Determining the Sustainability of Second Generation Photovoltaic Solar Panels: Metal Production and Recycling

by

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Dedication

This thesis is dedicated to Tonya and Gordon Tewnion, my loving mother and father. Thank you for all the support and encouragement you have given me, I love you.

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Abstract

Second-generation photovoltaic solar panel use is increasing worldwide, thus the demand for resources, such as metals, used to make the panels is increasing as well. The main driver of this study is the United Nations and World Wildlife Fund's '50% solar by 2050' goal to try and increase the use of solar panels worldwide. This gave an insight into the potential growth of demand for these high-efficiency panels. Tellurium, gallium, indium, and cadmium are rare metals used in the panels to increase the efficiency of the electricity production; however, these metals are not renewable resources and can be depleted if overused or not recycled. Using the compound annual growth rate of each metal and their previous production levels, the amount produced was calculated for the year 2050. It is then compared to the global reserves and recycling rates to determine the sustainability of second-generation panels in the future. The production of gallium and cadmium are enough to support the demand in 2050, however, the reserves for tellurium and indium are not enough to support the 2050 PV industry.

List of Abbreviations and Symbols

(CAGR) Compound annual growth rate

(CdTe) Cadmium Telluride

(CIGS) Copper indium gallium diselenide

(CIS) Copper indium diselenide

(CO_2) Carbon dioxide

(d_0) Demand

(DC) Direct current

(EOL) End-of-Life

(GW) Gigawatts

(kt) Kilotonnes

(PV) Photovoltaic

(R) Reserves

(t_0) Time

(TW) Terawatts

(W) Watts

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Introduction

Photovoltaic (PV) solar cells produce, on average, 49.9g CO_2-eq/kWh of greenhouse gas emissions in their lifetime; this is mostly during production and disposal of the panels (Nugent & Sovacool, 2013). Producing the PV cells require rare earth metals and heavy metals which are mined out of the ground and are not renewable resources (Nugent & Sovacool, 2013). This study will discuss how sustainable PV solar panels are given their electricity production, global electricity demand in 2050, available resources for production, and recycling methods of the panels.

Background

On average the surface of the earth collects $1.4x10^5$ terawatts (TW) of power, only about $3.6x10^4$TW is utilizable due to inaccessible areas or being emitted in non-usable form (i.e. infrared wavelength) (Hosenuzzaman et. al., 2014). In 2017, the world consumed 17.92TW of power; this is more than the usable energy available yearly, but solar could power a large portion of the demand (BP Global, 2018). Therefore, it would be possible to power most of the world with solar panels if the technology allowed for high-efficiency performance. PV solar cells use semiconductors, typically made from silicon, to convert the photons from the sun into free-flowing electrons (Aldous, 2004). The panels also have an electric field built in to force the electrons to flow in a certain direction to produce a direct current (DC), which is then drawn to metal contacts in the panel (Aldous, 2004). The current and voltage (from the electric field) determine the wattage produced in each panel (Aldous, 2004); on average the wattage of a residential solar panel is 294W, which would produce about 550kWh of energy per year (U.S. Department of Energy, 2018).

Between 2008 and 2018 the cost of PV solar panels significantly decreased at the same time the demand for green energy sources increased globally (Steinbuks et. al., 2017). This demand has resulted in more installations and development of PV solar cells, thus increasing the amount of impact the cells will have on the environment (Steinbuks et. al., 2017). There are three generations of models of PV solar panels. The newer third-generation organic model is not widely used and the technology behind it is still in the developmental stage, therefore, this study will not be exploring it (Brown & Wu, 2008). There are two common types of first-generation PV models, mono-crystalline silicon PV cells and multi-crystalline silicon PV cells; the latter generation is the most commonly utilized model globally today (Tyagi et. al., 2012). Since it is a commonly used type there is a significant amount of information readily available, thus continuing research would not be as beneficial as looking into the second generation (Tyagi et. al., 2012).

There are three common types of second-generation PV solar panel models, cadmium telluride (CdTe) cells, copper indium gallium diselenide (CIGS) cells, and copper indium diselenide (CIS) cells; CIGS and CIS models are often used synonymously due to the minimal differences between the two (Tyagi et. al., 2012). For this study, the CIGS and CIS models will be referred to as CIGS for simplification and uniformity. The study will focus only on second-generation PV panels as these panels are the most efficient type today and are cheaper than the first-generation (Tyagi et. al., 2012). This study will focus on this booming generation to give more insight into the availability of it as a large scale, global energy source.

The primary supply of the four focus metals (tellurium, gallium, indium, and cadmium) come as by-products of mining other elements such as tellurium extraction from copper ores (Redlinger et. al., 2015). This means that the extraction of required metals relies heavily on the demand and market for the source ores, and if there is low demand for copper tellurium availability would decrease as a result (Redlinger et. al., 2015). This is due to the limited volume of the metals in the crust, and the cost it would incur to mine only for the trace metals (Redlinger et. al., 2015). In the Earth's crust there is only trace amounts of the metals, 0.002ppm for tellurium, 0.005 for indium, 17ppm for gallium, and 0.1 for 0.5ppm is cadmium (Redlinger et. al., 2015; Faroon et. al., 2012). There are constraints on the PV solar industry due to the limited amount of metals available, which is why recovering used metals is important for the sustainability of this industry (Redlinger et. al., 2015).

Fossil fuels are the most common source of electricity generation today due to the fact the technology has been around longer than renewable technology, and there is more infrastructure in place (McLamb, 2011). As of 2014 only 13% of the world's energy came from renewable sources (Hosenuzzaman et. al., 2014), however, there is a global push towards developing more renewable sources to limit greenhouse gases and climate change (Ram et. al., 2017). Positive aspects of PV electricity generation are that the source (sun) does not deplete as we use its energy, and the generation of electricity does not produce CO_2 or other waste by-products (Hosenuzzaman et. al., 2014). Nonetheless, PV solar panels do create waste by-products such as acids, as well as CO_2 indirectly during production and disposal (Hosenuzzaman et. al., 2014).

Problem Statement

This study is to determine whether or not PV solar panels are sustainable given their consumption of rare earth metals, the future supply, future availability, and recycling rates of the metals.

Significance

There have been studies performed on the topic of metal availability for PV solar panels, however, the connection between increased future electricity demand, future predictions of the solar energy use, and element availability have not been discussed. This study will focus on second-generation PV solar cells for the purpose of examining the current and future sustainability of this electricity source for global use. As the demand for green, affordable electricity and energy increases it is expected that the use of PV solar panels will become more abundant globally (Nugent & Sovacool, 2013). Since this is a newer electricity source there are certain questions that need to be asked and answered; for example, what is the world's demand for PV solar panels; how much do we need to meet future demand in 2050? Are there enough available metals to produce the amount demanded?

This study aims to answer all of the aforementioned questions because, as society switches over from non-renewable sources, there needs to be information about how long this source can be used given the limited amount of metal resources. There also needs to be information on whether or not the switch to PV solar panels is feasible in the long term, and how much can be produced given the availability of required elements. This will give insight into how this source of electricity will globally impact the energy mix, as well as show that this green energy source is not guaranteed forever.

Research Question

1. Are there enough accessible metal resources to produce the amount of PV cells that will be demanded in the predicted future?

Hypotheses

1. The current and future availability of the required metals is not enough to sustain the growing demand for PV solar panels.
2. To have 50% PV solar there will need to be a decrease in global electricity demand and an increase in recovery to ensure it is a sustainable source.

Research Design

Common types and models of second-generation photovoltaic (PV) solar panels will be studied using a quantitative document analysis of the availability of cadmium, indium, tellurium, and gallium, and the metal intensity PV solar cells require. Then the future predicted electricity demand in 2050 will be used to estimate the amount of metal required to meet this. This will determine if PV solar power is sustainable or not based on available resources and production quantity. Peer-reviewed journal articles will be the primary source of information, supplementary data from other trusted sources will also be used but only to support the main findings. The main information will also be from recent articles between 2012 and 2019 to ensure the most up to date information is used in this study. Since this study is looking at global impacts and use of PV solar panels sources from all over the world will be used, given they are peer-reviewed.

The data collection is conducted via document analysis and shown in multiple charts to demonstrate the results. The study will determine how much of each metal is theoretically possible to produce, how much is available in reserves, and what will be needed in 2050. It will also determine the best method of recycling, which is defined as, “the method which yields the most metal recovery from the PV panels” in this study. This will give an estimation of how sustainable the PV industry is and how much will be left, if any, after 2050.

Theoretical Framework

As of 2015, CdTe and CIGS solar cells were only about 10% of the total solar power generation market, but due to their production potential and low cost the amount produced has been increasing yearly (Redlinger et. al., 2015). Every year more solar cells are manufactured, which increases the pool available to recycle metals from while simultaneously extracting more metals from the Earth (Tyagi et. al., 2012). Since metals take longer to form in the Earth than the 30-year lifespan of PV cells, eventually there will not be enough resources to sustain PV cell manufacturing if the cells are not recycled. That date is unknown due to events such as finding new reserves, better recycling methods for recovery, and electricity/PV cell demand.

CdTe and CIGS cells need a certain amount of each of the four metals to produce electricity. Using the World Wildlife Fund's (WWF) prediction of 50% of the world's electricity demand coming from PV solar power in 2050, the question is do we have enough to metals in and on the Earth as well as in current cells to reach that goal (WWF, 2011). A document analysis focusing on current known reserves, methods of recovery, and current electricity production vs. future demand will be performed to answer these questions. This includes a goal and scope definition, characterisation, and electricity output.

Scope, Limitations and Assumptions

Scope

The scope of this study will include only CdTe and CIGS solar cells, with a focus on cadmium, indium, tellurium, and gallium metals. This study will look at the global use of PV solar panels in relation to the aforementioned cells, so all countries with sufficient data will be included. Present data will be used to extrapolate future demand, use, rates, and possible technologies as the actual data is not yet known. The scope will not include the cost of metal extraction, recovery, or manufacturing of the PV cells. This study is focused on metal reserves and resources rather than the economic feasibility of the metal recovery.

Limitations

The first limitation is future data is not known and, as technologies are created quickly and change drastically, it is impossible to predict with 100% certainty where it will be at a given point in time. A second limitation is that the PV solar panels being recycled today are drastically different than the ones being produced today due to technology advancement; this may result in changes in the recycling process within another 30 years. The source of electricity for the production facilities will not be considered given the variance of locations that mass produce second-generation PV panels.

Assumptions

1. This study assumes that first-generation panels will no longer be used by 2050, and third-generation organic models will not be developed enough for global use within 50 years.
2. This study assumes trends predicted are correct, demands for energy and metals are accurate, and countries that do not have data will have similar future results to countries who currently use PV solar panels.
3. This study assumes metal reserve values are accurate and no new ones are found or exist.
4. This study assumes Compound Annual Growth Rates (CAGR) estimates from 2018 to 2025 are accurate, and the estimate CAGR from 2026 to 2050 is also accurate.
5. This study assumes metals are not used for any other product except second-generation PV panels.
6. This study assumes metal intensity values do not change in the future (panels do not increase in efficiency).

Summary

Generating electricity has caused environmental damage for centuries, now our society is attempting to find sources that are less impactful. PV solar energy is becoming more apparent as a future significant source of electricity worldwide, however, the required metals are not a renewable resource (WWF, 2011). This could limit the availability of PV solar as a global electricity source, as well as prevent reaching 50% PV solar by 2050.

Performing a document analysis on second-generation solar panels with the focus of whether or not it is a sustainable electricity source is necessary because alternative, green energy sources are where the world is heading towards (Steinbuks et. al., 2017). Canada is reliant on its tar sands because of the amount of money and resources that went to supporting that specific industry (Bisgaier, 2013). Now that oil prices have fallen the industry is in decline the country is forced to still extract to prevent huge economic losses (Bisgaier, 2013). It is important to avoid this similar scenario happening with solar due to a crash in the extraction or availability or the required metals, so knowing how long the PV solar electricity industry is sustainable is valuable information.

Definition of Terms

Second-generation PV solar cells: Thin film material types photovoltaic solar cells

Greenhouse gas: Gas (e.g. methane, carbon dioxide, nitrous oxide) that absorbs infrared radiation from the sun and radiates it within the Earth’s atmosphere causing warming by trapping heat.

Green energy source: A source of electricity that does not cause direct or indirect harm to the environment.

Sustainable: Ability to continue over a period of time.

Literature Review

Introduction

This chapter reviews the concept and current knowledge on second generation thin film photovoltaic (PV) solar panels. The mineral availability subject matter is well known as the four focus metals are used in many renewable energy sources, for example wind, thus the demand is expected to increase as the world switches to renewable energy (Steinbuks et. al., 2017). There is a formula, Eq. 1, that estimates the demand for solar panels based on current reserves, time, and demand (Valero et. al., 2018). This is used not just for current demand but can also be applied to the future to provide estimates of PV panels (Valero et. al., 2018). Recycling the panels to recover the rare metals in them is necessary to ensure future production and a sustainable energy source until at least 2050 (Granata et. al., 2014). Various methods are used to extract parts of panels, most focus on the glass and aluminum casing as that is the easiest to recycle, however other methods extract the rare metals (Granata et. al., 2014). Currently, the world relies on fossil fuels to reach the energy demand; nevertheless, it is moving towards renewable energy sources to meet climate goals and limit emissions (Henbest et. al., 2018). The future energy mix will likely include water, wind, solar, and other renewable sources, which will inevitably lower the world's reliance on fossil fuels (Jacobson et. al., 2017).

Mineral Availability and Photovoltaic Demand

A significant issue that is well known within the realm of renewable electricity is the requirement of earth metals and elements in the systems to increase efficiency (Steinbuks et. al., 2017). This is an issue because there is a finite amount of available global resources for these required elements, which leads to delayed and limited research and development of PV technology (Valero et. al., 2018). According to Valero et. al. (2018), the definition of resources is how much of the element is present in the Earth, whereas the reserves are the amount available for extraction and use. As aforementioned, cadmium, indium, tellurium, and gallium are the minerals that this paper is focusing on due to the increased efficiency of PV solar panels with their use (Tyagi et. al., 2012). The element reserves vary drastically but rely on the amount refined as well. Approximately 24,200 metric tons of cadmium are refined every year globally, and the global reserves are not fully known but are believed to be about 544 kilotonnes (U.S. Geological Survey, 2018; Blazev, 2016). The amounts on Indium in global reserves is between 15 and 30 kilotonnes, and there are between 1 part per million (ppm) and 100ppm of indium in every zinc ore deposit (U.S. Geological Survey, 2018). Global reserve of tellurium is approximately 31,000 metric tons but only 420 metric tons were refined in 2017 (U.S. Geological Survey, 2018). The global reserve of gallium is estimated to be around 100,000 metric tons, but only 315 metric tons were refined world-wide in 2017 (U.S. Geological Survey, 2018).

The demand for PV solar panels also affects how many panels will need to be produced; Valero et. al. (2018) created a curve of production based on their equation (Equation 1) which describes production in relation to the reserves (R) the unknowns time and demand (t_0, b_0) of which the maximum peak of production t_0.

Equation 1. $P_a{}^{(t)} = \frac{R}{b_0\sqrt{2\pi}} e^{\left(-\frac{1}{2}\right)(\frac{(t-t_0)}{b_0})^2}$

Using the bottom-up approach of equation 1 allows for the determination of the year when production decreases due to lack of reserves as well as an approximation of the future (Valero et. al., 2018). One useful application of this equation is determining if there are enough reserves to support the demanded production given the amount extracted yearly (Valero et. al., 2018).

The World Energy Council's *World Energy Resources* report in 2016 stated that Cadmium, Gallium, and Tellurium all have a high risk of causing supply constraint to the global solar industry, while Indium was rated at a medium risk (World Energy Council, 2016). This means that all four metals in this study pose a risk to hindering the development and execution of a global scale solar reliance (World Energy Council, 2016). Global solar electricity capacity in 2015 reached 227 GW, however, to reach 50% of the global demand by 2050 the capacity would have to increase by about 200GW per year (International Energy Agency, 2014). To reach this level of growth the demand for the rare metals would also increase exponentially with the PV growth (International Energy Agency, 2014). Another limitation to increasing global capacity quickly is the cost of the infrastructure; one estimate is $850 million CAD per GW in 2014 (National Energy Board, 2016). Many countries, companies, and individuals cannot afford such a high cost; however, the price has significantly decreased in the last decade due to new evelopemnt and is expected to continue that trend (National Energy Board, 2016).

Recycling Methods and Metal Recovery

Recycling the elements used in PV solar panels would reduce waste and their ecological footprint and would also increase the resources as there would be more available for future use (Valero et. al., 2018). There are different methods of recycling PV solar panels, for example some do not involve the recovery of elements but rather recycling the glass components by crushing the panel (Granata et. al., 2014). This method results in the inability to recycle the rest of the electrical components or elements within the panel (Granata et. al., 2014). It is a better disposal method than wasting all components, but it does not solve the issue of lack of mineral availability (Granata et. al., 2014). Disassembling PV panels are the most common form of recycling, yet it creates other waste outputs; it requires the transport of old panels, separation of the glass from the PV panels, and extraction of the reusable elements to fully recycle the PV panels (Choi & Fthenakis, 2014). Extraction of cadmium and tellurium can require sulfuric acid and hydrogen peroxide solution "baths" respectively to create precipitate for collection (Choi & Fthenakis, 2014). The extraction of gallium and indium from CIGS cells sometimes use acid leaching which causes separation in aqueous form (Zimmermann et. al., 2014). The baths are reused twice which reduces the waste, but the peroxide and acid wastes eventually have to be treated to ensure they do not contaminate the environment (Choi & Fthenakis, 2014). Recovering precious metals from used PV panels is viable to extend the use of the limited resources given the amount recovered and the cost associated with the reclamation (Simon et. al., 2013). Figure 1 illustrates the step by step general process of recovering the four earth metals from the PV cells, and is based on Xu et.al.'s (2018) work.

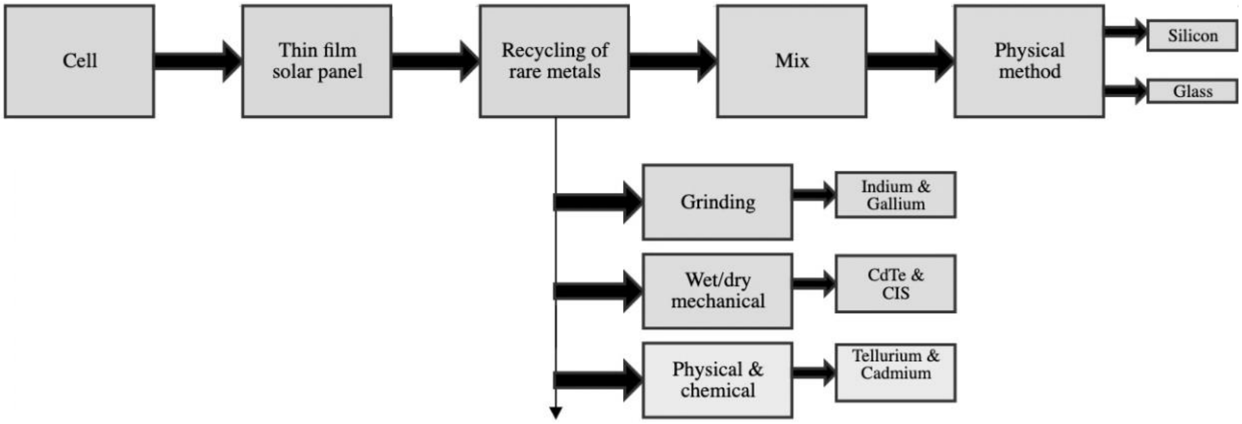

Figure 1. Modified flow chart from Xu et. al. (2018) depicting the general step-by-step process on second generation PV panel recycling and metal recovery.

Currently, there are minimal local and national policies and laws that necessitate solar panels to be recycled, and no policies that require the extraction of rare metals (Xu et. al., 2018). Recycling of panels and development into better methods is currently highest in Japan, the United States of America, and Europe (Xu et. al., 2018). There is an overall lack of commitment to recycling the end-of-life (EOL) solar panels, which is shown by not only the lack of policies requiring such but also the lack of places to take old panels to (Xu et. al., 2018). Solutions to this would be to create a recycling plant for solar panels or upgrade current waste management buildings to accommodate EOL panels (Xu et. al., 2018). Given the growth rate of the demand, and thus production, of these products has increased at a rate faster than any other renewable energy source there should be EOL management policies and plans in place before the 30-year lifespan is up and more panels will need to be replaced (Xu et. al., 2018). Within these plans, the requirement of extraction of rare metals in the panels would need to be in place to extend the ability to provide the world with solar powered energy (Xu et. al., 2018).

Electricity Demand and Energy Mix in 2050

World energy demand is expected to increase from 2.854TW in 2018 to approximately 4.418TW in 2050 (Henbest et. al., 2018). This is in part due to increasing population, increased access to electricity, and development within emerging countries in South Asia, the Middle East, and Africa (Henbest et. al., 2018). This is contrasted to the plateaued demand expected of the OECD (Organization for Economic Co-Operation and Development) countries, they are expected to have an overall decreased demand as efficiency increases (Henbest et. al., 2018). A roadmap released by Stanford University focused on the 2050 potential of the renewable sources wind, water and sunlight (WWS) (Jacobson et. al., 2017). The paper suggests the need for global implementation of renewable energy by using a mix of renewable sources and not a focus solely on solar; this could be done by policy changes such as carbon taxation (Jacobson et. al., 2017).

Land area for PV is an important consideration as many countries do not have enough of geographic area to allocate to PV systems; however, the land footprint required to meet the 50% goal would be about 0.22% of the world’s land area (Jacobson et. al., 2017). This land use does not come without trade-offs as the land could be used for other needs such as agriculture or housing (Hoffacker et. al., 2017). Even photovoltaics on water would results in trade-offs as there would be a loss of potential fishing area, loss of sunlight in the water cause harm to aquatic species etc.

(Hoffacker et. al., 2017). This being said, there are some areas on Earth's surface that could create useful land out of soiled land (Hoffacker et. al., 2017). For example, areas affected by nuclear disasters that are inhospitable could be used as land area for solar farms; resulting in the trade-off minimal and the land becomes more useful (Hoffacker et. al., 2017).

Certain countries are aiming to decrease emissions to ensure the peak CO_2 level is in the year 2050, scientists in Stockholm, Sweden have their own roadmap broken down by decade (Rockström, 2017). From 2017 to 2020 would involve the global implementation of climate policies such as cap-and-trade, feed-in tariffs, and quotas (Rockström, 2017). The primary goal of this stage is to change the global political view and actions utilizing the United Nations Framework Convention on Climate Change (UNFCCC) as a medium for countries and organizations to discuss the global roadmap (Rockström, 2017). Ending fuel subsidies by all countries is also an important step in this decade as G7 countries lower their reliance on fossil fuels (Rockström, 2017). In 2020, the goal is to have over one hundred industrialized cities across the world implement a decarbonization plan by 2050, this is to ensure a prioritized path (Rockström, 2017).

Methodology and Methods

Methodology

This study aims to determine the amount of cadmium, tellurium, gallium, and indium that will be available for photovoltaic (PV) solar cells; to do this a document analysis is performed. A document analysis was chosen because of the availability of information about metal resources, the materials needed for PV cells, and future electricity goals. However, there is a lack of complete analysis on the reserve amounts, the requirements for PV cells of each metal, and if there are enough of each to produce 50% of the world's electricity in the year 2050. Performing a document analysis on the known reserves and recycling methods and combining the information with renewable energy goals will give a full picture of the extent of the metal availability and the feasibility of a 50% solar electric world. Once the document analysis is completed the data will be collected into a global future stance for the required metals and PV infrastructure.

Methods

Document Analysis – Data Collection

A document analysis will be used to collect information about the specific metals needed for the production of CIGS and CdTe cells. Target information is reserve abundance, current and future demands of energy and metals, production levels, metal intensity [kt/GW], recycling methods, and compound annual growth rates (CAGR). All documents used are from 2012 or sooner and are either peer-reviewed or from a reliable institution, the main databases being used are Science Direct, NovaNet, and ProQuest. Grey literature is used to obtain statistics or hard numbers rather than core information about PV solar cells and recovery methods. Increasing demand for electricity is considered based on the industrialization of developing nations as well as the expected population increase.

Information that is being collected about the four main metals gives an indication as to how sustainable the PV solar industry is and will be in the year 2050. Knowing the amount in reserves gives information about how long we will have access to solar electricity as the PV cells require the metals to create electricity (Tyagi et. al., 2012). This information is collected from various reports globally, as well as some estimates as they are by-products of other mined metals. The production of each metal is used to estimate the amount of PV cells manufactured every year, which will then give an estimate to the amount of electricity produced via PV cells in that given year. Target values are the current amount of electricity produced (in 2018) by PV solar cells as well as how much will be needed to be produced in the year 2050 to meet 50% of the global electricity demand. Based on the yearly production values of each metal, the total reserve amount used gives an indication of how many years left of each metal if used towards PV cells if no metal recovery takes place. Since there are current metal recycling methods used to remove metals used in old PV cells the availability of the metals over time is longer than if they were not recovered (Tyagi et. al., 2012). Therefore, recovery methods are analysed to determine how much of each metal is recycled in each cell to be reused again which extends the length of sustainability of PV cells (table 1). Since there are a significant amount of methods currently being used and an unknown amount of future methods that will be used between now and 2050, the best method recovery rate is used based off of multiple sources and methods. Table 2 lists at least four end-of-life (EOL) recovery methods for each metal, with the best-case scenario, is used in this study.

Table 1. Known information of the four main PV cell required metals.

	Tellurium	**Gallium**	**Indium**	**Cadmium**
Known Reserves (kt)				
PV Demand [2014] (kt)				
Global Production [2014] (kt)				
Past Production [1972-2014] (kt)				
Total used for PV [2014] (kt)				
Percent used for PV [2014]				
Material Requirements in 2050 (kt)				
Capacity (EOL recycling) pre 2050 (kt)				

Table 2. Various metal recycling methods of end-of-life PV panels.

Recycling Method (EOL)	**Tellurium**	**Gallium**	**Indium**	**Cadmium**
Evaporation with Chloride and Heat (CIGS)				
GaCl3 production with NH4Cl and Al2O3(CIGS)				
NH4Cl Separation (CIGS)				
In Separation from Co with Residual Ga (CIGS)				
Ca Removal Via Wound Wire Rotation (CIGS & CdTe)				
Penicillium chrysogenum Microorganisms via Leaching (CdTe)				
Acidithiobacillus ferrooxidans Microorganisms via Leaching (CdTe)				
Acidithiobacillus thiooxidans Microorganisms via Leaching (CdTe)				
Penicillium simplicissimum Microorganisms via Leaching (CdTe)				
Crush and Separate via Chemical Dissolution, Mechanical, or Precipitation (CdTe)				
Chemical Stripping of Te via Electrodeposition (CdTe)				
Separation and Flotation of Metals (CIGS & CdTe)				
Recycling from Residuals and Production Excess (CIGS & CdTe)				
Recycled from Municipal Solid Waste in the USA (CIGS & CdTe)				
5N Plus Company Method				
Best Case Recycled Rate				

Electricity production from CdTe and CIGS PV cells vary based on location, model, and weather, thus, the average production of the cells based on 20 large producers is used (table 3). The global electricity demand and population in 2018 are used as a baseline demand to compare the 2050 electricity demand based on projected global population. Since there are currently countries in transition towards a developed economy and developing nations becoming transition nations there will be an increase in global electricity demand per person (United Nations, 2018). This increase is estimated based off the World Economic Situation and Prospects report from the

United Nations which estimates the future development of all nations in the next few years, as well as the New Energy Outlook 2018 report from Bloomberg New Energy Finance (2018).

Table 3. Average electricity production of CIGS and CdTe cells, in Watts, from 20 common producers (U.S. Department of Energy, 2018).

Output (W)	Minimum	Maximum	Average of all Models
Amerisolar	240	330	285
Axitec	250	350	287
Canadian Solar	225	350	287
Centro Solar	250	320	278
China Sunergy	290	320	306
ET Solar	250	340	295
Green Brilliance	230	300	266
Hanwha Q CELLS	245	390	304
Hyundai	220	360	283
Itek Energy	270	370	311
Kyocera	260	330	295
LG	275	405	337
REC Solar	240	350	289
Rene Solar	245	320	277
Renogy Solar	250	300	268
Seraphim	255	340	294
Silfab	250	370	305
Solar World	250	350	293
SunPower	235	435	337
Trina Solar Energy	245	345	284
Total Average			**294.05W**

The total amount of global electricity demanded in one year estimated from the aforementioned report is used to compare the amount available to be produced by the PV cells based on the yearly metal production. This then shows whether or not 50% of the electricity demand in 2050 can be met by PC solar cells given the availability of the four required metals if they are only used in PV cells.

Data Assembly

Data assembly is being performed to create utilisable data from many sources into one, larger set of data to determine the sustainability of the second-generation solar photovoltaic design. The first step being performed is calculating the theoretical production from 2014 to 2050 using the compound annual growth rate (CAGR) for each metal. The most current predictions give CAGRs from 2018 to 2025, since this is not a long enough time frame a second CAGR from 2026 will be used with an increase of 0.50% for each metal to use for the years 2026 to 2050. The 0.50% increase estimate comes from the global consensus that the use of PV panels will increase over time, thus increase in the required metals will also increase. The exact amount, however, cannot be known, so a conservative CAGR of 0.50% is used to predict a production level lower as to not overestimate the future demand. Equation 2 is used to create the 2050 production estimate.

Equation 2. $((\text{Year } n)*(\text{CAGR}_{\text{metal}})) + (\text{Year } n) = \text{Year } n+1$

The second step performed is the 'best method' recycling rate of each metal is multiplied by the total theoretical production of the metal from 2014 to 2049. It is then added to the year 2050 production to give the total theoretical supply in 2050 given all panels in the years 2014 to 2049 have been recycled via the best method rates. Equation 3, as described above, used is:

Equation 3. $((\text{Year } 1 + \ldots + \text{Year } 35)*(\text{Recycling Rate})) + (2050 \text{ production}) = \text{total metal supply in } 2050$

The supply of the panels is then compared to each metal intensity (mass of metal required to produce one unit of power) to determine the demand for each metal based on 50% of the predicted 2050 energy demand of 2.209TW (Henbest, 2018). The metal intensity is determined based on the average of 3 studies. Equation 4 is used to determine the mass in kilotonnes:

Equation 4 $(\text{Metal Intensity}_{\text{metal}} \text{ [kt/GW]})*(2209\text{GW}) = \text{kt}_{\text{metal}} \text{ demanded in } 2050$

This value is important because it gives the projected demand of each metal in 2050, whether or not that can be met is determined by comparing the demand by the known reserve amount.

The third step determines if the 2050 production can meet the energy demand given the metal intensity and theoretical production. Equation 5 shows this is done by multiplying the 2050 metal demand by the inverse metal intensity to get how many GW that amount of metal can produce.

Equation 5. (2050 metal demand [kt])$*$(1/Metal Intensity [kt/GW]) = Power production potential [GW]

Once the values are calculated it will provide insight into how much excess or shortage of metals the world can produce, or if production can even meet the predicted future demand given reserve values.

Results

Introduction

The purpose of this study is to provide further information to be able to attempt to answer two questions; are there enough accessible metals to produce enough photovoltaic solar panels to power 50% of the worlds power demands, and how many photovoltaic (PV) panels will be required to meet that demand. This was done by gathering information from various sources and previous studies and compiling it using equations, comparisons, and using answers to create three final results. Theoretical metal production in 2050, the recycled supply of metals, and what the global known reserves can produce if fully extracted.

Theoretical Metal Production – 2014 to 2050

As previously stated, as the demand for PV solar panels increases the demand for tellurium, gallium, indium, and cadmium also increase. The reason this is a theoretical production value because it does not take into account the global known reserves. The compound annual growth rate (CAGR) of tellurium from 2018 to 2025 is 3.00% and estimated to be 3.50% between 2026 and 2050; the best method recycling rate was determined to be 97.00%. The CAGR of gallium from 2018 to 2025 is 4.30% and estimated to be 4.80% between 2026 and 2050; the best method recycling rate was determined to be 100.00%. The CAGR of indium from 2018 to 2026 is 2.50% and estimated to be 3.00% between 2026 and 2050; the best method recycling rate was determined to be 94.00%. The CAGR of cadmium from 2018 to 2026 is 4.30% and estimated to be 4.80% between 2026 and 2050; the best method recycling rate was determined to be 98.50%. As stated in the methods chapter, the theoretical production amount uses the appropriate CAGR as well as the best method recycling rate. Figure 2 displays the increase of tellurium, gallium, and indium production, which have 2050 theoretical production of 35.163kt, 42.271kt, 56.544kt respectively. Figure 3 displays the increase and 2050 theoretical production of cadmium, which is 3076.131kt.

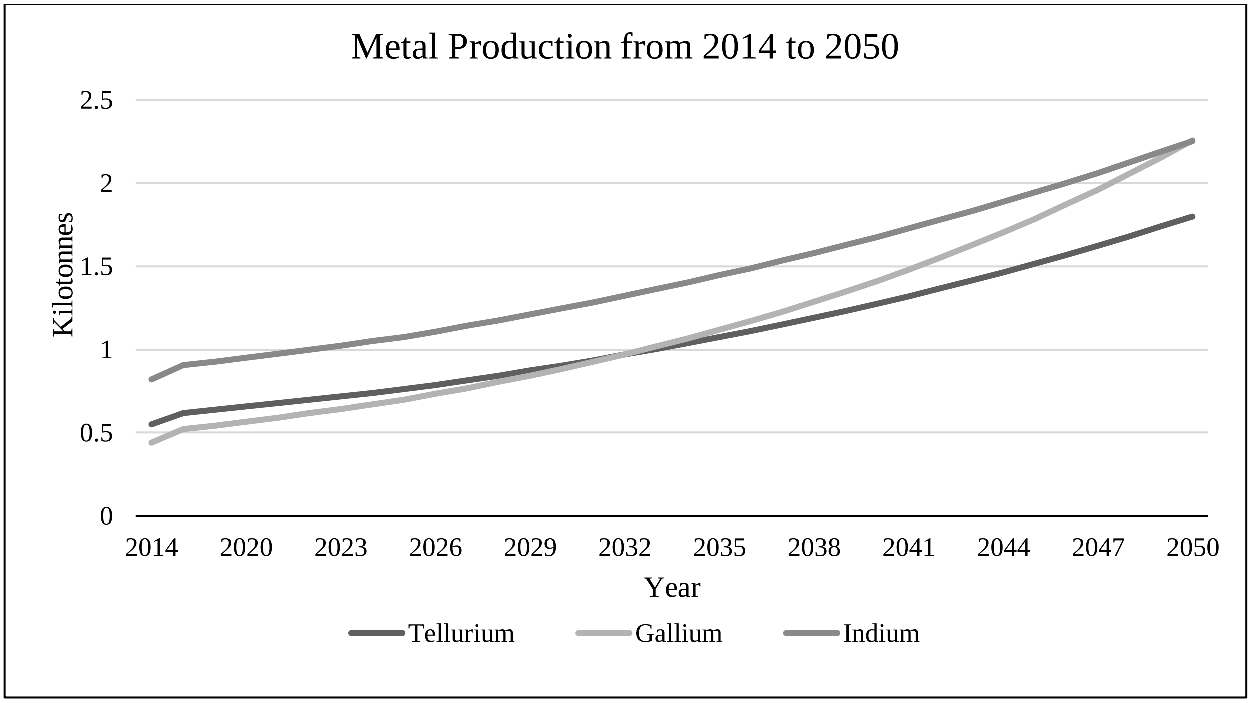

Figure 2. Predicted metal production increase of Tellurium, Gallium, and Indium from 2014 to 2050 (Technavio, 2018)(Shah, 2019)(Acumen Research and Consulting, 2019).

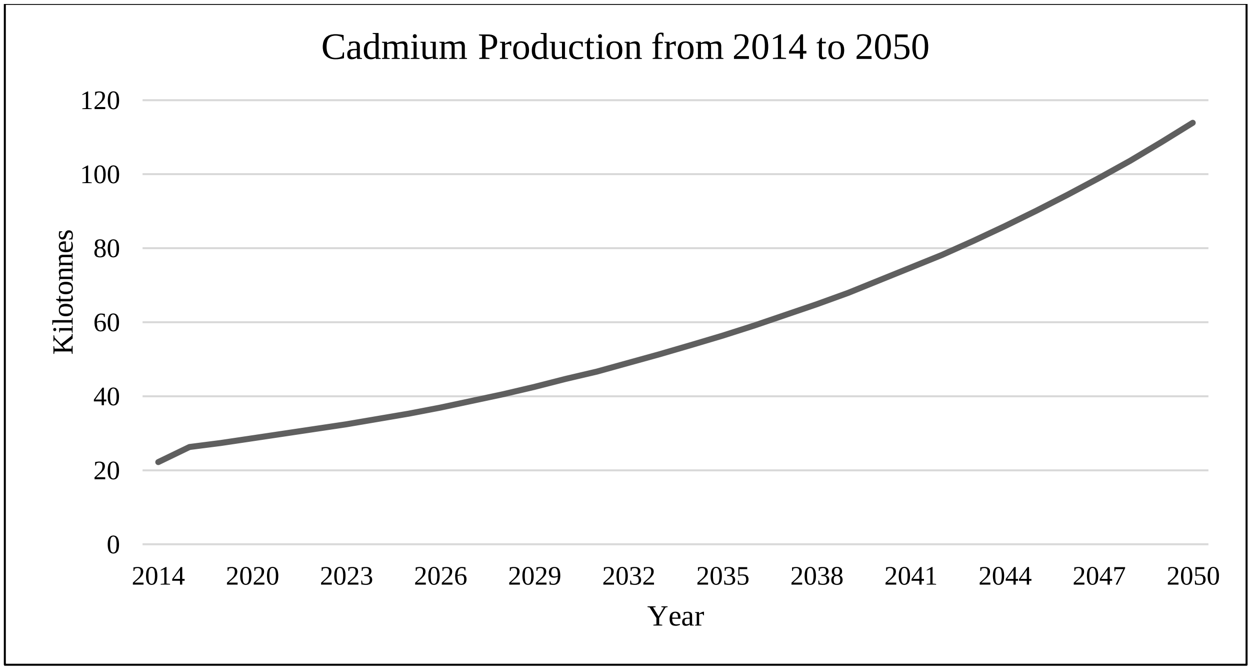

Figure 3. Predicted Cadmium production increase from 2014 to 2050 (Cullen & Maldonado, 2013).

Metal Reserves, Supply, and Demand

Metal reserves are a limiting factor to PV panel production, so even if there is a high theoretical production value it may not be possible because the amount present in the Earth is lower. The known global reserves of tellurium, as seen in figure 4, total 24kt (Davidsson & Hook, 2017). In 2050 the total supply (production) with recycling is 35.163kt, therefore there is a shortage of 11.163kt. The demand for tellurium in 2050 was determined to be 335.768kt, which is 300.605kt more than production and 311.768kt more than the reserves.

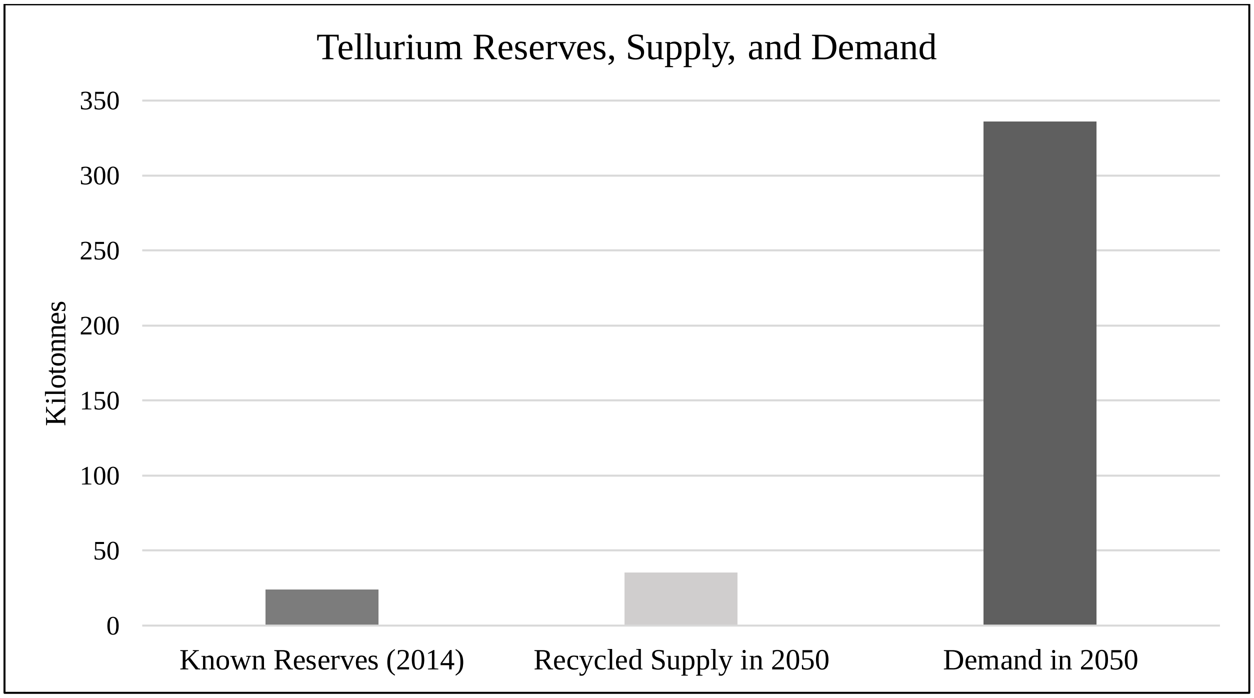

Figure 4. Tellurium geological reserves, recycled supply, and demand in 2050 (Davidsson & Hook, 2017) [2](Henbest, 2018).

The known reserves of gallium, as seen in figure 5, total 1873.34kt (Davidsson & Hook, 2017). In 2050 the total supply (production) with recycling is 42.271kt, therefore there is a surplus of 1831.069kt. The demand in 2050 was determined to be 19.881kt, which is and 22.390kt less than the supply and 1853.459kt less than the reserves.

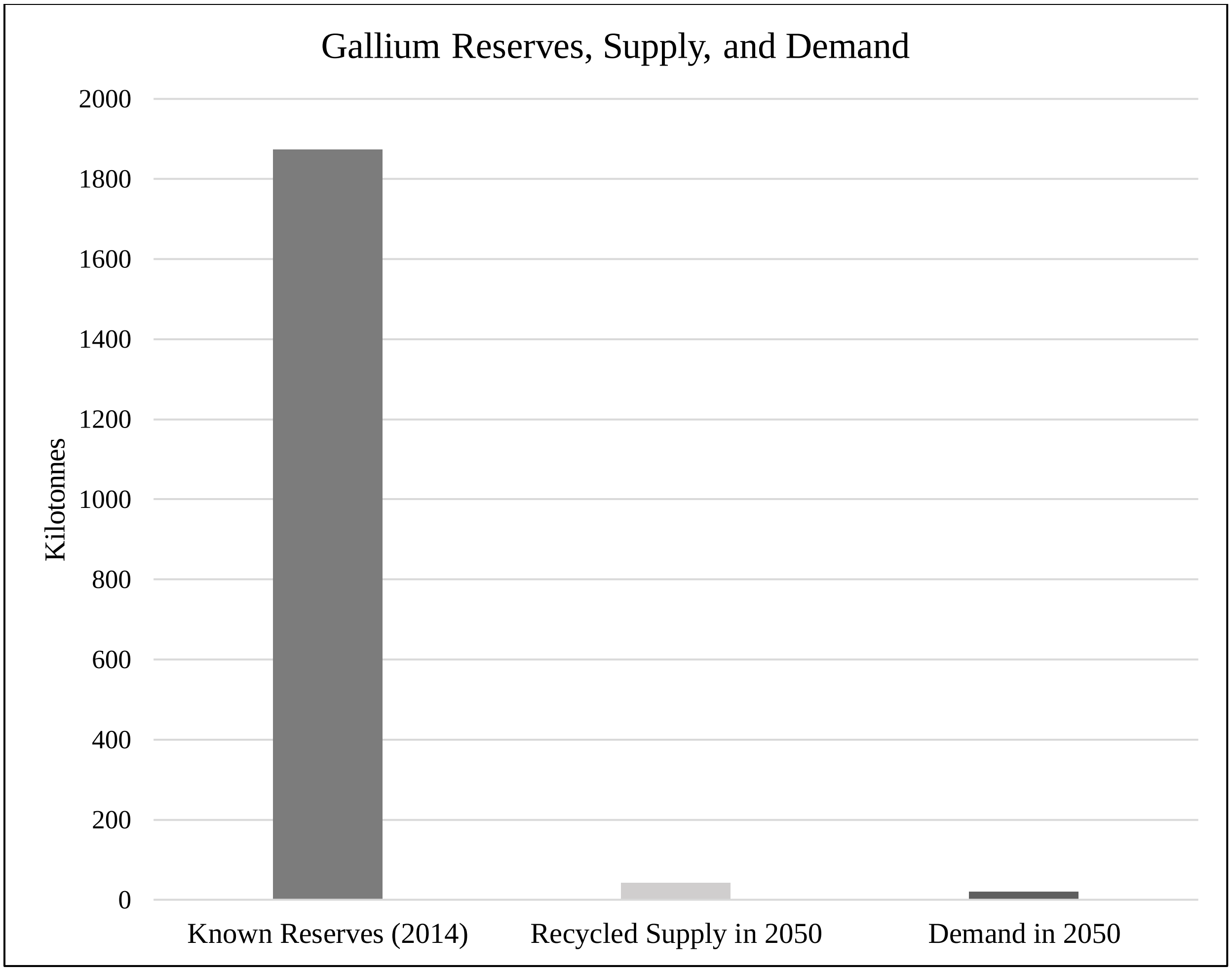

Figure 5. Gallium geological reserves, recycled supply, and demand in 2050 (Davidsson & Hook, 2017) 2(Henbest, 2018).

The known reserves of indium, as seen in figure 6, total between 15 and 30kt (Davidsson & Hook, 2017). In 2050 total supply (production) with recycling is 56.544kt, therefore there is a shortage between 26.544kt and 41.544kt. The demand in 2050 was determined to be 57.434kt, which is 0.890kt more than the supply and between 27.434kt and 42.434kt more than the reserves.

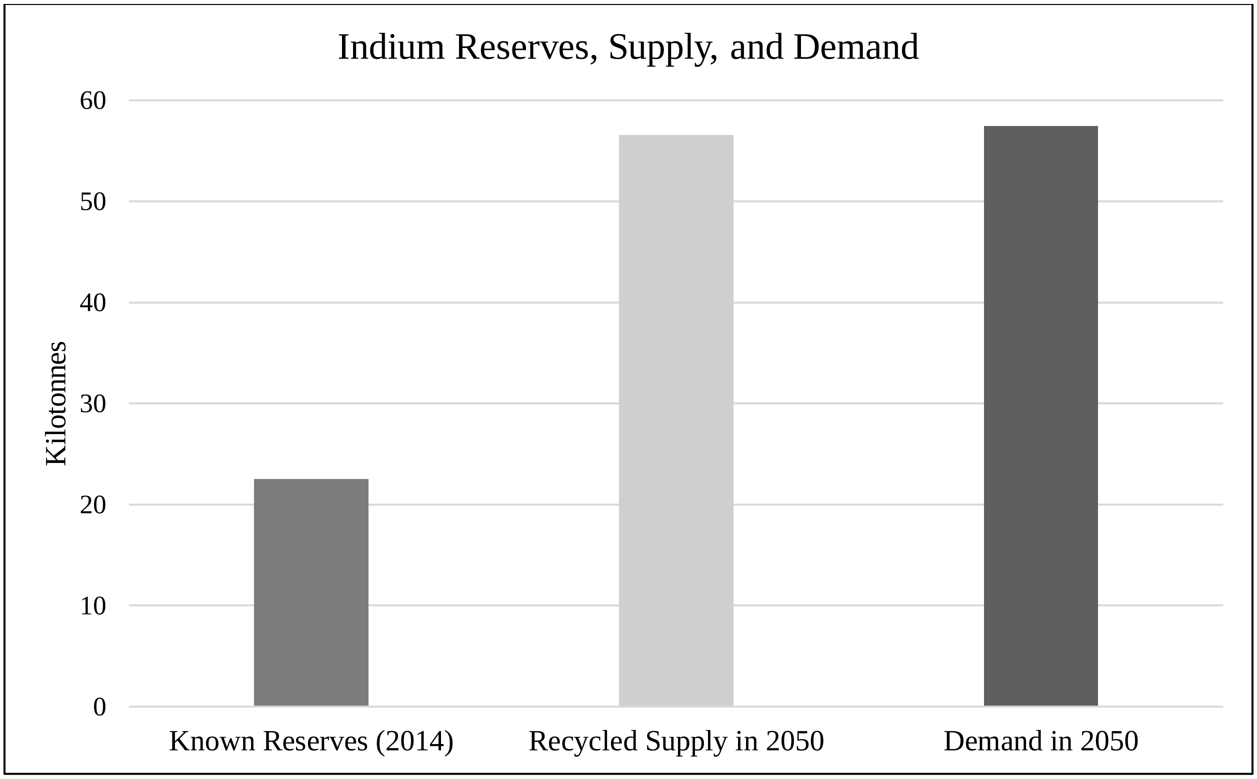

Figure 6. Indium geological reserves, recycled supply, and demand in 2050 (Davidsson & Hook, 2017) 2(Henbest, 2018).

The known reserves of cadmium, as seen in figure 7, total 544kt (Davidsson & Hook, 2017). In 2050 total supply (production) with recycling is 3076.131kt, therefore there is a shortage of 2532.131kt. The demand in 2050 was determined to be 304.842kt, which is 2771.289kt less than the supply and 239.158kt less than the reserves.

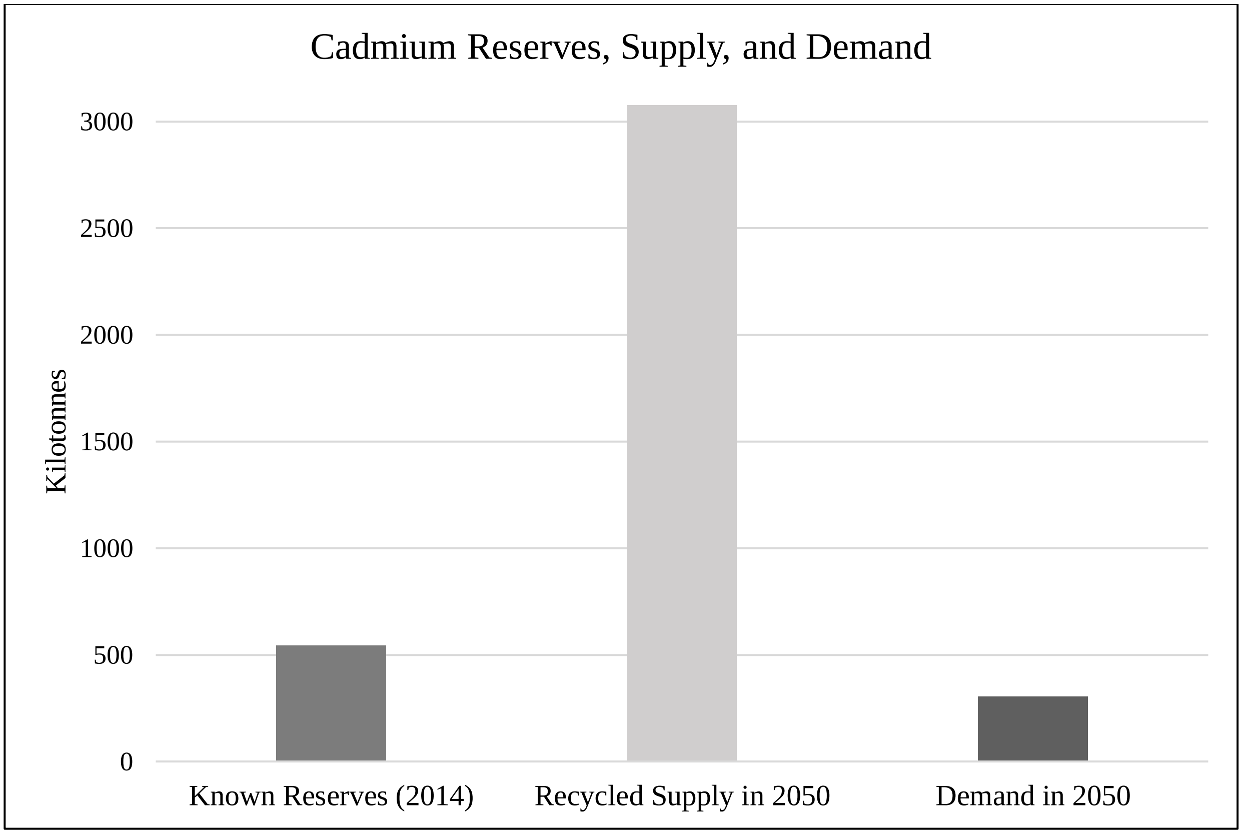

Figure 7. Cadmium geological reserves, recycled supply, and demand in 2050 (Davidsson & Hook, 2017) 2(Henbest, 2018).

Panel Output, Cost & Metal Intensity

Henbest (2018) reported that 50% of the global energy demand in 2050, 2209GW, can be used to estimate the number of panels that would be required to meet that goal. The United States Department of Energy provides the output of 20 of the most utilized solar panel companies, the average of all the brands and their models came out to be 294.05W. Therefore, to meet 50% of the demand the global infrastructure would have to equal 7.5×10^9 panels. The average cost of installing solar panels in Canada is $3.07/W without including any tax reduction or incentives (National Energy Board, 2019). To install 2209GW worth it would cost the world $6.78 quadrillion in the next 31 years to install enough solar panels to reach this goal.

Using the estimated 2050 energy demand of 2.209TW (2209GW), the metal demand (in kt), and the known metal intensities (kt/GW) the power production potential of the metal's 2050 supply was calculated. If the theoretical production level of tellurium was met, and it was the limiting factor it would be able to produce 222.551GW based on the metal intensity of

0.158kt/GW. If the theoretical production level of gallium was met, and it was the limiting factor it would be able to produce 4696.778GW based on the metal intensity of 0.009kt/GW. If the theoretical production level of indium was met, and it was the limiting factor it would be able to produce 2174.769GW based on the metal intensity of 0.026kt/GW. If the theoretical production level of cadmium was met, and it was the limiting factor it would be able to produce 22290.804GW based on the metal intensity of 0.138kt/GW.

Discussion

Introduction

This chapter discusses the results in more depth, with the goal of stating whether or not second-generation photovoltaic (PV) solar panels are sustainable. The production of tellurium, gallium, indium, and cadmium results are discussed further to emphasis any discrepancies, supply problems, and demand. The method of recycling of solar panels varies not only globally but locally, so even if the best method is used to get the results of this study other methods are discussed in this chapter. The significance of the results is reviewed as it shows why this study is useful not only in the future but also now. This leads to other areas of study and discussion could go given the results, as well as difficulties that happened in this study. Finally, general conclusions are made and briefly discussed.

Intention of this Study

The intention of this study was to determine if second-generation PV solar panels were sustainable given metal availability, recycling, and increased production, as well as determining if PV panels could power 50% of the world's demand in 2050.

Results

Production of Metals in 2050

Using the current compound annual growth rate (CAGR) of each metal allowed for a reasonable estimate of production from 2018 to 2025, after this point an increase of 0.5% was used from 2026 to 2050. This was a conservative estimate as it is likely that each metal's CAGR would increase much more to reach the production levels required to produce 2209GW of power. Therefore, the production levels of each metal could be much higher in the year 2050 than the results stated due to the low-end estimate. Even if the results are accurate the amount in the reserves for tellurium and indium would still hold back the production seen in figures 2 and 3.

The reserves of tellurium and indium are not large enough to support the growing PV panel production. If all tellurium reserves were emptied, they could only extract 24kt (Davidsson & Hook, 2017). This clearly shows it would not come close to the 2050 (conservative) demand calculation of 335.77kt. The known reserves of indium were the most varied and there is not an exact known amount but rather a range; this poses an even bigger margin of error since the reserve amount ranges somewhere between 15 and 30kt. Even if the larger reserve estimate of 30kt was used and fully extracted, there still is not enough to meet the 2050 demand calculation of 57.43kt. These two metals prove a treat to the sustainability of the PV industry as there is not enough physical supply to support and industry that may grow to produce 50% of the world' energy demand.

The known reserve volume of gallium and cadmium would be enough to supply the calculated 2050 demand even if the reserves were not fully extracted. Known reserves of gallium total 1873.34kt and the 2050 calculated demand is 19.88kt which is considerably lower (Davidsson & Hook, 2017). Therefore, this metal is not likely to threaten the sustainability of the PV industry before 2051. Known reserves of cadmium total 544kt with a calculated 2050 demand of 304.84kt (Davidsson & Hook, 2017). This is not as large of a difference as gallium, but it is large enough that the supply for cadmium will not be a hindrance to the PV industry before 2051.

Recycling

The recycling of all four focus metals is based on the calculated production from the CAGRs and production amount in 2014. For tellurium, indium, and cadmium the recycled supply is then larger than the known reserves. Consequently, the determining factor for these metals is the restriction of availability of metals in the Earth rather than production or lack of recycling. Gallium has a large global reserve and thus the production and recycling of this metal are what limits its availability rather than physical supply.

Tellurium's best method of recycling provides a recovery rate of 97%, this means that per panel 97% of the tellurium in it gets recycled for secondary use. This, however, may not be the case for all recycling sites or countries as methods ranged from 0% to 97%; therefore, some places may not recycle tellurium at all whereas others recover almost all of it. The chance that not all methods use the highest recovery rate lowers the available metals in the future, but since the reserves are so low in comparison to the supply with best method recycling the likelihood of the range discrepancy does not affect supply as much as the small reserves do.

Gallium's best methods of recycling provides a recovery rate of 100%. Thus, if this method is used for every solar panel the reserves will never be depleted due to PV use as the recycled supply is more than the calculated 2050 demand, as seen in figure 5. The range of recovery of 5 different recycling methods was 1.4% to 100%, therefore, it is likely not all gallium is recovered. Though, as already stated, the reserves of gallium are so large that the metal is not a concern for the PV industry up to 2051.

Indium’s best method of recycling provides a recovery rate of 94%, however, the recycled supply is still significantly more than the global reserves as seen in figure 6. The recovery rates for four different recycling methods ranged from 1% to 94%, but since the reserves are the limiting factor the low recycling rates for some methods is not the factor limiting future PV production. The sustainability of indium in the PV industry is based on how much volume is left in the reserves, and thus the need for recycling metal already extracted is still important.

Cadmium’s best method of recycling provides a recovery rate of 98.5%, however, this provides a supply significantly more than the known global reserves. Therefore, the reserves are the limiting factor of this metal since it is not possible to recycle and produce more than is physically present in the Earth. The range of four recycling methods of cadmium is from 14% to 98.5%; since the reserves of 544kt are not much more than the 2050 demand of 304.84kt, recycling is important for this metal to ensure the sustainability of the PV solar industry.

Significance of Results

These results are significant because they provide insight into the future availability of tellurium, gallium, indium, and cadmium on the global scale in reference to PV energy. This study predicts that tellurium and indium reserves will not be able to supply enough to reach the demand in 2050, and gallium and cadmium reserves will be able to. The use of this data provides knowledge of the need to recycle the current PV panels in use, as well as the data to suggest that the 50% solar by 2050 goal may not be feasible given current production rates and metal reserves.

Study Impediments, Difficulties, and Possible Improvements

Impediments

The main impediment for this study was the lack of free, accessible information for the general public. A significant number of databases were blocked unless you were part of a business, organization, or paid for access. Since paying for information was not viable for this study, either information about PV was not included due to it being inaccessible or it was sourced through secondary parties who had access and provided statements with that information included. Finding free, credible sources with the specific data included impeded this study and added a significant amount of time to the research process. Another impediment to this study was that the timeframe of most academic papers ended around 2025; however, the timeframe and scope of this study is from about 2014 to 2050. Therefore, a lot of the estimates did not go far enough into the future and another realistic prediction had to be made from the years 2026 to 2050. This possibly dilutes the results as the data gets farther from the present, however, this is what the study had to use given there is no possible way to know the future data with absolute certainty. The third impediment to this study was the available literature, in general, is about the first generation of PV solar panels; this generation consists of crystalline silicon cells that do not focus on the use of the four metals of this study. There was enough data about second-generation PV cells, but more solar panels that are in use today are first-generation (Tyagi et. al., 2012). Given their higher use, more information on recycling and resource availability is known then the newer second-generation (Tyagi et. al., 2012).

Difficulties

One of the most time-consuming difficulties of this study was finding out the specific information for not just one rare metal but four. Finding the reserves for cadmium was difficult because it is such a universally used metal across electronics that countries such as the United States do not release their reserves freely (U.S. Geological Survey, 2019). Therefore, to determine the known global reserves the calculation of how much is extracted from zinc cores is used to determine reserve mass (U.S. Geological Survey, 2019). This had to be done for the reserves of indium as well, however, the calculation was a lot harder to conclude given varying results from multiple sources. Assembling the data into coherent graphs and charts was also difficult due to ensuring all data was accurately sourced and included. Though this is not shown much in the results, the appendix section gives a slight insight into the challenges associated with collecting large amount of data from various sources. The most difficult part of this study was deciding on reasonable, educated future predictions of metal demand and production based on known data, past growth, and future increased demand for PV panels. This also had to be done using conservative estimates because of the high probability of the estimates and predictions not being 100% accurate. Ensuring that the data provided from this study is as accurate as possible required conservative estimates with reserve and production data that cannot be entirely known. Thus, creating results that can be used to make decisions about future use of second-generation PV panels was difficult in its entirety.

Potential Improvements on this Study

There are many improvements that could have been made to better this study, though due to the timeframe allowed and the resources available it was limited. One such improvement was to reduce the timeframe from 2050 to 2025. This could have been more in line with current estimates and predictions, which may have given more accurate results. However, this study's goal was to determine if it is possible to supply 50% of the 2050 energy demand using PV solar. Limiting this timeframe would have changed the entire purpose of the study, or given a stepping stone to the data for 2050. Another improvement of this study would have been to purchase the articles as they are primary data for reserve amounts, demand data, and production rates and growth. There was no funding for this study so, as stated above, the access to this primary data was not possible.

Another way to have improved the accuracy of this study would have been to include all three generations of PV solar panels as they are likely to be used in 2050 to reach the goal. There is limited data about the third-generation as it is so new still and not widely produced, so information on this generation would have been even more restricted. The first-generation panels are used more today because they were the first commercially available, this being said they are less efficient thus more companies and producers are focusing on the use of second-generation panels (Redlinger et. al., 2015).

Including a supply chain of the metals to document where they come from thus predicting possible supply issues would benefit the knowledge of the social accessibility of the metals rather than how sustainable they are. Using the location of origin would be useful for the tracking of environmental damage due to shipping and using that for sustainability reasons would be logical, however that could be another study in and of itself.

Restricting the study down to one rare metal may have improved the study as there would be more focus on that one metal. Nevertheless, this would not allow for the comparison of use nor the broad knowledge that more than one metal is constricting the future use of PV electricity production. Including the financial considerations of mining and using 1 or 4 metals would have broadened the use of this study including the environmental sustainability of PV panels, but this is outside the scope of this study as it would have included too much to include in such a short study.

A final improvement on this study would be to reduce the number of assumptions made at the beginning. Seven assumptions were made to ensure the final results made sense using predictions of the future and current known data. Though the option to open the scope more to state that the focus metals are also used in other products is possible, it would create a much larger study that would require wither large generalizations about electronics or mass amounts of data and various models and makes of a multitude of items. This is why the assumptions were made, though there is a lot they are all reasonable given current knowledge and the inability to accurately know the future.

Further Areas of Study

There are many topics within the realm of the sustainability of PV solar panels, due to the scope of this thesis there are others outside that could be analysed at a future time. This paper bases some future predictions of the World Wildlife Fund's (WWF) *The Energy Report*, however, there are at least two other world scenarios that should be researched. The first being that the WWF overestimated the need for energy thus requiring fewer PV panels to power the world, which would mean PV solar electricity would have a lower environmental impact due to the lower demand. The second scenario would be that the WWF underestimated the future electricity demand, which would require more PV panels to reach the 50% solar electricity model thus increasing the global impact.

The societal impacts of increasing PV production and mining use globally as well as decreasing the production of fossil fuels is not discussed in this study. Doing this would incorporate years of international discussions as well as tests to determine what would happen. The increase of tellurium, gallium, indium, and cadmium would affect only certain parts of the world (e.g. Asia) as that is where the metals are most concentrated in the crust (Ting & Seaman, 2013). This could be both positive and negative as it could provide countries with more wealth and prosperity, but also create conflicts over the limited resources (Ting & Seaman, 2013). The decrease of fossil fuel production, export, and use could shift global powers to countries that switched to renewable sources first; this could also lead to a rise in global conflict. These are just a few societal impacts that could happen when switching to solar power as the main source, there are more possible ones that have not been mentioned.

As mentioned previously, supply chains of the rare metals could be further areas of study on this topic as it would help create a larger picture. The input of metal from certain countries, where the panels are assembled, and where they are most used are all good case studies to be investigated. The ownership of production companies, metal mines, PV panel realtors could also be further reviewed as they will be large stakeholders if the 50% goal is reached.

A similar study could be performed on first and third generation PV panels as they require resources to be made; for example, the large demand for silicon in first generation panels (Tyagi et. al., 2012). Though silicon is not a rare element and is found in many places worldwide, if the demand is large enough the production may not be able to supply what is needed (U.S. Geological Survey, 2018). Third-generation cells are cheaper to produce than second-generation and can be more efficient, therefore, they may take over soon, as the most produced cell (Gangadharan et. al., 2016). A study into the resource requirement and availability would give a better idea to the longevity of the solar cell industry and allow for more improvements to be made on current PV cells (Gangadharan et. al., 2016).

Conclusions

There are many factors that can increase or decrease the sustainability of the PV industry, some do not even involve the resources used. Low to no demand for panels, high production with little consumption, and not financial stability could all be factors that lead to an unsustainable industry. These factors were not discussed in depth in this study, so even if the results show that the resources make the industry unsustainable there are other factors at play that may sway the industry in another direction. The fact that tellurium, gallium, indium, and cadmium are not renewable resources proves a problem for the PV industry as it relies on the availability of them to produce electricity. Given the rate of increase needed in production (200GW globally per year in infrastructure), the lack of tellurium and indium reserves, and the low 2050 production supply leaves the second-generation PV industry unsustainable by 2050. This means that the reserves for at least one of the metals will run out, and the supply (even with recycling) will not be enough to meet the calculated demand.

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Appendix

Table 4. Metal availability, production, demand, and photovoltaic capacity.

	Tellurium	Gallium	Indium	Cadmium
Known Reserves (kt)	24[1]	1873.34[5]	15-30[2]	0.063[3,4]
PV Demand [2014] (kt)	2.9-24[1]	0.31-1.4[1]	1.1-4.3[1]	2.6-21[1]
Global Production [2014] (kt)	0.4-0.7[1]	0.44[1]	0.82[1]	22.2[1]
Past Production [1972-2014]	-	3.4[1]	11.7[1]	1160[1]
Total used for PV [2014] (kt)	0.296[1]	0.015[1]	0.048[1]	0.262[1]
Percent used for PV [2014]	420-6000[1]	70-320[1]	130-530[1]	12-97[1]
Material Requirements in 2050 (kt)	120-725[1]	11-42[1]	39-131[1]	107-641[1]
Capacity (EOL recycling) pre 2050 (kt)	15-25.2[1]	0.93-1.41[1]	2.99-4.38[1]	13-22.3[1]

[1](Davidsson & Hook, 2017) [2](Lokanc et. al., 2015) [3](U.S. Geological Survey, 2019) [4](U.S. Geological Survey, 2019) [5](Grandell & Hook, 2015).

Table 5. Methods of recycling second generation photovoltaic panels and percent recovery.

Recycling Method (EOL)	**Tellurium**	**Gallium**	**Indium**	**Cadmium**
Evaporation with Chloride and Heat (CIGS)		100%[1]	60%[1]	
GaCl3 production with NH4Cl and Al2O3(CIGS)		100%[1]		
NH4Cl Separation (CIGS)		97%[1]		
In Separation from Co with Residual Ga (CIGS)		1.40%[1]	93.60%[1]	
Ca Removal Via Wound Wire Rotation (CIGS & CdTe)				98.50%[2]
Penicillium chrysogenum Microorganisms via Leaching (CdTe)	93%[3]			
Acidithiobacillus ferrooxidans Microorganisms via Leaching (CdTe)	5%[3]			
Acidithiobacillus thiooxidans Microorganisms via Leaching (CdTe)	31%[3]			
Penicillium simplicissimum Microorganisms via Leaching (CdTe)	16%[3]			
Crush and Separate via Chemical Dissolution, Mechanical, or Precipitation (CdTe)	80%[4]			
Chemical Stripping of Te via Electrodeposition (CdTe)	95%[4]			
Separation and Flotation of Metals (CIGS & CdTe)	12.20%[5]		35.30%[5]	
Recycling from Residuals and Production Excess (CIGS & CdTe)	97%[5]			95%[5]
Recycled from Municipal Solid Waste in the USA (CIGS & CdTe)	0%[6]	18%[6]	1%[6]	14%[6]
5N Plus Company Method	95%[7]			95%[7]
Best Case Recycled Rate	**97%**	**100%**	**93.60%**	**98.50%**

[1] (Gustafsson et. al., 2015) [2] (Abbar et. al., 2018) [3] (Chakankar et. al., 2018) [4] (Fthenakis, 2012) [5] (Marwede et. al., 2013) [6] (Goe & Gaustad, 2014) [7] (Marwede & Reller, 2012).

Table 6. Metal recycling, future production, availability, metal intensity, and industry demand.

	Tellurium	**Gallium**	**Indium**	**Cadmium**
Most Efficient Method Recycling Rate[1,2,3]	97%	100%	94%	98.50%
2050 Production (kt)[1]	1.7991	2.2574	2.2527	113.8974
2050 Available Metal (kt)[1]	35.1625	42.2711	56.5442	3076.1306
Average Metal Intensity (kt/GW)[1]	0.156	0.009	0.026	0.138
PV Industry Demand 2050 (kt)[1]	335.768	19.881	57.434	304.842

[1](Davidsson & Hook, 2017) [2](Lokanc et. al., 2015) [3](Kavlak et. al., 2015).

Table 7. Compound annual growth rate of the four focus metals.

Compound Annual Growth Rate	**Tellurium**	**Gallium**	**Indium**	**Cadmium**
2018-2025	3%[1]	4.30%[2]	2.50%[3]	4.30%[4]
2026-2050 (Estimated growth)	3.50%	4.80%	3.00%	4.80%

[1](Technavio, 2018) [2](Shah, 2019) [3](Acumen Research and Consulting, 2019) [4](Cullen & Maldonado, 2013).

Table 8. Production estimates from 2014 to 2050. Black line indicates start of predicted CAGR.

Kilotonnes per Year	Tellurium	Gallium	Indium	Cadmium
1972-2013[1]	-	3.4	11.7	1160
2014[1]	0.55	0.44	0.82	22.2
2018	0.619	0.5207	0.9051	26.2719
2019	0.63757	0.5430901	0.9277275	27.4015917
2020	0.6566971	0.56644297	0.95092069	28.5798601
2021	0.67639801	0.59080002	0.9746937	29.8087941
2022	0.69668995	0.61620442	0.99906105	31.0905723
2023	0.71759065	0.64270121	1.02403757	32.4274669
2024	0.73911837	0.67033737	1.04963851	33.821848
2025	0.76129192	0.69916187	1.07587948	35.2761874
2026	0.78793714	0.73272164	1.10815586	36.9694444
2027	0.81551494	0.76789228	1.14140054	38.7439778
2028	0.84405796	0.80475111	1.17564255	40.6036887
2029	0.87359999	0.84337916	1.21091183	42.5526657
2030	0.90417599	0.88386136	1.24723918	44.5951937
2031	0.93582215	0.92628671	1.28465636	46.735763
2032	0.96857593	0.97074847	1.32319605	48.9790796
2033	1.00247608	1.0173444	1.36289193	51.3300754
2034	1.03756275	1.06617693	1.40377869	53.7939191
2035	1.07387744	1.11735342	1.44589205	56.3760272
2036	1.11146315	1.17098639	1.48926881	59.0820765
2037	1.15036436	1.22719373	1.53394688	61.9180161
2038	1.19062712	1.28609903	1.57996528	64.8900809
2039	1.23229907	1.34783178	1.62736424	68.0048048
2040	1.27542953	1.41252771	1.67618517	71.2690354
2041	1.32006957	1.48032904	1.72647072	74.6899491
2042	1.366272	1.55138483	1.77826484	78.2750667
2043	1.41409152	1.62585131	1.83161279	82.0322699
2044	1.46358472	1.70389217	1.88656117	85.9698189
2045	1.51481019	1.78567899	1.94315801	90.0963702
2046	1.56782855	1.87139158	2.00145275	94.4209959
2047	1.62270255	1.96121838	2.06149633	98.9532037
2048	1.67949713	2.05535686	2.12334122	103.702958

2049	1.73827953	2.15401399	2.18704146	108.680699
2050	1.79911932	2.25740666	2.2526527	113.897373
Total (2018-2049)	34.3952754	36.6137093	46.0569532	1847.3434
Recycled[2,3,4]	33.3634171	36.6137093	43.293536	1819.63325
Past Recycled and 2050	35.1625364	42.2711159	56.5441887	3076.13062

[1](Davidsson & Hook, 2017) [Growth rates from Table 4, estimation after 2025] [2](Technavio, 2018) [3](Shah, 2019) [4](Acumen Research and Consulting, 2019).

Table 9. Twenty common second generation photovoltaic panel producers and their power outputs.

Output in Watts	**Min**	**Max**	**Average of all Models**
Amerisolar	240	330	285
Axitec	250	350	287
Canadian Solar	225	350	287
CentroSolar	250	320	278
China Sunergy	290	320	306
ET Solar	250	340	295
Green Brilliance	230	300	266
Hanwha Q CELLS	245	390	304
Hyundai	220	360	283
Itek Energy	270	370	311
Kyocera	260	330	295
LG	275	405	337
REC Solar	240	350	289
ReneSola	245	320	277
Renogy Solar	250	300	268
Seraphim	255	340	294
Silfab	250	370	305
SolarWorld	250	350	293
SunPower	235	435	337
Trina Solar Energy	245	345	284
Total Average			**294.05W**

(U.S. Department of Energy, 2018).