# The Impact of Silicon Smelting on Crystal Silicon Solar Panel Carbon Footprints

## ABSTRACT

A literature review of Life Cycle Assessments (LCA) and Carbon Footprint (CFP) estimations of crystal silicon solar panels (c-Si SPs) reveals that the silicon smelting process was not included in the reviewed studies. c-Si SPs are the most prevalent type of SPs currently in use. The source of the c-Si, Metallurgical Grade Silicon (MGSi), comes from the mining of Quartzite rock (Silicon Dioxide, $SiO_2$) and the energy-intensive and Greenhouse Gas (GHG) emitting silicon smelting process. A silicon smelter's emissions consist of hundreds of thousands of tons of GHGs (plus other pollutants) per year from the reduction of SiO2 by fossil fuel (coal) and biomass (woodchips, charcoal) reductants, and from the consumption of graphite electrodes.

Several reviewed papers discuss the Intergovernmental Panel on Climate Change (IPCC) accounting methods for biomass emissions, and challenge the concept that biomass emissions account for zero CO2 emissions in energy and industrial sectors. Several papers also challenge the assumption of rapid forest regeneration and atmospheric carbon rebalance from biomass combustion. Investigation into Life Cycle Assessment (LCA) methods reveals significant complexity and considerable subjectivity, and implementation of various methods for allocating environmental burdens often results in conflicting LCA outcomes. General guidelines for LCA are established, but a single, standardized LCA method does not currently exist. Investigation into the concept of "Green" labelling of products and processes shows that a clear and quantifiable definition of "Green" does not currently exist.

Using emissions estimations and raw material quantities for a proposed silicon smelter in Newport, Washington, two different methods for calculating the smelter's contribution to the carbon footprint of c-Si SPs were performed. A conventional "economic" Method 1 calculation uses the facility's Emission Factor (EF) to allocate the annual mass percent of emissions that correspond to the mass percent of the MGSi product specific for c-Si SPs. The alternative "environmental" Method 2 allocates the facility's total annual mass of emissions to a given mass percent of the MGSi product specific for c-Si SPs (essentially an EF for a specific product quantity). Calculations include both fossil fuel and biomass emissions, and also include the impact of the carbon sink loss due to the harvest of trees for wood chips.

At 5% MGSi for c-Si SPs, Method 1 and 2 emissions CFP values from silicon smelting differ by 20-fold. Both Methods 1 and 2 at all per cent MGSi values for SPs reveal a carbon (CO2 sink loss) debt from tree harvest for wood chips extending beyond the c-Si SP lifetime of 30 years, suggesting that c-Si SPs account for more atmospheric CO2 than they save.

### Key words

Carbon Footprint, Crystal Silicon Solar Panels, Global Warming Potential, Greenhouse Gases, Life Cycle Assessment, Metallurgical Grade Silicon, Silicon Smelter.

### Abbreviations used in this paper

CO2: Carbon dioxide. CO2e: Carbon dioxide equivalent. CFP: Carbon footprint. CSL: Carbon sink loss. CRR: Carbon sink loss recovery rate. c-Si: Crystal silicon. EF: Emission Factor. GWP: Global warming potential. IPCC: Intergovernmental Panel on Climate Change. kWh: Kilowatt hours. LCA: Life Cycle Assessment. LCI: Life Cycle Inventory. MGSi: Metallurgical-grade silicon. MT: Metric tonnes. PV: Photovoltaics. SAF: Submerged arc furnace. SP: Solar panel.
**Note:** a glossary of terms and concepts is provided in Section 9 of this paper.

## INTRODUCTION

The proposed HiTest/PacWest* Newport silicon smelter (August, 2017) in the small rural community of Newport, Washington drew citizen concern due to potential health and environmental impacts from smelter emissions. It was initially stated that 50% of the smelter's Metallurgical Grade Silicon (MGSi) product would be used for SPs and that the facility would be a "green facility" [1]. A review of the solar industry showed that current market demands of MGSi for c-Si SPs are estimated to be approximately 2 – 12% of the total MGSi produced [2] [3] [4]. It was later suggested that 5% (or less) of the HiTest/PacWest smelter's MGSi might be used for SPs by REC Silicon [5].
** Note: Canadian "HiTest Sands" was changed to "PacWest" for the USA smelter. "HiTest/PacWest" is used in this paper to include references from both named sources.*

The potential location of the silicon smelter in Newport prompted investigation into the silicon smelting process and the calculation methodology used to determine the carbon footprint (CFP) of c-Si SPs. Can an upstream heavy industrial facility that produces a product, of which only a fraction is used for solar panels, be considered a “green” facility? What is the appropriate method for calculating the CFP of c-Si SPs, and what method is used for calculating the emissions and energy use from the upstream smelting process that are embodied in the downstream c-Si SPs?

A literature search was undertaken to address the above questions regarding the “green” facility designation and the methods used for calculating CFPs of silicon smelters and c-Si SPs. Silicon smelter raw materials, energy use, and emissions estimations were obtained from HiTest/PacWest publications and the Washington State Dept. of Ecology (DOE) [1] [6]. Background information describing the silicon smelting process, the Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI) accounting tools, and Carbon Footprint (CFP) calculation methods was obtained from free-access and open access articles and papers on the internet.

The literature review revealed several issues that are addressed: (1) the apparent exclusion of the silicon smelting process in published c-Si SP CFP studies, (2) the exclusion of biogenic emissions from the silicon smelting process, (3) the lack of accounting for the carbon sink loss due to tree harvest for supplying silicon smelter woodchips, (4) the lack of a clear methodology for allocating emissions to co-products and by-products, (5) the overall lack of consistency and clarity of LCA/LCI and CFP calculation methodologies, and (6) the lack of a clear and quantifiable definition of “green” products and processes.

**Paper Organization**. This paper is organized in the following sections:

1. GOAL
2. SCOPE and SCOPE DIAGRAM
3. THE SILICON SMELTING PROCESS
4. LITERATURE REVIEW. Includes excerpts, summaries and comments. 4.1 c-Si SP LCIs and CFPs excluding Si smelting. 4.2 Exclusion of biomass emissions. 4.3 LCA, LCI, and CFP Calculation Methods. 4.4 “Green” definitions.
5. CALCULATIONS. Includes CFP Equation (1), and Equations (2) and (3). Smelter raw materials, emissions, energy use, biomass carbon sink losses, and MGSi product yield quantities to be used for SPs. Two different calculation methods are used to determine the smelting contribution to c-Si CFPs. Calculations and Results (Tables 1 – 44).
6. RESULTS. Tables 45 – 47.
7. DISCUSSION. The SP CFP Equation: Equations (1), and (4), (5), and (6). LCA, LCI Calculation Methodology. The IPCC Biomass Emissions Accounting method. Balance of Tree Growth and Bio-Carbon Combustion. “Green” Terminology. Potential Alternatives to c-Si SPs. Green Designation of a Silicon smelter (Tables D8 and D9).
8. CONCLUSIONS
9. GLOSSARY OF TERMS AND CONCEPTS
10. RAW MATERIALS. Background information on raw material properties, procurement, and environmental impacts.
11. REFERENCES
12. APPENDICES: Additional Calculations. Appendix A**:** Calculation of Lodgepole Pine Tree Volume, the frustum of a cone, Equation (7). Appendix B: Calculation of Fossil Fuel (f) and Biomass (b) Reductants percent Contributions to c-Si SP CFPs, Tables 13 and B1. Appendix C: Carbon Sink Loss for Tree Ages of 50 and 60 years, Table C1, Equation (2). Appendix D: Green Designation of the Silicon Smelter, Tables D1 – D9.

## 1. GOAL

The goal of this study is to estimate the impact of the silicon smelting process on the carbon footprint of downstream c-Si SPs, and to assess the “green facility” designation of the proposed silicon smelter. This study was undertaken to provide citizens concerned with environmental and alternative energy issues with background information for assessing carbon footprint (CFP) methods, Life Cycle Assessment (LCA) methods, and “green” designation determinations.

## 2. SCOPE

*(Note: References are included where used in subsequent sections).*

This analysis is a “Cradle-to-Gate” type study and is specific for the proposed Newport silicon smelter. Since this study focuses on the CFP component of an Environmental Footprint, only emissions of the Greenhouse Gasses CO2, CH4, and N2O are addressed in calculations. Two different GHG emissions estimations (1 and 2) for the proposed smelter were available from smelter's consulting firm and the Washington Dept. of Ecology, and are listed in Table 3 of the Calculations Section. Emissions estimation 2 was selected for all subsequent calculations in this study (see Emissions Note 1 at the end of the Scope section). Due to the uncertainty of the percent of MGSi that will be used for SPs, calculations include emissions and energy determinations at 5%, 50%, and 100% MGSi designated for SPs. Two different calculation methods to determine the smelter GHG emissions per downstream c-Si SP are used (see "Departures from LCI/LCA Conventions").

Calculations are presented in a table format with all inputs and outputs clearly identified in order to maintain transparency. Global Warming Potential (GWP) values for 100 years (Section 9.2) are used. All emissions and all materials are expressed as mass values. Materials are expressed as metric tonnes (MT), kilograms (kg) or grams (g). Emissions are expressed as MT of carbon dioxide equivalent (MT CO2e) and grams of carbon dioxide equivalent (gCO2e). The smelter emission factor (EF) is the MT of GHGs emitted per MT of MGSi product per year. All energy uses are expressed as megawatts (MW) or kilowatt hour (kWh) values. All calculations are for materials, emissions, and energy use during a 1-year time period. Elements of LCA and LCI were followed as much as possible; however, limitations of available information and alternative perspectives regarding methodology result in some departures from conventional LCA and LCI methods. Due to limitations of information regarding various contributors to the silicon smelter and upstream processes, the results of this study can only be considered as a partial estimation of the smelter's MGSi production impact on the CFP of downstream c-Si SPs, and cannot be considered as a complete or formal LCA.

**Functional Unit**. The functional unit for this study is the mass of the smelter's MGSi product required for one 72-cell commercial crystal silicon solar panel. The silicon wafer dimensions of 156 mm x 156 mm x 200 µm and the density of silicon (2.33g/cm$^3$) are used to determine the wafer mass value of 11.4 g per each solar cell, and subsequently the mass of 0.8 kg of silicon in a 72-cell c-Si SP. To accommodate downstream silicon ingot or boule processing losses, wafer sawing kerf losses, and other losses; a 50% kerf allowance is applied to the required mass of MGSi designated for SPs. A value of 1.6 kg (or 0.0016 g), designated as "2xSP", is used to denote the mass of MGSi required per finished solar panel.

Annual Energy Output of the 72-cell c-Si SP is based on the calculation equation and variables from the US EPA "Green Power Equivalency Calculator - Calculations and References" document. The annual potential energy output for a 72-cell c-Si SP in the USA was determined to be approximately 421 kWh per year (Section 5, Table 38).

### Factors Included in the Study

Two different emissions and energy use calculation methods are used: Method 1 ("economic") and Method 2 ("environmental"). The two calculation methods are performed concurrently (see Departures from LCA conventions).

1. **Smelter Facility** (Scope 1)
   (1) The proposed silicon smelter facility furnace GHG emissions from coal, woodchips and graphite electrodes used for the SiO2 reduction process to produce MGSi. Note: Calculations Section 5, Table 2 raw materials lists "Blue gem coal and charcoal" at 150,000 tons (136,080 MT) per year. Since individual quantities of coal and charcoal are not listed, the quantity of 150,000 tons (136,080 MT) per year is used exclusively for smelter coal emissions, energy use and Blue Gem coal rail transport.
   (2) Silica Fume. A percentage of smelter emissions and energy use for the MGSi product are allocated to the silica fume by-product as supplemental information for calculation Method 1 only, and is applied after concurrent Method 1 and 2 calculations are completed.
2. **Energy** (Scope 2)
   (1) Electric energy. 105 MegaWatts used for the smelter facility including two submerged arc furnaces (SAF).
3. **Upstream Contributors** (Scope 3)
   (1) Blue Gem coal Rail transport (one-way) from Kentucky to Newport, WA: GHG emissions and energy use. See Note for Blue gem coal and charcoal in: Smelter Facility (Scope 1), item (1) above.
   (2) Forest tree harvest for smelter woodchips (Met chips): the carbon sink loss due to the harvest of live trees, and the carbon sink loss recovery time to replace the harvested trees (see Departures from LCA conventions).

### Factors Not Included in the Study

1. **Smelter Facility** (Scope 1)
   (1) Smelter facility, raw material extraction, and transport emissions other than GHG emissions: e.g., Sulfur Oxides, volatile organic compounds (VOCs), Lead (Pb), Mercury (Hg) Arsenic (As), Cadmium (Cd) Fluorides, Particulate Matter (PM), Silica Particulates, and other pollutants are not included.

    (2) Slag. Quantitative information regarding the amount of slag produced from silicon smelting was not found.
    (3) Smelter facility site construction, supporting infrastructure construction (access roads, railroad spur, etc.), land alteration, water resource allocation, and smelter site deforestation.
    (4) Routine business and employee transportation to and from the smelter: emissions and energy use.
2. **Energy** (Scope 2) See Raw Materials and Resources Section 10.4, Energy.
    (1) Box Canyon Dam is a hydroelectric dam with a capacity of 90 MW and is approx. 50 miles north of Newport in Pend Oreille county. Box Canyon Dam is operated by the Pend Oreille County Public Utility District (PUD) and serves Pend Oreille County residents and businesses. Boundary Dam is a hydroelectric dam with a capacity of more than 1,070 MW, and is approx. 80 miles north of Newport in Pend Oreille County. Boundary Dam is operated by Seattle City Light, and most of its energy serves the city of Seattle. Information regarding the amount of hydroelectric energy that could be used by the smelter, and how much electricity generated from other sources would be required was not available. Emissions information from potential energy sources was not available.
3. **Upstream Contributors** (Scope 3)
    (1) Blue Gem coal mine Methane emissions and coal mining energy use and emissions.
    (2) Coal rail transport return trips, emissions and energy use.
    (3) Emissions and energy use for tree harvesting, wood chipping, and transport of logs and wood chips.
    (4) Emissions and energy use from Charcoal manufacture and transport.
    (5) Emissions and energy use for Quartzite mining and transport.
    (6) Emissions and energy use for graphite electrode manufacture and transport.

**Departures from LCA Conventions**

1. **Biomass Emissions**. This study accounts for biomass CO2 emissions at the point of combustion during the smelting process. The IPCC does not account for biomass (woodchips, charcoal) CO2 emissions from the silicon smelting point of combustion. The practice of not accounting for biomass CO2 emissions at the point of combustion is currently under growing debate (see Literature Review).

2. **CO2 Sink Loss from Tree Harvest for Woodchips and CO2 Sink Loss Recovery Rate**.
   The CO2 sink loss (CSL) from the harvest of trees for woodchips per SP is included as a CO2 sink loss debt (gCO2). A tree age of 40 years at harvest is assumed, and a successful restocking of the harvested trees is also assumed. A linear growth rate of restocked trees is assumed. The CO2 debt is applied at year 1, and a corresponding linear CO2 sink loss recovery rate (CRR) is applied per SP over a period of 40 years to subtract the CO2 sink loss debt. At year 40, the CO2 sink loss will equal zero. A solar panel lifetime of 30 years is assumed. The CO2 sink loss debt extends 10 years beyond the solar panel lifetime if trees are harvested at 40 years of age. See Tables 23, 40, 41 and Appendix C.

3. **Two different emissions calculation methods are employed**. Calculation method 1 uses a conventional type method where the smelter emissions per downstream SPs is the % smelter metric tonnes (MT) of GHGs per year divided by the corresponding % MT of MGSi used per year for downstream c-Si SPs per year (essentially the smelter Emission Factor, EF). Calculation Method 2 uses the total smelter MT of GHGs per year divided by the % MT of MGSi designated for downstream c-Si SPs per year (essentially an EF based on the percentage of MGSi used for SPs).

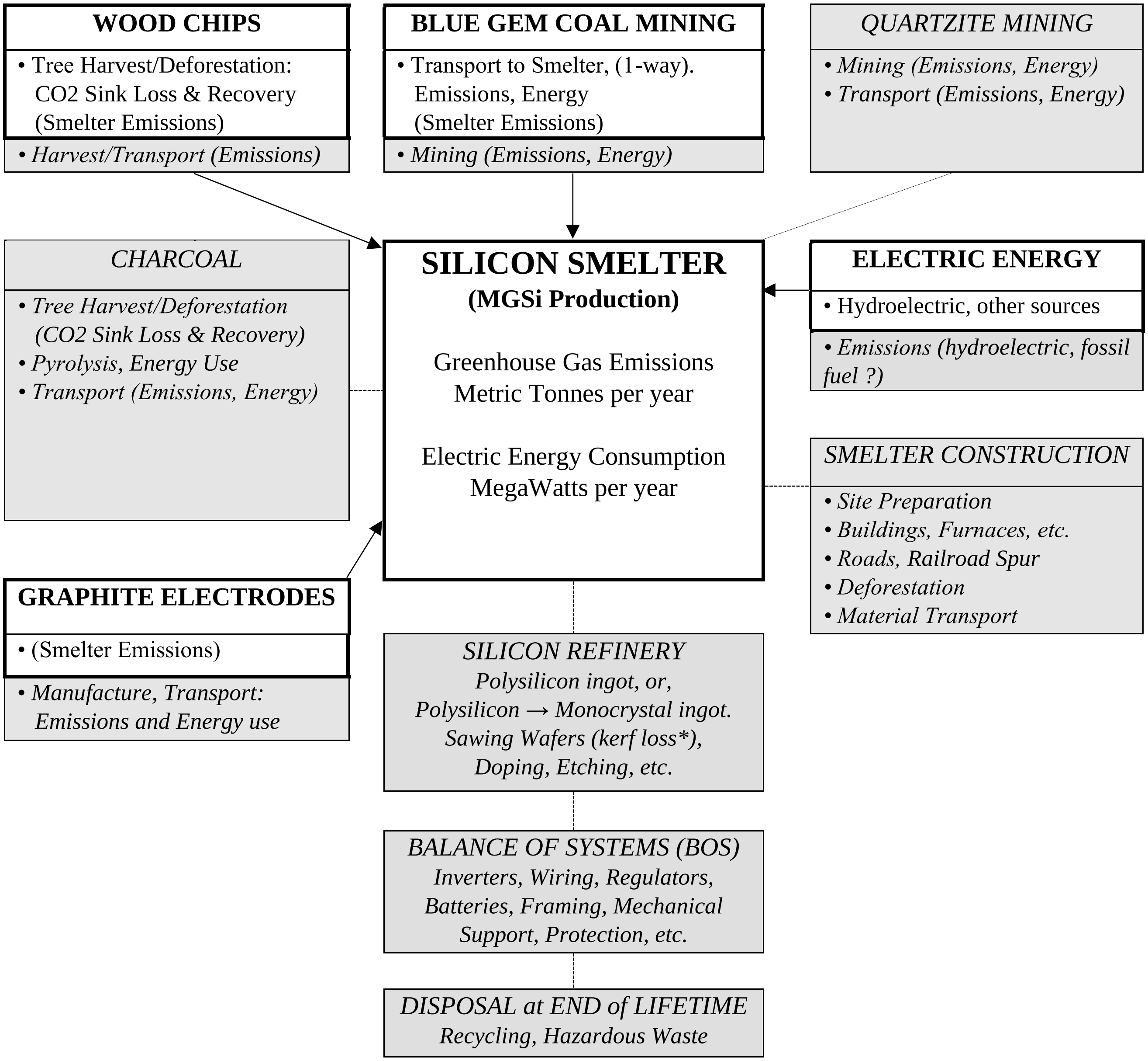
**Note 1: GHG Emissions.**

Two different emissions estimations for the proposed smelter were available from the smelter's consulting firm; only GHG estimations from the total smelter emissions estimations are used. The two different GHG emissions estimations (E1 and E2) are listed in Table 3 of the Calculations Section 5. The difference between the two estimations is greater than two-fold. To investigate the disparity between the two estimations, a third emissions estimation (E3) was performed using mass balance calculations based on smelter raw materials and products listed in Tables 2 and 4 of the Calculations Section 5. The mass balance calculation (E3) includes emissions from coal, graphite electrodes, and biomass woodchips. Table 2 raw materials lists "coal and charcoal" at 150,000 tons (136,080 MT) per year. Since individual quantities of coal and charcoal are not listed, the quantity of 136,080 MT represents only coal emissions in the (E3) estimation.

Emission Factors (EF) were determined for each of the three emissions estimations (EF1, EF2, EF3) and compared.
The mass balance EF3 agrees more closely with EF2 than does EF1, therefore the published GHG emissions from E2 was selected to be used for all subsequent calculations.

**SCOPE DIAGRAM**

The processes included in the carbon footprint calculations are in the white, bolded boxes. The grayed-out boxes and sections are not included in this study.



**The scope of calculations include**:(1) emissions and energy use from the transport of coal (1-way), (2) smelter emissions from coal, (3) tree harvest for woodchips as a carbon sink loss, (4) smelter emissions from woodchips, (5) smelter emissions from graphite electrode consumption, (6) smelter energy use (MW, kWh). Smelter emissions estimations for the MGSi product are determined and projected onto the downstream c-Si SP product expressed as CFP values per SP.

**The scope of calculations does not include**: (1) blue gem coal mining emissions and energy use, (2) Tree harvesting, transport, and wood chipping emissions and energy use, (3) Charcoal manufacture, transport, energy use, and smelter emissions, (4) Quartzite mining emissions, energy use, and transport, (5) Graphite electrode manufacture and transport, (6) emissions from energy generation, (7) smelter site and facility construction, (8) downstream refining and processing of MGSi*, (9) Balance of systems (BOS), (10) Disposal: recycling, hazardous waste treatment.
**Note: a refined silicon ingot kerf loss is accounted for in the upstream silicon smelter MGSi calculations, Section 5.6.*

## 3. THE SILICON SMELTING PROCESSS

The predominant types of SPs currently in use are composed of Crystal Silicon (c-Si) [7]. The source of the c-Si, “Metallurgical Grade Silicon” (MGSi), comes from the mining of Quartzite rock (Silicon Dioxide, $SiO_2$) and the energy-intensive and Greenhouse Gas (GHG) emitting silicon smelting process. The “carbo-thermic” reduction smelting process takes place in Submerged Arc Furnaces (SAF) and typically uses a mix of coal (fossil fuel), and wood chips and possibly charcoal (biomass) as carbon reductants to extract the Oxygen atoms from SiO2 under intense heat. This Oxidation-Reduction reaction of $SiO2 + C \rightarrow Si + CO$ (and subsequently CO2) involves the transfer of electrons from Carbon to SiO2 in exchange for Oxygen (O) atoms from SiO2, yielding elemental Si + Carbon Monoxide (CO). The CO ultimately is converted to CO2 from Oxygen near the top of the SAF [8] [9]. In addition to serving as a carbon reductant, wood chips also provide physical features that facilitate the smelting process [10].

### Metallurgical Grade Silicon (MGSi)

Silicon smelter SAFs use three graphite electrodes that require a constant supply of electrical energy for providing temperatures greater than 3,000°F to obtain SiO2 in a molten state. Carbon from the mix of coal, charcoal, and wood chips provides a reducing atmosphere near the bottom of the furnace and electrode tips, and constitutes an inner reaction zone [9] [11]. The extreme temperature at the tips of the electrodes volatilizes the quartzite, and the silicon dioxide vapor reacts with carbon to form carbon monoxide, silicon monoxide, silicon carbide and eventually silicon metal [9]. A layer of glassy material known as “slag” forms above the molten material. Slag consists of oxides and impurities from the metal ore extracted during the smelting process, and provides a protective layer over the smelted metal [12]. Carbon monoxide gas rises through the burden and slag and oxidizes to form carbon dioxide in the oxidizing atmosphere of the outer reaction zone near the top of the furnace [9]. The molten silicon is tapped from the furnace through a tap-hole at the bottom, and refined by slag treatment or gas purging. After slag removal, the molten silicon is allowed to cool in a mold, and then crushed to a specified size [11].

### Silica Fume by-product

In addition to Carbon monoxide, Silicon monoxide gas also rises through the burden and slag. While the carbon in the reducing zone of the furnace strips the oxygen from most of the silicon monoxide, some of it escapes to the upper oxidizing zone of the furnace and the reaction of silicon monoxide to silicon dioxide results in a by-product known as “silica fume” [9]. The silica fume that reaches the top of the furnace is carried up into a hood at the top of the furnace by powerful bag house fans and is captured in bag houses. The fume is then transferred to silos for storage until packaged or shipped for use [9]. The submicron size of the spherical-shaped silica fume particles has a number of industrial uses (e.g., the concrete industry) [9]. A silicon furnace produces about 0.2 to 0.4 tons of condensed silica fume per ton of silicon metal [11].

### Slag by-product

Slag is a by-product that forms a “glassy” layer above the molten metal that has been extracted from its ore during the smelting process. Slag consists of a mixture of metal oxides and other impurities and provides a protective layer that helps minimize re-oxidation of the extracted metal [12]. When the smelting process is complete, the molten silicon is removed through a tap-hole at the bottom of the furnace [11] [13]. Slag is separated from the silicon metal, cooled, and is further processed. Slag is used in many industrial processes, such as mixing with concrete and other uses [14].

### Metallurgical Grade Silicon (MGSi)

The silicon smelting process yields relatively pure (approximately 98.5 – 99.5% pure) silicon product, known as Metallurgical-Grade Silicon (MGSi) [4]. The MGSi from the smelter will be directly suitable for the Aluminum Alloy Casting industry and the Chemistry Industry (silicones, etc.). The MGSi will need to be refined further to attain the higher purity requirements for the photovoltaic industry and the electronics industry [4]. Annual silicon smelter emissions consist of hundreds of thousands of tons of GHGs plus other pollutants per year from the reduction of SiO2 by fossil fuel coal and biomass reductants, and from the consumption of graphite electrodes.

Production of MGSi begins with the mining of relatively pure Quartzite rock and transport to the smelter site; the mining of Blue Gem coal and transport to the smelter site; and the procurement and transport of the biogenic reductants woodchips and charcoal [15].

For the proposed silicon smelter, Quartzite would be obtained from the HiTest Quartzite mine near Golden, BC Canada, and would be transported via rail or truck to Newport in northeast Washington State [1] [6]. Blue Gem coal is very rare, and is found in only a few locations (Kentucky USA, and Colombia and Venezuela South America) [15] [16]. Blue Gem coal would be mined, and then shipped by rail from Kentucky; or by boat and rail if from South America [6] [16]. Approximately 117,936 MT (Table 4) of woodchips per year will be required [1] [6]. The source of the woodchips may be from forests in the Newport area, but this has not been clearly specified. A plan for replacing the lost "carbon sink" of forest trees used for woodchips has not been provided. Details regarding the potential use and sources of charcoal have not yet been provided [1] [6]. Raw materials and emissions estimates are in Section 5, Tables 1 through 5.

The proposed HiTest/PacWest smelter would consist of two submerged arc furnaces (SAF) and would have one 157-foot tall emissions stack. The smelter would require a continuous, 24/7 supply of 105 Megawatts of electric energy [6] [17]. Market demands for MGSi for Solar Panels range from 2% to 12% of the total MGSi produced [2] [3] [4]. According to SolarFeeds (2019), the US is likely to install 3 million solar panels in 2021 and 4 million panels in 2023 [18].

## 4. LITERATURE REVIEW

A number of papers and articles were reviewed; and excerpts, summaries and comments from 17 of the reviewed papers are included below. This review discusses some of the issues regarding silicon smelting and c-Si SP CFPs, biomass emissions accounting, LCA/LCI calculation methodology, and the "green" designation of industries and products.

### 4.1. Literature Revealing the Exclusion of Silicon Smelting in c-Si Solar Panel LCI and CFP Studies

A literature search to find the contribution of silicon smelting to c-Si SP CFPs was performed. A number of papers were reviewed, and four of the reviewed papers describing c-Si SP LCI and LCA information are summarized and discussed.

**Paper 1.**
Environmental life cycle inventory of crystalline silicon photovoltaic module production. Wild-Scholten, Alsema, 2005; *Presented at Materials Research Society Fall 2005 Meeting, November 2005, Boston, USA* [19].

**Paper 1 Summary**
Paper 1 shows a scope of study diagram that delineates the boundary of the study, and the scope diagram clearly shows that MGSi (silicon smelting) was not included in the study [19]. The text description of this paper suggests that the data covers all processes from silicon feedstock production (smelting) up to module manufacturing, but it is unclear as to whether *from, and including,* silicon feedstock, or if *from, but not including*, silicon feedstock is meant. However, it is helpful that the scope diagram clearly shows that MGSi (silicon smelting) is not included in this study [19].

**Paper 2.** Environmental Impacts of Crystalline Silicon Photovoltaic Module Production. Erik A. Alsema and Mariska J. de Wild-Scholten**.** *November 2005* [20].
**Paper 3.** Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status. Vasilis Fthenakis, and Erik Alsema, 2006, Progress in Photovoltaics: Research and Applications [21].

**Papers 2 and 3 Summary**
Papers 2 and 3 [20] [21] do not include scope of study diagrams, but c-Si SP CFP values are determined. Paper [20] uses the data collected from paper [19], which contains the scope diagram that clearly shows that MGSi (silicon smelting) is not included in the study. The range of c-Si SP CFP values reported or referenced among papers [20], [21], and [22] are all in approximate agreement.

**Paper 4.** Photovoltaics: Life-cycle analyses. V.M. Fthenakis, H.C. Kim, Solar Energy 85 (2011), 1609-1628 [22].

**Paper 4 Summary**
Paper 4 includes a diagram showing the major components of the c-Si SP manufacturing process, starting from quartz acquisition up to the manufacturing stage of PV systems, but does not delineate the scope of the study [22]. The text description explains that the study includes data starting from the production stage of solar-grade Si and up to module manufacturing. Solar grade silicon involves the purification or refinement of the MGSi feedstock, which is obtained from

the upstream smelting process. Since production of solar grade silicon occurs after the silicon smelting production of MGSi feedstock, it can be inferred that silicon smelting is not included in this paper's LCI.

***Comments (Papers 1 – 4, and others)**. Text descriptions of the steps that are included or excluded in c-Si SP LCIs and CFP determinations in many of the reviewed papers can be confusing and seem to suggest that "complete" LCIs have been done. However, further study and comparison of the reviewed papers reveal that: quartz mining and processing, coal mining and processing, tree harvest and processing for woodchips and charcoal, and the carbo-thermic silicon smelting process to produce the MGSi feedstock have not been included in c-Si SP LCIs and CFP determinations.*

*A firm knowledge of terminology and the complete "cradle-to-grave" process for c-Si SPS is required to fully understand and to assess literature reporting of c-Si SP CFPs and LCIs. From the papers reviewed in this study, it is concluded that the silicon smelting process has not been included in the CFP calculations of C-Si SPs. Only one of the papers provided a scope diagram that clearly delineates processes that are both included and not included in the LCI, and clearly shows that the silicon smelting process to produce MGSi feedstock is outside the scope of the study.*

### 4.2 Literature Discussing the Exclusion of Biomass Emissions from Si Smelting and the Biomass Energy Industry

Excerpts are provided and discussed.

**Paper 5.**

The Use of Biocarbon in Norwegian Ferroalloy Production. Bodil Monsen, SINTEF Materials Technology, Morten Grønli, SINTEF Energy Research, Lars Nygaard, FESIL ASA, Halvard Tveit, ELKEM ASA. June 2001 [23].

**Excerpt 5-1**. From 2, Introduction: "The Kyoto agreement encouraged increased attention to be paid to emissions of CO2 due to its role in potential global warming. From a global reference, CO2-emissions from a process using biological carbon combined with hydropower should be very small if there is a balance between the carbon in the process and the growth of the trees used to produce the biological carbon." [23].

***Comment 5-1**. The 2nd statement above identifies the critical necessity of a balance between biological carbon used in a smelting process and the growth of trees used to produce the biological carbon. A method for determining the balance of biological carbon combustion and the growth of trees for smelting facilities is not included. A simplified method for quantifying the carbon sink loss from tree harvest for wood chips used in silicon smelting, and projecting the carbon sink loss onto downstream c-Si solar panels is described in Section 5 of this paper. This provides a mechanism for determining whether-or-not the impact of silicon smelter woodchips combustion on downstream SPs balances out with tree growth.*

**Excerpt 5-2**. From Section 6, Experience from Using Charcoal in a Pilot Furnace: "In the production of silicon, a share of 10% Fixed Carbon from wood chips is considered typical, but still nearly 1400 kg coal is needed per tonne. By replacing these reductants by biocarbon it may be possible to nearly eliminate the fossil CO2-emissions, as shown in Figures 5 and 6. The remaining CO2-emissions will be due to the consumption of electrodes." [23].

***Comment 5-2**. The above statements seem to imply that replacing fossil fuel (coal) reductants with biomass reductants will leave only the fossil fuel-derived graphite electrodes as the sole source of CO2 emissions. This suggests that biomass CO2 emissions may not accounted for at the smelter point of combustion.*

**Paper 6.**

1996 International Panel on Climate Change (IPCC), INDUSTRIAL PROCESSES
*Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual* [24].

**Excerpt 6-1.** From: 2.13 CO2 Emissions from Metal Production. 2.13.1 CO2 from Metal Production-General Methodology. page 2.26.
"With a few exceptions, commercial production of metals from ores requires the use of carbon as a reducing agent. The metal may be reduced by using coal, coke, prebaked anodes and coal electrodes. Wood chips and charcoal may also be used in some of the processes, but the resulting CO2 emissions are not counted in Chapter 2 as net emissions. These net emissions of CO2 should, however, be reported in the Land-Use Change and Forestry Chapter." [24].

***Comment 6-1**. Excluding the CO2 emissions from wood chips and charcoal in net metal production emissions does not give an accurate measure of the total carbon footprint of the smelting process. To exclude these CO2 emissions from the industrial source of combustion and move them to a separate chapter significantly underestimates the reality of the actual CO2 emissions from the industrial process, and results in additional complexity of tracking these emissions.*

**Excerpt 6-2.** From: 2.13.4 Ferroalloys. 2.13.4.1 Overview. 2.13.4.2 Emission Estimation Methodology for CO2, p 2.30. "Ferroalloy production may more or less be based on biological carbon (wood and wood waste). To the extent that the biocarbon is replaced and that electricity is produced from e.g., hydro power, the production of ferroalloys may in principle be CO2 free." [24].

***Comment 6-2**. The exclusion of combusted biogenic materials as sources of CO2 emissions assumes that they do not emit CO2, and have no impact on atmospheric CO2 levels. Woodchips typically come from mature trees. In addition to the CO2 and other GHGs emitted by the smelter from burning woodchips and charcoal, the impact of harvesting trees goes beyond the immediate emissions impact since it takes decades to replace the lost carbon sink of mature trees. Also, it should be noted that some Hydroelectric dams can contribute significant Methane emissions to the atmosphere* [25] [26].

**Paper 7**.
2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 1, Chapter 1, Introduction to National GHG Inventories, 1.1 Concepts, **Treatment of CO2, CH4 and N2O emissions from combustion of biomass or biomass-based products** pages 1.5 and 1.6 [27].

**Excerpt 7-1**. (page 1.5) "Carbon dioxide (CO2) emissions from the combustion of biomass or biomass-based products are captured within the CO2 emissions in the AFOLU sector through the estimated changes in carbon stocks, e.g. from biomass harvest, even in cases where the emissions physically take place in other sectors (e.g., energy). This approach to estimate and report all CO2 emissions from biomass or biomass-based products in the AFOLU was introduced in the first IPCC guidelines for national greenhouse gas emissions (IPCC 1995), reflecting close linkages with data on biomass harvesting, and for the pragmatic reason to avoid double counting." [27]. *Note: AFOLU = Agriculture, Forestry, and Other Land Use.*

***Comment 7-1**. The above statements suggest that the IPCC practice of not accounting for biomass CO2 emissions at the point of combustion was adopted primarily for ease of accounting purposes.*

**Excerpt 7-2**. (page 1.6). "In the Energy sector, CO2, methane (CH4) and nitrous oxide (N2O) emissions from combustion of biomass or biomass-based products for energy are estimated, but the CO2 emissions are recorded as an information item that is not included in the sectoral total emissions for the Energy sector. This provides a complete picture of a country's energy system and avoids double counting of these emissions with those reported in the AFOLU sector. The CH4 and N2O emissions from the combustion of biomass or biomass-based products for energy are reported and included in the sectoral total emissions in Energy sector, as these are not covered by the estimation methods in the AFOLU sector." [27].

***Comment 7-2**. The above section states that biomass CO2 emissions are recorded as an information item that is not included in the sectoral total emissions for the Energy sector, and also states that this provides a complete picture of a country's energy system. It can be argued that this is not true. The non-reporting of biomass CO2 emissions at the point of combustion does not provide a complete picture of emissions in the Energy sector. The additional artifact of segregating CH4 and N2O biomass emissions from CO2 biomass emissions is a "disconnect" from the actual spatial and temporal reality of CO2, CH4, and N2O biomass combustion emissions.*

**Paper 8**.
Frequently Asked Questions. 1. IPCC Task Force on National Greenhouse Gas Inventories (TFI), general guidance and other inventory issues. 1.1. Questions about IPCC National Greenhouse Gas Inventories Programme, **2. Energy, Q2-10** [28].

**Excerpt 8-1**. **"2. Energy. Q2-10**. According to the IPCC Guidelines CO2 Emissions from the combustion of biomass are reported as zero in the Energy sector. Do the IPCC Guidelines consider biomass used for energy to be carbon neutral?"

“**A**: The overall IPCC approach to estimating and reporting bioenergy greenhouse gas emissions at the national level requires complete coverage of all IPCC sectors, including the AFOLU and Energy sectors. All CO2 emissions and removals associated with biomass are reported in the AFOLU sector. Therefore, CO2 emissions from biomass combustion used for energy are only recorded as a memo item in the Energy sector; these emissions are not included in the Energy sector total to avoid double counting. The approach of not including these emissions in the Energy Sector total should not be interpreted as a conclusion about the sustainability, or carbon neutrality of bioenergy.” [28].

***Comment 8-1***. *The statement: “Therefore, CO2 emissions from biomass combustion used for energy are only recorded as a memo item in the Energy sector…” could be reversed to record the CO2 emissions in the Energy or Industrial Sector where they occur, and then record the CO2 emissions as a “memo” item in the AFOLU sector. This would capture the actual spatial and temporal reality of combustion, and would also avoid double counting. The statement: “The approach of not including these emissions in the Energy Sector total should not be interpreted as a conclusion about the sustainability, or carbon neutrality of bioenergy.” seems to have contributed to widespread interpretation that biomass combustion is considered to be “carbon neutral”* [29] [30].

**Excerpt 8.2**.“While individual methodologies and emission factors provided in the IPCC Guidelines may be relevant for estimating CO2 emissions from the use of bioenergy at an individual facility or industry, the IPCC Guidelines as an overall framework for a national GHG inventory do not provide an analytical approach for assessing the full bioenergy emissions at sub-national entities such as industry sectors.” [28].

***Comment 8-2***. *The IPCC Guidelines for national GHG inventory that do not account for bioenergy CO2 emissions at the point of combustion in energy and industrial sectors seem to have been carried down to and implemented at sub-national entities* [29] [30]. *The IPCC’s non-accounting for biomass emissions at the point of combustion seems to have resulted in an interpretation that all biomass combustion is carbon neutral.*

**Excerpt 8.3**. “Thus, the IPCC Guidelines do not automatically consider or assume biomass used for energy as “carbon neutral”, even in cases where the biomass is thought to be produced sustainably.” [28].

***Comment 8-3***. *From the previous* ***Excerpt 6-2*** *of the 1996 IPCC Guidelines* [24]: *“Ferroalloy production may more or less be based on biological carbon (wood and wood waste). To the extent that the biocarbon is replaced and that electricity is produced from e.g., hydro power, the production of ferroalloys may in principle be CO2 free.” The underlined statement suggests that replacing fossil fuel reductants with biomass reductants would result in ferroalloy production that is CO2 free, essentially saying that biomass combustion is carbon neutral. This seems to contradict the IPCC’s statement in Excerpt 8-3 regarding its position on the carbon neutrality of biomass emissions.*

**Paper 9**.
Woody Biomass for Power and Heat: Impacts on the Global Climate. Research Paper, Duncan Brack Environment, Energy and Resources Department | February 2017, Chatham House [31].

**Excerpt 9-1.** From the CONCLUSION: “The use of woody biomass for energy cannot be considered to be automatically carbon-neutral under all circumstances, though most policy frameworks treat it as though it is. In reality, carbon dioxide and methane will be emitted from the combustion of woody biomass (generally at higher levels than from the fossil fuels it replaces) and from its supply chain of harvesting, collecting, processing and transport. In addition, where the feedstock derives from harvesting whole trees, net carbon emissions will increase from the foregone carbon sequestration that would have occurred had the trees been left growing.” [31].

***Comment 9-1***. *This paper identifies two sources of the assumption that biomass fuels are carbon neutral. The first assumption is that biomass CO2 emitted by burning wood for energy is balanced out by forest growth. The author shows that woody biomass is less energy dense than fossil fuels, and that burning wood for energy usually emits more GHG per unit of energy than that of fossil fuels. Also, tree harvest for energy results in the loss of carbon sequestration, which results in a net increase of CO2 emissions. The second assumption derives from IPCC rules intended to avoid double-counting of biomass CO2 emissions that are accounted for in the Land Sector, and not where they actually occur.*

**Paper 10**.
John D Sterman et al. Does replacing coal with wood lower CO2emissions? Dynamic lifecycle analysis of wood bioenergy. 2018 Environ. Res. Lett.13 015007. 2018. https://doi.org/10.1088/1748-9326/aaa512. [32].

**Excerpt 10-1.**
From the Abstract: "Because combustion and processing efficiencies for wood are less than coal, the immediate impact of substituting wood for coal is an increase in atmospheric CO2 relative to coal. The payback time for this carbon debt ranges from 44–104 years after clearcut, depending on forest type—assuming the land remains forest." [32].

**Excerpt 10-2.**
From Methods, 2.1 Model Structure: "C-ROADS is a member of the family of simple climate models, consisting of a system of differential equations representing the carbon cycle, budgets and stocks of GHGs, radiative forcing and the heat balance of the Earth." [32].

**Excerpt 10-3.**
From the Conclusion: "In sum, although bioenergy from wood can lower long-run CO2 concentrations compared to fossil fuels, its first impact is an increase in CO2, worsening global warming over the critical period through 2100 even if the wood offsets coal, the most carbon-intensive fossil fuel. Declaring that biofuels are carbon neutral as the EU and others have done, erroneously assumes forest regrowth quickly and fully offsets the emissions from biofuel production and combustion. The neutrality assumption is not valid because it ignores the transient, but decades to centuries long, increase in CO2 caused by biofuels." [32].

***Comment 10-1, 2, 3.*** *This paper uses the C-ROADS climate modeling software to evaluate climate dynamics. The model focused on wood harvested for electricity generation, and simulates substitution of wood for coal in power generation.*

### 4.3 Literature Discussing Carbon Footprint (CFP) and Life Cycle Assessment (LCA) Methods and Issues

**Paper 11**.
Carbon footprint: current methods of estimation. Divya Pandey, Madhoolika Agrawal, Jai Shanker Pandey. 2010 [33].

**Paper 11 Summary**
This paper suggests that although the carbon footprint concept is commercialized in many areas of life and economy, there is little coherence of carbon footprint definitions and calculation methods found among many studies. It is also revealed that scientific literature on the carbon footprint studies is scarce, and that many studies have been carried out by private organizations or companies more for business reasons rather than for environmental concerns [33].

***Comments (Paper 11).*** *This paper illustrates some of the critical concerns regarding published CFP determinations.*

**Paper 12**.
European Platform on Life Cycle Assessment, Environmental Footprint. ILCD International Life Cycle Data system [34].

**Excerpt 12-1.**
**From** the web page opening paragraph: "The ISO 14040 and 14044 standards provide an important framework for LCA. This framework, however, leaves the individual experts, practitioners and data developers, with a range of important choices that can be individually interpreted, leading towards differences in consistency, reliability and comparability of the results of the assessment. Equally, the methodological assumptions behind the life cycle data can differ widely, so that data from different sources can be not interoperable." [34].

***Comments (Paper 12)****. The inherent amount of ambiguity and inconsistency with LCA/LCI methodologies highlights the complexity of the industrial relationship with the environment, and also highlights the need to improve clarity, transparency, and consistency with LCA/LCI methods. A unifying, reproducible baseline methodology is needed.*

**Paper 13**
Xin Li, Lizhu Chen, and Xuemei Ding. Allocation Methodology of Process-Level Carbon Footprint Calculation in Textile and Apparel Products. Published: 18 August 2019. Sustainability 2019, 11, 4471;doi:10.3390/su11164471 [35].

**Paper 13 Summary**
This paper reveals that allocation methodology of CFP calculations is a significant and controversial issue, and can be a major source of LCA uncertainty. Allocation methodology significantly impacts data collection and system boundaries, and different outcomes can be obtained for apparently similar systems by using different allocation methods [35].

***Comments (Paper 13)****. The issues with allocation methods used in LCA calculations seems pervasive. A method that does not involve allocation of emissions among co-products could be a valuable tool for harmonizing LCIs and LCAs. The environmental Method 2 calculation used in this paper does not involve allocation of emissions among co-products.*

### Paper 14

Frank Werner and Roland W. Scholz, Ambiguities in Decision-Oriented Life Cycle Inventories. The Role of Mental Models, LCA Methodology, 2002. Int J LCA 7 (6) 330 - 338 (2002) [36].

**Paper 14 Summary**
This paper suggests that a generic LCA-methodology that includes methodological options cannot be defined, and modelling a product system with a life cycle inventory (LCI) is an ambiguous undertaking. Despite available guidelines for conducting LCAs (e.g., ISO 14 040 standards), reliance on subjective decisions remain. This paper further suggests that the influence of subjective decisions within an LCA makes it extremely difficult to attribute life cycle impacts from complex, "socio-economic" systems in an unambiguous way [36]. The conclusion offers a number of points describing features that product systems and their LCIs and LCAs should have. Several of the listed points include: completeness, comparability, transparency, rapid recalculation capability, and also be as site-specific and case-specific as possible [36].

***Comments (Paper 14)****. In addition to a "socio-economic" perspective, addressing overall "environmental" impacts of an individual product manufacture (without allocation to co-products) and obtaining a baseline environmental assessment could remove ambiguity and provide a unifying framework for LCIs and LCAs. Using conclusion points ("site-specific", "rapid calculation capability", etc.) [36], and using a total process or facility environmental impact calculation method (without co-product allocation), more objective and comparable LCI/LCAs and CFPs might be attainable.*

### Paper 15
Tomas Ekvall (September 24th 2019). Attributional and Consequential Life Cycle Assessment, Sustainability Assessment at the 21st century, María José Bastante-Ceca, Jose Luis Fuentes-Bargues, Levente Hufnagel, Florin-Constantin Mihai and Corneliu Iatu, IntechOpen, DOI: 10.5772/intechopen.89202 [37].

**Paper 15 Summary**
This paper describes two different LCA methods, the attributional LCA (ALCA) and the Consequential LCA (CLCA). The two methods differ on what input data is used, and how allocation problems are dealt with. The author further reveals that it has been known for some time that results from different LCAs can contradict each other, and this issue persists despite attempts to standardize and regulate LCA. It is also suggested that LCA should not be viewed as a single method, but should be considered as a "family" of methods [37].

***Comments (Paper 15)****. This paper reveals that contradictory LCA results continue to be a problem, and a family of methods has not yet solved allocation issues or unified LCAs. Incorporating a method that does not involve allocation of environmental impacts to co-products into the family of LCA methods could provide a step toward harmonizing LCAs.*

## 2.4 Literature Discussing "GREEN" Terminology (Papers 16 – 17)

### Paper 16
Defining Green Products. Air quality Products, Air Quality Sciences, Inc. 2010 [38].

**Paper 16 Summary**
This article discusses the term "green" and suggests that "green" can be defined in many different ways and its definition can be modified to support different points of view. The article further suggests that while "green" generally refers to environmentally favorable products or processes; a single, universal definition of green does not currently exist [38].

***Comment (paper 16)**. Without a clear, quantifiable definition, the expression "green" has little meaning or value.*

**Paper 17**

Green Industry Analysis 2020 - Cost & Trends, Franchise Help, *Matt Sena* [39].

**Paper 17 Summary**

This article suggests that while any environmental efforts are positive, many companies are guilty of "greenwashing" as they only go through motions to claim being green. The article further suggests that truly green organizations apply sustainable and environmentally conscious practices at decision points throughout their operations [39].

***Comments (paper 17)**. Identifying operation or process decision points where environmentally conscious decisions are made (or not made) will be critical in attempts to establish a quantifiable definition of "green."*

### Literature Review Summary

### 4.1. Literature Revealing the Exclusion of Si Smelting in c-Si Solar Panel LCI and CFP Studies

Reviewed papers show that the silicon smelting process was not included in the CFP calculations of C-Si SPs. There was also some ambiguity in the text descriptions of the scopes of the studies. Only reviewed Paper 1 [19] gave a clear scope diagram and showed the silicon smelting process to produce MGSi was outside the scope of the study.

### 4.2 Literature Discussing the Exclusion of Biomass Emissions from Si Smelting and the Biomass Energy Industry

The IPCC has taken the lead in addressing climate change and accounting for GHG emissions at the national level, but the handling of biomass CO2 emissions is problematic. The IPCC's method of accounting for biomass combustion CO2 emissions from industrial and energy sources in the Agriculture and Other Land Use (AFOLU) sector, instead of where the combustion occurs, seems to have originated from a "pragmatic" accounting perspective.

It is not clear as to whether-or-not the IPCC assumes rapid uptake of biomass CO2 emissions by the environment, thereby suggesting "carbon neutrality" of biomass combustion. The assumption of rapid CO2 "rebalance" from wood biomass combustion seems to ignore the loss of active carbon sinks due to tree harvest. Papers 9 [31] and 10 [32] provide evidence that challenges assumed rapid assimilation of CO2 emissions from combustion of biomass derived from forests and trees.

### 4.3 Literature Discussing Carbon Footprint (CFP) and Life Cycle Assessment (LCA) Methods and Issues

Overall, a lack of agreement and comparability among LCAs, LCIs, and CFPs seems to be pervasive. Emission allocation methodologies for co-products among LCAs are at the core of reproducibility issues. A single, unifying method for allocating emissions in LCAs does not currently exist.

### 4.4 Literature Discussing "GREEN" Terminology

A standardized, quantifiable definition of "Green" does not currently exist. "Greenwashing" will remain an issue until a standardized and verifiable Green definition is in place.

**Other papers of interest**:

Why do we burn coal and trees to make solar panels? Thomas A. Troszak, 2019 [15].
*This document gives an excellent overview of the entire silicon solar panel manufacturing process.*

The embodied CO2e of sustainable energy technologies used in buildings: A review article, Stephen Finnegan, Craig Jones, Steve Sharples, 2018 [40].
*This paper suggests that LCA methodologies can present information which has a significant degree of inaccuracy.*

Carbon Loophole: Why Is Wood Burning Counted as Green Energy? YaleEnvironment360, Fred Pearce, 2017 [41].
*This paper discusses the burning of wood pellets for energy as a replacement for coal in Europe, and the impacts of deforestation from wood harvest in both the USA and Europe to supply energy based on wood burning.*

## 5. CALCULATIONS: SMELTER CONTRIBUTION TO c-Si SOLAR PANEL CARBON FOOTPRINTS

### List of Calculation Tables and Equations

**5.0. Calculations: Smelter contribution to c-Si Solar Panel Carbon Footprints**

**Abbreviations Used:**

CO2: Carbon dioxide. CO2e: Carbon dioxide equivalent. CFP: Carbon footprint. CSL: Carbon sink loss. CRR: Carbon sink loss recovery rate. c-Si: Crystal silicon. EF: Emission Factor. GWP: Global warming potential. IPCC: Intergovernmental Panel on Climate Change. KA: Kerf Allowance. KL: Kerf Loss. LCA: Life Cycle Assessment. LCI: Life Cycle Inventory. MGSi: Metallurgical-grade silicon. MT: Metric tonnes. SAF: Submerged arc furnace. SiF: Silica Fume. SP: Solar panel. 2xSP: 2x MGSi allotted per SP for kerf allowance due to 50% kerf loss.

**Assumptions**

**Coal/Charcoal.**

(1) Coal will be mined and transported via rail from Kentucky. The amount and source of charcoal is unknown.

(2) Carbon content of Blue Gem coal is 60% [42]. Charcoal carbon content can range from 65% to 85 % [43]. Since the amount of charcoal and carbon content are not provided, a carbon content of 60% is used for the combined coal/charcoal amount of 150,000 tons/yr [6] (136,080 MT/yr). Note: 60% carbon content of coal/charcoal is a minimal estimation.

**Woodchips.**

(1) Predominant source for woodchips is Lodgepole Pine and harvested at an approx. age of 40 years [32] [44] [45]. See Raw materials section 10.3.3 Forest/Timber Management.

(2) Harvested trees will be restocked successfully within 1 year from harvest.

(3) A constant, linear growth rate of trees is assumed; and restocked trees will not succumb to disease, insect damage, drought, wildfire, or other detrimental events. The line equation “$y = -mx + b$” is used to estimate a carbon sink loss recovery rate. Note: The complex nature of tree growth is more rigorously described using differential or other equations.

(4) Woodchips are obtained from managed forest lands. See Raw Materials Section 10.3.3.

**c-Si Solar Panels**

(1) A 50 % kerf loss during sawing of silicon ingots to obtain silicon wafers is assumed. See Section 5.6 for references.

**Note**: Due to rounding, some calculations may result in values that differ from results carried to further decimal places.
**Note**: There may be updated values and information that are not included in this study.

## 5. CALCULATIONS: SMELTER CONTRIBUTION TO c-Si SOLAR PANEL CARBON FOOTPRINTS

The carbon footprint calculation for Solar Panels is represented in equation (1) below [46]:

(1)

$$\text{CO2 emission rate [g-CO2 /kWh]} = \frac{\text{Total CO2 emission during life-cycle [g CO2]}}{\text{Annual power generation [kWh/year] x Lifetime [years]}}$$

### 5.1 Proposed Smelter Product Yield, Raw Materials, Energy Use, and GHG Emissions Estimations

Two estimations of annual product yield, raw material requirements, and energy use requirements; and two emissions estimations for the proposed smelter are listed in tables 1,2, and 3 below.

**Table 1. MGSi Yield, Raw Materials and Energy Use: First Estimation**

| **Silicon Metal (MGSi)** | **Tonnes (MT) MGSi per Year*** |
|---|---|
| Estimated Annual MGSi Yield | 60,000 |
| **Raw Materials** | **Tonnes per Tonne MGSi produced*** |
| High Purity Quartz Rock | 2.5 |
| Metallurgical Coal and/or Charcoal | 0.8 |
| Woodchips | 2.0 |
| **Energy** | **MegaWatts (MW)** |
| Electric | 105 (constant) |

*Adapted from the HiTest Silicon Proposed Newport Silicon Metal Facility Project Overview Slide Presentation, 2017* [1].

**Table 2. MGSi Yield, Raw Materials and Energy Use: Second Estimation**

| **Silicon Metal (MGSi)** | **Tons per Year** |
|---|---|
| Estimated Annual MGSi Yield | 73,000 tons |
| **Raw Materials** | **Tons per year** |
| Quartz rock | 170,000 tons |
| Blue gem coal and charcoal | 150,000 tons |
| Wood chips | 130,000 tons |
| **Energy** | **MegaWatts (MW)** |
| Electricity | 105 (constant) |

*Adapted from the PacWest Silicon Smelter Project, Washington State Department of Ecology* [6].

**Table 3. 1st and 2nd Preliminary GHG Emissions Estimations for PSD Protocols** (Ramboll Environ) [47] [48]

| **PSD Pollutant** | **Preliminary Project Emissions Increases, tons per year (tpy)** | |
|---|---|---|
| | **Emissions Estimation 1, (tpy)** | **Emissions Estimation 2* (tpy)** |
| NOx | 700 | 935 |
| **Greenhouse Gases (GHG)** | 320,256 | 766,131 (766,000)* |

Table 3 is adapted (condensed) from two separate Emissions Estimations [6] [47] [48]. Only GHG and NOx are shown. PSD = Prevention of Significant Deterioration. *Note: Washington State DOE lists 766,000 tpy [6], this is the value used.

Materials listed in Tables 2 and 3 are expressed in "tons" or "short tons" instead of conventional metric tonnes (MT). The short ton values are converted to metric tonnes using the conversion factor of 0.9072 MT/ton.

**Table 4. Smelter Raw Materials: 2nd Estimation conversion from tons to Metric Tonnes (MT)**

| **Silicon Metal (MGSi)** | **Amount per year** | | | | |
|---|---|---|---|---|---|
| Annual MGSi Yield | 73,000 tons | x | 0.9072 MT/ton | = | **66,226 MT** |
| **Raw material** | **Amount per year** | | | | |
| Quartz rock | 170,000 tons | x | 0.9072 MT/ton | = | **154,224 MT** |
| Blue gem coal and charcoal | 150,000 tons | x | 0.9072 MT/ton | = | **136,080 MT** |
| Wood chips | 130,000 tons | x | 0.9072 MT/ton | = | **117,936 MT** |

**Table 5. Greenhouse Gas Estimations from Table 3: Conversion from tons to MT**

| Greenhouse Gases (GHG) | Amount per year | | | | |
|---|---|---|---|---|---|
| Emissions Estimation 1 | 320,256 tons* | x | 0.9072 MT/ton | = | 290,536 MT |
| Emissions Estimation 2 | 766,000 tons* | x | 0.9072 MT/ton | = | **694,915 MT** |

**Table 3*

### 5.2 Smelter Emission Factors EF1, EF2 and EF3

An **Emission Factor (EF)** is a value that relates the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. EFs are usually expressed as the mass of pollutant divided by a unit mass, volume, distance, or duration of the activity emitting the pollutant [49]. The unit mass of 66,226 MT MGSi annual product yield in Estimation 2 (Table 4) is used for subsequent calculations.

Three different smelter emission estimates are used to determine EFs based on 66,226 MT of MGSi product (Table 4). EF1 uses GHG Emissions Estimation 1 (Table 5), EF2 uses GHG Emissions Estimation 2 (Table 5), and EF3 uses mass balance calculations based on raw material mass values listed in Table 4, and the NOx emissions value from Estimation 2 in Table 3. EF3 calculations are found in Tables 8 – 14. Per cent difference between EFs 1,2, and 3 are determined to evaluate the agreement among the three EFs.

EF calculations for smelter reductants (coal/charcoal, woodchips) use the 2006 IPCC tier 1 expression of MT CO2/MT Product (Table 4.5, vol3, ch4, p 4.37) [50], and EF3 uses the tier 2 calculation for Graphite Electrode EF of 3.54 MT CO2/MT Reducing Agent (Table 4.6, p 4.38) [50].

**Table 6. Emission Factors EF1, EF2, and EF3**

| GHG (CO2e) Emissions | MT CO2e per year | | MT MGSi per year | | Smelter Facility EF MT CO2e/MT MGSi |
|---|---|---|---|---|---|
| Estimate 1 (EF1) | 290,536* | ÷ | 66,226 MT | = | **4.387** |
| Estimate 2 (EF2) | 694,915* | ÷ | 66,226 MT | = | **10.493** |
| Estimate 3 (EF3) | 792,210** | ÷ | 66,226 MT | = | **11.962** |

**Table 5. **Table 13. Note: Emissions Estimation 3 calculations are included in Calculation Tables 8-14.*

**Table 7. Percent Difference between EF 1, 2, 3 Values. (A – B) ÷ [(A + B) ÷ 2] x 100 = % Difference**

| | | | | | |
|---|---|---|---|---|---|
| **EF2, EF1** | (10.493 – 4.387) = **6.106** | (10.493 + 4.387) ÷ 2 = **7.440** | (6.106 ÷ 7.440) x 100 | = | **82%** |
| **EF3, EF1** | (11.962 – 4.387) = **7.575** | (11.962 + 4.387) ÷ 2 = **8.175** | (7.575 ÷ 8.175) x 100 | = | **93%** |
| **EF3, EF2** | (11.962 – 10.493) = **1.469** | (11.962 + 10.493) ÷ 2 = **11.228** | (1.476 ÷ 11.228) x 100 | = | **13%** |

EF1 differs significantly from EF2 and EF3, and EF2 and EF3 are in closer agreement. Based on the approximate agreement of EF2 and EF3 estimations, the published GHG Emissions Estimation 2 is used for the following calculations.

### 5.3 Smelter Emissions Estimation 3 and EF3: Mass Balance Calculations

#### Coal: smelter CO2 emissions based on Carbon and CO2 gram-atomic weights

Since the proportion of coal and charcoal reductants is not available, only coal will be used in calculations. Carbon content of Blue Gem coal is approx. 60% (0.6) [42], and minimal carbon content of charcoal is approx. 65% [43]. The value of 136,080 MT in Table 4 and Table 8 below includes both coal and charcoal. Since the carbon content of coal is less than that of charcoal, the calculated MT of Carbon per year will be a conservative estimate.

**Table 8. MT of Blue Gem Coal/Charcoal Required per year and MT of Carbon from Coal**

| MT Coal per year* | | Carbon Content, 60%** | | MT of Carbon from Coal per year |
|---|---|---|---|---|
| 136,080 | x | 0.6 | = | **81,648** |

**Table 4. **[42].*

### GRAM ATOMIC WEIGHT VALUES

Carbon (C) MW = 12 g/mole. Oxygen (O) MW = 16 g/mole. Carbon Dioxide (CO2) MW = 44g/mole.

**Table 9. MT of CO2 formed per MT of Carbon in Coal per year (Coal and Charcoal)**

| CO2, g | | Carbon, g | | g CO2 per g C | | MT CO2 per MT C | | MT C from Coal/yr* | | MT of CO2 from Coal/Charcoal per yr |
|---|---|---|---|---|---|---|---|---|---|---|
| 44 | ÷ | 12 | = | 3.67 | = | **3.67** | x | 81,648 | = | **299,648** |

**Table 6.*

### WOOD CHIPS: SMELTER FACILITY CO2 EMISSIONS

**Carbon Content of Wood (Wood Chips)**: approximately 50% (species dependent) [51] [52].

**Table 10. MT of CO2 Emitted per MT of Wood chips (equivalent to amount of CO2 absorbed)**

| MT CO2 per MT C* | | MT Carbon per MT Wood (50%) | | MT CO2 per MT Wood Chips | | MT Wood Chips per year** | | MT CO2 from Wood Chips |
|---|---|---|---|---|---|---|---|---|
| 3.67 | x | 0.5 | = | **1.835** | x | **117,936** | = | **216,413** |

**Table 9. **Table 4.*

### CO2 FROM GRAPHITE ELECTRODES

Aprroximately**100 kg of graphite electrode** are required to produce 1 MT of silicon [53].
**Prebaked Electrodes Emission Factor (EF)**: 3.54 MT CO2 per MT Prebaked Electrode (Si smelter) [50].

**Table 11. MT CO2e per MT MGSi Graphite Electrode (GE) Used per Year**

| Kg GE per MT MGSi | | MT/ kg | | MT GE/ MT MGSi | | MGSi MT/yr* | | GE MT/yr | | GE EF MT CO2/MT GE | | GE CO2e MT/yr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | x | 0.001 | = | **0.1** | x | 66,226 | = | **6,623** | x | 3.54 | = | **23,445** |

**Table 4.*

### NITROGEN OXIDES (NOx)

The NOx emissions mass value from GHG Estimation 2 in Table 2 is used, and is multiplied by the "Global Warming Potential" (GWP). See Section 9.2.

**Table 12. NOx (N2O), MT CO2e per Year**

| Tons NOx per year* | | MT/ton | | MT NOx Per year | | GWP** Factor (N2O) | | $N_2O$ MT CO2e |
|---|---|---|---|---|---|---|---|---|
| 935 | x | 0.9072 | = | 848 | x | 298 | = | **252,704** |

**Table 3, Emissions Estimate 2. **Section 9.2, Terms and Concepts.*

### SMELTER CO2e EMISSIONS ESTIMATION 3 and EMISSION FACTOR 3

**Table 13. MT of CO2e Emissions from Coal, Wood Chips, and GE**

| CO2e Emission Source | Calculation | MT CO2e from 66,226 MT MGSi |
|---|---|---|
| Blue Gem Coal/Charcoal | Table 9 (Carbon Content, CO2 only) | 299,648 |
| Wood Chips | Table 10 (Carbon Content, CO2 only) | 216,413 |
| Graphite Electrode (GE) | Table 11 (IPCC 2006 EF) | 23,445 |
| NOx (N2O), GWP 298 | Table 12 (and Table 3) | 252,704 |
| | **TOTAL** | **792,210** |

**Table 14. Smelter Emission Factor 3 (EF3)**

| Total CO2e Emissions per year* | | MT of MGSi per year** | | MT CO2e per MT MGSi (Emission Factor) |
|---|---|---|---|---|
| 792,210 | ÷ | 66,226 | = | **11.962** |

**Table 13. **Table 4.*

### 5.4 Calculation Methods: Method 1 (Economic) and Method 2 (Environmental)

Annual Raw Materials Estimation 2 values (Table 4); and smelter GHG Estimation 2 **695,915 MT** (Table 5) and EF2 **10.493 MT CO2e/MT MGSi** (Table 6) values are used to calculate the CFP of c-Si SPs. Calculations include three %MGSi projection values for SPs: 100%, 50%, and 5%. *Note:* "2x g MGSi per 2x SP" in Tables 15, 16 and 17 refers to a 2x "kerf allowance" that accommodates a 50% kerf loss of the final downstream silicon wafer. See following Section 5.6.

**METHOD 1**. Captures energy use and emissions by the facility as a *fraction* of the total energy use and total emissions expended per year to produce the corresponding fraction of feedstock for a specific downstream product.

**METHOD 2**. Captures the *total* energy use and emissions that are expended by a facility per year while producing the required fraction of its feedstock for a specific downstream product.

**Example, Method 1: Smelter Emission Factor (EF), MT CO2e per MT MGSi for Solar Panels (SPs)**
**Table 15**. The %MGSi for SPs is multiplied by the total MT CO2e/year to obtain the fraction of MT CO2e/yr for 2xSP. The smelter MT CO2e/yr for 2x SP is then divided by the % MT MGSi values for 2xSP/yr to obtain the EF.

**Table 15. METHOD 1: Smelter Emission Factor (EF), MT CO2e per MT of MGSi for SPs**

| %MGSi for SP | Mult. Factor | | MT CO2e/yr | | MT CO2e/yr for 2xSP | | MT MGSi for 2xSP/yr | | MT CO2e per MT MGSi (EF) |
|---|---|---|---|---|---|---|---|---|---|
| **100%** | 1.0 | x | 694,915.0 | = | **694,915.0** | ÷ | 66,226 | **=** | **10.493** |
| **50%** | 0.5 | x | 694,915.0 | = | **347,457.5** | ÷ | 33,113 | **=** | **10.493** |
| **5%** | 0.05 | x | 694,915.0 | = | **34,745.8** | ÷ | 3,311 | **=** | **10.493** |

**Example, METHOD 2: Smelter Emission Factor (EF), MT CO2e per MT MGSi for Solar Panels (SPs)**
**Table 16**. The %MGSi for SPs multiplication factor is multiplied by the total smelter MT MGSi/yr to obtain the MT MGSi for 2xSP/yr. The total smelter MT CO2e/yr is then divided by the MT MGSi for 2xSP/yr to obtain the EF.

**Table 16. METHOD 2: Smelter Emission Factor (EF), MT CO2e per MT of MGSi for SPs**

| %MGSi for SP | Mult. Factor | | MT MGSi/yr | | MT MGSi for 2xSP/yr | | MT CO2e/yr | | MT MGSi for 2xSP/yr | | MT CO2e/MT MGSi (EF) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***100%*** | *1.0* | x | *66,226* | = | ***66,226*** | | *694,915* | ÷ | *66,226.0* | **=** | ***10.493*** |
| **50%** | 0.5 | x | 66,226 | = | **33,113** | | 694,915 | ÷ | 33,113.0 | **=** | **20.986** |
| **5%** | 0.05 | x | 66,226 | = | **3,311** | | 694,915 | ÷ | 3,311.3 | **=** | **209.861** |

**Calculation Methods Summary**
Method 1 shows that EF values are the same for all %MGSi values, and are the same as Method 2 100% MGSi values. Since the Method 1 EF calculation is included in the 100% MGSi category of Method 2 calculations, Method 1 and 2 calculations are concurrent. *Method 1 values are included in italic font in 100% rows of Method 2 Calculation Tables.*

The Method 2 EF increases as the %MGSi for SPs decreases. The EF at 100% MGSi is for 100% of a specific downstream product. For other specific downstream product %MGSi values, the total smelter emissions divided by the specific % MGSi value corresponds to the EF for that product.

### 5.5 Method 1 and 2 Concurrent Calculations: gCO2e per SP

**Table 17. Method 1 & 2: Smelter gCO2e per SP.** ***Method 1 = 100% MGSi Row***

| % MGSi for SP | MT CO2e per MT MGSi /yr* | | gCO2e per g MGSi/yr | | 2x g MGSi per 2xSP** | | gCO2e per SP |
|---|---|---|---|---|---|---|---|
| **100%** | *10.493* | = | *10.493* | *x* | *1,600* | = | ***16,788.8*** |
| **50%** | 20.986 | = | 20.986 | x | 1,600 | = | **33,577.6** |
| **5%** | 209,861 | = | 209.861 | x | 1,600 | = | **335,777.6** |

**Table 16. **"2x g MGSi per 2x SP" is described in the following Section 5.6.*

### 5.6. Mass of Silicon per Solar Panel (72 Solar Wafers): Functional Unit (72-cell commercial SP) [20] [54]

**Silicon Wafer Dimensions:** 156 mm x 156 mm x 200 µm (0.02 cm) [55] [56].
**Silicon Wafer Volume:** 15.6 cm x 15.6 cm x 0.02 cm = 4.9 $cm^3$
**Density of Silicon:** 2.33g/$cm^3$
**Number of Wafers (Solar Cells) per commercial Solar Panel (SP):** 72 [20] [54]. Note: Reference [20] 2005 paper's 72-cell SP consisted of 125 mm x 125 mm cells, but mentions that 150 x 150 mm wafers were growing in market share.

**Table 18. Mass of Silicon per Solar Panel, 72 Solar Wafers**

| Wafer vol., $cm^3$ | | Si density g/$cm^3$ | | g Si per Wafer | | No. Wafers Per SP | | g Si per SP | | kg/g | | kg Si per SP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.9 | x | 2.33 | = | **11.4** | x | 72 | = | 820.8 | x | 0.001 | = | **0.820** |

**Mass Determination of MGSi Required for a 72-Cell Solar Panel**
**Kerf Allowance and Kerf Loss.**
The MGSi produced by the smelter for Solar Panels will be processed further into polysilicon or monocrystalline ingots. The silicon ingots are cut with specialized saws in order to obtain thin silicon wafers. Current silicon ingot sawing methods incur a kerf loss of approximately 50 %. [57]. Total loss to be considered includes: the amount of scrap generated during ingot crystallization, cutting (kerf loss), sizing, and wafering processes. More than half of the in-going silicon may be lost [58].

Since approximately half of the mass of the silicon ingot is lost during ingot cutting and other steps, the total mass of silicon contained within the finished c-Si SPs will be about half of the total mass of MGSi feedstock supplied by the smelter. Therefore, the mass of MGSi required for finished c-Si SPs is 2x the mass of silicon that actually comprises the final c-Si SP. The smelter emissions and energy use for each c-Si SP are based on MGSi that is 2x the mass of the final c-Si SP. The downstream target number of c-Si SPs requires the upstream production of 2x the mass of MGSi feedstock (a 2x "kerf allowance") to accommodate the 2x loss of silicon during wafer cutting (kerf loss) and other processing losses.

Calculations of smelter emissions, energy use, and other upstream process to produce MGSi feedstock for c-Si SPs include a 2x Kerf Allowance factor. The 2x Kerf Allowance factor of MGSi feedstock gives emissions and energy use based on 2x upstream 1.6 kg MGSi per SP to accommodate the 2x kerf loss per downstream 0.8 kg of finished c-Si SP. As appropriate, a kerf allowance 2x MGSi SP, **"2xSP"**, is used for calculations of upstream smelter emissions, energy use, and other upstream process calculations that are projected onto downstream finished c-Si SPs. See Tables 19 and 20.

**Table 19. kg MGSi/ 2xSP, 2x kerf allowance (KA) and kg of c-Si/SP, 2x kerf loss (KL)**

| kg c-Si per SP* | | 2x Kerf Allowance | | Kg MGSi per 2xSP | | 2x Kerf Loss | | kg c-Si per SP |
|---|---|---|---|---|---|---|---|---|
| 0.8 | x | 2 | = | **1.6** | ÷ | 2 | = | **0.8** |

**Table 18 (value rounded to 1 decimal place).*

**Estimated Number of Solar Panels Produced from the Smelter's MGSi**
The proposed smelter initially projected that 50% of the MGSi produced would be for SP, but later suggested that 5% (or less) would be for SPs [5]. To accommodate the uncertainty in the projected percentages of MGSi that will be used for SP, calculations include three projection values: 100%, 50%, and 5%.

**Table 20. Number of c-Si SP per Year (100%, 50%, 5%): 2x MGSi Kerf Allowance (KA) and c-Si Kerf Loss (KL)**

| 2X Kerf Allowance for MGSi for Solar Panels | | | | | | | | | | Total No. of SP |
|---|---|---|---|---|---|---|---|---|---|---|
| %MGSi for SP | Mult. Factor | MT MGSi per year for SP | | MT MGSi/SP, 2xSP (KA*) | | No. 2xSPs (KA)** | | 50% (KL) | | No. of finished SP/yr, (KL) |
| **100%** | 1 | 66,226 | ÷ | 0.0016 | = | **41,391,250** | ÷ | 2 | = | 20,695,625 |
| **50%** | 0.5 | 33,113 | ÷ | 0.0016 | = | **20,695,625** | ÷ | 2 | = | 10,347,813 |
| **5%** | 0.05 | 3,311 | ÷ | 0.0016 | = | **2,069,563** | ÷ | 2 | = | 1,034,782 |

**1.6 kg x 0.001 MT/kg = 0.0016 MT. **2xSP denotes Kerf Allowance (KA) of 2x MGSi per finished c-Si SP.*

### 5.7. Wood Chips: Carbon Sink Removal and Carbon Sink Loss (Forest Tree Harvest—Lodgepole Pine)

Assumptions: Lodgepole Pine harvest at average age of 40 years [32] [44] [45]. Linear Growth Rate up to 40 years. See Raw Materials Section 10.3.2 and 10.3.3. *Note: only CO2 emissions are considered; CH4, N2O are excluded*.

**Table 21. Wood Chips: Forest Tree Removal-g CO2 Sink Loss (CSL)**

| MT Wood Chips per year* | | MT CO2 abs per MT Wood Chips** | | CO2 Sink Loss, MT | | grams per MT | | CO2 Sink Loss, grams |
|---|---|---|---|---|---|---|---|---|
| 117,936 | x | 1.835 | = | 216,413 | x | 1,000,000 | **=** | **216,413,000,000** |

** Table 4. **Table 10.*

**Table 22. Wood Chips: gCO2 Sink Loss per SP (CSL), Year 1**

| % MGSi | CO2 Sink Loss, grams* | | No. 2xSP* | | CSL, yr 1 gCO2/SP |
|---|---|---|---|---|---|
| **100** | 216,413,000,000 | ÷ | 41,391,250 | = | **5,228** |
| **50** | 216,413,000,000 | ÷ | 20,695,625 | = | **10,457** |
| **5** | 216,413,000,000 | ÷ | 2,069,563 | = | **104,569** |

**Table 21. **Table 20.*

**Table 23 Description: CO2 Sink Loss (CSL) and Carbon Sink Loss Recovery Rate (CRR)**

The following method uses the equation for a straight-line to determine the Carbon Sink Loss Recovery Rate (CRR).

(2)

$y = -mx + b$

*Where: (b) = y intercept = CSL at year 1. -(m) = slope = CRR/yr. (x) = years. The slope is negative since the initial CSL is reduced over time.* Since only atmospheric CO2 is readily absorbed by trees, other GHGs are excluded in calculations. This is a rough estimation. Tree growth involves numerous variables (species, environmental conditions, stand density, etc.) and generally has a more curved or sigmoidal graphic appearance. Differential equations or other complex calculations are typically used to characterize tree growth and CO2 absorption, but are beyond the scope of this study.

The Carbon Sink Loss (CSL) values determined in Table 22 are used in the following procedure and in Table 23.

1. Determine the Total gCO2 CSL/SP at year 1 (Table 22)
2. The Total gCO2 CSL/SP will be added to the Total Smelter Emissions gCO2e/SP to obtain the **Total gCO2e Debt/SP** (Table 40).
3. Assume trees harvested for Wood Chips were harvested at 40 years of age.
4. Assume successful replanting of trees within 1 year of harvest.
5. Assume a linear growth rate of successfully restocked trees up to 40 years.
6. Determine the gCO2 CSL/Year/SP over 40 years of tree growth. Divide the Total gCO2 CSL/SP, yr 1 by 40 (yrs). This becomes the CO2 Sink Recovery Rate (CRR) per Year (Table 16).
7. Multiply the gCO2 CRR value by the appropriate time interval to obtain the amount of gCO2 CSL recovered during that time period (Table 16).
8. Subtract the gCO2 CSL recovered (step 6) from the initial Total gCO2 CSL/SP + Total Smelter Emissions gCO2e/SP value (step 2) to obtain the Total gCO2e/SP at that time (Table (43)
9. At year 40, all of the CSL will be recovered, and the gCO2e/SP will be the original Total Smelter Emissions gCO2e/SP value (without the added gCO2 CSL/SP added in step 2).
10. This procedure is used for calculations included in Tables 23, 40, 41 and 42.

**Table 23. Wood Chips: gCO2 Sink Recovery Rate/SP (CRR) and CSL at 20, 30, 39, and 40 years**

| % MGSi | CSL, yr 1 gCO2/SP* | | Tree Age, yrs | | CRR CSL/yr | 1-20 yrs CRR x 20 | 20-30 yrs CRR x 10 | 30-39 yrs CRR x 9 | 39-40 yrs CRR x 1 |
|---|---|---|---|---|---|---|---|---|---|
| **100%** | ***5,228*** | ÷ | 40 | = | ***130.7*** | *2,614* | *1,307* | *1,176* | *131* |
| **50%** | **10,457** | ÷ | 40 | = | **261.4** | 5,228 | 2,614 | 2,353 | 261 |
| **5%** | **104,569** | ÷ | 40 | = | **2,614.2** | 52,284 | 26,142 | 23,528 | 2,614 |

**Table 22. Note: CSL at yr 1 = y intercept (b), CRR = negative slope (-m), and years = (x) in line equation (y = -mx + b).*

e.g.: 100% MGSi, gCO2/SP debt at 30 years: *y = (-130.7 x 30 yrs) + 5,228 = -(3,921) + 5,872 =* ***1,307*** *gCO2.*

In Table 40, Smelter gCO2/SP adds to CSL at year 1: *(16,975 + 5,228 = 22,203). y = -(130.7 x 30) + 22,203 =* ***18,282****.*

### 5.8 Wood Chips: Number of Trees and Managed Forest Acres Lost from Tree Harvest

See Appendix A for estimation of Lodgepole Pine tree volume and mass [59] [60]. Lodgepole Pine typically has little taper, and volume is calculated by using the "frustum" of a cone instead of a cylinder. Three different tree volume estimations using different diameter and height values are used to determine the weight of trees (Table 24).
Maximum Lodgepole pine yield in the Rocky Mountains was 20,000 fbm/acre at a density of 800 trees/acre, 1990 [44].

**Table 24. Lodgepole Pine: Frustum of a Cone Values for Calculating Tree Volume and Mass. See Appendix A**

| Tree Mass MT per Tree | dbh*: Bottom of Cone Frustum, in | Diameter: Top of Cone Frustum, in | Useable Tree Height, ft | Green Lodgepole Pine Density, kg/m$^3$ |
|---|---|---|---|---|
| **Estimation 1** | 8 inches | 6 inches | 60 feet | 625 |
| **Estimation 2** | 10 inches | 8 inches | 60 feet | 625 |
| **Estimation 3** | 12 inches | 9 inches | 70 feet | 625 |

**dbh = diameter at breast height (4.5 feet).*

Maximum Lodgepole pine yield in the Rocky Mountains was 20,000 fbm/acre at a density of 800 trees/acre, 1990 [44].

**Table 25. Approx. Number of Trees Harvested and Number of Forested Acres Lost per Year for Woodchips**

| Tree Mass MT per Tree | MT Wood Chips / year* | | MT per Pine Tree** | | No. of Trees Harvested / year | | Stocking Level, Trees/Acre*** | | No. of Acres |
|---|---|---|---|---|---|---|---|---|---|
| **Estimation 1** | 117,936 | ÷ | 0.292 | = | **403,890** | ÷ | 800 | **=** | **505** |
| **Estimation 2** | 117,936 | ÷ | 0.483 | = | **244,177** | ÷ | 800 | **=** | **305** |
| **Estimation 3** | 117,936 | ÷ | 0.758 | = | **155,588** | ÷ | 800 | = | **194** |

** Table 4. ** Appendix A. ***[44].*

### 5.9 Coal Mining Emissions, Coal Railroad Transport Emissions and Energy Use

Note: Specific information regarding Blue Gem coal mine locations, type of mines (surface mine or underground mine), and methane emissions was not available, therefore coal mining emissions are not included in calculations for this study. However, general information regarding coal mining emissions can be found in the Raw Materials Section 10 (items 10.2, 10.2.1, and 10.2.2).

**Coal Railroad Transport (one-way): GHG Emissions (Kentucky to Newport, WA)**

Freight or shipping activity is measured in *ton-miles*. One ton-mile is the equivalent of shipping one ton of product, one mile [61].
Coal rail car (gondola) capacity is approx. 120 tons of coal pe car [62].

**Table 26. Coal Transport: Tons of Coal and No. of Cars per Trip for 12 one-way Trips per year**

| MT Coal per Year* | | MT per Ton | | Tons Coal per Year | | Trips per yr | | Tons Coal/trip | | Tons coal per car** | | No. cars per trip |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 136,080 | x | 1.102 | = | 149,960 | ÷ | 12 | = | **12,497** | ÷ | 120 | = | 104 |

** Table 4. **[62].*

Distance from Kentucky to Newport: Approx. **2,268 miles** (highway) [63].

**Table 27. Coal Transport (one-way): Ton-Miles per Trip.**

| Tons Coal per Trip* | | Miles per Trip | | Ton-Miles per Trip |
|---|---|---|---|---|
| 12,497 | x | 2,268 | = | **28,343,196** |

**Table 26.*

Freight Railroad: lbs CO2 per ton-mile **= 0.056** [61] and kg CO2 per ton-mile =0.025 [64].

**Table 28. Grams CO2e per One 1-Way Trip for Railroad Transport of Coal**

| lbs CO2e per Ton-Mile | | kg/lb | | kg CO2e per Ton-Mile | | Ton-Miles per 1-way Trip* | | kg CO2e per 1-way Trip | | gCO2e per 1-way Trip |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.056 | x | 0.454 | = | 0.025 | x | 28,343,196 | = | 708,579.9 | = | **708,579,900** |

**Table 27.*

**Table 29. gCO2e for 12 Coal Railroad (1-Way) Trips per Year**

| gCO2e per 1-way Trip* | | Total No. of 1-Way Trips/yr | | Coal Transport, gCO2e/yr |
|---|---|---|---|---|
| 708,579,900 | x | 12 | = | **8,502,958,800** |

**Table 28.*

**Table 30. Coal Rail Transport Emissions (one-way): gCO2e per SP**

| % MGSi | Coal transport, gCO2e/yr* | | No. 2xSP/yr (KA)** | | Coal Transport, gCO2e per SP |
|---|---|---|---|---|---|
| **100%** | 8,502,958,800 | ÷ | 45,625,000 | = | **186.37** |
| **50%** | 8,502,958,800 | ÷ | 22,812,500 | = | **372.73** |
| **5%** | 8,502,958,800 | ÷ | 2,281,250 | = | **3,727.32** |

**Table 29. **Table 20.*

### Coal Railroad Transport: Energy Consumption (Kentucky to Newport, WA)

**Calculation Units:**

Freight Rail Energy Intensity of 270 BTU per ton-mile (for 2015) [65], and 1 BTU = 0.00029307 kWh [66].

**Table 31. Coal Rail Transport: kWh per Net Ton-Mile**

| BTU per Ton-Mile | | kWh per BTU | | kWh per Ton-Mile |
|---|---|---|---|---|
| 270 | x | 0.00029307 | = | **0.079** |

**Table 32. Coal Transport (one-way): kWh per Year**

| Ton-Miles per Trip* | | KWh/Net Ton-Mile** | | kWh per Trip | | No. Trips | | kWh per Year |
|---|---|---|---|---|---|---|---|---|
| **28,343,196** | x | 0.079 | = | 2,239,112 | x | 12 | = | **26,869,344** |

**Table 27. **Table 31.*

**Table 33. Coal Rail Transport (one-way): kWh per SP**

| % MGSi | Coal transport, kWh/yr* | | No.2x SP/yr (KA)** | | KWh per SP |
|---|---|---|---|---|---|
| **100%** | 26,869,344 | ÷ | 41,391,250 | = | **0.65** |
| **50%** | 26,869,344 | ÷ | 20,695,625 | = | **1.30** |
| **5%** | 26,869,344 | ÷ | 2,069,563 | = | **12.98** |

**Table 32. **Table 20.*

### 5.10: Smelter Energy Requirement per Year, KiloWatt hours (kWh)

The smelter requires a continuous supply of 105 MegaWatts (MW) of electricity [1] [6].

**Table 34. KWh Required per 66,226 MT MGSi per Year (For 105 MW)**

| MW Required* | | kW/MW | | kW | | Hours per day | | kWh per day | | Days per yr | | kWh per year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 105 | x | 1,000 | = | 105,000 | x | 24 | = | 2,520,000 | x | 365 | = | **919,800,000** |

**Table 1.*

**Table 35. Smelter Facility Energy Use: kWh per Solar Panel per year**

| % MGSi | Total kWh/yr * | | MT MGSi/yr | | kWh per MT MGSi/yr | | MT per 2xSP | | kWh per SP |
|---|---|---|---|---|---|---|---|---|---|
| **100%** | *919,800,000* | ÷ | *66,226* | = | *13,889* | *x* | *0.0016* | = | ***22.22*** |
| **50%** | 919,800,000 | ÷ | 33,113 | = | 27,778 | x | 0.0016 | = | **44.44** |
| **5%** | 919,800,000 | ÷ | 3,311 | = | 277,801 | x | 0.0016 | = | **444.48** |

**Table 34.*

### 5.11. Energy Consumption per SP: Smelter Facility and Coal Rail Transport

**Table 36. Energy Consumption per SP: Smelter Facility and Coal Rail Transport**

| %MGSi for SP | Smelter Facility: kWh/SP* | | Coal Transport: kWh/SP** | | Total kWh/SP |
|---|---|---|---|---|---|
| **100%** | *22.22* | + | *0.65* | = | ***22.87*** |
| **50%** | 44.44 | + | 1.30 | = | **45.74** |
| **5%** | 444.48 | + | 12.98 | = | **457.46** |

**Table 35. **Table 33.*

### 5.12. Calculation of a 72-cell c-Si SP Total Potential Energy Generation

Calculation equation and variables are from the US EPA "Green Power Equivalency Calculator - Calculations and References" document [67]. Calculating annual PV solar system output is a function of the following equation:

(3)

**E** = **A** x **r** x **H** x **PR**, in which:

**E =** Energy **(kWh)**.

**A** = Total solar panel **Area (m$^2$)**.

**r** = Solar panel efficiency (%). **r = 15.2% (0.152)** solar panel efficiency of PV module (NREL 2019, Annual Technology Baseline, Solar Distributed Commercial PV: capacity factor for an average mid-resource location, Kansas City, MO).

**H** = Annual average solar radiation on tilted panels (shadings not included). **H = 1,839.6 kWh/m$^2$/year** annual average solar radiation for an average mid-resource location, Kansas City, MO (5.04 kWh/m$^2$/day x 365 days) (NREL 2020, PVWatts Calculator).

**PR** = Performance ratio, coefficient for losses (range between 0.5 and 0.9). **PR = 86% (0.86)** performance ratio (NREL 2020, PVWatts Calculator: 14% system losses) [67].

**Table 37. Surface Area of a 72-cell SP with 0.156 m x 0.156 m (156 mm x 156 mm) Silicon Wafers**

| meter (m) | | meter (m) | | m$^2$ | | No. Wafers per SP | | Surface Area per Solar Panel, m$^2$ |
|---|---|---|---|---|---|---|---|---|
| 0.156 | x | 0.156 | = | 0.0243 | x | 72 | = | **1.75** |

Estimated lifetime of c-Si SPs is approx. 30 years [68].

**Table 38. c-Si SP kWh per year and Total kWh over a 30-year Lifetime in the USA**

| SP Area m$^2$* | | Efficiency, r** | | Radiation, H kWh/m$^2$/ yr** | | Performance Ratio, PR** | | kWh per yr | | Lifetime years | | Total kWh (30 years) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.75 | x | 0.152 | x | 1,839.6 | x | 0.86 | = | **420.8** | x | 30 | = | **12,624** |

**Table 37. **Equation (3)*

**Table 39. Adjusted kWh/SP Generated over 30 yrs - kWh/SP Consumed**

| % MGSi for SP | kWh/SP, Lifetime* | | kWh Consumed per SP** | | Adjusted kWh/SP, 30-year Lifetime |
|---|---|---|---|---|---|
| **100%** | ***12,624*** | - | ***22.87*** | = | ***12,601*** |
| **50%** | **12,624** | - | **45.74** | = | **12,578** |
| **5%** | **12,624** | - | **457.46** | = | **12,167** |

**Table 38. **Table 36.*

### 5.13. Summary of Silicon Smelter Emissions, Energy Use, and c-Si SP Lifetime kWh: Tables 17, 23, 30, 36. 39

**Table 17. Smelter gCO2e per SP**

| % MGSi for SP | MT CO2e per MT MGSi /yr* | | gCO2e per g MGSi/yr | | 2x g MGSi per 2xSP** | | gCO2e per SP |
|---|---|---|---|---|---|---|---|
| **100%** | *10.493* | = | *10.493* | *x* | *1,600* | = | ***16,788.8*** |
| **50%** | 20.986 | = | 20.986 | x | 1,600 | = | **33,577.6** |
| **5%** | 209,861 | = | 209.861 | x | 1,600 | = | **335,777.6** |

**Table 16. **"2x g MGSi per 2x SP" is described in Section 5.4, Mass of Silicon per SP: Functional Unit.*

**Table 23. Wood Chips: gCO2 Sink Recovery Rate/SP (CRR) and CSL at 20, 30, 39, and 40 years**

| % MGSi | CSL, yr 1 gCO2/SP* | | Tree Age, yrs | | CRR CSL/yr | 1-20 yrs CRR x 20 | 20-30 yrs CRR x 10 | 30-39 yrs CRR x 9 | 39-40 yrs CRR x 1 |
|---|---|---|---|---|---|---|---|---|---|
| **100%** | ***5,228*** | ÷ | 40 | **=** | ***130.7*** | *2,614* | *1,307* | *1,176* | *131* |
| **50%** | **10,457** | ÷ | 40 | **=** | **261.4** | 5,228 | 2,614 | 2,353 | 261 |
| **5%** | **104,569** | ÷ | 40 | **=** | **2,614.2** | 52,284 | 26,142 | 23,528 | 2,614 |

**Table 22. Note: CSL at yr 1 = y intercept (b), CRR = negative slope (-m), and years = (x) in line equation (y =-mx + b)*

e.g.: 100% MGSi, gCO2/SP debt at 30 years: *y = (-130.7 x 30 yrs) + 5,228 = -(3,921) + 5,872 =* ***1,307*** *gCO2.*

In Table 40, Smelter gCO2/SP adds to CSL at year 1: *(16,975 + 5,228 = 22,203). y =-(130.7 x 30) + 22,203 =* ***18,282****.*

**Table 30. Coal Rail Transport Emissions (one-way): gCO2e per SP**

| % MGSi | Coal transport, gCO2e/yr* | | No. 2xSP/yr (KA)** | | Coal Transport, gCO2e per SP |
|---|---|---|---|---|---|
| **100%** | 8,502,958,800 | ÷ | 45,625,000 | = | **186.37** |
| **50%** | 8,502,958,800 | ÷ | 22,812,500 | = | **372.73** |
| **5%** | 8,502,958,800 | ÷ | 2,281,250 | = | **3,727.32** |

**Table 29. **Table 20.*

**Table 36. Energy Consumption per SP: Smelter Facility and Coal Rail Transport**

| %MGSi for SP | Smelter Facility: kWh/SP* | | Coal Transport: kWh/SP** | | Total kWh/SP |
|---|---|---|---|---|---|
| **100%** | *22.22* | + | *0.65* | = | ***22.87*** |
| **50%** | 44.44 | + | 1.30 | = | **45.74** |
| **5%** | 444.48 | + | 12.98 | = | **457.46** |

**Table 35. **Table 33.*

**Table 39. Adjusted kWh/SP Generated over 30 yrs - kWh/SP Consumed**

| % MGSi for SP | kWh/SP, Lifetime* | | kWh Consumed per SP** | | Adjusted kWh/SP, 30-year Lifetime |
|---|---|---|---|---|---|
| **100%** | *12,624* | - | *22.87* | = | ***12,601*** |
| **50%** | 12,624 | - | 45.74 | = | **12,578** |
| **5%** | 12,624 | - | 457.46 | = | **12,167** |

**Table 38. **Table 36.*

## Section 5.14. Smelter Contribution to c-Si SP Carbon Footprints: Method 1 and Method 2 Calculations

**Table 40. Emissions Estimation with Wood Chips CO2 Sink Loss (CSL) up to 40 years** *(see Tables 17, 23, 30)*

| Row No. | CO2e Emissions and CO2 Carbon Sink Loss | gCO2e/ Solar Panel, 100% MGSi | gCO2e/ Solar Panel, 50% MGSi | gCO2e/ Solar Panel, 5% MGSi |
|---|---|---|---|---|
| 1 | **Calculation Method** | ***Method 1* and 2** | **Method 2** | **Method 2** |
| **2** | **WOODCHIPS CCR*** | ***130.7*** | **261.4** | **2,614** |
| 3 | **Smelter Emissions** | *16,788.8* | 33,577.6 | 335,777.6 |
| 4 | **Coal Transport Emissions** | *186.37* | 372.73 | 3,727.32 |
| **5** | **Process Emissions Subtotal** | ***16,975*** | **33,950** | **339,505** |
| **6** | + WOODCHIPS CSL, year 1‡ | +*5,228* | +10,457 | +104,569 |
| **7** | **Total gCO2e Debt/SP, yr 1** | ***= 22,203*** | **= 44,407** | **= 444,074** |
| 8 | - CSL, 20 years** (20 x CCR) | *-2,614* | -5,228 | -52,284 |
| **9** | **20 yrs Total gCO2e Debt/SP** | ***= 19,589*** | **= 39,179** | **= 391,790** |
| **10** | - CSL, **30 years**** (10 x CCR) | *-1,307* | -2,614 | -26,142 |
| **11** | **30 yrs Total gCO2e Debt/SP** | ***= 18,282*** | **= 36,565** | **= 365,648** |
| 12 | - CSL, 39 years** (9 x CCR) | *-1,176* | -2,353 | -23,528 |
| **13** | **39 yrs Total gCO2e Debt/SP** | ***= 17,106*** | **= 34,212** | **= 342,120** |
| 14 | - CSL, 40 years** (1 x CCR) | *-131* | -261 | -2,614 |
| **15** | **40 yrs Total gCO2e Debt/SP** | ***= 16,975*** | **= 33,951** | **= 339,506** |

‡**Row 6** Woodchips "CO2 Sink Loss" (CSL) gCO2/SP at **year 1** + the Process Emissions Subtotal **Row 5** = Total gCO2e Debt/SP, yr 1, **Row 7**. ** CSL values for 20, 30, 39 and 40 years are subtracted from the appropriate previous year Total gCO2/SP values. The **Row 2** CO2 Sink Recovery Rate **(CRR*)** x time interval (yrs) = the CSL per interval at the listed time. **Example: For 100% MGSi at -30 years**, time interval from the previous -20 yrs = 10 yrs. 10 x 130.7 (CCR) = 1,307 (**Row 10**). **Row 9** (Total gCO2e/SP at 20 yrs) **19,589** – 1,307 = **18,282** (Total gCO2e/SP at 30 yrs) **Row 11**. **Row 15**, Year 40 gCO2e Debt/SP = the Process Emissions Subtotal in **Row 5** since the Woodchips CSL would be paid back if SP lifetimes were 40 years (instead of 30 years). Note: Total gCO2e = gCO2e emissions + gCO2 CSL

**Table 41. 30-year Lifetime kWh/SP and g CO2e/kWh/SP.** Woodchips Carbon Sink Loss and Debt/SP over 40 Years. 100% Rows = Method 1 and 2. 50% and 5% Rows = Method 2. **30 Years = end of SP Lifetime**.

| Carbon Sink Loss, yrs | % MGSi for SP | gCO2e per SP* | | SP Lifetime kWh** | | gCO2e per kWh/SP | CSL per interval/SP* | CSL Debt/SP (gCO2/SP)* |
|---|---|---|---|---|---|---|---|---|
| **Year 1**<br>Total CSL | **100%** | *22,203* | ÷ | *12,601* | = | ***1.8*** | - | *5,228* |
| | **50%** | 44,407 | ÷ | 12,578 | = | **3.5** | **-** | 10,457 |
| | **5%** | 444,074 | ÷ | 12,167 | = | **36.5** | **-** | 104,569 |
| **20 Years**<br>-20 yrs CSL | **100%** | *19,589* | ÷ | *12,601* | = | ***1.6*** | *2,614* | *2,614* |
| | **50%** | 39,179 | ÷ | 12,578 | = | **3.1** | 5,228 | 5,228 |
| | **5%** | 391,790 | ÷ | 12,167 | = | **32.2** | 52,284 | 52,284 |
| **30 Years**<br>-10 yrs CSL | **100%** | *18,282* | ÷ | *12,601* | = | ***1.5*** | *1,307* | *1,307* |
| | **50%** | 36,565 | ÷ | 12,578 | = | **2.9** | 2,614 | 2,614 |
| | **5%** | 365,648 | ÷ | 12,167 | = | **30.0** | 26,142 | 26,142 |
| **39 Years**<br>-8yrs CSL | **100%** | *17,106* | ÷ | *12,601* | = | ***1.4*** | *1,176* | *131* |
| | **50%** | 34,212 | ÷ | 12,578 | = | **2.7** | 2,353 | 261 |
| | **5%** | 342,120 | ÷ | 12,167 | = | **28.1** | 23,528 | 2,614 |
| **40 Years**<br>-1 yr CSL | **100%** | *16,975* | ÷ | *12,601* | = | ***1.3*** | *131* | *0* |
| | **50%** | 33,951 | ÷ | 12,578 | = | **2.7** | 261 | 0 |
| | **5%** | 339,506 | ÷ | 12,167 | = | **27.9** | 2,614 | 0 |

**Table 40. **Table 39.*

Comments: CSL Balance at 39 years = CRR (Table 40). At year 40, the CSL Debt would be paid back.

Year 1 gCO2e includes the total tree harvest gCO2 CSL debt/SP for wood chips. For subsequent years (20, 30, 39, 40), the CSL per interval (gCO2/SP) is subtracted from the previous CSL Debt/SP to give a new (lower) CSL debt/SP.

**Table 42. Methods 1 and 2, gCO2e/kWh/SP and Woodchips CSL gCO2 Sink Debt:** 1, 20, 30, 39 and 40 Years

| Woodchips CO2 Sink Loss, yrs | per cent MGSi for SP | Method 1 | | Method 2 | |
|---|---|---|---|---|---|
| | | **gCO2e/kWh/SP** | **Woodchips gCO2 Debt/SP** | **gCO2e/kWh/SP** | **Woodchips gCO2 Debt/SP** |
| **year 1** | **100%** | 1.8 | 5,228 | 1.8 | 5,228 |
| | **50%** | 1.8 | 5,228 | 3.5 | 10,457 |
| | **5%** | 1.8 | 5,228 | 36.5 | 104,569 |
| **20 years** | **100%** | 1.6 | 2,614 | 1.6 | 2,614 |
| | **50%** | 1.6 | 2,614 | 3.1 | 5,228 |
| | **5%** | 1.6 | 2,614 | 32.2 | 52,284 |
| **30 years Solar Panel Lifetime** | **100%** | 1.5 | 1,307 | 1.5 | 1,307 |
| | **50%** | 1.5 | 1,307 | 2.9 | 2,614 |
| | **5%** | **1.5** | **1,307** | **30.0** | **26,142** |
| **39 years** | **100%** | 1.4 | 131 | 1.4 | 131 |
| | **50%** | 1.4 | 131 | 2.7 | 262 |
| | **5%** | 1.4 | 131 | 28.1 | 2,614 |
| **40 Years** | **100%** | 1.3 | 0 | 1.3 | 0 |
| | **50%** | 1.3 | 0 | 2.7 | 0 |
| | **5%** | 1.3 | 0 | 27.9 | 0 |

*Values in this table are obtained from Table 41. SP Lifetime = 30 years, gCO2e Debt/SP is determined at year 30.*

**Allocation of Silica Fume (SiF) for Calculation Method 1:** ***Supplemental Information***

A silicon smelter produces about 0.2 to 0.4 tons of condensed silica fume per ton of silicon metal [11]. The midpoint of the value of 0.3 tons of SiF is selected. The reference values are in tons, and this paper works with metric tonnes (MT). The ratio of 0.2 – 0.4 remains the same. Note: Since Method 2 addresses the *total* smelter emissions impact on given downstream products, emissions allocation is not relevant. Tables 43 and 44 provide supplemental information only.

**Table 43. Allocation of Silica Fume (SiF) to Method 1 Calculations at 0.3 MT/MT MGSi**

| MGSi/yr MT | | MT SiF / MT MGSi | | Total SiF, MT | | MGSi/yr MT | | Total MT | MGSi Fraction: (66,226 ÷ 86,094) |
|---|---|---|---|---|---|---|---|---|---|
| 66,226 | x | 0.3 | = | **19,868** | + | 66,226 | = | 86,094 | **0.769** |

**Table 44. Method 1: SP g CO2e Emissions and g CO2 Debt for 76.9% MGSi with Silica Fume Allocation**

| Woodchips CO2 Sink Loss, yrs | g CO2e per kWh/SP | | | | | Woodchips gCO2e Debt/SP | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **g CO2e per kWh/SP*** | | **Fraction of MGSi** | | **g CO2e per kWh/SP**** | **Woodchips g CO2 Debt/SP*** | | **Fraction of MGSi** | | **Woodchips gCO2 Debt/SP**** |
| **year 1** | 1.8 | x | 0.769 | = | **1.4** | 5,228 | x | 0.769 | = | **4,020** |
| **20 years** | 1.6 | x | 0.769 | = | **1.2** | 2,614 | x | 0.769 | = | **2,010** |
| **30 years** | 1.5 | x | 0.769 | = | **1.2** | 1,307 | x | 0.769 | = | **1,005** |
| **39 years** | 1.4 | x | 0.769 | = | **1.1** | 131 | x | 0.769 | = | **101** |
| **40 years** | 1.3 | x | 0.769 | = | **1.0** | 0 | x | 0.769 | = | **0** |

**Table 42. ** g CO2e per kWh/SP and g CO2 Debt /SP are the same across 100%, 50%, and 5% MGSi dedication to SPs using Method 1 as shown in Tables 15 and 42. This Table 44 is supplemental information only.*

## 6. RESULTS

**Table 45 Smelter Emissions and Woodchips Carbon Debt (CSL) Impact on the CFP of c-Si SPs at Year 30**

| % MGSi for SPs | Method 1 Calculation* | | Method 2 Calculation* | | Method 1 with SiF Allocation** | |
|---|---|---|---|---|---|---|
| | Emissions gCO2e/SP | Woodchips CSL gCO2 Debt/SP | Emissions gCO2e/SP | Woodchips CSL gCO2 Debt/SP | Emissions gCO2/SP | Woodchips CSL gCO2 Debt/SP |
| 100% | 1.5 | 1,307 | 1.5 | 1,307 | 1.2 | 1,005 |
| **50%** | **1.5** | **1,307** | **2.9** | **2,614** | 1.2 | 1,005 |
| **5%** | **1.5** | **1,307** | **30.0** | **26,142** | 1.2 | 1,005 |

**Tables 41 and 42. CSL = carbon sink loss. **Table 44 (Method 1 with SiF allocation is supplemental information only).*

**Method 1, All %** of MGSi for SP. **CFP = 1.5 gCO2e/kWh/SP**; CSL debt of **1,307 g CO2/SP** 10 years post SP lifetime.
**Method 2, 50%** of MGSi for SP. **CFP = 2.9 gCO2e/kWh/SP**; CSL debt of **2,614 g CO2/SP** 10 years post SP lifetime.
**Method 2, 5%** of MGSi for SP. **CFP = 30.0 gCO2e/kWh/SP**; CSL debt of **26,142 g CO2/SP** 10 years post SP lifetime.

As expected, the difference between Method 1 and Method 2 gCO2e/SP at 5% MGSi for SPs is significant. The Fold-Difference values for Method 2 are inversely proportional to the % MGSi used for SPs, as is the increase in gCO2e/SP.

**Table 46. Fold-Difference Between Method 2 (M2) and Method (M1) Results. WC = Woodchips**

| %MGSi for SPs | M2 GHG gCO2e/SP* | | M1 GHG gCO2e/SP | | Fold Difference | M2 WC Debt gCO2/SP* | | M1 WC Debt gCO2/SP | | Fold Difference |
|---|---|---|---|---|---|---|---|---|---|---|
| **100%** | 1.5 | ÷ | 1.5 | = | **1** | 1,307 | ÷ | 1,307 | = | **1** |
| **50%** | 2.9 | ÷ | 1.5 | = | **~2** | 2,614 | ÷ | 1,307 | = | **2** |
| **5%** | 30.0 | ÷ | 1.5 | = | **~20** | 26,142 | ÷ | 1,307 | = | **20** |

**Table 45.*

**Table 47. Method 2 (M2): GHG and WC gCO2e Debt per SP at various % MGSi Values (25%, 20%, 10%, 2%)**

| %MGSi for SPs (x) | *x*/100 | 1/*x* | | 100% MGSi gCO2e/SP | | M2 GHG gCO2e/SP | | 1/*x* | | WC Debt gCO2/SP | | M2 WC Debt gCO2/SP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **25%** | 0.25 | 4.0 | x | 1.5 | = | **6.0** | | 4.0 | x | 1,307 | = | **5,228** |
| **20%** | 0.20 | 5.0 | x | 1.5 | = | **7.5** | | 5.0 | x | 1,307 | = | **6,535** |
| **15%** | 0.15 | 6.7 | x | 1.5 | = | **10.0** | | 6.7 | x | 1,307 | = | **8,757** |
| **10%** | 0.10 | 10 | x | 1.5 | = | **15.0** | | 10 | x | 1,307 | = | **13,070** |
| **2%** | 0.02 | 50 | x | 1.5 | = | **75.0** | | 50 | x | 1,307 | = | **65,350** |

**Table 46.*

**Key Points.**

1. Calculations include three MGSi projection values: 100%, 50%, and 5% to accommodate the uncertainty of the projected percentages of MGSi designated for SP.
2. Two different methods of GHG emission and energy use calculations were evaluated: Method 1 (Economic Method) and Method 2 (Environmental Method).
    - 2.1 **Method 1** captures the energy use and emissions of the smelter facility as a *fraction* of the total energy use and total emissions expended by the facility per year to produce the corresponding fraction of feedstock for a specific downstream product. Method 1 results are represented in the 100% MGSi for SPs in Method 2 calculation tables.
    - 2.2 **Method 2** captures the *total* energy use and emissions that were expended by the smelter facility per year while producing the required fraction of feedstock for a specific downstream product.
3. The energy and emissions expended by the smelter facility are embodied in the feedstock product (MGSi) and in the downstream c-Si-SP product.
4. The mass of the MGSi feedstock for SPs includes a 2x kerf allowance factor to account for a 50% kerf loss of the downstream refined silicon used for c-Si SPs [57] [58].
5. **Woodchips**. The harvest of trees for woodchips results in the loss of an active, natural carbon sink. Lodgepole Pine was selected as the source of woodchips (see Raw Materials Section 10.3.4). An estimated 40 years of age of Lodgepole Pine at harvest time was used, and a linear growth rate for the regeneration of trees over a period of 40 years was assumed for replacement of the lost carbon sink.

**5.1** The lost carbon sink, gCO2/SP, at the time of harvest (year 1) is added to the total Smelter Process gCO2e emissions/SP as a carbon debt to give a total gCO2e emissions and debt value/SP at year 1. A calculated amount of replacement of the carbon sink debt, gCO2/SP/yr, is subtracted from the total emissions in a linear manner and is represented at 20, 30, 39 and 40-year intervals. A successful tree restocking and linear growth rate of the restocked trees is assumed. See Tables 23, 40. Note: a linear growth rate is a rough assumption; see Appendix C.

**6.** The current recognized lifetime of c-Si Solar Panels is approximately30 years [68].

**7.** Allocation of smelter emissions to the silica fume (SiF) by-product is included in the Method 1 calculation as supplemental information.

## 7. DISCUSSION

### 7.1. The SP CFP Equation

The literature review of CFP calculations for c-Si Solar SPs reveals that the silicon smelting process for obtaining the critical feedstock component, MGSi, has been omitted in many published SP LCAs and CFP calculations. This omission is perplexing, since silicon metal is the most critical component of c-Si solar panels.

The carbon footprint of SPs is typically expressed as shown earlier in equation (1) [46]:

(1)

$$\underline{\text{CO2 emission rate [gCO2e /kWh]}} = \frac{\text{Total CO2 emission during life-cycle [g CO2e]}}{\text{Annual power generation [kWh/year] x Lifetime [years]}}$$

The equation only addresses the amount of energy generated by the SPs, but does not include the energy used during manufacture. The gCO2e/SP accounts for emissions only, and does not include other upstream processes that contribute to overall SP Carbon Debt (e.g., removal of active carbon sinks). The total emissions (fossil fuel and biomass), the loss of active carbon sinks, and the amount of energy used during manufacturing need to be included in the SP CFP equation.

Electricity generated by c-Si SPs is considered as “emission-free” (i.e., SP’s do not emit GHGs while they generate electricity). However, c-Si SPs carry an embodied GHG debt (gCO2e) from the production lifecycle; and also carry an unrecoverable “carbon debt” (gCO2) due to the active carbon sink loss (CSL) from tree harvest for woodchips. The CSL from tree harvest extends beyond the life time of c-Si SPs; therefore, c-Si SP electricity is not “carbon debt free”.

A more detailed equation for SPs is suggested. In addition to gCO2e emissions and energy generation (kWh), impacts of active carbon sink losses (CSL) need to be included, as well as energy used during the life cycle. A notation mechanism to identify emissions sources, % fossil fuel (%f) and % biomass (%b), could also be included *(See Appendix B)*.

**Suggested SP CFP Equation:**

(4)

$$\frac{\text{gCO2e/SP}}{\text{kWh/SP}} = \frac{\text{Total gCO2e Emissions during Lifetime (\%f:\% b)*}}{\text{[(kWh gen – kwh used)/year x Lifetime years]}} + \begin{array}{l}\text{gCO2 CSL debt at end of Lifetime and}\\ \text{number of debt payback years after Lifetime}\end{array}$$

**See Appendix B*

**Suggested Equation for Method 1 at 5% MGsi**

(5)

$$\frac{\text{gCO2e/SP}}{\text{(kWh gen - kWh used) x LT}} = \frac{\text{18,282 gCO2e/SP*}}{\text{12,601 kWh LT/SP*}} = \frac{\textbf{1.5 gCO2e (66f:34b)}}{\textbf{kWh}} + \begin{array}{c}\textbf{1,307 gCO2 debt*(b100)}\\ \textbf{(10 yrs Post Lifetime)}\end{array}$$

**Tables 41 and 42*

**Suggested Equation for Method 2 at 5% MGSi**

(6)

$$\frac{\text{gCO2e/SP}}{\text{(kWh gen - kWh used) x LT}} = \frac{\text{365,648 gCO2e/SP*}}{\text{12,167 kWh LT/SP*}} = \frac{\textbf{30 gCO2e (66f:34b)}}{\textbf{kWh}} + \begin{array}{c}\textbf{26,142 gCO2 debt*(b100)}\\ \textbf{(10 yrs Post Lifetime)}\end{array}$$

**Tables 41 and 42. See Appendix B for Calculation of Fossil Fuel (f) and Biomass (b) % Contributions to SP CFPs.*

The suggested equation incorporates the calculation of the silicon smelting contribution to c-Si SP CFPs. The calculation includes the smelter coal, graphite electrodes (GE), and biomass woodchips combustion GHG emissions (gCO2e) per SP, and also the active carbon sink loss (CSL) due to the harvest of living trees for wood chips (gCO2) per SP. The loss of the overall CO2 absorption capacity by living trees (gCO2) at the age of harvest (40 years) during 1 year of smelter operation is captured as an estimated gCO2 debt value for the replacement of the harvested trees carbon sink loss, and is added to the total gCO2e smelter emissions per SP. A SP lifetime of 30 years is assumed. The overall tree gCO2 absorbed at a tree age of 40 years is added to the total gCO2e emissions from one year of smelter operation. The gCO2 absorbed by the harvested trees over 40 years is subtracted from the smelter annual gCO2e emissions per SP in a linear manner up to tree replacement time of 40 years. If the c-Si SP lifetime was 40 years (instead of 30 years), the CO2 sink loss from tree harvest would theoretically be replaced, and the c-Si SPs would not carry a carbon sink loss debt. However, since a c-Si SP lifetime of 30 years is assumed, the c-Si SPs carry a gCO2 debt that extends 10 years beyond the SP lifetime.

The smelter gCO2e/kWh emissions (30-yr lifetime) per SP and CSL (tree gCO2 absorption over 40 years) per SP:

gCO2e Emissions (coal, GE, woodchips)/kWh per SP
+ gCO2 absorption over 40 years (tree harvest age) per SP
= **Total gCO2e/kWh per SP**

**Total gCO2e/kWh per SP**
− gCO2 absorption over 30-year SP lifetime per SP
= **SP gCO2e/kWh + 10-year gCO2 debt from lost tree CO2 absorption**

The gCO2e/kWh per c-Si SP includes the smelter GHG emissions per SP, plus the 10-year gCO2 CSL debt due to tree harvest for woodchips to give a total gCO2e/kWh per SP. The total gCO2e per SP is divided by the net kWh of electricity generated per SP to give gCO2e/kWh/SP. The 10-year gCO2 CSL debt per SP value from tree harvest is also provided (without division by kWh generated) as a separate value since the debt extends beyond the energy generating lifetime of the SP. Since only atmospheric CO2 is readily absorbed by trees, other GHG are not included in CSL calculations.

The carbon sink loss from tree harvest for wood chips shows that c-Si SPs carry a carbon (CO2 sink loss) debt that extends beyond their lifetime, and suggests that c-Si SPs account for more atmospheric CO2 over their 30-year lifetime than they save.

### 7.2. LCA, LCI Calculation Methodology

A single, standardized method for performing LCI/LCAs and CFP studies was not found in the literature review. In this study, two different calculation methods were employed to determine the impact of the silicon smelting upstream process on the downstream c-Si SP product: Method 1 (economic perspective) and Method 2 (environmental perspective).

A number of reviewed papers alluded to inconsistency of LCAs and the lack of clear methodologies for allocating environmental impacts in the LCIs of upstream processes onto downstream products [34] [35] [36] [37] [69]. Allocation methodology for creating life cycle inventories is frequently discussed and debated, but allocation methodology remains in a state of flux. [69] A recurring theme is the idea that methodological choices in LCA depend on the goal of the study, but guidance that matches goal with approach is still lacking. What also continues to be lacking is a unifying theory that can explain what allocation method is justifiable in any given situation [69].

Two different LCA approaches for allocating environmental impacts, Attributional LCA (ALCA) and Consequential LCA (CLCA) models are frequently discussed [37]. Both have positive and negative attributes; but overall, a significant amount of subjectivity seems to be involved in LCI/LCA methods currently being used. Despite attempts to standardize LCA, inconsistencies persist. A single LCA method does not currently exist, and it is suggested that considering LCA as a “family of methods” will be useful [37].

The calculation Method 2 implemented in this study does not involve allocation of environmental impacts among by-products or co-products within an industrial process or facility. All emissions and energy use by a facility are incorporated into the specific quantity of a product for a specific downstream use. This gives a quantifiable measure of the overall environmental impact due to a facility’s annual operation during the production of a specific downstream product.

The Method 1 (economic) calculation asks the question: What percentage of the total smelter emissions per year should be charged to a given percentage of MGSi for a specific downstream product per year? From the economic perspective, the fractional amount of MGSi dedicated to a downstream product per year embodies a corresponding fractional amount of the total smelter emissions. The fractional amount of emissions per year is divided by the fractional amount of MGSi per year to obtain the CFP for the fractional amount of MGSi, which is essentially the emission factor of the smelter facility. (see Table 15).

The fractional amount of emissions per corresponding fractional amount of MGSi per year for a specific product or use can be visualized as a fractional column of emissions partitioned from the total smelter emissions plume per year. This only captures a fraction of the smelter's total emissions for a specific product, but the environment is exposed to the total facility emissions. As the amount of MGSi produced for a specific downstream use increases or decreases, the corresponding column of emissions would increase or decrease by the same rate, thus giving the same quantity of emissions, per unit product, for all quantities of a specific product. The EF would remain constant, as would the emissions burden per SP (See table 42). However, this is not the reality of what the environment is exposed to.

The Method 2 (environmental) calculation asks the question: What is the total amount of emissions released into the environment per year by the smelter facility while producing a given percentage of MGSi for a specific downstream product per year? From the environmental perspective, the environment is exposed to the total amount of the facility's emissions per year while producing the required fractional amount of MGSi dedicated to a downstream product per year. Therefore, the fractional amount of MGSi dedicated to a downstream product per year embodies the total amount of GHG emitted to the environment by the smelter per year. The total amount of the smelter emissions per year is divided by the fractional amount of MGSi per year to obtain the smelter's CFP contribution per SP; essentially an EF for a specific quantity of MGSi used for a specific downstream product. (See Table 16).

Method 2 emissions can be visualized as the overall annual emissions plume in the atmosphere. As the amount of MGSi for SPs decreases, the facility's emissions plume remains constant, but the emissions burden per SP increases. (Table 42).

The goal of Calculation Method 2 is to determine the impact of the total smelter GHGs emitted into the environment while producing its MGSi product (and by-products), and projecting that impact onto a specific downstream use (e.g., MGSi for SPs). Therefore, allocation of emissions to smelter co-products for the Method 2 calculation is not relevant.

The calculation Method 2 may be useful as a "constant" or "baseline" quantitative tool for comparing LCAs of different facilities that produce the same or similar products, since emissions allocation among co-products is not a factor. This may be particularly useful for heavy industrial processes such as smelting, refining, mining, pulp and paper, textiles, etc. The total mass of facility LCA emissions per given mass quantity of a specific product will be directly comparable to other facility LCAs for the same or similar product. This may help to reduce subjectivity and the lack of comparability among LCAs, and may also be useful as a quantitative tool for assessing "green" designations of facilities and products.

The environmental Method 2 calculation needs to be included in the "family of LCA methods". It seems that most emission estimation methods use the human "economic" perspective with regard to emissions and energy use. Allocation of emissions for a specific product often corresponds to the quantity of that specific product. For example, if 10% of a facility's total production per year is for solar panels, then 10% of the facility's total emissions per year are charged to solar panels, despite the reality that the environment experiences the full burden of the facility's annual emissions.

### 7.3 The IPCC: Biomass Emissions Accounting

The IPCC has taken the lead to examine and account for anthropogenic impacts on climate change. The extensive and expansive documents describing the methodology for GHG emissions accounting are impressive and invaluable, and provide a critical framework for addressing climate change. However, the IPCC's non-accounting for biomass emissions at the point of combustion in energy and industry sectors is problematic, in that it underestimates emissions from industrial and energy facilities that use biomass as reductants or fuels. The IPCC's explanation of not accounting for biomass CO2 emissions at the point of combustion is difficult to grasp, and seems to go against the spatial-temporal science of combustion. While the IPCC is focused on GHG emissions accounting at the national level, its guidelines are often used at the industrial level. Unfortunately, the IPCC's non-accounting for biomass emissions at the point of combustion seems to have led to a widespread assumption that biomass combustion is carbon-neutral. This assumption significantly underestimates actual GHG emissions from energy and industrial facilities that use biomass from trees.

### 7.4. Biomass: Balance of Tree Growth and Bio-Carbon Combustion

The issue of: “balance between the carbon in the process and the growth of the trees used to produce the biological carbon” (Excerpt 5.1 of the Literature Review section) [23], can be addressed by determining the tree harvest carbon sink loss at time of harvest, and determining a carbon sink loss recovery time for restocked trees. A simple straight-line linear method was used to estimate a carbon sink recovery time in this paper (Tables 23 and 40). A more rigorous model using differential equations or other complex equations for determining a carbon sink loss recovery time from tree harvest for biomass combustion could be used. The loss of natural carbon sinks from tree harvest and the carbon sink loss recovery time need to be included as a carbon debt in CFP calculations. There is no guarantee that lost carbon sinks of forest trees will be replaced successfully. Accounting for both fossil fuel and biomass emissions can include the fraction or percentage of each emission source, and a carbon debt due to tree harvest for fuels or reductants can be captured as described in the suggested SP CFP Equations (4), (5) and (6) in Section 7.1.

### 7.5. “Green” Terminology

Since the industrial revolution, it has been recognized that industrial enterprises can have negative impacts on the environment. As the prime manufacturer of the goods and services that societies consume, the industrial sector has a critical role to play in reducing and ameliorating the negative environmental impacts from its operations [70]. Replacing polluting and inefficient technologies through innovation; and adopting a mindset where the environment and the economy are of at least equal importance will be key to addressing climate change.

The terms Green Facility, Green Industry, Green Product, and Green Energy are often used; but these terms are not clearly defined. Various publications provide verbal descriptions, but lack a quantitative definition. Some articles describe quantifiable metrics, but this is typically at the national level. The lack of a clear, quantifiable definition at the industrial level has led to significant “greenwashing”—deceptive marketing claims used to convince the public that products or processes are environmentally friendly [38] [71] [72].

A clear set of criteria needs to be established for determining what constitutes a “Green Facility”. The criteria should include quantifiable metrics; LCAs, LCIs, Environmental footprints, and Carbon footprints. Criteria should also include: site-specific impacts on the surrounding environment; potential alternatives to processes and raw materials currently being used; and complete transparency.

### 7.6. Examples of Potential Alternatives to Silicon Smelting and Crystal Silicon Solar Panels

A number of potential alternatives to silicon extraction and the use of silicon for SPs can be found in the literature. and several examples are discussed below.

**Alternative to Carbo-Thermic Reduction**. A more sustainable way to make silicon at much lower temperatures and without carbon reductants has been devised at the UW-Madison. This process mimics the 1886 “Hall-Héroult process” that transformed aluminum oxide ($Al_2O_3$) into elemental aluminum. In the Hall-Héroult process, $Al_2O_3$ is dissolved in a salt electrolyte: $Al_2O_3$ undergoes chemical reduction, Oxygen is released and aluminum metal remains [73].

The Hall-Héroult process is adapted to silicon extraction by using the common mineral calcium silicate (Ca2SiO4), which can be dissolved in a mixture of molten salts that melt at a relatively low 650 °C to dissolve the Ca2SiO4. A supporting electrolyte (calcium oxide) aids oxygen transfer. Much less energy is used and far fewer GHGs are emitted as compared with carbothermic reduction. This electrolysis process could potentially be used to produce lower purity silicon for large-scale material and energy applications. [73].

**Alternatives to Silicon for SPs**.

Perovskite solar cells have recently shown efficiency values that meet or exceed the efficiency of c-Si solar cells. Perovskites, calcium titanate (CaTiO3), and the class of compounds which have similar crystal structures to CaTiO3, do not require the carbothermic reduction smelting process as is the case with c-Si SPs [74]. However, current Perovskites require the use of the neurotoxic metal Lead (Pb) to achieve efficiency similar to c-Si SPs [75] [76]. An alternative to lead needs to be found before perovskite SPs can become a viable source of solar energy. Other types of solar panels include Cadmium-Telluride (CdTe) [77] [78] and Copper Indium Gallium Selenide (CIGS) [79] [80]. There are environmental and health concerns regarding materials and processes involved in both CdTe and CIGS solar panel manufacture. For example, Cadmium is highly toxic and Tellurium is a rare earth element. Further discussion of some of the impacts of the solar energy industry are included in reference [81].

### 7.7. Silicon Smelter Green Designation: % Increase of SP gCO2e and CO2 Sink Loss Debt from Silicon Smelting

The Literature Review Section 4.1 revealed that the reviewed papers did not include the silicon smelting process in c-Si SP CFP determinations. Since c-Si SPs in reviewed papers did not include the smelting process, the GHG emissions (gCO2e/kWh/SP) from the silicon smelter determined in this paper can be used to assess the impact of silicon smelting on reported c-Si CFP values.

Three c-Si SP CFP estimates (20, 30, and 40 gCO2e/SP) based on a range of values from reviewed literature are used to determine the % increase of the CFP/SP from the upstream smelting process on downstream c-Si SP CFPs. The smelter gCO2e/kWh/SP debt values (Tables 45 and 47) are added to reported c-Si SP CFPs to determine the % CFP increase due to the smelting process. The impact of the silicon smelting process on downstream c-Si SPs CFPs is evaluated based on two values: (1) the smelter emissions gCO2e/kWh/SP debt % increase on reported SP CFP values, and (2) the Carbon Sink Loss (CSL) gCO2/SP debt from tree harvest for Wood Chips. See Appendix D for calculation details.

Since a formal, quantifiable method for assessing "Green" designations for an industrial process is not available, a GHG emissions increase of 50% or more of the reported gCO2e/kWh/SP CFP values of c-Si SPs due to the silicon smelting process was chosen as a metric for determining "Green" (G) or "Not Green" (NG) designations. A CSL gCO2/SP debt from the harvest of trees for woodchips that extends beyond the SP lifetime of 30 years also constitutes a NG designation. Calculations are based on various quantities of the smelter MGSi product that will be used for SPs. Both Method 1 and Method 2 calculations used in this paper are included. See following Tables D8 and D9, and see Appendix D for calculation details.

**Table D8. Green Designation of the Silicon Smelter based on % Increase of Smelting on Downstream c-Si SPs**

| G = Green<br>NG = Not Green | **Range of Reported SP CFPs of 20, 30 and 40 gCO2e/kWh per SP:<br>% Increase of Emissions over Reported SP CFPs due to the Silicon Smelter** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **%MGSi** | **100%** | | **50 %** | | **25%** | | **15%** | | **10 %** | | **5%** | |
| **Method 1** | 5.7% | G | 5.7% | G | 5.7% | G | 5.7% | G | 5.7% | G | 5.7% | G |
| **Method 2** | 5.7% | G | 10.9% | G | 22.5% | G | 37.5% | NG/G* | 56.5% | NG | 113.0% | NG |

*Table D4: 15% MGSi, SP CFP of 20 gCO2e/kWh/SP % increase = 50% (NG). Midpoint of 3 values = 37.5% (G).

**Table D9. Green Designation of the Silicon Smelter based on Woodchips CSL Debt/SP: End of 30-yr Lifetime**

| G = Green<br>NG = Not Green | **CSL from Woodchips, gCO2 per SP<br>At End of SP 30-Year Lifetime** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **%MGSi** | **100%** | | **50 %** | | **25%** | | **15%** | | **10 %** | | **5%** | |
| **Method 1** | 1,307 | NG | 1,307 | NG | 1,307 | NG | 1,307 | NG | 1,307 | NG | 1,307 | NG |
| **Method 2** | 1,307 | NG | 2,614 | NG | 5,228 | NG | 8,757 | NG | 13,070 | NG | 26,142 | NG |

## 8. CONCLUSIONS

1. The articles and papers reviewed in this study show that LCAs and CFPs for c-Si Solar Panels did not include the silicon smelting process, and therefore do not represent complete LCAs or CFPs for c-Si Solar Panels.

2. Many of the reviewed CFP papers did not provide clear text descriptions of the scope of the studies, making it difficult to discern whether-or-not the silicon smelting process was included in LCAs. Only one reviewed paper used a clearly delineated Scope diagram showing that silicon smelting was not included. Clear scope diagrams showing both what is included, and what is not included need to be provided in all LCAs.

3. Actual calculations with clearly identified inputs and outputs were difficult to find in many of the reviewed papers. Only references to computer software computations (e.g., ecoinvent) or data from other sources were shown. Site-specific data for LCAs and CFPs are critical, but obtaining adequate information from industries may be an obstacle.

4. The current CFP equation for c-Si SPs is not clearly defined and is not complete. SP CFPs need to include: smelter emissions from both fossil fuel and biomass sources, carbon sink losses and recovery times from tree harvest for woodchips and charcoal, and energy use during manufacture. An equation similar to equation (4) could be used.

5. Emissions from biogenic sources are not being accounted for at the point of combustion in the industry and energy sectors of IPCC guidelines. Biomass emissions need to be accounted for at the point of combustion (as are fossil fuels) and need to be reported as part of the total emissions of an industrial process or product. Biomass emissions could be listed as a "memo" in the Land Use (AFOLU) sector of IPCC Guidelines to avoid double counting.

6. LCA/LCI methodologies are yielding inconsistent and non-comparable results, and are highly subjective. A "constant" or "benchmark" LCA allocation method that will provide standardization of LCAs is needed. Calculation Method 2 used in this paper could provide some standardization and consistency for heavy industrial processes, as allocation of co-product emissions is not required. In addition to other allocation methods, LCAs could include a method similar to Method 2 as a baseline; this could provide a unifying standard that will be directly comparable to other LCAs.

7. The term "Green" is not clearly defined. Quantifiable metrics need to be included to give "Green" credibility.

8. **"Green" Designation for Silicon Smelter Contribution to c-Si SP CFPs. See Discussion Section 7.7**

   **(1)** Green Designation based on reported c-Si SP CFP value % increases (≥ 50%) due to Smelter emissions gCO2e/kWh/SP values determined in this paper.
   **Method 1 Calculations:** All quantities of %MGSi for SPs are designated "Green" (Table D8).
   **Method 2 Calculations:** At %MGSi for SPs below 15%, the impact of the silicon smelter emissions results in 50% or greater increases in the downstream c-Si SP CFPs, and are therefore designated as "Not Green" (Table D8).

   **(2)** Green Designation based on the Carbon Sink Loss (CSL) from the harvest of trees for Woodchips (Table D9).
   **Method 1 and Method 2 Calculations:** For all quantities of MGSi for downstream SPs and for both Method 1 and Method 2 calculations, a CSL debt exists for all downstream c-Si SPs, and are therefore designated as "Not Green". Since the CSL from tree harvest for the silicon smelting process results in a carbon (CO2 sink loss) debt that extends beyond the SP 30-year lifetime, it is suggested that downstream c-Si SPs account for more atmospheric CO2 throughout their life cycle than they save.

9. Solar, Wind, Hydrogen, and other alternative energy sources are important tools for addressing climate change. Every energy generating system will have drawbacks; but exploring possibilities for reducing drawbacks via alternatives to fossil fuels and silicon smelting, etc., needs to continue. A transparent, comparable, standardized, and accessible accounting method for capturing the full environmental impact of energy, industrial, and land-use systems needs to be a priority.

**Closing Comment**. Extraction of fossil fuels and minerals from the earth, metals from ores, and trees from our forests has been key to our success. We are now experiencing adverse impacts from our extraction methods and our use of extracted materials, as evidenced by climate change and environmental degradation. We need to re-connect with our earth, and recognize that using our earth's resources requires a commitment to maintain a healthy balance across all ecosystems. If we don't put environmental concerns at the top of our priorities, we will face ever increasing threats to our quality of life.

## 9. GLOSSARY OF TERMS AND CONCEPTS

### 9.1 Balance of systems (BOS)

**Balance of system** (**BOS**) includes all components of a photovoltaic system other than the photovoltaic panels. Wiring, switches, mounting systems, inverters, battery banks and chargers, etc. constitute the BOS [82].

### 9.2 Carbon Dioxide equivalent, CO2e and Global Warming Potential

**$CO_2$ equivalent ($CO_2$-eq) emission.** IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. See ref [83]. "The amount of *carbon dioxide ($CO_2$)* emission that would cause the same integrated *radiative forcing* or temperature change, over a given time horizon, as an emitted amount of a *greenhouse gas (GHG)* or a mixture of GHGs. There are a number of ways to compute such equivalent emissions and choose appropriate time horizons. Most typically, the $CO_2$-equivalent emission is obtained by multiplying the emission of a GHG by its global warming potential (GWP) for a 100-year time horizon." [83]. *Note. In this paper "$CO_2e$" can include a mixture of GHGs, including $CO_2$. "$CO_2$" typically, refers to $CO_2$ only.*

**Carbon dioxide (CO2).** IPCC Fourth Assessment Report: Climate Change 2007, Publications and Data. Annex II, Glossary, p77. See ref [84]. "A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal, of burning biomass and of land use changes and other industrial processes. It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1". [84].

**Global Warming Potential (GWP).** IPCC Fourth Assessment Report: Climate Change 2007, Publications and Data. Annex II, Glossary, p 81. See ref [84]. "An index, based upon radiative properties of well mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well mixed greenhouse gas in today's atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation. The Kyoto Protocol is based on GWPs from pulse emissions over a 100- year time frame". [84].

**GWP values for CO2, CH4, and N2O**

From the United States Environmental Protection Agency (EPA), Understanding global Warming Potentials [85]:
$CO_2$, by definition, has a GWP of 1 regardless of the time period used, because it is the gas being used as the reference.
Methane ($CH_4$) is estimated to have a GWP of 28–36 over 100 years.
Nitrous Oxide ($N_2O$) has a GWP 265–298 times that of $CO_2$ for a 100-year timescale. *Note: N2O GWP of 298 is used in this paper.*

### 9.3 Carbon Footprint (CFP) for Energy Generation

A carbon footprint (CFP) is the total amount of CO2 and other GHGs emitted over the full life cycle of a process or product. For electric energy generation, a CFP is expressed as grams of CO2e per kilowatt hour of generation (gCO2eq/kWh) [86].

### 9.4 Crystal Silicon (c-Si) Solar Cell, Solar Module, Solar Panel

**Monocrystalline silicon PV cells** are made from silicon wafers that are cut from cylindrical, single-crystal silicon ingots.
**Polycrystalline or multi crystalline silicon PV cells** are made from silicon wafers cut from cast square block ingots. Polycrystalline PV cells are less expensive to produce than monocrystalline silicon PV cells, but are less efficient.
**Silicon solar cells** are solar wafers that have been treated by doping, etching, coating, etc.
**Solar Modules and Solar Panels** are used interchangeably, and consist of solar cells connected in series and sometimes also in parallel to increase voltage. The connected solar cells are encased in protective material and a frame [87].

### 9.5 Emission Factor (EF)

An **emissions factor (EF)** is a value that relates the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. EFs are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant [49]. For example, the EF for a silicon smelter can be expressed as MT GHGs per MT of MGSi product.

Emissions data can be obtained through direct measurement of releases from a process or activity, where a sample of the process emissions is collected and analyzed. The emissions rate for the source, expressed in terms of mass of pollutant emitted per time unit can be calculated as the arithmetic average of the quality-assured test data. The emissions rate for a specific process can also be determined by using a mass balance approach. In general, mass balances are appropriate for use in situations where the mass of all the materials entering and exiting a process can be quantified [88].

The EF for silicon smelting (IPCC, tier 1): Metric Tonnes (MT) of GHG Emissions divided by MT of Product [50].

**9.6 IPCC**. The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988, and was endorsed by UN General Assembly in 1988. The IPCC's initial task was to prepare a comprehensive review and recommendations with respect to the state of knowledge of the science of climate change; the social and economic impact of climate change, and potential response strategies and elements for inclusion in a possible future international convention on climate [89].

### 9.7 Life Cycle Assessment (LCA)

LCA descriptions below are obtained from: **European Platform on Life Cycle Assessment Life Cycle Assessment (LCA)** European Commission website [90].

LCA is defined by the ISO 14040 as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. LCA is based on 4 main phases: 1) goal and scope 2) inventory analysis, 3) impact assessment, 4) interpretation [90].

In the **goal and scope** phase, the aims of the study are defined, namely the intended application, the reasons for carrying out the study and the intended audience. Main methodological choices are made in this step, in particular the exact definition of the functional unit, the identification of the system boundaries, the identification of the allocation procedures, the studied impact categories and the Life Cycle Impact Assessment (LCIA) models used, and the identification of data quality requirements [90].

The **Life Cycle Inventory (LCI)** phase involves the data collection and the calculation procedure for the quantification of inputs and outputs of the studied system [90].

In the **Life Cycle Impact Assessment (LCIA)** phase, LCI results are associated to environmental impact categories and indicators [90].

Finally, in the **Life Cycle Interpretation phase**, results from LCI and LCIA are interpreted in accordance to the stated goal and scope [90].

### 9.8 Oxidation-Reduction ("ReDox")

An oxidation-reduction (redox) is a chemical reaction that involves a transfer of electrons between two species. In an oxidation-reduction reaction, the oxidation number of a molecule, atom, or ion changes by gaining or losing an electron [91]. A **reducing agent** (or **reductant**) is an element or compound that loses (or "donates") an electron to an electron receiving element or compound (oxidizing agent) in a redox chemical reaction [92].

### 9.11 photovoltaic (PV) array

An interconnected system of PV modules that function as a single electricity-producing unit. The modules are assembled as a discrete structure, with common support or mounting. In smaller systems, an array can consist of a single module [93].

### 9.12 photovoltaic (PV) system

A complete set of components for converting sunlight into electricity by the photovoltaic process, including the array and balance of system components [93].

### 9.13 Refining

Refining involves removal of impurities from a metal. Essentially, the final material is chemically identical to the original material, only purer [94].

### 9.14 Smelting

The extraction of a metal from its ore, or oxide. Significant heat is applied to obtain molten ore along with a reducing agent or reductant. Carbon sources, such as coal or coke are often used as reductants to extract the oxygen atoms from the ore while donating electrons to the metal. The carbon source is "oxidized" to carbon monoxide and carbon dioxide while the ore is "reduced" to its metal. Smelting results in a chemical change of a raw material [94].

### 9.15 Scope 1 Emissions

Scope 1 emissions are direct greenhouse (GHG) emissions that occur from sources that are controlled or owned by an organization (e.g., emissions associated with fuel combustion in boilers, furnaces, vehicles) [95].

### 9.16 Scope 2 Emissions

Scope 2 emissions are indirect GHG emissions associated with the purchase of electricity, steam, heat, or cooling. Although scope 2 emissions physically occur at the facility where they are generated, they are accounted for in an organization's GHG inventory because they are a result of the organization's energy use [95].

### 9.17 Scope 3 Emissions

Scope 3 emissions are the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly impacts in its value chain [96].

## 10. RAW MATERIALS and RESOURCES

### 10.1 Raw Materials: Quartzite

Quartz is extracted from open pit mines. Since quartz is easily damaged due to its hardness, explosives are rarely used. For the most part, mining operations use bulldozers and backhoes to remove soil and clay to expose the quartz crystal veins in the rock [97].

### 10.2 Raw Materials: Metallurgical Grade Coal--Blue Gem coal

Silicon smelting requires the use of a very specialized type of metallurgical grade coal known as "Blue Gem Coal". Blue Gem Coal has a high carbon content, low sulfur content, low ash fusion temperature, and high silicon reactivity. Blue Gem coal is very rare, and is found in southeastern Kentucky, USA; and in Colombia, South America. The Blue Gem coal of southeastern Kentucky is widely considered as one of the best coal-carbon sources for silicon metal in the world [15] [16].

### 10.2.1 Coal Mining Methods

**Surface Mining**. For coal seams near the surface, coal is often extracted using "open cut" mining methods (also referred to as "strip mining", "open cast", "open pit", or "mountaintop removal") [98]. Re-mining a strip-mined area can be done by further strip mining, and also by "highwall" mining. "Highwall Auger" mining for two Blue Gem coal seams in Tennessee is described by the Coal Creek Watershed Foundation, Inc [99].

**Underground Mining**. Many coal seams are too deep underground for opencast mining and require underground mining, a method that currently accounts for about 60 percent of world coal production [98].

### 10.2.2 Coal Mining Emissions

Coal mines can be a source of methane, as the gas escapes from coal seams and is often siphoned off through ventilation systems to ensure a safe environment for miners. Coal-mine methane (CMM) is relatively understudied. But in its most recent World Energy Outlook (WEO), published in November 2019, the International Energy Agency (IEA) estimated a global total of 40 million Metric Tonnes (MT) of methane each year from operational coal mines [100] [101].

### 10.3 Raw Materials: Forest Products

### 10.3.1 Charcoal

Charcoal is not included in this study, however, several references that provide some background information on charcoal are included: [102] [103] [104].

### 10.3.2 Wood Chips

Wood chips provide some of the carbon for chemical reduction, but are primarily used to provide bulk and surface area in the furnace charge. The contributions from woodchips include:
(1) Providing a large surface area for chemical reactions to take place more completely and at improved rates, (2) Maintaining a porous charge and promoting gentle and uniform gas venting, (3) Helping to regulate smelting temperatures, (4) Reducing conductivity, (5) Allowing deep electrode penetration, (6) Preventing bridging, crusting, and agglomeration, (7) Smelting of finely divided raw materials without sintering, and (8) Reducing dust, metal vapor, and heat loss [10].

The form of wood best suited for electric smelting is the metallurgical or "met chip". Met chip specifications can range from 2.5 inches square by 0.5 inches thick to 8 inches square by 1 inch thick. Roundwood specifications for chippers can range from log diameters of 16 to 18 inches to accommodate for crook, swell, and knots [10].

### 10.3.3 Local Forests: Timber Types

Conifer trees constitute the predominant timber type in the forests near Newport and in the Inland Northwest region. Douglas Fir, Grand Fir, Ponderosa Pine, Western Larch, are common; Western Red Cedar, Western White Pine, Western Hemlock and Lodgepole Pine are also found. Engelmann Spruce and Subalpine Fir are mostly found in the higher elevations [105].

### 10.3.4 Forest/Timber Management

#### Lodgepole Pine (Woodchips)

Specific details regarding the desired species, age, diameter, and height of the trees to be used for the smelter wood chips have not been provided, and specifications for woodchips were not available. Lodgepole Pine was selected as the timber type for this study since Lodgepole Pine has an extensive range in the western USA, and growth characteristics and management literature were available. Based on information from reference [32] and references below, an average *minimal* tree age of 40 years was selected for this study. A minimal tree age of 40 years may or may not be sufficiently mature for smelter use. It is assumed that the trees used for woodchips would come from managed lands. The IPCC managed land definition: "Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions." From: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use, Annex 4A.1 Glossary for Forest Land, page 4.76 [106].

Lodgepole pine has a wide range of environmental tolerance, and grows in association with many plant species. The lodgepole pine forest type is the third most extensive commercial forest type in the Rocky Mountains [44].
For Lodgepole Pine even-aged systems, the minimum initial stocking recommended is 1,200 to 1,500 stems per acre at age 10 years. This density ensures that at least 1,000 stems per acre will survive to age 30 years, without reduction in height or diameter growth [45]. Maximum yield in the Rocky Mountains was 280 $m^3$/ha (20,000 fbm/acre) at a density of 1,980 trees per hectare (800 trees/acre) [44]. Culmination of total cubic volume occurs as early as 40 years in severely stagnated stands, and between 50 and 80 years for overstocked, but not greatly stagnated stands. Merchantable volume culmination in overstocked but not stagnated stands occurs between 110 and 140 years [44].

Lodgepole pine can be maintained best in a vigorous, productive forest by using a silvicultural method that regenerates even-aged stands. This often may be accomplished by clearcutting and by relying upon natural regeneration or planting [44]. On an average site (index 60) with a 20-year cutting cycle, trees reach 10 inches d.b.h (diameter at breast height, 4.5 ft.) at 56 to 100 years of age for the growing stock level (GSL) range of 40 to 160 [45].

Because lodgepole pine has little taper and thin bark it produces a higher volume of wood for a given diameter and height than many of its associates [44]. Trees in the Blue Mountains of Oregon average 30 cm (about 12 in) in d.b.h. and 23 m (about 75 ft) tall at 100 years of age [44].

### 10.3.5 Forests. Trees as a Carbon Sink

#### Photosynthesis, Respiration, and Carbon Sequestration

**Photosynthesis**. Plants use the energy from sunlight to transform atmospheric carbon dioxide into organic molecules. These molecules become the building elements for growth and the basic material to maintain existing components of vital functions. Approximately half of the dry biomass of plants is made up of carbon molecules [107].
**Respiration**. Some of the carbon absorbed by plants returns back to the atmosphere as respired carbon dioxide. Respiration is the basic cellular process to obtain chemical energy from the oxidation of organic molecules, and CO2 results as a waste product of the overall metabolism. Generally, about half of the absorbed carbon from Photosynthesis is released via respiration [107].
**Carbon Sink**. From the US EPA: "Trees are composed largely of carbon and continue to take in carbon as they grow. By fixing carbon during photosynthesis and storing it as biomass, growing trees act as a sink for CO2." [108].

### 10.4 Energy

### 10.4.1 Hydroelectric Dams

Box Canyon Dam is a hydroelectric dam on the Pend Oreille River with a capacity of 90 MW and is approximately 50 miles north of Newport in Pend Oreille County [109]. Box Canyon Dam is operated by the Pend Oreille County Public Utility District (PUD). A Public Utility District is a community-owned, locally regulated utility [110].

Boundary Dam is a hydroelectric dam on the Pend Oreille River with a capacity of approx. 1,070 MW and is about 80 miles north of Newport in Pend Oreille County. Boundary Dam is owned by Seattle City Light [109].

Details regarding the amount of hydroelectric power from Box Canyon Dam, and possibly Boundary Dam, that would be available to the proposed smelter are not available. Information regarding potential requirement for other sources of electrical energy was also not available.

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## Appendix A. Lodgepole Pine Tree Weight for Estimating Number of Trees and Harvested Acres

The volume of a tree is estimated, and the density of the tree wood (green weight) is used to determine tree mass (weight).

The volume of a tree or log can be determined by calculating the volume of a cylinder using the equation: $\pi \times r^2 \times h$, where r = radius and h = height. Note: Lodgepole Pine typically has minimal taper [45].

If a tree or log has detectable taper, the volume of the "frustum" of a cone can be used to make a more accurate volume determination. The frustum of a cone consists of a bottom circle, and a top circle sliced through the cone at a desired height above the bottom circle below the apex of the cone.
The formula for the frustum of a cone (7): $\mathbf{v = (\pi \times h)/3 \times [R^2 + Rr + r^2]}$, where h = height, R = the radius of the bottom circle, and r = the radius of the smaller top circle.

The frustum of a cone is used to estimate the volume of a tree, and the tree volume is used to determine the green tree weight of lodgepole pine. The density value of 625 kg per cubic meter ($m^3$) for Lodgepole Pine green weight is used [60]. The weight of a lodgepole pine is used to estimate the potential number of lodgepole pine trees to be harvested and the number of acres harvested per year to supply the smelter with woodchips.

**Estimation 1.**
Useable tree height, h = 60 ft. Bottom circle: dbh = 8 in. Top circle dia = 6 in.
Bottom circle dia = 8 in. 8 in ÷ 12 in/ft = 0.67 ft. 0.67 ft ÷ 2 = **0.34 ft = R**
Top circle dia = 6 in. 6 in ÷ 12 in/ft = 0.50 ft. 0.50 ft ÷ 2 = **0.25 ft = r**

(7)
$\mathbf{v = (\pi \times h)/3 \times [R^2 + Rr + r^2]}$

(3.14 x 60 ft) ÷ 3 = **62.8**
$[(0.34^2) + (0.34 \times 0.25) + (0.25^{\,2})] = [0.1156 + 0.0850 + 0.0635\} =$ **0.2631**
62.8 x 0.2631 = $\mathbf{16.52\ ft^3}$ x 0.02832 $m^3/ft^3$ = $\mathbf{0.4678\ m^3}$
0.4678 $m^3$ x 625 $kg/m^3$ = 292.375 kg x 0.001 MT/kg = **0.292 MT**

**Estimation 2.**
Useable tree height, h = 60 ft. Bottom circle: dbh = 10 in. Top circle dia = 8 in.
Bottom circle dia = 10 in. 10 in ÷ 12 in/ft = 0.83 ft. 0.83 ft ÷ 2 = **0.42 ft = R**
Top circle dia = 8 in. 8 in ÷ 12 in/ft = 0.67 ft. 0.67 ft ÷ 2 = **0.34 ft = r**

$\mathbf{v = (\pi \times h)/3 \times [R^2 + Rr + r^2]}$
(3.14 x 60 ft) ÷ 3 = **62.8**
$[(0.42^2) + (0.42 \times 0.34) + (0.34^2)] = [0.1764 + 0.1428 + 0.1156\} =$ **0.4348**
62.8 x 0.4348 = $\mathbf{27.31\ ft^3}$ x 0.02832 $m^3/ft^3$ = $\mathbf{0.7734\ m^3}$
0.7734 $m^3$ x 625 $kg/m^3$ = 483.375 kg x 0.001 MT/kg = **0.483 MT**

**Estimation 3.**
Useable tree height, h = 70 ft. Bottom circle: dbh = 12 in. Top circle dia = 8 in.
Bottom circle dia = 12 in. 12 in ÷ 12 in/ft = 1.00 ft. 1.00 ft ÷ 2 = **0.5 ft = R**
Top circle dia = 9 in. 9 in ÷ 12 in/ft = 0.75 ft. 0.75 ft ÷ 2 = **0.38 ft = r**

$\mathbf{v = (\pi \times h)/3 \times [R^2 + Rr + r^2]}$
(3.14 x 70 ft) ÷ 3 = **73.3**
$[(0.50^2) + (0.50 \times 0.38) + (0.38^2)] = [0.2500 + 0.1900 + 0.1444\} =$ **0.5844**
73.3 x 0.5844 = $\mathbf{42.84\ ft^3}$ x 0.02832 $m^3/ft^3$ = $\mathbf{1.2132\ m^3}$
1.2132 $m^3$ x 625 $kg/m^3$ = 758.25 kg x 0.001 MT/kg = **0.758 MT**

## Appendix B. Estimation of Fossil Fuel (f) and Biomass (b) Reductants % GHG Contributions to c-Si SP CFPs

Both Emissions Estimations (EE) 2 and 3 are used to estimate % Fossil Fuel (f) and Biomass (b) contributions to c-Si SP CFPs. GHG sources are not segregated in EE2, and separate CO2 and N2O emissions from Coal and Woodchips also are not determined in EE2 or EE3. Since segregated CO2 contributions from Coal (f) and Woodchips (b) are determined for EE3 (Table 13), EE3 CO2 values for coal and woodchips are used. N2O emissions from Coal and Woodchips EE3 are determined using Nitrogen content estimations of wood and coal found in literature. Total smelter N2O mass from EE2 is multiplied by the N2O GWP (Tables 12, 13) to give a total value of 252,704 MT N2O. Methane (CH4) is not included.

**1.** Nitrogen (N) content of wood: approximately **0.1%** [111]. Nitrogen (N) content of coal: **0.5 – 3%** [112].
**Total smelter N2O (with GWP) = 252,704 MT/yr** (Table 13)

**2. Woodchips (WC), N2O per year**
Total smelter N2O (with GWP) = 252,704 MT/yr (Table 13). Determine WC N2O first, since N content of wood = 0.1%.
MT Woodchips per year = 117,936 MT. CO2 from WC = 216,413 MT CO2/yr.
Nitrogen (N) content of wood: 0.1% (0.001x) [109].
117,936 MT (WC) x 0.001 (N) = **118 MT N** from WC.
**gram-atomic weights**: N = 14g, Oxygen (O) = 16g, N2O = [(14 x 2) + 16] = 28g (N) + 16 g (O) = **44 g N2O**.
44g N2O ÷ 28g N = 1.57g N2O/g N = **1.57 MT N2O/MT N**.
1.57 MT N2O/N x 118 MT N (from WC) = **185 MT N2O from WC**.
185 MT N2O x 298 (GWP) = **<u>55,130 MT CO2e from WC N2O</u>**
Total CO2e from N2O = 252,704 MT. [55,130 MT CO2e (N) ÷ 252,704 MT CO2e (N)] x 100 = **22% from WC**

**3. Coal, N2O per year**
MT Coal per year = 136,080 MT. CO2 from coal = 299,648 MT CO2/yr
Nitrogen (N) content of coal: 0.5 – 3% (0.005x – 0.03x) [110]
Total smelter N2O (with 298 GWP) = 252,704 MT CO2e from N2O.
252,704 MT – 55,130 MT (WC N2O) = **<u>197,574 MT CO2e from Coal N2O</u>**.
194,574 MT CO2e ÷ 298 (GWP) = **663 MT N2O**. 663 MT N2O ÷ 1.57 MT N2O/MT N = **422 MT N from coal**.
422 MT N ÷ 136,080 MT coal = 0.003 **(approx. 0.3% N)**. 0.3% is less than the 0.5-3% estimated range of N in coal.
Total CO2e from N2O = 252,704 MT. [197,574 MT CO2e (N) ÷ 252,704 MT CO2e (N)] x 100 = **78% from coal**.
22% N2O from WC + 78% N2O from coal = 100%. Note: Carbon content of charcoal is typically > 65%

**Table 13. MT of CO2e Emissions from Coal, Wood Chips, and GE**

| CO2e Emission Source | Calculation | MT CO2e from 66,226 MT MGSi |
|---|---|---|
| Blue Gem Coal/Charcoal | Table 9 (Carbon Content, CO2 only) | 299,648 |
| Wood Chips | Table 10 (Carbon Content, CO2 only) | 216,413 |
| Graphite Electrode (GE) | Table 11 (IPCC 2006 EF, CO2 only) | 23,445 |
| NOx (N2O), GWP 298 | Table 12 (and Table 3) | 252,704 |
| | **TOTAL** | **792,210** |

**Table B1. % GHG from Coal and Graphite (f) and %GHG from Woodchips (b)**

| Reductants | GHG Source | MT | Percent (f) and (b) Determination |
|---|---|---|---|
| **Woodchips (b)** | CO2 from Carbon Content* | 216,413 | 271,543 ÷ 792,210 = 0.343 **(34%)** |
| | CO2e from Nitrogen Content** | 55,130 | |
| | **Sum** | **271,543** | |
| **Coal (f)** | CO2 from Carbon Content* | 299,648 | 520,667 ÷ 792,210 = 0.657 **(66%)** |
| | CO2e from Nitrogen Content** | 197,574 | |
| **Graphite (f)*** | CO2 from Graphite Electrode* | 23,445 | |
| | **Sum** | **520,667** | |
| **Total GHG** | Overall Total GHG, Coal, Graphite, Woodchips | **792,210** | **100%** |

**Table 13. **Woodchips and Coal N2O calculations 2 and 3 above.* Note: Since coal/charcoal proportions were not given, only coal was used in calculations; thereby giving a higher % of fossil fuel than actually may be the case.

## Appendix C. WOOD CHIPS. gCO2 Sink Recovery Rate/SP (CRR) and CSL at 30 yrs for Tree Ages 50 and 60 yrs

***Note:*** The following method uses the straight-line Equation (2): y = **-**mx + b, to determine the CRR. This is a rough estimation. Tree growth and CO2 absorption involve numerous variables (species, environmental conditions, stand density, etc.) and generally have a more curved or sigmoidal graphical appearance instead of a straight line. Overall tree CO2 absorption is usually lower at seedling and sapling stages, increases over time to maturity and harvestable stages, and then may slow down during late and senescent stages [113]. Differential equations or other complex calculations are typically used to characterize tree growth and CO2 absorption, but are beyond the scope of this study.

The tree age of 40 years at harvest used in calculations is a conservative age estimate. Table C1 below uses the line equation (2): *y = -mx +b*, to estimate the gCO2/SP debt at the end of SP 30-year lifetime from trees harvested at ages of 50 and 60 years. The gCO2/SP debt at the end of the 30-year SP lifetime increases as the age of harvested trees increases. CRR = Carbon Sink Loss Recovery Rate. CSL = Carbon Sink Loss. 30 years = end of SP lifetime.

**Table C1. WOOD CHIPS. gCO2 Sink Recovery Rate/SP (CRR) and CSL at 30 yrs for Tree Ages 50 and 60 yrs**

| **% MGSi** | **CSL, yr 1 gCO2/SP*** | | **Tree Age, yrs** | | **(CRR, CSL/yr) *-m*** | | ***yrs x*** | | ***CSL, yr 1 b*** | | **gCO2/SP, 30 yrs y** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **100%** | ***5,228*** | ÷ | **40** | = | *130.7* | x | *30* | + | *5,228* | = | ***1,307*** |
| | | ÷ | **50** | = | *104.6* | | | | | = | ***2,090*** |
| | | ÷ | **60** | = | *87.1* | | | | | = | ***2,615*** |
| **50%** | **10,457** | ÷ | **40** | = | 261.4 | x | 30 | + | 10,457 | = | **2,615** |
| | | ÷ | **50** | = | 209.1 | | | | | = | **4,184** |
| | | ÷ | **60** | = | 174.3 | | | | | = | **5,228** |
| **5%** | **104,569** | ÷ | **40** | = | 2,614.2 | x | 30 | + | 104,569 | = | **26,143** |
| | | ÷ | **50** | = | 2,091.4 | | | | | = | **41,827** |
| | | ÷ | **60** | = | 1,742.8 | | | | | = | **52,285** |

**Table 22. Note: the linear CO2 Sink Recovery Rate (CRR) can be expressed as a line equation: y = -mx + b (b) = y intercept = CSL at year 1. -(m) = slope = CRR/yr. (x) = years. The slope is negative since the initial CSL is reduced over time.*

e.g.: 100% MGSi, gCO2/SP debt at 30 years: *y = (-130.7 x 30 yrs) + 5,228 = -(3,921) + 5,872 =* ***1,307*** *gCO2*

## Appendix D. Green Designation of the Silicon Smelter: Impact on Downstream c-Si SPs

The impact of the silicon smelting process on downstream c-Si SPs CFPs is evaluated based on two values: (1) the smelter emissions gCO2e/kWh/SP debt, and (2) the Carbon Sink Loss (CSL) gCO2/SP debt due to tree harvest for Wood Chips that extends beyond the 30-year SP lifetime.

Smelter GHG emissions gCO2e/kWh/SP per year and the associated Carbon Sink Loss due to tree harvest for Wood Chips, CSL/SP per year, are used to assess the silicon smelter's impact on downstream c-Si SP CFPs. Values of reported c-Si SP CFP values found in the literature range from approx. 20 – 40 gCO2e/kWh/SP. The Literature Review Section 4.1 revealed that the reviewed papers did not include the silicon smelting process in c-Si SP CFP determinations. Three c-Si SP CFP estimates (20, 30, and 40 gCO2e/kWh/SP) based on a range of values from reviewed literature are used to determine the % increase of gCO2e/kWh/SP from the upstream smelting process onto the 3 downstream c-Si SP CFPs. A CFP increase of 50% or greater from smelter GHG emissions is used to conclude a Not Green (NG) designation.

%MGSi values designated for SPs are used to determine the emissions gCO2e/kWh/SP increase and the CSL gCO2/SP debt at the 30-year end of SP lifetime. The % increase in gCO2e/kWh/SP and the CSL gCO2/SP debt are determined separately. Tables 45 and 47 from the Results Section 6 are used, and are included below.

**Table 45 Smelter Emissions and Woodchips Carbon Debt (CSL) Impact on the CFP of c-Si SPs at Year 30**

| % MGSi for SPs | Method 1 Calculation* | | Method 2 Calculation* | | Method 1 with SiF Allocation** | |
|---|---|---|---|---|---|---|
| | **Emissions gCO2e/SP** | **Woodchips CSL gCO2e Debt/SP** | **Emissions gCO2e/SP** | **Woodchips CSL gCO2e Debt/SP** | **Emissions gCO2e/SP** | **Woodchips CSL gCO2e Debt/SP** |
| 100% | 1.5 | 1,307 | 1.5 | 1,307 | 1.2 | 1,005 |
| **50%** | **1.5** | **1,307** | **2.9** | **2,614** | 1.2 | 1,005 |
| **5%** | **1.5** | **1,307** | **30.0** | **26,142** | 1.2 | 1,005 |

**Tables 41 and 42. CSL = carbon sink loss. **Table 44 (Method 1 with SiF allocation is supplemental information only).*

**Table 47. Method 2 (M2): GHG and WC gCO2e Debt per SP at various % MGSi Values (25%, 20%, 10%, 2%)**

| %MGSi for SPs (x) | x/100 | 1/x | | 100% MGSi gCO2e/SP* | | M2 GHG gCO2e/SP | | 1/x | | WC Debt gCO2e/SP* | | M2 WC Debt gCO2e/SP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **25%** | 0.25 | 4.0 | x | 1.5 | = | **6.0** | | 4.0 | x | 1,307 | = | **5,228** |
| **20%** | 0.20 | 5.0 | x | 1.5 | = | **7.5** | | 5.0 | x | 1,307 | = | **6,535** |
| **15%** | 0.15 | 6.7 | x | 1.5 | = | **10.0** | | 6.7 | x | 1,307 | = | **8,757** |
| **10%** | 0.10 | 10 | x | 1.5 | = | **15.0** | | 10 | x | 1,307 | = | **13,070** |
| **2%** | 0.02 | 50 | x | 1.5 | = | **75.0** | | 50 | x | 1,307 | = | **65,350** |

**Table 45.*

**Table D1. Method 1 (100% MGSi**): % Increase of SP CFPs of 20, 30, & 40 gCO2e/kWh/SP from the Si Smelter**

| Before Smelter gCO2e/kWh/SP | | Smelter gCO2e/kWh/SP* | | Total gCO2e/kWh/SP | % Increase Calculation | | % CFP increase from smelting |
|---|---|---|---|---|---|---|---|
| 20 | + | 1.5 | = | **21.5** | [(21.5 - 20) / 20] x 100 | = | **7.5%** |
| 30 | + | 1.5 | = | **31.5** | [(31.5 - 30 / 30)] x 100 | = | **5.0%** |
| 40 | + | 1.5 | = | **41.5** | [(41.5 - 40 / 40)] x 100 | = | **3.8%** |

**Table 45. **Method 1 calculation results yield the same gCO2e/kWh/SP across all %MGSI values.*

**Table D2. Method 2 (50% MGSi): % Increase of SP CFPs of 20, 30, and 40 gCO2e/kWh/SP from the Si Smelter**

| Before Smelter gCO2e/kWh/SP | | Smelter gCO2e/kWh/SP* | | Total gCO2e/kWh/SP | % Increase Calculation | | % CFP increase from smelting |
|---|---|---|---|---|---|---|---|
| 20 | + | 2.9 | = | **22.9** | [(22.9 - 20) / 20] x 100 | = | **14.5%** |
| 30 | + | 2.9 | = | **32.9** | [(32.9 - 30) / 30] x 100 | = | **9.7%** |
| 40 | + | 2.9 | = | **42.9** | [(42.9 - 40) / 40] x 100 | = | **7.3%** |

**Table 45.*

**Table D3. Method 2 (25% MGSi): % Increase of SP CFPs of 20, 30, and 40 gCO2e/kWh/SP from the Si Smelter**

| Before Smelter gCO2e/kWh/SP | | Smelter gCO2e/kWh/SP* | | Total gCO2e/kWh/SP | % Increase Calculation | | % CFP increase from smelting |
|---|---|---|---|---|---|---|---|
| 20 | + | 6.0 | = | **26.0** | [(26.0 - 20) / 20] x 100 | = | **30.0%** |
| 30 | + | 6.0 | = | **36.0** | [(36.0 - 30) / 30] x 100 | = | **20.0%** |
| 40 | + | 6.0 | = | **46.0** | [(46.0 - 40) / 40] x 100 | = | **15.0%** |

**Table 47.*

**Table D4. Method 2 (15% MGSi): % Increase of SP CFPs of 20, 30, and 40 gCO2e/kWh/SP from the Si Smelter**

| Before Smelter gCO2e/kWh/SP | | Smelter gCO2e/kWh/SP* | | Total gCO2e/kWh/SP | % Increase Calculation | | % CFP increase from smelting |
|---|---|---|---|---|---|---|---|
| 20 | + | 10.0 | = | **30.0** | [(30.0 - 20) / 20] x 100 | = | **50.0%** |
| 30 | + | 10.0 | = | **40.0** | [(40.0 - 30) / 30] x 100 | = | **33.0%** |
| 40 | + | 10.0 | = | **50.0** | [(50.0 - 40) / 40] x 100 | = | **25.0%** |

**Table 47.*

**Table D5. Method 2 (10% MGSi): % Increase of SP CFPs of 20, 30, and 40 gCO2e/kWh/SP from the Si Smelter**

| Before Smelter gCO2e/kWh/SP | | Smelter gCO2e/kWh/SP* | | Total gCO2e/kWh/SP | % Increase Calculation | | % CFP increase from smelting |
|---|---|---|---|---|---|---|---|
| 20 | + | 15.0 | = | **35.0** | [(35.0 - 20) / 20] x 100 | = | **75.0%** |
| 30 | + | 15.0 | = | **45.0** | [(45.0 - 30) / 30] x 100 | = | **50.0%** |
| 40 | + | 15.0 | = | **55.0** | [(55.0 - 40) / 40] x 100 | = | **38.0%** |

**Table 47.*

**Table D6. Method 2 (5% MGSi): % Increase of SP CFPs of 20, 30, and 40 gCO2e/kWh/SP from the Si Smelter**

| Before Smelter gCO2e/kWh/SP | | Smelter gCO2e/kWh/SP* | | Total gCO2e/kWh/SP | % Increase Calculation | | % CFP increase from smelting |
|---|---|---|---|---|---|---|---|
| 20 | + | 30.0 | = | **50** | [(50 - 20) / 20] x 100 | = | **150%** |
| 30 | + | 30.0 | = | **60** | [(60 - 30) / 30] x 100 | = | **100%** |
| 40 | + | 30.0 | = | **70** | [(70 - 40) / 40] x 100 | = | **75%** |

**Table 45.*

**Table D7. % Increase of SP CFPs of 20, 30, and 40 gCO2e/kWh/SP from Smelter (Midpoint of % Increase Values) and CSL gCO2 Debt/SP from Woodchips**

| %MGSi | % Increase gCO2e/kWh/SP | | | CSL Debt: End of SP Lifetime |
|---|---|---|---|---|
| | % Increase Mid-Point (Range ÷ 2)* | | % Increase | Woodchips CSL gCO2 Debt/SP** |
| **100%** | (7.5 + 3.8) / 2 | **=** | **5.7%** | 1,307 |
| **50%** | (14.5 + 7.3) / 2 | = | **10.9%**. | 2,614 |
| **25%** | (30.0 + 15.0) / 2 | = | **22.5%**. | 5,228 |
| **15%** | (50.0 + 25.0) / 2 | = | **37.5%**. | 8,757 |
| **10%** | (75.0 + 38.0) / 2 | = | **56.5%**. | 13,070 |
| **5%** | (150.0 + 75.0)/2 | = | **113.0%** | 26,142 |

**Tables D1 – D7. **Tables 45 and 47.*

Summary Tables D8 and D9 are found on the following page 52.

## Appendix D Summary Tables

**Table D8. Green Designation of the Silicon Smelter based on % Increase of Smelting on Downstream c-Si SPs**

| G = Green<br>NG = Not Green | **Range of Reported SP CFPs of 20, 30 and 40 gCO2e/kWh per SP: % Increase of Emissions over Reported SP CFPs due to the Silicon Smelter** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **%MGSi** | **100%** | | **50 %** | | **25%** | | **15%** | | **10 %** | | **5%** | |
| **Method 1** | 5.7% | G | 5.7% | G | 5.7% | G | 5.7% | G | 5.7% | G | 5.7% | G |
| **Method 2** | 5.7% | G | 10.9% | G | 22.5% | G | 37.5% | NG/G* | 56.5% | NG | 113.0% | NG |

**Table D4: 15% MGSi, SP CFP of 20 gCO2e/kWh/SP % increase = 50% (NG). Midpoint of 3 values = 37.5% (G). Values in Table D8 are from Table D7.*

**Table D9. Green Designation of the Silicon Smelter based on Woodchips CSL Debt/SP: End of 30-yr Lifetime**

| G = Green<br>NG = Not Green | **CSL from Woodchips, gCO2e per SP At End of SP 30-Year Lifetime** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **%MGSi** | **100%** | | **50 %** | | **25%** | | **15%** | | **10 %** | | **5%** | |
| **Method 1** | 1,307 | NG | 1,307 | NG | 1,307 | NG | 1,307 | NG | 1,307 | NG | 1,307 | NG |
| **Method 2** | 1,307 | NG | 2,614 | NG | 5,228 | NG | 8,757 | NG | 13,070 | NG | 26,142 | NG |

*Values in Table D9 are from Table D7.*