg to Orbit/Year)</th>
<th>Surface Transport Distance (km)</th>
<th>Capacity Utilization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cradle-to-Gate (&amp; Cradle-to-Use) Scenario Analysis</td>
<td>One-Tether Initial Space Elevator</td>
<td>Base Technical Design</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>86,000</td>
<td>5,096,000/5,096,000</td>
<td>10,019</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Two-Tether Initial Space Elevator</td>
<td>Indorsed Business Plan</td>
<td>1</td>
<td>2</td>
<td>14</td>
<td>4</td>
<td>86,000</td>
<td>10,192,000/10,192,000</td>
<td>10,019</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Additional One-Tether Space Elevator</td>
<td>Base Design Deployed w/Previous Space Elevator</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>0</td>
<td>5,096,000/5,096,000</td>
<td>3,340</td>
<td>100%</td>
</tr>
<tr>
<td>Cradle-to-Use Only Sensitivity analysis</td>
<td>90% Utilization One-Tether Initial Space Elevator</td>
<td>Base Design w/90% Utilization Capacity</td>
<td>1</td>
<td>2</td>
<td>14</td>
<td>4</td>
<td>86,000</td>
<td>5,096,000/4,586,000</td>
<td>10,019</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>10% Utilization One-Tether Initial Space Elevator</td>
<td>Base Design w/10% Cradle-to-Use Phase Utilization</td>
<td>1</td>
<td>2</td>
<td>14</td>
<td>4</td>
<td>86,000</td>
<td>5,096,000/509,600</td>
<td>10,019</td>
<td>10%</td>
</tr>
</tbody>
</table>

Capacity utilization is the proportion of designed capacity actualized in use \[\text{capacity utilization} = (\text{actual output} / \text{potential output}) \times 100\%\]. To evaluate the three primary designs...
discussed and presented in Swan, cradle-to-use scope capacity utilization was evaluated at 100%. Therefore, sensitivity analysis was used to evaluate two alternate utilization capacity cases in the cradle-to-use scope: 90% Utilization of the One-Tether Initial Space Elevator and 10% Utilization of the One-Tether Initial Space Elevator scenarios. These two alternate utilization capacity sensitivities were evaluated using the 1-tether space elevator base technical design; 90% capacity utilization was used to evaluate the base scenario’s sensitivity to a 10% reduction in annual/lifetime utilization.

The annual payload delivered to orbit with the 10% capacity utilization 1-tether space elevator would be approximately 510 metric tons per year. 108.2 metric tons was launched into space in 2017, with the Federal Aviation Administration (FAA) forecasting 137 tons launched in 2018 (FAA, 2018). This puts annual payload to orbit for the 10% utilization scenario within an order of magnitude of the current cost prohibitive orbital transportation system rate.

The space elevator can deliver payloads and satellites to almost any of Earth’s orbits, however, geosynchronous earth orbit (GEO) was considered the primary destination orbit of space elevator payloads. In that respect, whenever the term orbit has been used without specific orbital designation, it should be taken as reference to GEO. Transportation and shipping distances of payloads to the space elevator from their points of origin were assumed uniformly distributed around the globe. Furthermore, most space elevator designs recommend the anchor node, or space elevator terrestrial port facility, be located near the equator. Since the world’s population is normally distributed around the equator, the uniform distribution assumption holds. The circumference of the Earth at the equator is approximately 40,075 km, and thus 10,019 km the average transportation distance estimate for a single global space elevator port system (Carroll & Ostlie, 2017). This 10,019-km estimate is then multiplied by a third, to produce the 3,340 km estimate for the average transportation distance for an optimally placed second space elevator port system.

The methods section from this point forward is organized by each major step of the LCA process. This paper evaluates the construction and use of the space elevator design proposed by Swan et al. (2013). In addition, this paper investigates impacts of additional scenarios and sensitivities for space elevator development and deployment.
6.2.1. Goal and Scope

The goal of this LCA was to evaluate the life-cycle environmental impacts of a space elevator and to identify ways in which environmental benefits could be realized as space elevator technologies evolve; by doing this we identify areas during design and production where reductions in environmental impacts can be realized (aka hot spots). In addition, this LCA aimed to identify potential tradeoffs and unintended consequences of future space elevator production, deployment, and use. Two system scopes were evaluated in this LCA: the cradle-to-gate scope evaluated the construction and deployment of the space elevator, and the cradle-to-use scope evaluated and compared the construction, deployment and use of the space elevator with additional space elevator configurations. The functional unit for the cradle-to-gate scope was one complete space elevator system deployed and ready for operation, and the functional unit for the cradle-to-use study was one kilogram (kg) transported from the Earth’s surface to geosynchronous Earth orbit (GEO).

A hybrid LCA (combining process-LCA and EIO-LCA methods) was used in this study. Process-LCAs utilize and tally large datasets including emissions, flows, and resource usage for each process in the system, whereas EIO-LCA results rely on sector-level averages. Hybrid LCAs utilize both methods in various combinations; for this study a process-LCA model was built first, and missing data were supplemented with EIO-LCA data. A sensitivity analysis of the LCIA results to changes in capacity utilizations was performed. Uncertainty was evaluated via a pedigree matrix and the overall scenario analysis addressed elements of both uncertainty and sensitivity. When more data become available, Monte Carlo analysis is advised.

6.2.2. System Boundary and Functional Unit

The system boundary (Figure 6. 2) included two overlapping scopes described in the previous section to allow for improved resolution and interpretation of results: a cradle-to-gate scope including production, construction, and deployment, with a functional unit of a complete space elevator system; and infrastructure and a cradle-to-use scope including production, construction, deployment, and use, with a functional unit of 1 kg safely transported from the Earth’s surface to geosynchronous Earth orbit (GEO).
Figure 6.2. System Boundary Diagram for the Space Elevator Life Cycle Assessment. The cradle-to-gate system boundary (orange) contains production and deployment of the space elevator. The cradle-to-use system boundary (blue) contains production, deployment, and use. The green system processes are EIO-LCA based, and the blue system processes are process-LCA based. Elementary flows are included but not individually listed.

LCAs often do not include construction of major infrastructure because the impacts of construction amortized over the system lifetime are assumed to fall below a 1% cutoff criterion (Simonen, 2014). However, because the construction and deployment of a space elevator is of such a large scale and is a capital investment for future infrastructure, its associated impacts were also included and considered. Though included in the scope and boundary, extensive analysis of the emissions from combustion of rocket fuel during launch was not possible in this study. The only impact category included for rocket fuel combustion at this time is global warming potential (GWP). This is because of the relatively simple calculation of CO₂ emissions from kerosene combustion. However, this does not account for any other emissions or impacts from rocket launch, including emissions throughout the height of the atmosphere as the rocket reaches orbit.

The end-of-life (EOL) was excluded from all system boundaries. Space elevator design inherently allows for ejection of the tether and orbital nodes into space causing minimal earth impacts in case of emergency. The design of the space elevator can also allow for the carbon
nanofiber ribbon to be recycled in orbit thereby reducing the ultimate cradle-to-grave impact of the space elevator. Future studies should include this aspect of the full space elevator lifecycle.

6.2.3. Life cycle inventory (LCI)

All design specifications and scenario values were based on a recent comprehensive design for production, deployment, and use of a space elevator, as detailed in the book *Space Elevators: An Assessment of the Technological Feasibility and the Way Forward* (P. A. Swan et al., 2013). This book compiles and expands on years of NASA funded research and academic publications by the book’s authors (Edwards, 2000; Edwards & Westling, 2003; D. Raitt, 2017; D. Raitt & Edwards, 2004; D. Raitt, Gyger, & Woods, 2001; D. I. Raitt, 2015; C. W. Swan, 2015; C. W. Swan & Swan, 2006; C. W. Swan, Swan, Knapman, & Raitt, 2015; P. A. Swan, 2015). Other LCI data values were collected via a thorough literature review and the use of existing LCI databases. Efforts were made to ensure the reliability and suitability of the data selected for the model. Minimal sustainability literature and data were located for this study; therefore, single point values with significant uncertainty were used. This LCA assumes that all values and datasets adequately represent the average for the variables and systems characterized. However, all data assumptions were made conservatively, i.e., biased towards increasing the associated impact as opposed to underestimating the potential consequences.

The space elevator design used this study was based on the 2013 Swan et al. study. This space elevator design includes the production, deployment, and use of two space elevators to improve the business case for the plan through economies of scale. The primary benefit of deploying the second and all subsequent space elevators is the lack of requiring the launching of roughly 86 metric tons of material into orbit for initial deployment. All space elevators following the first can be deployed into orbit using the previous space elevator. Table 6.2 shows the primary source data for the space elevator design used for this LCA. Table 6.1 contains the primary source data for the space elevator system.
Hybrid LCAs use a combination of process data and EIO-LCA data to compile data for upstream processes. This study uses process data from ecoinvent version 3.1. EIO-LCA data was used from the USEIO-LCA database with a base year of 2002 with producer prices (Hauschild, Rosenbaum, & Olsen, 2017). Cost data summarized in Table 6.2 was reported in 2013; these values were converted to 2002 (-22.8% cumulative rate of inflation) to match EIO-LCA input data (http://www.usinflationcalculator.com/). Table 6.3 shows the LCI system processes and modeling input parameters with the associated LCA database for each process upstream dataset.
Table 6.3. Space Elevator LCA Model Input Parameters and System Processes for both Cradle-to-Gate and Cradle-to-Use System Boundary Scopes for the scenario and sensitivity analyses presented in this study. Process-LCA data were derived from ecoinvent v3.1 and is identifiable by non-$USD units. EIO-LCA data were derived from the CMU model (CMU, 2002) and USEIO-LCA, and is identifiable by $USD2002 in the units column. Both cradle-to-gate and cradle-to-use input data is represented for the One-Tether Initial Space Elevator, Two-Tether Initial Space Elevator, and Additional One-Tether Space Elevator scenarios, while only cradle-to-use input data is required for the 90% Utilization One-Tether Initial Space Elevator and 10% Utilization One-Tether Initial Space Elevator sensitivities. NAICS = “North American Industry Classification System,” alloc. = “allocation,” S = “system process,” GLO = “global,” RoW = “rest of world.”

<table>
<thead>
<tr>
<th>Unit Process</th>
<th>Unit</th>
<th>Scope (Cradle-to-)</th>
<th>One-Tether Initial Space Elevator</th>
<th>Two-Tether Initial Space Elevator</th>
<th>Additional One-Tether Space Elevator</th>
<th>90% Utilization One-Tether Initial Space Elevator</th>
<th>10% Utilization One-Tether Initial Space Elevator</th>
<th>ecoinvent process or NAICS Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Lifespan Design Payload to Orbit</td>
<td>Total kg to Orbit</td>
<td>--</td>
<td>2.55E+08</td>
<td>5.10E+08</td>
<td>2.55E+08</td>
<td>2.29E+08</td>
<td>2.55E+07</td>
<td>not applicable – reference flow value</td>
</tr>
<tr>
<td>Carbon Nanofiber (CNF) Materials Production</td>
<td>kg CNF/kg to Orbit</td>
<td>Gate</td>
<td>3.15E+04</td>
<td>6.30E+04</td>
<td>3.15E+04</td>
<td>--</td>
<td>--</td>
<td>not applicable – system process</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>1.24E-04</td>
<td>1.24E-04</td>
<td>1.24E-04</td>
<td>1.37E-04</td>
<td>1.24E-03</td>
<td></td>
</tr>
<tr>
<td>• Benzene Production (for CNF)</td>
<td>kg Benzene/kg to Orbit</td>
<td>Gate</td>
<td>1.48E+05</td>
<td>2.96E+05</td>
<td>1.48E+05</td>
<td>--</td>
<td>--</td>
<td>market for benzene, alloc. default, S - GLO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>5.81E-04</td>
<td>5.81E-04</td>
<td>5.81E-04</td>
<td>6.46E-04</td>
<td>5.81E-03</td>
<td></td>
</tr>
<tr>
<td>• Hydrogen Sulfide Production (for CNF)</td>
<td>kg H₂S/kg to Orbit</td>
<td>Gate</td>
<td>6.30E+03</td>
<td>1.26E+04</td>
<td>6.30E+03</td>
<td>--</td>
<td>--</td>
<td>hydrogen sulfide production, alloc. default, S - RoW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>2.47E-05</td>
<td>2.47E-05</td>
<td>2.47E-05</td>
<td>2.75E-05</td>
<td>2.47E-04</td>
<td></td>
</tr>
<tr>
<td>• Hydrochloric Acid Production (for CNF)</td>
<td>kg HCl/kg to Orbit</td>
<td>Gate</td>
<td>5.04E+05</td>
<td>1.01E+06</td>
<td>5.04E+05</td>
<td>--</td>
<td>--</td>
<td>hydrochloric acid production, from the reaction of hydrogen with chlorine, alloc. default, S - RoW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>1.98E-03</td>
<td>1.98E-03</td>
<td>1.98E-03</td>
<td>2.20E-03</td>
<td>1.98E-02</td>
<td></td>
</tr>
<tr>
<td>• Hydrogen Production (for CNF)</td>
<td>kg H₂/kg to Orbit</td>
<td>Gate</td>
<td>5.42E+04</td>
<td>1.08E+05</td>
<td>5.42E+04</td>
<td>--</td>
<td>--</td>
<td>market for hydrogen, liquid, alloc. default, S - RoW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>2.13E-04</td>
<td>2.13E-04</td>
<td>2.13E-04</td>
<td>2.36E-04</td>
<td>2.13E-03</td>
<td></td>
</tr>
<tr>
<td>Energy Production (for CNF)</td>
<td>MJ/kg to Orbit</td>
<td>Gate</td>
<td>7.95E+07</td>
<td>1.59E+08</td>
<td>7.95E+07</td>
<td>--</td>
<td>--</td>
<td>electricity, high voltage, production mix, alloc. default, S - US</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>3.12E-01</td>
<td>3.12E-01</td>
<td>3.12E-01</td>
<td>3.47E-01</td>
<td>3.12E+00</td>
<td></td>
</tr>
<tr>
<td>Anchor Node (Offshore Platform) Production</td>
<td>Platforms/kg to Orbit</td>
<td>Gate</td>
<td>2.00E+00</td>
<td>4.00E+00</td>
<td>2.00E+00</td>
<td>--</td>
<td>--</td>
<td>offshore platform production, petroleum, alloc. default, S - GLO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>7.85E-09</td>
<td>7.85E-09</td>
<td>7.85E-09</td>
<td>8.72E-09</td>
<td>7.85E-08</td>
<td></td>
</tr>
<tr>
<td>Unit Process</td>
<td>Unit</td>
<td>Scope (Cradle to-)</td>
<td>Scenario analysis</td>
<td>Sensitivity analysis</td>
<td>ecoinvent process or NAICS Code</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------------------------</td>
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<td>--------------------</td>
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<td>----------------------</td>
<td>---------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operation Center Construction</strong></td>
<td>m³/kg to Orbit</td>
<td>Gate</td>
<td>4.09E+03</td>
<td>--</td>
<td>building construction, multi-storey, alloc. default, S - RoW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>1.60E-05</td>
<td>1.20E-05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Climber Production</strong></td>
<td>$USD2002/kg</td>
<td>Gate</td>
<td>3.76E+08</td>
<td>--</td>
<td>1 USD guided missile and space vehicle manufacturing - US NAICS Code 336414</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>to Orbit</td>
<td>Use</td>
<td>1.48E+00</td>
<td>1.48E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Space Node Production</strong></td>
<td>$USD2002/kg</td>
<td>Gate</td>
<td>3.59E+08</td>
<td>--</td>
<td>1 USD guided missile and space vehicle manufacturing - US NAICS Code 336414</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>to Orbit</td>
<td>Use</td>
<td>1.41E+00</td>
<td>1.41E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Launch Mass for Initial Tether Deployment</strong></td>
<td>kg Launch/kg</td>
<td>Gate</td>
<td>8.60E+04</td>
<td>--</td>
<td>not applicable – system process</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>to Orbit</td>
<td>Use</td>
<td>3.38E-04</td>
<td>1.69E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rocket Cost for Initial Tether Deployment</strong></td>
<td>$USD2002/kg</td>
<td>Gate</td>
<td>5.40E+08</td>
<td>--</td>
<td>1 USD guided missile and space vehicle manufacturing - US NAICS Code 336414</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>to Orbit</td>
<td>Use</td>
<td>2.12E+00</td>
<td>1.06E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Liquid Oxygen (LOX) Production for Initial Tether Deployment</strong></td>
<td>kg LOX/kg to Orbit</td>
<td>Gate</td>
<td>7.45E+06</td>
<td>--</td>
<td>market for oxygen, liquid, alloc. default, S - RoW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>2.92E-02</td>
<td>1.46E-02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rocket-Grade Kerosene (RP-1) Production for Initial Tether Deployment</strong></td>
<td>kg RP-1/kg to Orbit</td>
<td>Gate</td>
<td>2.91E+06</td>
<td>--</td>
<td>market for kerosene, alloc. default, S - RoW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>1.14E-02</td>
<td>5.71E-03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Payload Shipment to Space Elevator</strong></td>
<td>t³km/kg to Orbit</td>
<td>Gate</td>
<td>--</td>
<td>--</td>
<td>transport, freight, lorry &gt;32 metric ton, EURO6, alloc. default, S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use</td>
<td>1.00E+01</td>
<td>1.00E+01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Production Cost</strong></td>
<td>$USD2013/kg</td>
<td>Gate</td>
<td>8.84E+09</td>
<td>3.85E+01</td>
<td>market for benzene, alloc. default, S - GLO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>to Orbit</td>
<td>Use</td>
<td>3.47E+01</td>
<td>2.27E+01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2.4. **Life cycle impact assessment (LCIA)**

Impact assessment was completed using TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.1 V1.01) midpoint impact characterization methodology developed by the EPA for the US (J. Bare, 2011). Midpoint impacts reflect environmental impact potentials, a link in the cause-effect chain, while endpoints reflect the effect itself (J. C. Bare, Hofstetter, Pennington, & De Haes, 2000). The following 10 TRACI impact categories were calculated and interpreted: global warming, eutrophication, acidification, ecotoxicity, ozone depletion, smog formation, resource depletion, and human health: carcinogenics, non-carcinogenics, and respiratory effects.

In addition to the 10 TRACI impact categories, a producer cost impact category was also calculated using the space elevator strategic investment layout presented in the Swan et al. study (2013) and listed in Table 6.2. Because the 2008 TRACI normalization factors do not include a producer cost impact category, the 2008 US national gross domestic product (GDP), $14.7 trillion, and 2008 US gross national income (GNI) per capita, $49,330, as reported by the World Bank (Bank, 2008) for a common reference benchmark normalization factor for the producer cost impact category. A preliminary producer cost-to-orbit estimate was established by taking the producer cost divided by the mass delivered to orbit ($/kg to GEO).

6.2.4.1. **Uncertainty Analysis**

In addition to the scenario (3 space elevator configurations) and sensitivity (2 utilization capacities of the space elevator’s base design) analyses described in previous sections, uncertainty analysis was completed via a pedigree matrix. A pedigree matrix is a method to quantify and evaluate the representativeness of the LCI data to the stated goals, as well as to examine the uncertainty as they relate to the final LCIA results. The five data quality indicators empirically determined from the “improved pedigree matrix” approach were: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation (B. P. Weidema et al., 2013). The pedigree matrix in Table 6.4 and Table 6.5 have data quality scores and averages ranging between 1 (lowest quality) and 5 (highest quality).
Table 6.4. Improved Pedigree Matrix. Includes five data quality indicators: reliability, completeness, temporal correlation, geographical correlation, and technological correlation, to evaluate the uncertainty and representativeness of the model’s input parameters from 1 (lowest data quality) to 5 (highest data quality) as described in matrix text (B. P. Weidema et al., 2013).

<table>
<thead>
<tr>
<th>Data Quality Indicators &amp; Scores ↓</th>
<th>Reliability</th>
<th>Completeness</th>
<th>Temporal Correlation</th>
<th>Geographical Correlation</th>
<th>Technological correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (Highest Quality)</td>
<td>Verified data based on measurements</td>
<td>Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations</td>
<td>Less than 3 years of difference to the time period of the dataset</td>
<td>Data from area under study</td>
<td>Data from enterprises, processes and materials under study</td>
</tr>
<tr>
<td>4</td>
<td>Verified data partly based on assumptions or non-verified data based on measurements</td>
<td>Representative data from &gt;50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations</td>
<td>Less than 6 years of difference to the time period of the dataset</td>
<td>Average data from larger area in which the area under study is included</td>
<td>Data from processes and materials under study (i.e. identical technology) but from different enterprises</td>
</tr>
<tr>
<td>3</td>
<td>Non-verified data partly based on qualified estimates</td>
<td>Representative data from only some sites (&lt;&lt;50%) relevant for the market considered or &gt;50% of sites but from shorter periods</td>
<td>Less than 10 years of difference to the time period of the dataset</td>
<td>Data from area with similar production conditions</td>
<td>Data from processes and materials under study but from different technology</td>
</tr>
<tr>
<td>2</td>
<td>Qualified estimate (e.g. by industrial expert)</td>
<td>Representative data from only one site relevant for the market considered or some sites but from shorter periods</td>
<td>Less than 15 years of difference to the time period of the dataset</td>
<td>Data from area with slightly similar production conditions</td>
<td>Data on related processes or materials</td>
</tr>
<tr>
<td>1 (Lowest Quality)</td>
<td>Non-qualified estimate</td>
<td>Representativeness unknown or data from a small number of sites and from shorter periods</td>
<td>Age of data unknown or more than 15 years of difference to the time period of the dataset</td>
<td>Data from unknown or distinctly different area</td>
<td>Data on related processes on laboratory scale or from different technology</td>
</tr>
</tbody>
</table>
Table 6.5. Uncertainty and Representativeness of LCI Data to the Space Elevator System via the Improved Pedigree Matrix. System process averages of the five data quality indicators are provided.

<table>
<thead>
<tr>
<th>Data Quality Indicators → &amp; Processes ↓</th>
<th>Reliability</th>
<th>Completeness</th>
<th>Temporal Correlation</th>
<th>Geographical Correlation</th>
<th>Technological correlation</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Nanofiber (CNF) Production</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3.6</td>
</tr>
<tr>
<td>Anchor Node (Offshore Platform)</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>3.8</td>
</tr>
<tr>
<td>Operation Center Construction</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3.6</td>
</tr>
<tr>
<td>Climber Production</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3.2</td>
</tr>
<tr>
<td>Space Node Production</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3.2</td>
</tr>
<tr>
<td>Launch Mass for Initial Tether Deployment</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Rocket Cost for Initial Tether Deployment</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4.2</td>
</tr>
<tr>
<td>Liquid Oxygen (LOX) Production for Initial Tether Deployment</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Rocket-Grade Kerosene (RP-1) Production for Initial Tether Deployment</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Payload Shipment to Space Elevator</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Total Production Cost</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>3.8</td>
</tr>
</tbody>
</table>

6.3. Results and discussion

This space elevator environmental LCA quantified and evaluated the potential impacts from the production, deployment, and use of the space elevator system proposed by Swan et al. (2013). Three space elevator design configurations/business plans were presented by Swan and evaluated in this study for both cradle-to-gate and cradle-to-use scopes: One-Tether Initial Space Elevator, Two-Tether Initial Space Elevator, Additional One-Tether Space Elevator. The One-Tether Initial Space Elevator scenario was the base primary technical design configuration,
while the *Two-Tether Initial Space Elevator* scenario represented the recommended business plan configuration. The *Additional One-Tether Space Elevator* scenario represented future space elevator systems deployed with a previous space elevator (without the need for initial rocket deployment). The *Additional One-Tether Space Elevator* scenario showed the lowest environmental impact, while the *Two-Tether Initial Space Elevator* scenario showed the lowest production cost per unit mass delivered to orbit.

A detailed comparison of process contributions to the three-primary space elevator design scenarios for the cradle-to-use scope is shown in Figure 6.3, a conventional representation of LCIA results. The vertical axis was normalized to show the *One-Tether Initial Space Elevator* total impact set at 100%. Each TRACI impact category showed incremental reduction in impacts from the *One-Tether Initial Space Elevator* to the *Two-Tether Initial Space Elevator* to the *Additional One-Tether Space Elevator* scenario. The producer cost impact category, however, showed the lowest cost for the *Two-Tether Initial Space Elevator* scenario. It was notable that all process contributions for all three-primary cradle-to-use scenarios were equal other than for initial launch deployment impact contributions (dark blue) and use/payload shipment impact contributions (brown).

In half of the 10 TRACI impact categories, the use phase alone contributed to 40% or more to all impacts over the life-cycle. The inherently low number of space elevator ports to payload sources produces larger impacts per unit payload mass. The 5 impact categories dominated by source-to-launch-pad-transportation are acidification, eutrophication, smog formation, resource depletion, and respiratory effects. The other 5 TRACI impact categories, i.e., ecotoxicity, global warming, ozone depletion, and both carcinogenic and non-carcinogenic human health effects, had the most significant process contribution from a combination of four different inputs, namely anchor node, climber, space node, and launch vehicle construction. All the use phase transportation impacts could be reduced by improving the transportation fuel types and energy efficiency for all payload delivered to the space elevator from its source.
Figure 6.3. Life Cycle Impact Assessment Cradle-to-Use Results for Three Primary Space Elevator Design Configurations. All three design plans modeled were based on Swan et al. (2013). Cradle-to-use system process individual contributions for each quantified impact category are illustrated for the primary design scenarios: 1-Tether Initial Space Elevator, 2-Tether Initial Space Elevator, and Additional 1-Tether Space Elevator. The vertical axis scale was set by normalizing to the 1-Tether Initial Space Elevator scenario impacts at 100%. Cost impacts were included in the figure but not itemized for each system process contribution.
The energy required for CNF production had a significant process contribution (>10%) in acidification, eutrophication, smog formation, and respiratory effects impact categories. These could be improved by utilizing sustainable energy systems and grids for terrestrial manufacture and construction of space elevator infrastructure and components. Anchor node (offshore platform) construction had a significant process contribution (>10%) in acidification, eutrophication, carcinogens, smog formation, and respiratory effects. These impacts could be reduced by using sustainable engineering and design practices when optimizing the offshore platform construction for its intended purpose. Or they could be reduced by reusing and repurposing retired offshore platforms as other space elevator designs suggest (Edwards, 2000; Edwards & Westling, 2003). Space node production and tether climber production both had significant process contributions (>15% each) in ecotoxicity, global warming potential, carcinogenics, non-carcinogenics, and ozone depletion. Because these processes were EIO-LCA based, specific recommendations for reducing these impacts cannot be made. Further in-depth quantitative sustainability assessments of such spacecraft production and launch systems, processes, and products are required.

6.3.1. Capacity Utilization Sensitivity Analysis

The One-Tether Initial Space Elevator (100% Utilization) scenario was also compared with two alternate utilization capacity sensitivities within the cradle-to-use scope. The 90% Utilization One-Tether Initial Space Elevator and 10% Utilization One-Tether Initial Space Elevator cradle-to-use cases were normalized to and compared with the 100% utilization capacity One-Tether Initial Space Elevator cradle-to-use scenario (Figure 6. 4).

The only impact category that showed a direct inversely correlated response to the 10% capacity utilization scenario (red) was producer cost. That is, a tenfold decrease in capacity utilization caused a tenfold increase in producer cost per kg to orbit. All other impacts showed a less sensitive inverse correlation to reduction in utilization. The ecotoxicity, carcinogenics, non-carcinogenics, and ozone depletion impact categories, in addition to producer cost, all showed greater than an eightfold increase response in sensitivity to the tenfold decrease in utilization. Only the resource depletion and respiratory effects impact categories showed less than a fivefold increase response in sensitivity to the tenfold utilization decrease. For the 90% capacity utilization scenario (green), there was little more than 11% increase in any impact category due
Figure 6.4: Cradle-to-Use Space Elevator Capacity Utilization Sensitivity Analysis and Comparison to space elevator base design. A sensitivity analysis of capacity utilization was completed in this LCA. Two alternate capacity utilization scenarios were evaluated for system sensitivity within the cradle-to-use scope: 90% Utilization One-Tether Initial Space Elevator in green and 10% Utilization One-Tether Initial Space Elevator in red, then normalized and compared to the base design One-Tether Initial Space Elevator (100% Utilization) in blue.

To the 10% decrease in utilization. This suggests the space elevator LCIA results are not overly sensitive to proportional changes in percent capacity utilization.

However, the tenfold sensitivity required a deeper investigation into the significance of the direct inverse correlation between capacity utilization and producer cost. With the average consumer cost to transport payloads to orbit roughly $20,000/kg, and the current listed commercial rate for the discount orbital transportation provider used for this study at $15,423/kg to GEO (spacex.com), the $346.84/kg to GEO estimated producer cost impact from the 10% utilization the space elevator should still be attractive to investors. The more realistic 90% utilization space elevator scenario producer cost estimate was $38.54/kg to GEO. If the actual consumer price for the space elevator is as projected in Swan et al. (2013) at $500/kg to GEO,
the possible profits range from $153.16 to $461.46 per kilogram delivered to GEO. The estimated annual profits then range from $78 million to $4.9 trillion per year between all the space elevator scenarios evaluated in this LCA.

The pedigree matrix uncertainty analysis (scores provided in Table 6.4) showed that the LCI data related to space vehicle production show the greatest uncertainty, with both climber and space node production process average data quality scores of 2.8/5. The average of all scores was 3.7/5. This further highlights the need for future sustainability assessments of the space elevator design as well as existing orbital transportation technologies.

6.4. Conclusions

The LCA results showed the space elevator to be an environmentally sustainable and economically viable option for future orbital transportation, and highlighted system elements for targeted impact reduction. These results showed that use-phase impacts could be reduced by improving the transportation systems used to deliver payloads to the space elevator port from around the globe, and by optimally placing future space elevator ports to reduce the transportation impacts for both systems. These results also point to the need for the application of sustainability engineering and quantitative sustainability assessment methodologies to the spacecraft and orbital transportation systems and industries. The LCA results also showed the space elevator to have minimal producer cost sensitivity to reduced capacity utilization, with the potential for significant positive economic impact. Furthermore, if the cost-to-orbit and structural requirements of the existing orbital transportation system were significantly reduced, humans would have greater access to the vast and valuable resources of space. These results lead to the conclusion that the space elevator is a potentially sustainable path to those virtually untapped space resources, which could significantly enhance the continued sustainable development on Earth.

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6.5. References


CHAPTER SEVEN

ENVIRONMENTAL AND COST LIFE CYCLE ASSESSMENT OF ORBITAL TRANSPORTATION SYSTEMS INCLUDING MEGAPROJECT INFRASTRUCTURE COMPARISONS

Modified from a paper to be submitted to

*Science*

Tyler M. Harris\(^1,2\), Pragnya L. Eranki\(^2,3\), Amy E. Landis\(^2,4\)

Cartoon by Johnny Robinson\(^5\), 1981

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2 Department of Civil and Environmental Engineering, Colorado School of Mines.
3 Contributing author; Assistant Research Professors.
4 Research advisor; Professor.
5 Published by the L5 society, 1981; Used with permission from the National Space Society, see Appendix C; space.nss.org/l5-news-resources-of-space-cartoon-by-johnny-robinson
Abstract

This research was the first environmental life cycle assessment and producer cost comparison of existing and proposed orbital technology systems. The systems evaluated were the Falcon 9, Falcon Heavy, and Delta IV Heavy rocket launch systems. The proposed orbital transportation system modeled and assessed was a comprehensive space elevator design. This space elevator model was also compared to existing terrestrial megaproject infrastructure models to evaluate the capital investment impacts of producing and deploying the first space elevator.

Results showed the environmental and cost impacts of the proposed space elevator system were significantly lower than all existing rocket launch orbital transportation systems modeled. The Falcon Heavy rocket launch system showed the lowest impacts of the three rocket launch systems modeled in all categories aside from resource depletion, where it was just over 10% larger than the Delta IV Heavy system. The capital infrastructure investment required for producing and deploying the first space elevator falls within range of the existing terrestrial megaprojects modeled in terms of the lifecycle environmental and cost impacts evaluated.

This research appears to be the first of its kind in assessing and comparing the environmental impacts of existing and proposed orbital transportation systems. It is highly recommended that investments be made into producing process-LCA datasets of rocket launch and other orbital transportation systems for future sustainability research with greater resolution and certainty.

**Keywords:** Quantitative Sustainability Assessments, Life Cycle Assessment (LCA), Orbital Transportation Systems, Geosynchronous Earth Orbit (GEO), Rocket Launch, Space Elevator

7.1. Introduction

The average cost to transport material payloads from Earth’s surface to space has been roughly $20,000 per kilogram (Coopersmith, 2011) with the global space economy accounting for $344.5 billion of activity in 2016 (FAA 2018). However, the cost of orbital transportation via rocket-launched spacecraft has been decreasing with the growing number of commercial orbital launch services. The Hubble Space Telescope and International Space Station (ISS) are in low earth orbit (LEO) <1,000 km altitude, Global Positioning System (GPS) satellites are in a medium earth orbit (MEO) ~22,000 km altitude, and weather/communication satellites are commonly in GEO ~35,800 km – the minimum high earth orbit (HEO) which maintain its
position in orbit relative to a spot on the Earth’s surface. Figure 1 illustrates different earth orbits. Published prices in 2018 from active commercial rocket orbital transportation services for insured delivery to LEO) from the Falcon 9 at $2,719.30/kg (SpaceX.com) to $4,644.06/kg for the Atlas V (ULAlaunch.com). Delivery to geosynchronous earth orbit (GEO, aka GSO) range from the near proven Falcon Heavy system at $5,357/kg (SpaceX.com), to approximately $51,215/kg for the Delta IV Heavy (DOD, 2017). However, not represented in these prices are the high physical tolerance and resilience required of the satellites or other payloads delivered to space.

If the high costs and structural requirements for orbital transportation services were significantly reduced, humankind would have greater access to the vast and valuable resources of space. A little known but well researched and reportedly feasible orbital transportation system design, the space elevator, has an estimated cost to GEO of $500/kg and aims to make orbital transportations a regular, safe, and easy occurrence (Swan, Raitt, Swan, Penny, & Knapman, 2013). However, no published quantitative sustainability research was found on any of the various existing or proposed orbital transportation systems to allow a fair comprehensive quantitative lifecycle comparison between the two technological systems.

A proven method for reducing costs and negative impacts for any system or product, while also increasing system efficiency and environmental performance, is the application of sustainable engineering principals and methodologies (B. R. Allenby, 2011). Sustainability engineering attempts to optimize and balance the needs, impacts, and benefits of the complex interactions between society, economy, and environment – with the goal being the long-term survival and *thrive*al of humankind (Fitch, 2006) through sustainable development, industrial ecology, and earth systems engineering and management (B. Allenby, 2007).

Life cycle assessment (LCA) is a vetted and standardized sustainability engineering methodology that quantifies and assesses the environmental impact of a product, service, process, or activity throughout its life-cycle. LCA examines environmental and other impacts to identify impact hotspots, evaluate the impact tradeoffs between scenarios, and anticipate and avoid unintended consequences. Evaluation, improvement, and comparison of services and technologies such as orbital transportation systems are some of the benefits of performing quantitative sustainability assessments like LCA.
The sustainability of space activities, or space sustainability, is important to all three (social, economic, and environmental) pillars of sustainability. Economic sustainability applies to space sustainability not only from the enhanced incomes, standards of living, and economic activity produced by the $345 billion per year global space economy, but also the economic benefits of sustainably tapping the virtually untouched space resource base. The term space resources generally encompass the infinite supply and variety of energy, materials, area, and conditions. Those of greatest near-term interest and value include lunar mining, space solar power, space manufacturing and 3D printing; technologies may eventually extend to rare earth elements, critical materials, and He$_3$ as a fusion power fuel component. This study included a potential producer cost impact for quantification and evaluation of existing and proposed orbital transport systems; not included is a techno-economic analysis, i.e., evaluation of the economic benefits from the reduced structural and design requirements of satellites and other orbital payloads of the space elevator system compared to traditional systems.

Environmental sustainability also has various nuances and applications when it comes to space sustainability. In this study, traditional terrestrial earth environmental impacts, such as global warming potential (GWP) and acidification, were considered for all systems studied. However, environmental sustainability and methodologies for impact quantification and assessment for various extraterrestrial (off earth) activities have not been established herein. These range from orbital debris (space junk) accumulation to forward contamination of microbes to other terrestrial bodies.

Social sustainability includes welfare and wellbeing, social equality and justice, as well as other political and cultural impacts and considerations. This encompasses vast multidisciplinary considerations including astronaut and space traveler health, safety, and wellbeing; social equity in the distribution of the benefits of space exploration and resources; space law, policy, rights, and governance; as well as many hypothetical scenarios explored in space science fiction over the last century such as the various Star Trek series, films, and novels (Costanza, 1999; Geraghty, 2005). Social sustainability is beyond the scope of this study, which was performed to quantify and assess only the other two pillars of sustainability, namely economic and environmental.
7.1.1. Orbital Transportation Systems Overview

Traditional rocket technology has been the only method regularly used to transport payloads to space (and various rapid descent modules the only method regularly used for returning from space) since space exploration began in the 1950s and 60s. Traditional rockets include the retired Apollo Program’s Saturn 5 and NASA’s Space Shuttle. Existing rockets include ULA’s Delta IV Heavy and SpaceX Falcon 9 and Heavy. However, there are many other systems and designs that could theoretically transport goods to and from space. These include air launch to orbit (e.g. Virgin Galactic SpaceShipTwo), electromagnetic propulsion tubes (e.g. railgun launch), and the space elevator design. Other designs and plans to mine the Lunar surface for ice to use as rocket fuel to transport payloads between various earth orbits have also been proposed (Sowers, 2016).

Rocket engines have been the only means of delivering payloads into space as of 2018 (high-altitude balloon record is 53km attitude). The first-stage of space launch has most commonly been to launch and propel using rocket engines (i.e. rocket launched) whereas other space launches have a jet engine first-stage for a higher altitude initial rocket launch (i.e. air-launched rocket). Air-launched rocket orbital transportation systems have been used to launch to LEO (Figure 7.1) only and has had a relatively high failure rate in research and development testing. The Pegasus is the only regularly used air-launched rocket orbital transportation system with the last use in 2016 (SpaceLaunchReport.com). The developing suborbital space tourism industry such as Virgin Galactic and Blue Origin utilize such air-launched rocket technology.

Of the approximately 5441 total orbital launch attempts in human history (planet4589.org) the majority have been rocket-launched. Such rocket launch vehicles include the Saturn V and its 13 Apollo Program launches (space.com); the Space Shuttle system and its 135 launches (space.com); the 100% reliable Delta IV and its 35 launches (FAA, 2018); the Falcon 9 and its 46 launches (FAA, 2018); and all other launch vehicles that have carried the 533 total humans sent to orbit (quora.com). The Falcon 9 manufactured by SpaceX has been the most successful commercial space launch venture, with a total of 46 launches and 98% reliability between 2010 and 2017 (FAA, 2018).

SpaceX has also been in the final stages of certifying its groundbreaking Falcon Heavy rocket launch vehicle design that could considerably reduce the cost of orbital transportation by reusing two of its first-stage booster rockets (SpaceX.com). Rocket engines typically use a fuel combination of liquid oxygen and liquid hydrogen (LOX/LH2) – such as the Delta IV Heavy –
or fuel combination of liquid oxygen and rocket grade kerosene (LOX/RP1) – such as the Falcon 9 and Heavy. However, the regularly used Soyuz launch vehicle uses both LOX/RP1 and a fuel combination of dinitrogen tetroxide and unsymmetrical dimethylhydrazine (N2O4/UDMH). Another regularly used fuel combination is LOX and liquified natural gas (LOX/LNG). Solid rocket motors are another technology in use that requires solid rocket fuel that is less expensive but also less versatile. Therefore, solid rocket motors and fuel are most often only used for booster or upper stage thrust elements (FAA, 2018).

The space elevator is a proposed orbital transportation system that deploys and collects satellites and payloads to and from any of Earth’s orbits, as well as to and from cislunar or interplanetary space (Pugno, 2013). The space elevator is an Earth-satellite tethered system that connects a counterbalance in far-earth orbit to an offshore platform on the Earth’s Equator by a large carbon nanofiber (CNF) ribbon (Figure 7.1). The orbiting counterbalance satellite node provides tension to the CNF tether through centrifugal forces, while the surface anchor node (and tether system center of mass) holds the counterbalance satellite node in GEO via centripetal forces (Swan et al., 2013). Space vessels called tether climbers then transverse the taut CNF tether, delivering payloads to a GEO satellite node for final payload delivery to GEO and other desirable Earth orbits.

The main setback to space elevator transport use would be the long travel times to and from GEO (7 days each way) compared to existing rocket technologies with transport times as low as several hours. Another setback to the space elevator could be the high capital investment required to reap the benefits of the system. Various estimates on the total cost of producing and deploying space elevators range from $6 billion to $20 billion USD (Raitt, 2017). The underlying infrastructure and technological development of the rocket launch orbital transportation industry likely cost far more than this estimate for the space elevator, e.g. the ISS alone has been estimated to have cost $150 billion USD so far; however, governments fronted the initial capital costs for national defense and military purposes, and it is already built in to the system.
Figure 7.1. Illustration of Earth Orbits and Space Elevator Design. Payload to GEO for existing rocket technologies accounts for less than 12% of the total rocket mass at liftoff. Furthermore, the high physical tolerances required make a large portion of that 12% mass structural in nature. While the space elevator payload to GEO would account for 70% of the total space elevator climber departure mass (including its renewable power source) while providing a safe and gentle ride to orbit (Swan et al., 2013).

In this study, we compared existing and proposed orbital transport systems to megaprojects for perspective. A megaproject has been generally defined as a major business or construction project or undertaking. Swan et al. (2013) further defined a megaproject as one that takes over ten years and $1 billion to complete. Ten successful megaproject examples of equivalent scale and uncertainty as the space elevator design was also presented by Swan et al. (2013); examples included the Three Gorges Dam, One World Trade Center, the Atlanta Falcons Stadium, Jubail Industrial City, and the ISS. The potential environmental and cost impacts of the production, deployment, and use of existing orbital transport systems, namely, Delta IV Heavy, Falcon 9, Falcon Heavy; and a proposed orbital transport system i.e., the space elevator design, were assessed and compared. Impacts from these systems were also compared to existing terrestrial megaprojects, namely the Empire State Building, the Pentagon, an oil refinery and pipeline, an airport and its aircraft, and a seaport and its ships.
7.2. Methods

Life Cycle Assessment (LCA) is a method used to quantify the environmental impacts of a product or process throughout its entire lifetime, from raw materials extraction, including production, use and ultimately through end-of-life. The process-LCA methodology is defined by the ISO 14040 series and includes four steps: 1. Goal and scope definition, 2. Life Cycle Inventory (LCI), 3. Life Cycle Impact Assessment (LCIA), and 4. Interpretation and improvement (ISO 14040, 2006). LCAs start with an explicit statement of the goal, scope and system boundaries of the study. The second step, LCI, is the most data intensive part of an LCA, where all the inputs and outputs for the product are quantified. The third step, LCIA, converts and presents the inventory data in meaningful terms, such as global warming potential, energy return on investment, and ecosystem impacts. The details of these steps are outlined in the materials and methods section. Finally, in the interpretation step, covered in the results and discussion section, the findings of the LCA are evaluated in relation to the defined goal to develop conclusions and make recommendations.

An attributional, hybrid LCA methodology was employed in this study because of the lack of LCA data on the orbital transportation industry. Attributional LCAs quantify and assess environmental impacts from each activity, product, or method (i.e. unit and system processes) included in the system boundary. Economic input-output LCA (EIO-LCA) is an alternate method for performing LCA by determining the average environmental impact per dollar spent in a specified industrial classification. This EIO-LCA methodology was developed and is maintained by researchers at Carnegie Mellon University (CMU); it utilizes linear algebra based on Leontief economic principals (Shrake, Bilec, & Landis, 2013; Simonen, 2014). EIO-LCA estimates environmental emissions resulting from economic activities (i.e. purchases) in the major sectors of the economy using input-output tables derived from the bureau of labor statistics (CMU, 2002). Some products, processes, and services do not have such process-LCA datasets available; such is the case for orbital transportation systems and the space industry. In such cases, hybrid LCA methodologies can be used to establish a process-LCA model while filling any gaps in the LCA databases with EIO-LCA results; therefore, this study applied these hybrid LCA methodologies. Because research on the sustainability of orbital transportation systems and the space industry is rare, EIO-LCA methodology was used for all spacecraft production processes in the model.
This study developed four orbital transportation system LCA models: Delta IV Heavy, Falcon 9, Falcon Heavy, and a space elevator. For perspective in investment and impact, these space industry systems were compared with other megaprojects, namely the Empire State Building, the Pentagon, an oil refinery and pipeline, an airport and its aircraft, and a seaport and its ships. The scope of this LCA consisted of two system boundaries: the cradle-to-gate scope evaluated and compared the construction and deployment of a space elevator with other megaprojects projects (e.g. seaport and its ships), and the cradle-to-use scope evaluated and compared the construction, deployment, and use of existing rocket launch orbital transportation systems with the proposed space elevator design.

7.2.1. **System Boundaries**

Two system boundary scope comparisons were considered: i) a cradle-to-gate scope including production, construction, and deployment with a functional unit of 1 complete megaproject infrastructure (e.g. space elevator with climbers versus a seaport with ships versus an airport with aircraft) and ii) a cradle-to-use scope including production, construction, deployment, and use with a functional unit of 1 kg transported from the Earth’s surface to GEO.

LCAs often do not include construction of major infrastructure because the impacts of construction amortized over the system lifetime are assumed to fall below a 1% cutoff criterion (Simonen, K. (2014). Life cycle assessment, Routledge.). However, because the construction and deployment of a space elevator is of such a large scale and is a capital investment for future infrastructure, its associated impacts were also included and considered. As such, megaproject infrastructures were modeled from cradle-to-gate to serve as a comparison for the initial space elevator port infrastructure production and deployment model. The system boundaries and scopes of all systems modeled as depicted in Figure 7.2.

Though included in the scope and boundary, extensive analysis of the emissions from combustion of rocket fuel during launch was not possible in this study. The only impact category included for rocket fuel combustion in this study is global warming potential (GWP) for the LOX/RP-1 fuel use only. This is included because of the relatively simple calculation of CO\textsubscript{2} emissions from kerosene combustion. However, this does not account for any other emissions or impacts from rocket launch, including emissions throughout the height of the atmosphere as the rocket reaches orbit. GWP emissions are not calculated for the LOX/LH2 fuels because the
primary emission is water vapor. Finally, the end-of-life (EOL) was excluded from all system boundaries. Space elevator design inherently allows for ejection of the tether and orbital nodes into space causing minimal earth impacts in case of emergency. However, the carbon nanofiber ribbon could be recycled in orbit reducing the ultimate cradle-to-grave impact of the space elevator. Future studies should include this aspect of the life-cycle where possible.

Figure 7. 2. System Boundary and Scope of (A) Space Elevator System (B) Rocket Launch Orbital Transportation and (C) Megaproject Infrastructure.

7.2.2. Life cycle inventory (LCI)

The orbital transportation systems assessed in this study included the Falcon 9, Falcon Heavy, Delta IV Heavy, and the space elevator. The earth megaprojects assessed for comparison were the Empire State Building, the Pentagon, an oil refinery and its pipeline, the Zurich International
Airport and its aircraft, and the Hamburg Seaport and its ships. The primary LCI input data for all infrastructure systems are given in Table 7.1. Upstream LCI data used to construct each model are described for each system in the subsequent sections. Primary input data in Table 7.1 were collected via a thorough literature review and life-cycle inventory database search. Efforts were made to ensure the reliability and suitability of the data selected for the model. Only a minimal amount of sustainability literature and data were located for this study; therefore, single point values with relatively high uncertainty were used.

Table 7.1. Primary Inventory Data Values, Units, and Sources for All Systems and Infrastructures Modeled.

<table>
<thead>
<tr>
<th>Inventory Data</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
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<tbody>
<tr>
<td><strong>Rocket Launch</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Falcon 9 Launch Consumer Cost (Advertised)</td>
<td>6.2E+07</td>
<td>$USD2018/Launch</td>
<td>SpaceX.com</td>
</tr>
<tr>
<td>Falcon Heavy Launch Consumer Cost (Advertised)</td>
<td>9.00E+07</td>
<td>$USD2018/Launch</td>
<td>SpaceX.com</td>
</tr>
<tr>
<td>Delta IV Heavy Launch Consumer Cost (Estimated)</td>
<td>3.37E+08</td>
<td>$USD2018/Launch</td>
<td></td>
</tr>
<tr>
<td>Falcon 9 Launch Total Payload to GEO* (Advertised)</td>
<td>4.02E+03</td>
<td>kg/Launch</td>
<td>SpaceX.com</td>
</tr>
<tr>
<td>Falcon Heavy Launch Total Payload to GEO* (Advertised)</td>
<td>1.68E+04</td>
<td>kg/Launch</td>
<td>SpaceX.com</td>
</tr>
<tr>
<td>Delta IV Heavy Launch Total Payload to GEO (Advertised)</td>
<td>6.58E+03</td>
<td>kg/Launch</td>
<td>ULAlaunch.com</td>
</tr>
<tr>
<td>Falcon 9 Launch Total Launch Mass (Advertised)</td>
<td>5.49E+05</td>
<td>kg/Launch</td>
<td>SpaceX.com</td>
</tr>
<tr>
<td>Falcon Heavy Launch Total Launch Mass (Advertised)</td>
<td>1.42E+06</td>
<td>kg/Launch</td>
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<td>Delta IV Heavy Launch Total Launch Mass (Advertised)</td>
<td>7.33E+05</td>
<td>kg/Launch</td>
<td>ULAlaunch.com</td>
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<tr>
<td>Falcon 9 Launch Empty Vehicle Mass** (Estimated)</td>
<td>3.27E+04</td>
<td>kg/Launch</td>
<td>SpaceLaunchReport.com</td>
</tr>
<tr>
<td>Falcon Heavy Launch Empty Vehicle Mass** (Estimated)</td>
<td>5.55E+04</td>
<td>kg/Launch</td>
<td>SpaceLaunchReport.com</td>
</tr>
<tr>
<td>Delta IV Heavy Launch Empty Vehicle Mass** (Estimated)</td>
<td>3.69E+04</td>
<td>kg/Launch</td>
<td>SpaceLaunchReport.com</td>
</tr>
<tr>
<td>Delta IV Heavy Fuel Mixture Ratio (LOX:LH₂) by Mass</td>
<td>5.97</td>
<td>LOX:LH₂ (by mass)</td>
<td>Spaceflight101.com</td>
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### Table 7.1. Continued.

<table>
<thead>
<tr>
<th>Inventory Data</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
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<tr>
<td><strong>Space Elevator</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Nanofiber (CNF) Production</td>
<td>6.30E+03</td>
<td>kg CNF/1-Tether</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Benzene Production (for CNF)</td>
<td>4.70E+00</td>
<td>kg Benzene/kg CNF</td>
<td>Khanna et al. 2008</td>
</tr>
<tr>
<td>Hydrogen Sulfide Production (for CNF)</td>
<td>2.00E-01</td>
<td>kg H₂S/kg CNF</td>
<td>Khanna et al. 2008</td>
</tr>
<tr>
<td>Hydrochloric Acid Production (for CNF)</td>
<td>1.60E+01</td>
<td>kg HCl/kg CNF</td>
<td>Khanna et al. 2008</td>
</tr>
<tr>
<td>Hydrogen Production (for CNF)</td>
<td>1.72E+00</td>
<td>kg H₂/kg CNF</td>
<td>Khanna et al. 2008</td>
</tr>
<tr>
<td>Energy Production (for CNF)</td>
<td>2.52E+03</td>
<td>MJ/kg CNF</td>
<td>Khanna et al. 2008</td>
</tr>
<tr>
<td>Tether Design Lifespan</td>
<td>1.00E+01</td>
<td>Years/Tether</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Space Elevator Design Lifespan</td>
<td>5.00E+01</td>
<td>Years/Space Port</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Cost to Produce 14 Climbers (for 2 Tethers)</td>
<td>9.74E+08</td>
<td>$USD2013/14-Climbers</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Number of Climbers per Each Tether</td>
<td>7.00E+00</td>
<td>Climbers/1-Tether</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Cost to Produce Space Nodes (for 2 Tethers)</td>
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<td>$USD2013/2-Space Nodes</td>
<td>Swan et al. 2013</td>
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<tr>
<td>Cost to Produce 2 Tethers</td>
<td>4.55E+09</td>
<td>$USD2013/2-Tethers</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Cost of Operations Center (for 2 Tethers)</td>
<td>9.55E+08</td>
<td>$USD2013/Operations Center</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Cost to Produce 2-Tether Space Elevator</td>
<td>1.16E+10</td>
<td>$USD2013/2-Tether Space Elevator</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Cost to Launch Initial Seed Tether</td>
<td>7.00E+08</td>
<td>$USD2013/Seed Tether Launch</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Operations Center Area (for 2 Tethers)</td>
<td>2.04E+03</td>
<td>m²/2-Tether Space Elevator</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Building Height</td>
<td>3.00E+03</td>
<td>m/Floor</td>
<td>Estimate***</td>
</tr>
<tr>
<td>Operations Center Volume (for 2 Tethers)</td>
<td>6.13E+03</td>
<td>m³/2-Tether Space Elevator</td>
<td>calculation</td>
</tr>
<tr>
<td>Launch Mass for Initial Tether Deployment</td>
<td>8.60E+04</td>
<td>kg/Seed Tether Launch</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td>Rocket Payload to GEO</td>
<td>4.02E+03</td>
<td>kg to Orbit/Launch</td>
<td>Spacex.com</td>
</tr>
<tr>
<td>Fuel Mass per Rocket</td>
<td>4.84E+05</td>
<td>kg fuel/Launch</td>
<td>SpacelaunchReport.com</td>
</tr>
<tr>
<td>Annual Design Payload to Orbit per 1-Tether</td>
<td>5.10E+06</td>
<td>kg to Orbit/Year 1-Tether Space Elevator 100% Utilization</td>
<td>Swan et al. 2013</td>
</tr>
<tr>
<td><strong>Transportation to Spaceports</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equatorial Radius of the Earth</td>
<td>6.38E+03</td>
<td>km</td>
<td>Carroll et al. 2017</td>
</tr>
</tbody>
</table>
Table 7.1. Continued.

<table>
<thead>
<tr>
<th>Inventory Data</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>Megaprojects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empire State Building Floorspace</td>
<td>9.49E+05</td>
<td>m²/Empire State Building</td>
<td>Softschools.com</td>
</tr>
<tr>
<td>Empire State Building Producer Cost</td>
<td>4.09E+07</td>
<td>$USD1949/Empire State Building</td>
<td>Softschools.com</td>
</tr>
<tr>
<td>Pentagon Floorspace</td>
<td>3.44E+05</td>
<td>m²/Pentagon</td>
<td>Britannica.com</td>
</tr>
<tr>
<td>Pentagon Producer Cost</td>
<td>8.30E+07</td>
<td>$USD1943/Pentagon</td>
<td>Wikipedia.org</td>
</tr>
<tr>
<td>Total Number of US Refineries</td>
<td>1.37E+02</td>
<td>#/Pentagon</td>
<td>Wikipedia.org</td>
</tr>
<tr>
<td>Refinery Producer Cost</td>
<td>1.00E+10</td>
<td>$USD2002/Refinery</td>
<td>Quara.com</td>
</tr>
<tr>
<td>Pipeline Producer Cost</td>
<td>1.50E+04</td>
<td>$USD2002/km Pipeline</td>
<td>Ingaa.org</td>
</tr>
<tr>
<td>Total US Crude Oil Pipeline Distance</td>
<td>1.16E+05</td>
<td>km Pipeline/US</td>
<td>Pipeline101.org</td>
</tr>
<tr>
<td>Airport Average Number Flights per Day</td>
<td>7.35E+02</td>
<td># Flights/Day</td>
<td>Zurich-Airport.com</td>
</tr>
<tr>
<td>Airport Producer Cost</td>
<td>2.00E+10</td>
<td>$USD2002/Airport</td>
<td>Airport-Technology.com</td>
</tr>
<tr>
<td>Aircraft Producer Cost</td>
<td>7.47E+07</td>
<td>$USD2002/Airport</td>
<td>Airport-Technology.com</td>
</tr>
<tr>
<td>Hamburg Port Container Vessels in 2016</td>
<td>4.16E+03</td>
<td>#</td>
<td>HK24.de</td>
</tr>
<tr>
<td>Hamburg Port Tankships in 2016</td>
<td>1.56E+03</td>
<td>#</td>
<td>HK24.de</td>
</tr>
<tr>
<td>Seaport Producer Cost</td>
<td>6.00E+09</td>
<td>$USD2002</td>
<td>PortConsultantsRotterdam.nl</td>
</tr>
<tr>
<td>Ship Producer Cost</td>
<td>5.00E+07</td>
<td>$USD2002</td>
<td>(Scott Brown &amp; Savage, 1996)</td>
</tr>
</tbody>
</table>

*SpaceX advertises prices for rocket launch payload delivery for both the Falcon 9 and Heavy either to GTO or to Mars, not GEO. The “Payload to Mars” advertised values were used as a substitute for GEO delivery comparisons.

**Empty vehicle mass is also referred to as burnout mass.

***This estimate is based on an average building story height of 3 meters for calculating the building construction volume for LCI database system process input unit requirement.

7.2.2.1. Space Elevator

The space elevator system modeled was based on the 2013 Swan et. al study (Swan et al., 2013). A more comprehensive space elevator LCA with several design scenarios and a sensitivity analysis of its utilization capacity (based on designs proposed by Swan et al.) was completed in chapter 6. The One-Tether Initial Space Elevator Scenario that was described and evaluated in that study was used in this model, thus the LCI data and modeling assumptions are not repeated here. All space elevators systems produced after the first can be deployed into orbit using the previous space elevator eliminating the need for rocket launch initial seed tether deployment system process. However, deployment of additional space elevators following the first one was not included in this study, as the initial capital investment of the initial space
elevator needs to be assessed when comparing it to the already established orbital transportation systems.

7.2.2.2. **Falcon 9, Falcon Heavy, & Delta IV Heavy**

Process-LCA data were not available for the spacecraft production system processes, therefore hybrid LCA methodologies were employed to utilize EIO-LCA data for the NAICS code 336414 “guided missile and space vehicle manufacturing.” The unit processes and LCI databases used to construct LCA are given in Table 7.2. Producer cost for the rocket launch systems were estimated from the published consumer cost at the standard assumption of 60% profit markup (BusinessInsider.com) for each system modeled and adjusted to dataset’s $USD2002 input unit.

Table 7.2. Upstream data used in the LCI for spacecraft systems. If a NAICS code is given, the upstream data were taken from CMU’s EIO-LCA tool. All other processes are ecoinvent.

<table>
<thead>
<tr>
<th>Unit Process</th>
<th>Unit</th>
<th>Falcon 9</th>
<th>Falcon Heavy</th>
<th>Delta IV Heavy</th>
<th>ecoinvent process or NAICS Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Delivered to GEO per Launch</td>
<td>Total kg to Orbit</td>
<td>4.02E+03</td>
<td>1.68E+04</td>
<td>6.58E+03</td>
<td>not applicable – reference flow value</td>
</tr>
<tr>
<td>Liquid Oxygen (LOX) Production</td>
<td>kg LOX/kg to Orbit</td>
<td>9.16E+01</td>
<td>5.73E+01</td>
<td>8.45E+01</td>
<td>market for oxygen, liquid, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Rocket-Grade Kerosene (RP-1) Production</td>
<td>kg RP-1/kg to Orbit</td>
<td>3.58E+01</td>
<td>2.24E+01</td>
<td>--</td>
<td>market for kerosene, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Hydrogen (LH₂) Production</td>
<td>kg LH₂/kg to Orbit</td>
<td>--</td>
<td>--</td>
<td>1.41E+01</td>
<td>market for hydrogen, liquid, alloc. default, S - Row</td>
</tr>
<tr>
<td>Producer Cost</td>
<td>$USD2018/kg to Orbit</td>
<td>9.25E+03</td>
<td>3.21E+03</td>
<td>3.07E+04</td>
<td>1 USD guided missile and space vehicle manufacturing - US NAICS Code 336414</td>
</tr>
<tr>
<td>Payload Shipment to Launch Pad</td>
<td>t*km/kg to Orbit</td>
<td>4.00E-01</td>
<td>4.00E-01</td>
<td>4.00E-01</td>
<td>transport, freight, lorry &gt;32 metric ton, EURO6, alloc. default, S</td>
</tr>
</tbody>
</table>

7.2.2.3. **Megaproject Infrastructure Systems**

The earth megaproject infrastructure systems were modeled with rough detail for comparative purposes only. These megaproject models relied solely on ecoinvent LCA datasets. Each unit process used to build the inventory is given in Table 7.3 and was based on the primary input data given in Table 7.1.
Table 7.3. Unit processes used to construct upstream inventory for megaproject infrastructure systems.

<table>
<thead>
<tr>
<th>Unit Process</th>
<th>Value</th>
<th>Unit</th>
<th>ecoinvent process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empire State Building Construction</td>
<td>9.49E+05</td>
<td>m³/Building</td>
<td>building construction, multi-storey, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Empire State Building Producer Cost</td>
<td>4.28E+8</td>
<td>$USD2002</td>
<td>not applicable – producer cost impact</td>
</tr>
<tr>
<td>Pentagon Construction</td>
<td>1.03E+06</td>
<td>m³/Building</td>
<td>building construction, multi-storey, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Pentagon Producer Cost</td>
<td>1.19E+09</td>
<td>$USD2002</td>
<td>not applicable – producer cost impact</td>
</tr>
<tr>
<td>Oil Refinery Construction</td>
<td>1.00E+00</td>
<td># Units/Refinery</td>
<td>petroleum refinery construction, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Pipeline Construction</td>
<td>8.46E+02</td>
<td>km Pipeline/Refinery</td>
<td>pipeline construction, petroleum, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Refinery and Pipeline Producer Cost</td>
<td>1.00E+10</td>
<td>$USD2002</td>
<td>not applicable – producer cost impact</td>
</tr>
<tr>
<td>Airport Construction</td>
<td>1.00E+00</td>
<td># Units/Airport</td>
<td>airport construction, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Aircraft Production</td>
<td>7.35E+02</td>
<td># Units/Airport</td>
<td>aircraft production, long haul, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Airport and Aircraft Producer Cost</td>
<td>7.49E+10</td>
<td>$USD2002</td>
<td>not applicable – producer cost impact</td>
</tr>
<tr>
<td>Seaport Construction</td>
<td>1.00E+00</td>
<td># Units/Seaport</td>
<td>port facilities construction, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Freight Ship Production</td>
<td>8.01E+01</td>
<td># Units/Seaport</td>
<td>freight ship production, transoceanic, alloc. default, S - RoW</td>
</tr>
<tr>
<td>Tanker Ship Production</td>
<td>3.00E+01</td>
<td># Units/Seaport</td>
<td>tanker production, transoceanic, alloc. default, S - GLO</td>
</tr>
<tr>
<td>Seaport and Ship Producer Cost</td>
<td>1.45E+10</td>
<td>$USD2002</td>
<td>not applicable – producer cost impact</td>
</tr>
</tbody>
</table>
7.2.3. **Life cycle impact assessment (LCIA)**

Impact assessment was completed using the TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.1 V1.01) midpoint impact characterization methodology developed by the EPA for the US (J. Bare, 2011). Midpoint impacts reflect environmental impact potentials, a link in the cause-effect chain, while endpoints reflect the effect itself (J. C. Bare, Hofstetter, Pennington, & De Haes, 2000). The following 10 TRACI impact categories were calculated and interpreted: global warming, eutrophication, acidification, ecotoxicity, ozone depletion, smog formation, resource depletion, and human health: carcinogenics, non-carcinogenics, and respiratory effects.

In addition to the 10 TRACI impact categories, a producer cost impact category was also calculated using the space elevator strategic investment layout presented in the Swan study (Swan et al., 2013). Because the 2008 TRACI normalization factors do not include a producer cost impact category, the 2008 US national gross domestic product (GDP), $14.7 trillion, and 2008 US gross national income (GNI) per capita, $49,330, as reported by the World Bank (Bank, 2008) for a common reference benchmark normalization factor for the producer cost impact category. A preliminary producer cost-to-orbit estimate was established by taking the producer cost divided by the mass delivered to orbit ($/kg to GEO). And the cradle-to-gate total megaproject infrastructure producer cost impact comparisons were estimated from various sources as shown in Table 7.3.

7.2.3.1. **Uncertainty Analysis**

Uncertainty analysis was completed via a pedigree matrix. A pedigree matrix is a method to quantify and evaluate the representativeness of the LCI data to the stated goals, as well as to examine the uncertainty as they relate to the final LCIA results. The five data quality indicators empirically determined from the “improved pedigree matrix” approach were: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation (Weidema et al., 2013). The pedigree matrix is shown in Table 7.4 with data quality scores and averages ranging between 1 (lowest quality) and 5 (highest quality). Sensitivity analysis was not performed for this study.
Table 7.4. Uncertainty and Representativeness of LCI Data to the Space Elevator System via the Improved Pedigree Matrix. The improved pedigree matrix includes five data quality indicators (reliability, completeness, temporal correlation, geographical correlation, and technological correlation) to evaluate the uncertainty and representativeness of the model’s input parameters from 1 (lowest data quality) to 5 (highest data quality). System process averages of the five data quality indicators are also provided.

<table>
<thead>
<tr>
<th>Data Quality Indicators:</th>
<th>Reliability</th>
<th>Completeness</th>
<th>Temporal Correlation</th>
<th>Geographical Correlation</th>
<th>Technological correlation</th>
<th>Average</th>
</tr>
</thead>
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<tr>
<td><strong>Space Elevator (avg. 3.7)</strong></td>
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<tr>
<td>Carbon Nanofiber (CNF) Production</td>
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<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3.4</td>
</tr>
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<td>Anchor Node (Offshore Platform) Production</td>
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<td>4</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>4.2</td>
</tr>
<tr>
<td>Operation Center Construction</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
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<td>Climber Production</td>
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<td>2</td>
<td>4</td>
<td>3</td>
<td>2.8</td>
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<td>3</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3.2</td>
</tr>
<tr>
<td>Launch Mass for Initial Tether Deployment</td>
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<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
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<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4.6</td>
</tr>
<tr>
<td>Liquid Oxygen (LOX) Production for Initial Tether Deployment</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4.2</td>
</tr>
<tr>
<td>Rocket-Grade Kerosene (RP-1) Production for Initial Tether Deployment</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4.2</td>
</tr>
<tr>
<td>Payload Shipment to Space Elevator</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2.8</td>
</tr>
<tr>
<td>Total Production Cost of Space Elevator</td>
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<td>2</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Rocket Launch (avg. 4.3)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Payload Delivered to GEO per Launch</td>
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<td>5</td>
<td>5</td>
<td>5</td>
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<td>4</td>
<td>4</td>
<td>4.2</td>
</tr>
<tr>
<td>Rocket-Grade Kerosene (RP-1) Production</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4.2</td>
</tr>
<tr>
<td>Hydrogen (LH2) Production</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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7.3. Results and Discussion

A comparison of the cradle-to-use environmental and cost impacts of existing and proposed orbital transportation systems and megaproject infrastructure was completed (Figure 7.3). The Falcon 9, Falcon Heavy, and Delta IV Heavy rocket launch orbital transportation systems were assessed by payload mass delivered to orbit as well as the space elevator orbital transportation system design proposed by Swan et al. (2013). These results represent the cradle-to-use scope assessment that quantified the potential impacts of the construction, deployment, and use of the modeled orbital transportation systems. The LCA model for the proposed space elevator orbital transportation system exhibits less than 0.7% of the environmental impacts of all other existing orbital transportation system models.
Figure 7.3. Cradle-to-use environmental and cost impacts of orbital transportation systems by mass delivered to orbit. The space elevator orbital transportation system model was based on the design proposed by Swan et al. (2013). The Delta IV Heavy and Falcon 9 expendable rocket launch vehicles and the Falcon Heavy reusable booster rocket launch vehicle orbital transportation systems were modeled from direct and secondary web sources. The functional unit was one kilogram delivered to GEO. Each impact category was normalized to the system with the highest impact potential set at 100%.
The Delta IV Heavy showed the largest relative impacts compared to the other orbital transportation systems in all impact categories except for resource depletion. The Falcon 9 showed the greatest fossil fuel resource depletion potential impact, with the Falcon Heavy second highest. The Falcon 9, Falcon Heavy, and space elevator showed 42%, 19%, and 0.15% average relative impacts (respectively) to the 100% Delta IV Heavy baseline. In all cases, the Falcon Heavy showed lower impact potentials than the Falcon 9, 42% lower on average. This is because the more sustainable design of the reusable first stage booster rocket engines of the Falcon Heavy design allows for the spacecraft producer cost to be substantially reduced (>10,000/kg to GEO). The Falcon 9 and Heavy showed greater resource depletion impact potentials than the Delta IV Heavy because the Falcon systems use rocket grade kerosene (a petroleum product) as a fuel component, rather than liquid hydrogen like the Delta. In addition to resource depletion, the Falcon 9 showed the greatest relative impact in the eutrophication and respiratory effects categories (>50% of Delta IV Heavy). This resulted from the larger amount of liquid oxygen required for the Falcon 9 (92 kg LOX per kg to GEO) than required for the Delta IV Heavy (85 kg LOX per kg to GEO), despite lower overall impacts.

The producer cost to deliver one kilogram to GEO using the Falcon 9 was 30% the cost of the Delta IV Heavy, and 10% using the Falcon Heavy. Though the Delta IV Heavy has 100% launch success compared to the 98% launch success of the Falcon 9, this 2% difference in risk shouldn’t explain the >70% greater producer cost between the systems. The space elevator showed a producer cost impact of 0.11% to that of the Delta IV Heavy for delivering payloads to GEO.

It is unclear if the rocket launch orbital transportation producer cost estimates, particularly the Delta IV Heavy producer cost estimates, are realistic for calculating the spacecraft production impacts. Before the Falcon 9 disrupted the market by undercutting the price of their competitors, the existing orbital transportation industry (to include producers of the Delta IV Heavy) may have maintained higher consumer prices while producer costs were declining. More thorough process-LCA data would be required for all rocket launch orbital transportation systems so more representative results can be produced.

The cradle-to-gate environmental and cost impacts of existing megaproject infrastructures were compared to the space elevator orbital transportation system design proposed by Swan et al. (2013). These results represent the cradle-to-gate scope assessment that quantified the potential impacts of the construction and deployment megaproject infrastructures including the space
elevator. The space elevator system proposed by Swan was compared with other infrastructure megaprojects including the Empire State Building, the Pentagon, a refinery and its pipeline, an airport and its aircraft, and a seaport and its ships (Figure 7.4). The other orbital transportation systems were not included in this study because the infrastructure for these systems have been well established for decades. Keep in mind, this cradle-to-gate assessment had a functional unit of one completed (and deployed) megaproject infrastructure system, and the normalization in Figure 7.4 was not relatable to the Figure 7.3 functional unit and normalization.

The seaport infrastructure environmental impacts and cost were over five times greater than all other systems in all impact categories quantified except for producer cost, where airport infrastructure is over five times greater than all other megaproject infrastructures modeled. Construction of the proposed space elevator system impacts were the lowest in seven of the ten TRACI impact categories modeled when compared to the other megaprojects impact potentials.

Both the Empire State Building and Pentagon were lower than the space elevator in global warming, ozone depletion, and producer cost impacts. The building infrastructures were likely lower in those impact categories because, though these are well known large US buildings, they are actually small in size and scope compared with many other megaproject infrastructures. The refinery infrastructure was also lower than the space elevator in non-carcinogenics impact potential, however, further study of the LCA database with the petroleum refinery and pipeline construction system processes was not completed.

The ozone depletion and producer cost impact categories showed the greatest relative impact for the space elevator system when compared with other megaprojects. Only the airport and seaport were greater than the space elevator ozone depletion impact potential. The airport, seaport, and refinery all showed greater producer cost impacts than the space elevator, however, space elevator producer cost was the highest relative impact (11.8%) compared to the highest producer cost (airport infrastructure producer cost = 100%). The larger relative ozone depletion impact potential of the space elevator results from the relatively large ozone depletion impact potential of all orbital transportation systems, as the space elevator showed no greater relative impacts in ozone depletion than the rocket launch systems (Figure 7.3). This is a result of the spacecraft production system process from the EIO-LCA dataset and methodology, therefore further resolution is not available.

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Figure 7.4. Cradle-to-gate environmental and cost impacts for Earth megaprojects and the proposed space elevator orbital transportation system. Each impact category was normalized to the system with the highest impact potential set at 100% (i.e. seaport was 100% for all environmental impacts, and airport was 100% for cost). However, the vertical axis is displayed to 20% to show greater resolution of the differences between the other systems modeled.
In neither the cradle-to-use nor cradle-to-gate were the space elevator impacts the largest of the other systems modeled in any of the impact categories. For the cradle-to-use orbital transportation system comparison, the space elevator had a mean relative impact of less than 0.2% of the largest system modeled (0.7% maximum relative impact in resource depletion). For the cradle-to-gate megaproduction system comparison, the space elevator had a mean relative impact of less than of the largest system modeled (12% maximum relative impact in producer cost). These results suggest the space elevator system as proposed and modeled sustainable in terms of relative environmental and cost impacts.

Furthermore, this study appeared to be the first of its kind in assessing and comparing the environmental impacts of existing and proposed orbital transportation systems. As such, the results as examined through pedigree matrix uncertainty analysis showed notable uncertainty, with a total average score of 3.8/5. It is highly recommended that investments be made into producing process-LCA datasets of rocket launch and other orbital transportation systems so that future sustainability research can be completed with greater resolution and certainty.

Acknowledgements

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7.4. References


CHAPTER EIGHT

CONCLUSION

The six chapters of focused research and findings reported herein established novel methodologies and provided discerning recommendations associated with three transportation energy related research goals. In completion of research goal 1, *Macro Energy System Modeling*, sustainability risks of the US transportation sector’s energy systems were determined, evaluated, and assessed, and sustainability risk mitigation recommendations were provided. In completion of research goal 2, *Biofuel Production on Abandoned Mine Land Case Study*, the ability to sustainably cultivate biofuel feedstocks on ameliorated abandoned coal mine refuse piles in Appalachia was evaluated and reported. In completion of research goal 3, *Orbital Transportation Systems Case Study*, a proposed space elevator orbital transportation system as well as existing rocket launch orbital transportation systems were assessed via LCA to determine and compare the potential environmental impacts and sustainability risks.

A macro energy system modeling case study of US primary energy production and consumption data and proposed novel logistic growth curve modeling methodology was completed in chapter 2. This chapter contributed to the deeper understanding of the US energy system in three distinct ways: i) establishing a four-parameter multicycle logistic growth curve equation and modeling methodology ii) applying this modeling methodology to US primary energy production and consumption system dataset for a case study iii) testing the validity of this modeling methodology. This research found that the novel logistic modeling technique developed was a simple, effective, and valid means of creating fixed condition forecasts for a region or nation’s energy system. The research also suggested a possible US energy production/consumption deficit in the relatively near future unless continued sustainable development continues in all US primary energy production and consumption sources and technologies.

A US biofuel production and policy case study was completed in chapter 3 using the aforementioned logistic growth curve modeling methodology that was developed and presented in the previous chapter. A new means for evaluating energy policy outcomes by modeling historical datasets of US biofuel production and comparing them to the stated policy goals and mandates was completed in this research. The results of the US EPA 2010 Renewable Fuel
Standard (RFS2) annual volumetric production requirements set to 2022 were found to be unrealistic and ineffective. This research also demonstrated that the new logistic growth curve modeling methodology and fixed condition forecast output is a valid tool to establish future energy policy goals and to evaluate their outcomes.

The prospect of producing environmentally sustainable biofuel products from ameliorated abandoned coal mine refuse piles in Appalachia was evaluated via life cycle assessment (LCA) in chapter 4, which was published in the Journal of Cleaner Production. An initial LCA case study focused on an abandoned coal mine refuse pile in Mather, Pennsylvania. Results from an experimental greenhouse study demonstrated the viability and initial yield estimates of various biofuel feedstocks, cultivated in a 1:9 mix of an alkaline clay waste from the aluminum industry (bauxite residue), and ab origine Appalachian coal mine refuse material. This case-study was subsequently used as a baseline to perform a comparative LCA of the proposed amelioration of AML through industrial symbiosis for biofuel feedstock cultivation versus other AML reclamation activities. Results showed the industrial symbiosis amelioration alone was the best AML reclamation activity evaluated; additionally, there was the benefit of a new source of renewable transportation fuels.

The research in chapter 5 expanded the biofuel cultivation on AML LCA to three Appalachian states with large numbers of abandoned coal mine refuse piles, which was published in Procedia Engineering. GIS was used to locate and quantify the total area of AML suitable for amelioration and biofuel cultivation in Pennsylvania, West Virginia, and Virginia. LCA was used to assess the environmental impacts and implications. Results from these three Appalachian state biofuel cultivation on AML showed approximately 32,000 barrels of potential biofuel production per year, while offering the solution to sustainably develop these currently environmentally damaging abandoned coal mine refuse piles.

A proposed space elevator system was evaluated for improvements in design and development via LCA in chapter 6. The space elevator is an earth-orbital counterbalance space-tether system made of carbon nanofibers and traversed by tether climbers. The space elevator concept sidesteps the need to wrestle free from the planet’s large gravity well that sets a hard limit on the maximum efficiency of tradition rocket orbital transport technologies. Results from the space elevator LCA showed several environmental impact hotspots which could be reduced in future space elevator design and development iterations. Furthermore, several space elevator
design scenarios were evaluated, including subsequent space elevator system deployments using a previously deployed space elevator, to aid in the direction of future design options.

The results in chapter 7 reported on a quantitative environmental sustainability lifecycle assessment and producer cost comparison of existing and proposed orbital technology systems. The orbital transportation systems evaluated were the Falcon 9, Falcon Heavy, and Delta IV Heavy rocket launch systems. The proposed orbital transportation system modeled and assessed was a comprehensive space elevator design. Results showed the environmental and cost impacts of the proposed space elevator system were significantly lower than all existing rocket launch orbital transportation systems modeled. The Falcon Heavy rocket launch system showed the lowest of the three rocket launch systems modeled in all categories other than resource depletion where it was just over 10% larger than the Delta IV Heavy system. It is highly recommended investments be made into producing process-LCA datasets of rocket launch and other orbital transportation systems for future sustainability research with greater resolution and certainty.

8.1. **Future Work**

The novel logistic growth curve modeling methodology developed and presented herein has the potential to be used in a myriad of applications related to sustainability engineering. Logistic growth curve modeling with fixed condition forecasts can be combined with LCA impact assessment methodologies and results. It can be developed as a tool to help inform and evaluate local, state, and national energy policy decisions. The technological diffusion modeling of the logistic equation demonstrates the potential for the logistic growth curve modeling methodology and fixed condition forecasts to model and anticipate the development and acceptance of emerging technologies.

Another final study on the biofuel cultivation on ameliorated Appalachian abandoned coal mine lands (AML) is in progress. There are thirteen states in Appalachia, all with abandoned coal mine lands which are being evaluated for their potential to sustainably produce biofuel products from feedstock cultivated on abandoned coal mine refuse piles. Monte Carlo analysis is being used to ensure that the distributions of model input values are represented and evaluated in the study’s results and discussion.

The sustainable development of space exploration and resource utilization both on and off Earth has infinite potential. No other research directly applying Sustainability Engineering
methodologies to space exploration and resources was found up to the point of completion of the research mentioned herein. Another area for research, a proposed lunar impact category characterization methodology that is being established from a top-down impact assessment methodology for lunar mining operations, is also underway (see Appendix D).

This research stands as an example of how technologies can be sustainably designed, engineered, and developed for maximum benefit and minimum consequences and risks. By using such quantitative sustainability assessment tools and methodologies utilized herein, as well as taking advantage of the vast untapped resources of space, we can shape the future with our own hands and engineer a sustainable existence for the foreseeable future.
Other Energy Production Models

Despite its regular use, no examples of MARKAL modeling for comprehensive analysis of future US energy production and consumption was found in the literature, only examples of specific aspects such as US electricity production (Balash, Nichols, & Victor, 2013) and US energy diversity and resilience (Victor, Nichols, & Balash, 2014). Econometric modeling (which use stochastic economic relationships rather than equilibrium optimization) has also been applied to energy production to a limited extent (Brandt, 2010).

The US Department of Energy (DOE) Energy Information Administration (EIA) developed its own modeling technique called the National Energy Modeling System (NEMS) which is an energy-economic hybrid bottom-up/top-down optimization model requiring numerous input parameters including market assumptions and reserve quantities (Gabriel, Kydes, & Whitman, 2001). “NEMS projects the production, imports, conversion, consumption, and prices of energy, subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics.” (U. EIA, 2009) Results from the NEMS model published in the 2016 Annual Energy Outlook are somewhat linear to 2040 and show overall increases in all energy production sources except for coal which shows a gradual decline in production (select EIA data and forecasts in Figure A. 1.) (EIA, 2016a). Given criticisms of the NEMS model complexity and assumptions, evidence of past shortcomings (Gilbert & Sovacool, 2016; O’Neill & Desai, 2005), and the dynamic behavior of historical energy production and consumption trends, these energy production forecasts appear somewhat dubious.

As opposed to the NEMS, MARKAL, and other energy-economic models which rely on complex equations, dedicated software, and numerous assumptions and inputs, the logistic growth curve modeling outlined in this research only requires basic historical data and uses a simple fitting technique to find best-fit parameters for energy trend analysis. There are other growth curve modeling equations that produce s-shaped or bell-shaped curves which also only
require empirical fitting of historical data, including Gompertz, Bertalanffy, Gaussian, Weibull, and Richard, but they often have more differences in parameterization than in shape (Brandt, 2010; Höök, Li, Oba, & Snowden, 2011). However, differing from the symmetrical shapes of the logistic curves the Gompertz equation (developed for human population and mortality modeling prior to the logistic equation in 1825 (Gompertz, 1825)) produces a left-skewed growth curve which has faster initial production growth and slower final production or growth decline (Tsoularis & Wallace, 2002). The Gompertz model has been the next-most commonly used growth curve modeling technique for energy production besides the logistic model but in general has not produced more reliable fits to energy production data (Höök et al., 2011). Hybrid modeling techniques that employ s-shaped growth curves combined with economic and market factors have also been used to model energy production, but require multiple datasets and complex fitting techniques, and have also not conclusively provided more accurate trend forecasts than logistic models (Kaufmann, 1991; Kaufmann & Cleveland, 2001).

Figure A. 1. Select US Energy Production Data and Forecasts from the EIA and 2016 NEMS Model (EIA, 2016a, 2016b). Though there are some curves in the production forecasts from this complex model, they generally follow linear paths despite the non-linear trends of the historical data.
Parameter Fitting and Descriptive Statistics

Best fit parameters for all models were determined with the Microsoft (MS) Excel Analysis Add-in Solver tool using the Generalized Reduced Gradient (GRG) Nonlinear solver method with default settings, 0.000001 constraint precision, and 0.0001 convergence (Microsoft, 2013). Using the method of least squares, the difference between the model value and production data for each squared time interval were summed for the modeled time period and set as the objective to be minimized by altering the parameters of the logistic model. Descriptive statistics for the models’ quality of fit were determined with the MS Excel Data Analysis Add-in Regression Tool using the default settings with a 95% confidence interval (Microsoft, 2013). Both R-squared and P-values were determined, with R-squared values closer to 1 and P-values below 0.05 representing quality fits (i.e. the model was considered significant within a 95% confidence interval if the P-value was less than 0.05).

Hydroelectric Energy Alternate Fit Models

The lower R-squared for hydroelectric (Figure A. 2.) is a result of greater annual fluctuation in production because of weather variations (Kao et al., 2015) and the tendency for chaotic behavior to emerge after an s-shaped logistic trend reaches the high-plateau ($H$) (as found when calculating the iterates of the logistic difference equation (Wu & Baleanu, 2014)). When the R-squared was calculated for the hydroelectric logistic model from 1949 to 1980 (before the fluctuations but after reaching the high-plateau) the R-squared value became 0.952. With the first and third quartiles of the R-squares for energy production sources being 0.965 and 0.995 respectively, the 0.806 R-squared for the hydroelectric model was determined to be an outlier (i.e. outside 1.5 times the interquartile range below the first or above the third quartile), and the pre-fluctuation R-squared of 0.952 adequate to deem the model a suitable fit to the data.
Solar Energy Alternate Fit Models

The US solar energy logistic model showed two discrete growth phases, with the first small and short lived between 1988 and 1990, and the second starting around 2005 and still ongoing (Figure A. 3.). The best-fit logistic model showed solar energy just beyond the midpoint of its ongoing growth cycle in 2015, with the model reaching its high-plateau ($H = 0.66$ quad BTU) in the early 2020s. However, other non-best-fit logistic parameters could also produce reasonable fits with high-plateaus between 0.5 and 2.0 quadrillion BTU (see Supplementary Materials). With a study by the DOE proposing the possibility of total US solar energy production reaching 2.19 quadrillion BTU by 2030, and 4.94 quadrillion BTU by 2050 (DOE, 2012), the ongoing growth cycle could continue and/or a new growth cycle may begin before 2040.
Figure A.3. Multi-Cycle Logistic Model of US Solar Energy Production. The best-fit logistic model showed solar energy production approaching a high-plateau \((H)\) of 0.66 quadrillion BTU around 2022, however, alternate logistic models with manipulated high and low high-plateaus \((H)\) still produced reasonable fits to the data.

As the best-fit showed the solar energy growth curve only just beyond the midpoint \((M = 2014.40)\) of the second cycle in 2015, it is possible that the ongoing growth curve will not plateau at 0.66 quadrillion BTU and continue to grow. Furthermore, when parameters were manipulated to high-plateaus \((H)\) of 2.0 or 0.5 quadrillion BTU the models still produced suitable fits (both R-squares 0.996 and P-value <0.00001). Though monthly EIA production data through June 2016 appeared to support the best fit trend, because of the seasonable variability of solar energy production it could not be used to further substantiate any of the models (and thus not shown on the figure). The various logistic models all providing reasonable fits to the data serves as another reminder that logistic modeling does not predict the future, only reveals trends from available data. Regardless, as US solar energy production was less than 0.5% of total US

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production, even if it increased 1000%, it wouldn't play a significant role in counteracting the modeled decline in fossil fuel production.

References


Abstract

This research performed empirical logistic growth curve modeling on each US primary energy production source to estimate the ability to meet energy demands in the near future. Results showed the recent growth of petroleum and natural gas may be short lived, and renewable growth is likely approaching a plateau. Furthermore, even if substantial new growth cycles in all US primary sources begin immediately, including fossil fuel, nuclear, and renewables, total US energy production still appears likely to decline after 2017. The new growth needed to counteract the projected decline will require significant innovation to develop sustainably, being environmentally benign, economically sound, and socially beneficial. Additionally, with the necessity of continued petroleum imports, momentous innovation will be required to counteract increased greenhouse gas emissions and environmental consequences from renewed US fossil fuel production, as well as to maintain energy security and reduce environmental impacts.

Introduction and Background:

US energy production in 2015 was within 10% of consumption for the first time since 1982 (EIA, 2016), primarily resulting from unprecedented production growth in petroleum and natural gas since 2010, and also because of steady increases in renewables since 2000. Understanding where production trends may be heading helps determine where should focus efforts.

The logistic equation has been used to empirically model fossil fuel production since the 1950s (Hubbert, 1956; Maggio & Cacciola, 2009), and has been applied to renewable energy production more recently (Daim, Harell, & Hogaboam, 2012). It has also been used to model energy consumption trends (Suganthi & Samuel, 2012). However, no studies have used the
logistic equation to model each energy production sources, as well as total consumption, to develop a comprehensive overview of the energy landscape.

**Approach / Experimental**

US energy production and consumption data between 1949 and 2015 was obtained from the Department of Energy (DOE) Energy Information Administration (EIA) Annual Energy Review dataset (EIA, 2016). The energy unit of quadrillion BTU (equivalent to 1.055 exajoules) was used for all data and models.

A simple four-parameter, multi-cycle logistic growth curve modeling technique was developed for this research. Two forms of the logistic equation were each used to model the various sources of energy production based on their production nature, i.e. the bell-shaped logistic equation is used to model fossil fuel production sources, and the s-shaped (sigmoid) logistic equation is used to model renewables and nuclear. The s-shaped equation was also used to model energy consumption.

The bell-shaped logistic model is given by Equation B.1:

\[ P(t) = \frac{(H_Q-L_Q)e^{\frac{t-M}{W}}}{W \left(1+e^{\frac{t-M}{W}}\right)^2} \quad (B.1) \]

where \( P \) is the annual production rate, \( L_Q \) is the low-plateau of cumulative production, \( H_Q \) is the high-plateau of cumulative production, \( t \) is the production year, \( M \) is the midpoint of growth, \( W \) is the width factor; and \( e \) is Euler’s number. And the s-shaped logistic model is given by equation B.2:

\[ P(t) = \frac{(H_Q-L_Q)e^{\frac{t-M}{W}}}{W \left(1+e^{\frac{t-M}{W}}\right)^2} \quad (B.2) \]

where \( L \) is the low-plateau of annual production and \( H \) is the high-plateau of annual production. For multi-cycle growth, the multiple independent, overlapping best fit logistic models were summed (similar to the method used by Maggio et al. 2009).
Hypothetical new growth cycles for each energy source were created using the parameters from the largest previous cycle of the particular energy source and fit to start with a production of 0.5 quadrillion BTU in 2016.

**Results and Discussion**

Logistic growth curve modeling of US energy production and consumption to 2050 revealed a likely growing deficit between consumption and production after 2017 (Figure B. 1.). The total US energy production model showed a peak of 95 quadrillion BTU then subsequent decrease, with total consumption at a plateau of 98 quadrillion BTU. The production peak and subsequent decline resulted from the combination of the total renewable model approaching a plateau of 10.5 quadrillion BTU in 2017 and the individual dry natural gas and crude oil models approaching peaks in 2020 of 30.5 and 17.5 quadrillion BTU respectively.

![Figure B. 1. Logistic Growth Curve Models of US Energy Production and Consumption Data.](image-url)
These results are not intended to imply that new growth cycles in the various energy production sources will not occur. These models only reveal the trend of ongoing production cycles, and new cycles are likely to begin (or have already begun but the new growth is yet too small to reveal themselves). What these results do show is that significant effort to developing new sustainable energy production growth in the near future is needed. Therefore, models for new hypothetical growth cycle models were created based on past growth trends to create possible future energy landscape scenarios (Figure B. 2.).

The new hypothetical energy production growth cycles for crude oil, natural gas, coal, and renewables delays the modeled production peak to 2018 and increases it to 97.9 quadrillion BTU, as well as significantly mitigating the decline in production until 2039, when production begins to increase again. However, there remains a significant deficit between US energy production and consumption models after 2030, and as the renewable growth plays only a minor role, the same peaking problem would resurface. Furthermore, the renewed fossil fuel development and import would require additional efforts to mitigate the resulting climate change and environmental impact.

Figure B. 2. Hypothetical New Logistic Growth Cycle Models.
Summary and Conclusions:

Though it is easy to model these new hypothetical growth cycles, it is a different story to actually create significant new growth from these energy sources. Significant innovation, investment, research, and development is required to sustainably produce this new energy growth. Additionally, similar efforts to sustainably import energy sources to fill any future production/consumption deficits.

Acknowledgements

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References


APPENDIX C

PERMISSION TO USE L5 SOCIETY COMIC BY
JOHNNY ROBINSON IN CHAPTER SEVEN

From: jjackson <jjackson@colab.nss.org>
Sent: Wednesday, March 4, 2015 6:47 AM
To: asutyler@asu.edu
Subject: L5 Society Comic Use

Dear Tyler:

Thank you for requesting permission to use the comic in the L5 Society Newsletter. There have been a few people who have weighed in on the use of the comic. We believe that the comic is under the control of the NSS and it has been used in many presentations and publications. That being said, we do not have a way to contact the artist. The National Space Society agrees to the use of the comic as long as credit is given to the artist as well as the L5 Society publication that it appeared in.

Please let us know if you have any further questions or concerns.

Thank you and Ad Astra!

Jill Jackson
Membership Services
National Space Society

Cartoon by Johnny Robinson*, 1981

* Published by the L5 society, 1981; space.nss.org/l5-news-resources-of-space-cartoon-by-johnny-robinson

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Abstract

To help ensure long-term sustainability of the Moon, lunar resources, and the developing cis-lunar economy, a set of lunar life cycle impact assessment (LCIA) categories and preliminary characterization methodologies were established to enable lunar Life Cycle Assessment (LCA) modeling. These lunar LCIA categories were developed through a review of literature on lunar conditions and proposed lunar activities, and by amending standard terrestrial environmental impact categories such as the US EPA Tool for Reduction of Chemical and Environmental Impacts (TRACI) to reflect the lunar environment. These lunar LCIA categories were presented in the context of an LCA case study example on a lunar ice mining operation with preliminary results included.

The set of ten proposed lunar impact categories [and units] are: Surface Area Occupancy [square meter years: m²/yr], Indirect Area Effects [square meter years: m²/yr], Water/Ice Depletion [kilograms of water extracted: kg H₂O], Mineral/Other Resource Depletion [kilograms of material extracted: kg], Particulate Formation [kilograms of particulate matter equivalent to 2.5 microns in size: kg PM2.5 eq.], Emission Accumulation [kilograms of emissions accumulating in regolith: kg], Vacuum Pollution [grams of gaseous emissions per second: g/s], Lunar Mass Change [megatons of lunar mass change: MT], Forward Contamination [number of microbiological cells accumulating per cubic meter: cells/m³], and Human Health Effects [hours of human exposure on lunar surface: hr].

Introduction

Life cycle assessment (LCA) quantifies and evaluates environmental sustainability and other impacts throughout a system’s life-cycle. Such quantitative sustainability assessment methodologies have been shown to reduce costs and negative impacts for any system or product while increasing system efficiency and environmental performance (Allenby, 2011).
The cycle inventory (LCI) portion of LCA collects quantified system information including elementary material and energy flows, and waste, coproduct, and emission outputs via a bottom-up modeling approach. Life cycle impact assessment (LCIA) takes these data inventories and produces a set of vetted impact categories via established impact characterization methodologies. These LCIA impact categories and methodologies were developed from a hybrid top-down and bottom-up modeling approach to help ensure negative impacts, tradeoffs, and unintended consequences are not missed from the system’s bottom-up model.

As humankind plans for a return to the lunar surface, completing quantitative sustainability engineering assessments throughout the design, development, deployment, and operation of lunar activities will help ensure long-term sustainability of the Moon and its resources. An example would be the proposed business plan to mine the poles of the Moon for ice deposits to convert into rocket fuel for sale in low earth orbit (LEO) (Sowers, 2016). An example system boundary diagram of such a lunar mining operation is given in Figure D.1.

The functional unit for the example LCA was kilograms of rocket fuel produced from mining lunar ice (kg LOX/LH₂), and the scope was a gate-to-gate attributional process-LCA of the lunar mining operation. Traditionally, such an LCA would explore operations related to fuel production and use on the lunar surface only, and exclude equipment manufactured and launched from the Earth. The traditional LCI would be filled with values of the system model’s upstream and downstream elementary input, waste, and product flows. From this, an impact category such as direct land occupation could be quantified and assessed from these LCI data.

However, what may be overlooked by only using such an approach for developing lunar impact categories are indirect land occupation effects such as the kilometer-per-second sandblasting-like dust and debris plume created from the rocket takeoff and landings on the lunar regolith (dirt/soil) surface (Metzger, Li, Immer, & Lane, 2009). Therefore, the purpose of this research was to develop a set of lunar LCIA impact categories and preliminary characterization methodologies to enable such lunar LCAs.
Figure D. 1. System Boundary Diagram of Example Lunar Mining LCA.
Methods

The set of lunar LCIA impact categories were developed through review of literature on lunar surface conditions and proposed lunar mining operations, and by amending standard terrestrial environmental impact categories (e.g. US EPA Tool for Reduction of Chemical and Environmental Impacts, TRACI) to reflect the lunar environment. Additionally, experts in the Space Resources Program and other faculty at the Colorado School of Mines and other universities were consulted on the development of these impact categories (Christopher Dreyer, 2018).

The ten commonly used TRACI impact categories [and units] are (Bare, 2011): acidification [kg SO$_2$ eq.], ecotoxicity [CTUe], eutrophication [kg N eq.], global warming [kg CO$_2$ eq.], human health effects - carcinogens [CTUh], human health effects - non-carcinogens [CTUh], ozone depletion [kg CFC-11 eq.], photochemical ozone formation [kg O$_3$ eq.], resource depletion - fossil fuels [MJ surplus], and respiratory effects [kg PM$_{2.5}$ eq.]. Another regularly used European impact characterization methodology is the ReCiPe midpoint impact categories (Goedkoop et al., 2009). The ReCiPe midpoint impact categories exclusive from the TRACI impacts include: agricultural and urban land occupation [m$^2$*yr], ionizing radiation [kg U$_{235}$ eq.], and water depletion [m$^3$].

A paper by Needham and Kring (2017) suggests that the current lunar atmospheric loss rate is around 1-10 g/s. Therefore, if over 10 g/s of gaseous emissions are released on the lunar surface, a lunar “atmosphere” of sorts would likely begin to form. This reduction of the vacuum on the lunar surface would cause various unintended consequences and endpoint impacts.

A back-of-the-envelope calculation found that to move the moon’s orbital radius by one meter a change in mass of $5 \times 10^{16}$ kg would be required. A NASA estimate of the total ice on the moon is $6 \times 10^{11}$ kg (https://www.nasa.gov/mission_pages/Mini-RF/multimedia/feature_ice_like_deposits.html), therefore, removing all the ice from the Moon would not change its orbit. However, massive near-earth asteroids (NEA) have estimated masses as large as $10 \times 10^{16}$ kg. Therefore, one of these massive NEAs brought to the lunar surface or orbit could change the Earth-Moon orbital radius by over one meter.
Results and Discussion

The set of ten proposed lunar LCIA categories are: Surface Area Occupancy [square meter years: m²*yr], e.g. area occupied by mining, and other system operations; Indirect Area Effects [square meter years: m²*yr], e.g. projectile debris from operations including launches/landings; Water/Ice Depletion [kilograms of water extracted: kg H₂O], e.g. polar ice extracted for use as propellant; Mineral/Other Resource Depletion [kilograms of material extracted: kg], e.g. regolith mined for resources other than water; Particulate Formation [kilograms of particulate matter equivalent to 2.5 microns in size: kg PM₂.₅ eq.], e.g. dust created/distributed from surface operations; Emission Accumulation [kilograms of emissions accumulating in regolith: kg], e.g. accumulation of emissions and debris in regolith; Vacuum Pollution [grams of gaseous emissions per second: g/s], e.g. gaseous emissions greater than 10 g/s could pollute the surface vacuum; Lunar Mass Change [megatons of lunar mass change: MT], e.g. the mass of a half-million MT near earth asteroid (NEA) could alter the moon’s orbit; Forward Contamination [number of microbiological cells accumulating per cubic meter: cells/m³], e.g. forward contamination to areas capable of sustaining microbial life; Human Health Effects [hours of human exposure on lunar surface: hr], e.g. human exposure to occupational hazards on the lunar surface including ionizing radiation.

Example Lunar Mining LCA Preliminary Results

The preliminary lunar mining LCA results for 2% and 10% estimated water content in the icy regolith are presented in Figure D. 2. (Blair et al., 2002; Spudis & Lavoie, 2010). The results from the 10% water content scenario showed that solar power production system contributed to 83% of the land occupation impacts, icy regolith excavation contributed to 17%, and a negligible percentage contributed from other land occupation impacts. The 2% water content scenario results showed a near even split of 51% and 49% respectively (Figure D. 2.).
Other preliminary lunar mining LCIA results are shown in Table D. 1. Of note is the 11:1 ratio of regolith refuse produced to fuel mix produced. This refuse could initially be used to create a berm for the landing pad to minimize impingement of exhaust plume effects. However, a waste disposal site would be required with the intent for the regolith refuse to be further refined and utilized at a future time.

Table D. 2. Life Cycle Impact Assessment Preliminary Results.

<table>
<thead>
<tr>
<th>Impact</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>water depletion</td>
<td>1.22</td>
<td>kg water depleted/kg fuel mix produced</td>
</tr>
<tr>
<td>total area occupied</td>
<td>0.61</td>
<td>ha*yr/kg fuel mix produced</td>
</tr>
<tr>
<td>- area occupied (excavation)</td>
<td>0.10</td>
<td>ha*yr/kg fuel mix produced</td>
</tr>
<tr>
<td>- area occupied (solar power)</td>
<td>0.51</td>
<td>ha*yr/kg fuel mix produced</td>
</tr>
<tr>
<td>- area occupied (other: habitat, roads, &amp;c)</td>
<td>8.5E-07</td>
<td>ha*yr/kg fuel mix produced</td>
</tr>
<tr>
<td>coproduct (O₂) produced</td>
<td>0.22</td>
<td>kg O₂ produced/kg fuel mix produced</td>
</tr>
<tr>
<td>refuse produced</td>
<td>10.99</td>
<td>kg refuse produced/kg fuel mix produced</td>
</tr>
<tr>
<td>launches</td>
<td>1.9E-04</td>
<td>launches/kg fuel mix produced</td>
</tr>
<tr>
<td>humans</td>
<td>1.5E-01</td>
<td>hr/kg fuel mix produced</td>
</tr>
</tbody>
</table>
The total water resource depletion on the lunar surface is 144,000 kg water depleted and 118,000 kg fuel mix (LOX/LH₂, Hydrolox) per year for the Spudis plan and comes to 1.22 kg water depleted per kg fuel mix produced. The other 0.22 kg is produced as O₂ coproduct per kg fuel mix produced. This imbalance is a result of the combustion ratio for optimal rocket fuel being 6.5 parts O₂ to 1-part H₂ by mass while the electrolysis of water produced a ratio of 9 parts O₂ to 1-part H₂ by mass. Other preliminary impact estimates including direct human impacts and launches per kg fuel mix produced appear reasonably negligible (>0.001 launches and human * years per kg fuel mix produced).

Acknowledgements

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References


