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CdTe in thin film photovoltaic cells: Interventions to protect drinking water in production and end-of-life

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ABSTRACT

Solar energy harvesting is a crucial technology in the transition away from fossil fuels. However, in order to make a renewable energy source truly sustainable, it is necessary to understand and mitigate broader impacts. At the Water-Energy Nexus lies the question of trade-offs between energy sources in terms of their water footprint, through water use or water contamination. The purpose of this work is to analyze CdTe thin film photovoltaic cells to evaluate interventions that can prevent contamination of drinking water. We focus on drinking water because of its relevance to the United Nation's Sustainable Development Goal 6: clean water and sanitation. Thin-film PV cells use CdTe as a semiconductor material because of its advantageous band gap and high solar absorption efficiency. However, CdTe as well as cadmium and tellurium species can be toxic to aquatic and terrestrial ecosystems and pose serious health hazards to humans when present in drinking water. We propose a multiple criteria decision analysis (MCDA) that can be used by business leaders and politicians to aid in decision-making in regards to new interventions to protect drinking water. In this article we use a case study to demonstrate the use of the MCDA framework. The interventions analyzed in this review are regulation of recycling and disposal, bioreactors, and dye-sensitized solar cells. Protecting water supplies while increasing access to reliable electricity through low-cost solar is a critical path to meeting the UN Sustainable Development Goals as this renewable energy technology evolves.

Contents

Abbreviations: PV, Photovoltaic; CdTe, Cadmium telluride; Cd, Cadmium; Te, Tellurium; MCDA, Multiple Criteria Decision Analysis; CdS, Cadmium sulfide; VTD, Vapor Transport Deposition; $CdSO_4$, Cadmium Sulfate; $CdCl_2$, Cadmium Chloride; TeO_2, Tellurium Dioxide; TeO_4^{2-}, Tellurate Oxyanion; TeO_3^{2-}, Tellurite Oxyanion; EU, European Union; WEEE, Waste of Electrical and Electronic Equipment; RoHS, Restriction of Hazardous Substances; RRCA, Resource Recovery and Conservation Act; DOE, Department of Energy; DSSC, Dye-sensitized solar cells.

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1. Introduction

Global energy demand is expected to increase from 13 TW to 23 TW by 2050 (Mehmood et al., 2014). In 2018 alone, the energy demand rose 2.3%; the fastest it has in the last decade (International Energy Agency, 2019). In order to decrease negative impacts in the future at the Water-Energy Nexus, technologies that can harness alternative energy sources must be designed to accommodate the increase in demand without increasing contamination of the environment. One such technology is photovoltaic (PV) cells.[1] One type of PV that shows promise is CdTe (cadmium telluride) thin film PVs. These PVs have competitive efficiencies and low costs compared to other PV technologies, but there is a non-zero risk of contamination of water, including drinking water sources, throughout the life cycle of CdTe thin film PVs (National Renewable Energy Laboratory, 2019). Currently, CdTe thin film PVs are the second most commonly used PV after crystalline silicon PVs, making up about 5% of the global PV market (Department of Energy/Office of Energy Efficiency & Renewable Energy, 2019). As a technology emerging in popularity, it is imperative that proactive interventions are put in place to prevent contamination of drinking water by CdTe and other Cd and Te species to make CdTe thin film PVs a comprehensive solution to increasing energy demand.

The objective of this Critical Review is to understand how the Sustainable Development Goals (SDG) of "Clean Water and Sanitation" as well as "Affordable and Clean Energy" can be met synergistically, by thoughtfully considering and mitigating the potential impacts of an emerging renewable energy technology on drinking water. Searching for alternative green technologies and interventions and analyzing their impact on the environment is a complex task; many variables must be considered simultaneously as well as acknowledging existing data gaps. While scientists studying green technologies may be able to gather a holistic idea of the impacts of a technology, it is important for business leaders and politicians to gain an understanding as well in order to make informed decisions. We focus on drinking water because of the direct ties to human development indicators through SDG 6, while recognizing that all waters and therefore all life are potentially impacted by contamination. While the economic details are outside the scope of this work, energy costs of providing safe drinking water are also more directly measurable than other water quality and contamination indicators for trade-off against clean energy generation.

This Critical Review proposes a framework to simplify and aid in decision-making within the scope of implementing new green technologies and interventions. Although various life cycle assessments do exist focusing on the life cycle of CdTe thin film PVs (Kim et al., 2014; Yao and You, 2013; Goe and Gaustad, 2016), they largely focus on quantifying energy and raw material use, and exclude water-related aspects of the life cycle. This Critical Review does not include a life-cycle assessment; rather, it begins to address this knowledge gap by providing a qualitative framework that summarizes the environmental benefits, specifically related to water, of alternative technologies and interventions, including awareness of uncertainty and data gaps, to aid decision-making. A case-study is performed to illustrate the framework.

1.1. Properties that make CdTe an advantageous semiconductor material

The average module efficiency of commercial CdTe thin film PV cells is 16.4% (Market Watch, 2019a), which is slightly lower than the average module efficiency of commercial crystalline Silicon PVs, which have efficiencies ranging from 18%–22% (Department of Energy/Office of Energy Efficiency and Renewable Energy, 2019a). First Solar, an American photovoltaic manufacturer that produces 95% of thin film PV cells in the market, has designed a laboratory module with an efficiency of 21.1% (Market Watch, 2019a). The competitive efficiencies of CdTe thin film PVs are partially due to natural properties of CdTe that make it one of the most efficient thin film layers to absorb sunlight to-date. Birkmire and McCandless (2010) provides an in-depth review outlining how CdTe thin film PVs work.

CdTe has a band gap of 1.45 eV, which results in a relatively high photovoltaic conversion efficiency, a relatively large built-in voltage, and a relatively low amount of energy lost as heat, compared to other semiconductor materials (Table 1) (Britt and Ferekides, 1993). In addition to an advantageous energy gap, CdTe also has two other beneficial qualities: a direct energy gap, meaning the valence and the conduction bands occur at the same crystal momentum, and a steep absorption edge, which is a sharp discontinuity of absorption. These characteristics cause CdTe PV cells to absorb about 90% of the incoming solar light within a few micrometers of the material surface which makes CdTe an advantageous option for thin film PV technology (Bonnet, 1992; Ferekides and Britt, 1994). Thin film PVs require less material to make, are cheaper, and are more flexible, therefore, they can be mounted on more diverse materials (Ferekides and Britt, 1994).

1.2. CdTe sources and waste streams

Aside from the intrinsic properties that make CdTe a good absorber layer in a thin film PV, Cd and Te are also harvested as by-products of mining that would otherwise be disposed of as waste. Te is a by-product of mining copper, steel, and gold. Te is extracted from by-products because it is one of the rarest elements on the periodic table (Vesborg and Jaramillo, 2012). The material extracted while mining copper-sulfide contains 1.5 ppm (global average) Te, which is 4000 times less than the amount of copper-sulfide in the ore (Anctil and Fthenakis, 2012). Anctil and Fthenakis (2012) found that mining specifically for Te would increase the cumulative energy demand of the mining process,

[1] Note that while we use the term thin film photovoltaic (PV) cells, other terms are used in industry including but not limited to solar cells, solar panels, photovoltaic cells, photovoltaic modules, thin film solar cells, thin film solar panels, and thin film photovoltaic modules. Also noteworthy is the term "thin film". Photovoltaic cells is an umbrella term than includes thin film photovoltaic cells as well as other non-thin film photovoltaic cells. CdTe is only used in thin film PV cells.

Table 1
Bandgap sizes of various semiconductor materials (Kittel, 1986). CdTe has an optimal band gap in relation to the amount of energy provided by solar radiation and due to the characteristics that constitute an efficient absorber layer.

Material	Band Gap (eV)
ZnS (Zinc Selenide)	3.6
CdSe (cadmium selenide)	1.74
CdTe (cadmium telluride)	1.44
GaAs (gallium arsenide)	1.43
InP (indium phosphide)	1.27
Si (silicon)	1.11

resulting in higher emissions during the mining and smelting phase, compared to extracting it from by-products.

Cd is a by-product of mining zinc and steel. It exists in zinc ores at up to 5 ppm, resulting in about 3 kg of Cd extracted per ton of zinc (U.S. Department of Health and Human Services, 2012). Raugei and Fthenakis (2010) states that the global market demand for zinc and steel is higher than the demand for Cd, suggesting switching to mining specifically for Cd would not be advantageous. Additionally, Sinha (2013) states that economic growth has lead to an increase in zinc extraction, which has lead to an increased amount of extracted impure Cd regardless of an intended use.

Being by-products of other mining, not all of the Te and Cd by-products are harvested and used. For example, there is a 50% surplus of mined Cd over the market demand (Raugei and Fthenakis, 2010). As a result, some by-products containing Cd and Te are stockpiled as waste. These stockpiles are disposed of by the mining industry, often in tailing ponds, which can result in Cd and Te leaching into soils, groundwater, and surface water, posing a hazard to terrestrial and aquatic organisms. Unfortunately, the amount of Cd and Te disposed of in tailing ponds is often not quantified, thus the risks are uncertain (Sinha, 2013). Diverting Cd and Te from waste streams to build useful devices could be beneficial as long as the risks of contamination during the life cycle of the devices (i.e. extracting and processing Cd and Te, the use phase of the devices, and the disposal/recycling of the devices) is lower than disposal of Cd and Te by-products as mining waste (Fig. 1).

1.2.1. Potential pathways of contamination of the environment by CdTe and Cd and Te species

Separation and purification of Cd and Te from mining waste are stages of the life cycle that pose contamination risks affecting drinking water, agriculture, and natural ecosystems that need to be mitigated (Fig. 1). The independent processes employed to separate and purify Cd and Te from mining waste require high temperature and pressure autoclaving, and can take weeks (Bonificio and Clarke, 2014). Additionally, the processes require highly concentrated hazardous chemicals (Bonificio and Clarke, 2014). Often, Cd and Te are left behind in the autoclave "slime" (the waste left over from processing waste from zinc, copper, and gold mining) and the disposal of this waste can pose Cd and Te contamination risk (Bonificio and Clarke, 2014).

Manufacturing is another stage of the CdTe PV life cycle that poses water contamination risk either through direct contamination of the water via effluent or through particulate matter that can enter water systems (Fthenakis, 2004; Wiklund et al., 2018). However, the Reference Case model by Fthenakis (2004) indicates the contamination risk during manufacturing is lower than the risk during Cd purification and CdTe production. The two most common methods of manufacturing CdTe thin film PVs are electrodeposition and vapor transport deposition (VTD), also known as close-spaced deposition (Fthenakis et al., 2008). In electrodeposition, a CdTe thin film is deposited onto a cathode substrate from

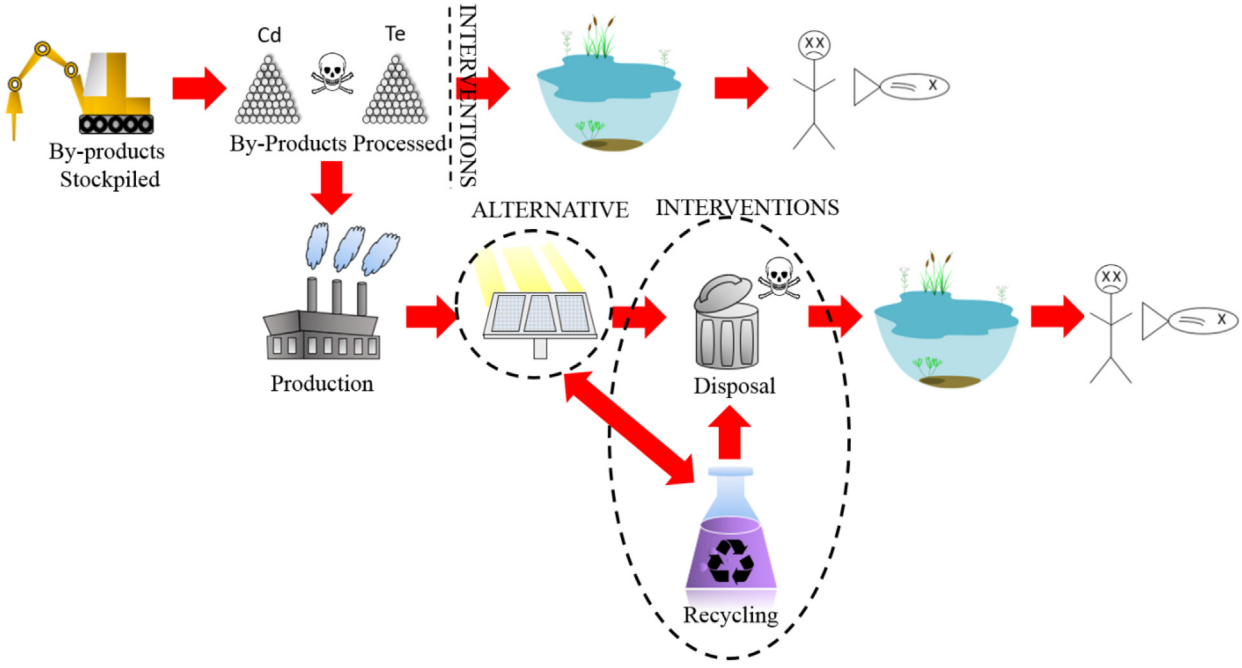

Fig. 1. A depiction of the relevant steps in the life cycle of CdTe thin film PV cells. By-products containing Cd and Te are acquired from Zn, Au, Cu and steel mining and processing. These by-products are processed to extract and purify Cd and Te. The extracted Cd and Te can be used to make useful devices, such as CdTe thin film PV cells. After the use phase of the PV cells, which is about 25–30 years, the PV cells can be inadequately disposed of in municipal landfills, risking contamination of the environment. However, some PV cells are recycled and the material can be used to produce new PV cells. Eventually, the PV cells will be disposed of and risk contamination of the environment. Based on this life cycle, we evaluate three interventions to decrease the risk of Cd and Te contamination of drinking water. The first is downstream regulation for "Disposal" and "Recycling". The second is implementing bioreactors to improve "Extracting By-products" and "Recycling of PV Cells". The third is replacing CdTe thin film PVs with an alternative technology, namely dye-sensitized solar cells. We discuss these interventions in further detail in Sections 2.1–2.3.

aqueous cadmium sulfate ($CdSO_4$) or cadmium chloride ($CdCl_2$), and tellurium dioxide (TeO_2). In this process, less than 1% of Cd and Te is not successfully deposited (Fthenakis, 2004). The un-deposited material is recycled and used to make the CdS layer via chemical surface deposition. The liquid Cd waste remaining after chemical surface deposition, about 1–10 ppb, can be recycled via a deionizing facility or disposed (Fthenakis, 2004). Alternately, VTD can be used, during which powders containing Cd and Te are sublimated at about 500–600 °C and condensed onto glass substrates (Fthenakis, Kim, and Alsema, 2008). The deposition process has a 35–70% deposition rate, however, the un-deposited material collects in the reactor and can be removed and reused (Fthenakis, 2004). Less than 1% of the vaporized material is transported in the waste stream, and then 99.97% efficient HEPA filters remove most of the Cd from the waste stream and the HEPA filters are disposed of as hazardous waste (Fthenakis, 2004). When properly implemented, contamination risks are minimal; however, any breakdown, either technical or procedural, in the process risks release of inherently hazardous Cd or Te materials.

The risk of contamination due to emissions during the use-phase of CdTe PVs is negligible. Raugei and Fthenakis (2010) and Fthenakis and Zweibel (2003) explain that the only way that the CdTe thin film PVs could cause adverse health effects during the use-phase is if the PV were ground to a fine dust, and the dust and fumes were inhaled. This is because CdTe vapors will not naturally be produced at ambient temperatures because the vapor pressure of CdTe at ambient conditions is zero (Fthenakis and Zweibel, 2003). In addition, the risk of contamination due to fire damage during the use-phase is low (Fthenakis et al., 2005). The typical temperatures of residential fires in the US are not high enough to vaporize CdTe (Fthenakis and Zweibel, 2003). The risk of contamination due to fire damage and accidental breakage is further lowered due to glass plate protective layers that encapsulate the CdTe during damage, preventing release in these situations (Fthenakis et al., 2005; Fthenakis and Zweibel, 2003; Raugei and Fthenakis, 2010b).

Current CdTe PVs last about 25–30 years (Fthenakis, 2004), after which most PV modules are disposed of in municipal landfills (Cyrs et al., 2014; Ramos-Ruiz et al., 2017). This poses serious health and environmental hazards as CdTe may leach out of the landfills and contaminate soil, groundwater, or surface water. Available leaching risk tests for CdTe and Cd and Te compounds provide inconclusive results (Cyrs et al., 2014; Fthenakis, 2004). Determining leaching risk is significant because hazardous waste disposal would lead to added cost to the life cycle of CdTe thin film PVs (Fthenakis, 2004).

Alternatively, PV modules may be recycled, prolonging increased costs if hazardous waste disposal is required. Recycling can be advantageous because it results in less materials going directly into landfills, as well as considerable energy and cost savings as compared to manufacturing thin film PVs from scratch (Goe and Gaustad, 2014). The energy payback time of CdTe thin film PV cells when no recycling occurs is 0.8 years according to a study performed by Goe and Gaustad in 2014 (Goe and Gaustad, 2014). With exhaustive recycling of all materials, the energy payback time of CdTe thin film PV cells is reduced to 0.3 years, a 62.5% reduction (Goe and Gaustad, 2014). The study assumes base-line efficiency of the CdTe thin film PV cells. However, to assess benefits to the entire system, water use would also need to be quantified through an life cycle assessment with appropriate boundaries.

Additionally, recycling may alleviate the insufficient supply of Te as more renewable energy technologies require the addition of the rare metalloid (Vesborg and Jaramillo, 2012). The Department of Energy (DOE) predicts that within the next nine years the demand for Te will outpace the supply at the current rate of use, extraction and recycling efficacy, and geochemical abundance (Bonificio and Clarke, 2014; Bradshaw et al., 2013). Moreover, Marwede and Armin (2012) suggest that by 2040, 10–50% of Te will need to come from recycled PVs. Fortunately, Fthenakis (2004) suggests that with proper forethought and control measures, recycling facilities could lead to approximately zero emissions associated with recycling/disposal of CdTe thin film PVs. Similarly, Sinha (2013) suggest CdTe PVs have the potential for almost closed-loop materials management and Fthenakis (2012) states that the feasibility is well confirmed. Fthenakis (2012) also states that small-scale recycling facilities have already been able to achieve 99.99% separation of Cd and Te from PVs at a cost of US\$0.02/W_p (watt-peak). Unfortunately, many resource recovery facilities are not yet technologically or logistically equipped to recover all materials in PV modules, and capable facilities are geographically scarce (Goe and Gaustad, 2014).

Scientists estimate that in 2050, global PV module waste will amount to 78 million tonnes (Mahmoudi et al., 2019). For reference, the entirety of the United States (2015 population 328 million) generated 238.5 million tonnes of municipal solid waste in 2015 as reported by the United States Environmental Protection Agency (Mukherjee et al., 2020). Recycling will reduce the amount of PV waste going into landfills, as well as potentially reduce energy intensity and cost. However, one trade-off that occurs with recycling is apparent. Recycling of Cd and Te in CdTe PV cells would mean less Cd taken from the harmful leftover stockpiles. The question is then, is it more environmentally sound to have leftover Cd- or Te-containing stock piles from zinc, steel, copper, and gold ore mining, or to have Cd and Te disposed in landfills at the end of life of a PV cell?

Lastly, the current recycling process requires two technologies: delamination and material separation and purification (Mahmoudi et al., 2019). The delamination process entails physical pre-treatment, chemical and thermal treatments, and solvent dissolution of the thin film cells (Mahmoudi et al., 2019). The delamination process could still be improved through the reduction of gaseous emissions and the reduction of temperature (Mahmoudi et al., 2019). Material separation and purification is a more involved process involving chemical treatment (etching), laser surface cleaning, electrodynamic eddy current separation, electrostatic separation technology, and hydrometallurgical treatment (Mahmoudi et al., 2019). One study recycled PV cells by cutting and crushing the cells into pea-sized fragments, leaching them in a solution of sulphuric acid and hydrogen peroxide, and then co-precipitating out Cd, Te, and Cu (Raugei and Fthenakis, 2010). The Cd, Te, and Cu precipitate was then re-processed to separate and purify the metals (Raugei and Fthenakis, 2010). The recycling process again employed 99.97% efficient HEPA filters to capture particulate Cd emissions from the crushing process of the thin film cells (Raugei and Fthenakis, 2010). In total, the current production and recycling operations of CdTe PV modules emit 0.4 mg Cd/kg Cd annually (Raugei and Fthenakis, 2010).

1.3. Interactions of CdTe and Cd and Te species in the aquatic environment

CdTe is unlikely to be released from CdTe thin film PVs during use or disposal (Fthenakis, 2004). Bonnet and Meyers (1998) even go as far to state that emissions from CdTe PVs are manageable and overall, the PV module will have a net benefit on the environment because it replaces fossil fuel and nuclear energy generation. The limited risk associated with CdTe thin film PVs exists during Cd and Te processing and CdTe production (Fthenakis, 2004). Concerns related to CdTe thin film PVs, therefore, focus more on other Cd and Te species, rather than CdTe itself. In this section we

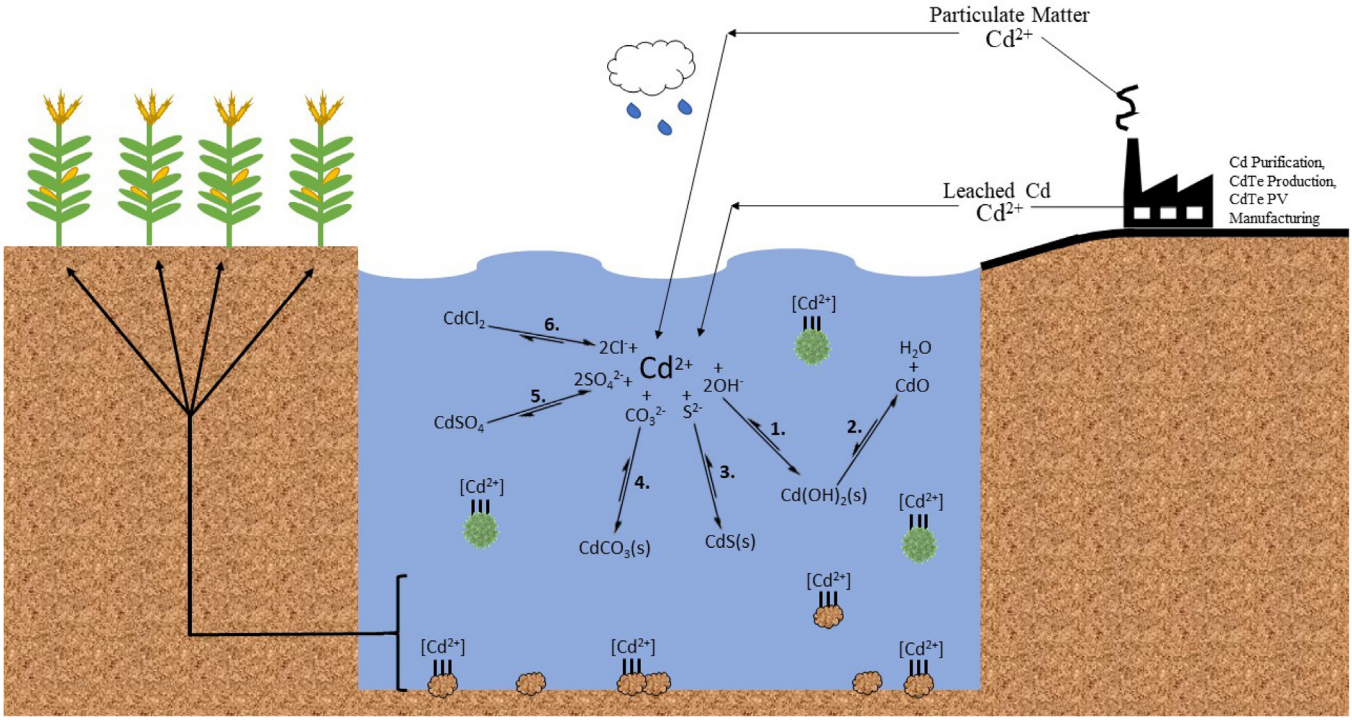

Fig. 2. Following the framework used by Fthenakis (2004), Cd^{2+} emissions during the life cycle of CdTe thin film PVs occurs only during Cd^{2+} purification, Cd^{2+} production, and CdTe PV manufacturing. During these processes, some Cd^{2+} is released as air pollutants in the form of particulate matter. Cd^{2+} can form solid species in the hydrosphere (i.e. reaction 1) that settle out into the soil (brown particles) and Cd^{2+} salts which have relatively higher solubility (i.e. reaction 5). They can also adsorb to natural organic material (green particles). Additionally, Cd^{2+} species can be taken up by plants, including crops. Ksp values can be found in Table A.1. Based on broad distribution in the ecosphere, Cd^{2+} is a concern for both drinking water and soil and crops. Note that species are aqueous unless otherwise indicated.

highlight the potential speciation of both Cd and Te in water if contamination occurs during processing and purification of CdTe and manufacturing of CdTe PVs.

1.3.1. Cadmium speciation in water

Cd is a toxic heavy metal causing a growing public health concern. Recent decades have seen an increase in Cd concentrations in water systems due to the increase in mineral exploitation, ore extraction, and refining activities; increased metal and metalloid use in devices; and inadequate disposal (Li et al., 2017). The People's Republic of China revealed in a nation-wide survey led by the Ministry of Environmental Protection and the Ministry of Land Resources in 2014 that >16% of soils in China (19% of which are agricultural soils) are polluted with heavy metals, and approximately 26 million ha are polluted with Cd (Li et al., 2017). The high amount of agricultural soils that are polluted has seriously impeded agricultural development, specifically rice production in the Hunan province, southern China (Li et al., 2017).

Cd is classified as a non-redox reactive soft metal cation (Maurer et al., 2012). Cd^{2+} is the only significant oxidation state of Cd under typical environmental pH (6–8) and thus, is the most common Cd species in the hydrosphere (National Research Council Committee on Zinc Cadmium Sulfide (NRCC on ZnCdS), 1997; van der Perk, 2006). Cd^{2+} species that are soluble in water tend to be more hazardous to humans and aquatic life because they are generally more bioavailable, whereas insoluble species tend to settle out in the soil (NRCC on ZnCdS, 1997).

Fig. 2 shows a web of reactivity of Cd^{2+} when it is introduced into the watershed. We used results from a life cycle impact analysis by Fthenakis (2004) to guide the qualitative allocation of Cd^{2+} emissions into the environment. According to the Reference Case model in Fthenakis (2004), Cd^{2+} emissions during the life cycle of CdTe thin film PVs occur only during Cd^{2+} purification, Cd^{2+} production, and CdTe PV manufacturing. Cd^{2+} species are not common air pollutants because Cd metal and salts have low volatility, however, Cd^{2+} species can be released in the form of particulate matter during separation, purification, and manufacturing (NRCC on ZnCdS, 1997). Fthenakis (2004) found that per ton of Cd produced, approximately 15 g of Cd is emitted, which corresponds to 0.02 total g Cd air emissions/GWh of electricity. The Reference Case model does not allocate the remaining Cd^{2+} emissions to CdTe thin film PVs, but rather to Zn mining, smelting, and refining because Cd^{2+} is a waste product produced during Zn mining and would otherwise be disposed of in tailing ponds (Fthenakis, 2004). Additionally, no emissions were allocated to the use-phase or to disposal/recycling phase because of the glass-to-glass encapsulation of the semiconductor layers during accidental breakage or fire which prevents the release of heavy metals and due to strict emissions controls during both processes (Fthenakis and Zweibel, 2003; Fashola et al., 2016; Fthenakis and Zweibel, 2003). However, there is rising concern about Cd^{2+} leaching from landfills following inadequate disposal (Ramos-Ruiz et al., 2017). Fthenakis (2004) states that proper recycling and disposal is feasible with appropriate forethought; however, even if some pieces enter municipal waste incinerators, the Cd^{2+} would become incorporated into the molten glass and be disposed of as solid waste.

Cd^{2+} that enters aquatic systems during purification, production, and manufacturing can precipitate as compounds with relatively low K_{sp} values that settle out into the soil as shown in Fig. 2 (i.e. reaction 1) or form soluble Cd salts (i.e. reaction 5). K_{sp} values for some common Cd compounds can be found in Table A.1. Two additional transformations that Cd^{2+} undergoes in the hydrosphere include: 1) sorption to sediments/coprecipitation of Cd^{2+} to metal hydroxides in the water, such as iron hydroxide

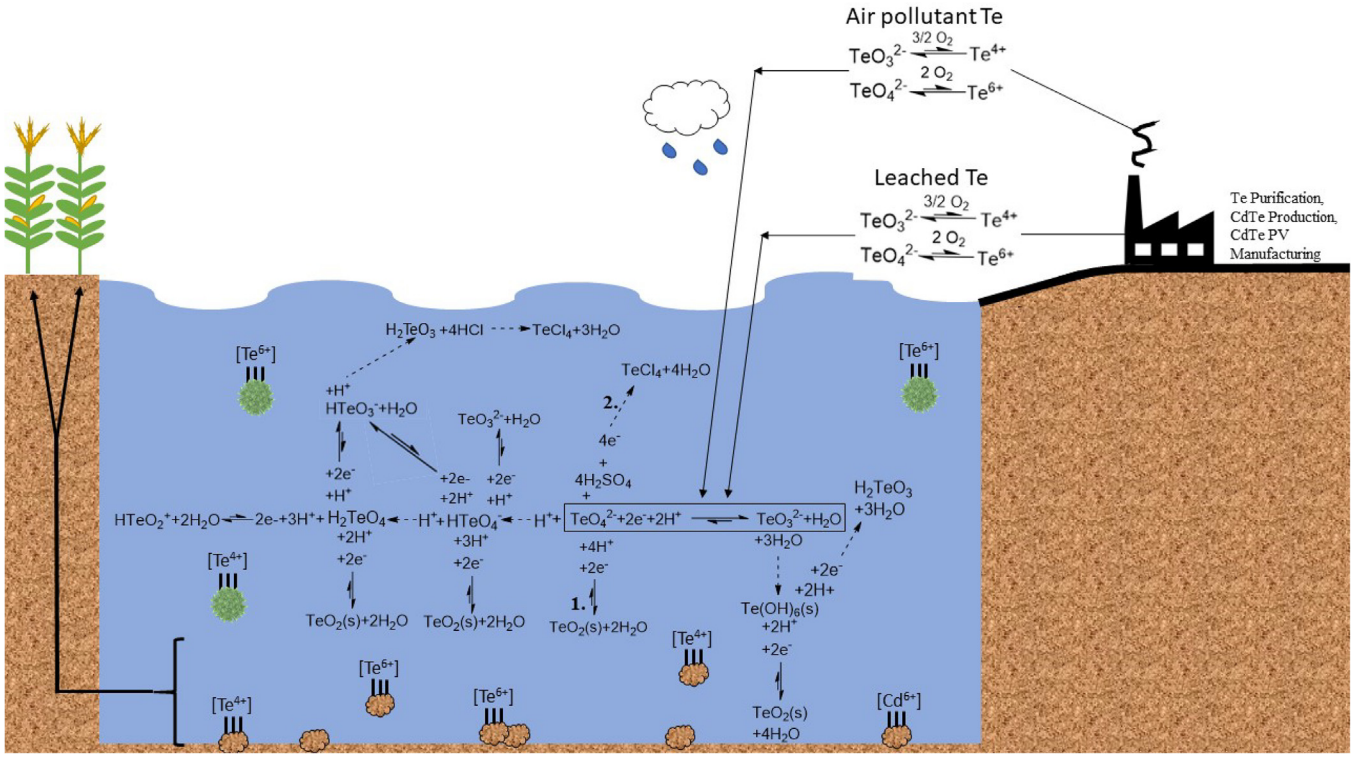

Fig. 3. Speciation of Te in water. In relation to CdTe thin film PVs, Te can be released into the environment as particulate matter air pollutants during processing of Te and PV manufacturing. Once in contact with oxygen, Te oxyanions form, which undergo various redox reactions and transformations in water. Te can form solid species in the hydrosphere (i.e. reaction 1) that settle out into the soil (brown particles) and Te species that have relatively higher solubility (i.e. reaction 3). Te species can also adsorb to natural organic material (green particles). Additionally, Te species can be taken up by plants, including crops. Solid arrows indicate known electrochemical potentials and dotted arrows represent unknown electrochemical potentials (See Table C.1). Based on electrochemical potential values and solubility, Te contamination is a greater concern for soil and crops than drinking water. Species are aqueous unless otherwise indicated.

(which removes Cd^{2+} from the hydrosphere) and 2) adsorption of Cd^{2+} to organic matter, including uptake into plants (i.e. crops). See Appendix B for more information.

Ultimately, Cd^{2+} contamination in the hydrosphere is a concern for drinking water, due to soluble and bioavailable compounds, and for contamination of crops and soil by both soluble and insoluble compounds (Zhang et al., 2019; Adesiyan et al., 2018; Shen et al., 2018; Khan et al., 2017). Prevention and remediation methods, therefore, need to focus on multiple contamination routes.

1.3.2. Tellurium speciation in water

Tellurium (Te) is a rare metalloid that is becoming more commonly used in the industrial sector, which has caused concern about the toxicity and potential environmental degradation caused by Te species in the environment. Te can exist in the oxidation states 2-, 2+, 4+, and 6+. It is most commonly found in the 6+ oxidation state in the hydrosphere in the form of the soluble tellurate oxyanion (TeO_4^{2-}). It can also be found in the hydrosphere in the 4+ oxidation state in the form of the soluble tellurite oxyanion (TeO_3^{2-}) (Qin et al., 2017). TeO_3^{2-}, and to a lesser extent TeO_4^{2-}, are toxic to bacteria at low concentrations, with the exception of Te resistant bacteria that can reduce Te species to Te^0. Te^0 is insoluble in water, making it less mobile and toxic (Qin et al., 2017).

Fig. 3 shows a web of reactivity describing the states of Te when it is introduced into the watershed. Allocation of Te is similar to that of Cd because it is also acquired as a waste product, specifically from copper, gold, and steel mining. As with Cd, the use-phase and recycling/disposal phase pose no risk due to the glass-to-glass encapsulation of the semiconductor layers during accidental breakage or fire which prevents the release of heavy metals and due to strict emissions controls during both processes (Fthenakis and Zweibel, 2003; Fashola, et al., 2016; Fthenakis and Zweibel, 2003). There is rising concern about Te^{2-} species leaching from landfills after inadequate disposal of CdTe thin film PVs (Ramos-Ruiz et al., 2017); however, proper forethought when designing recycling/disposal can mitigate concern (Fthenakis, 2004).

In regards to the CdTe thin film PVs, Te enters the environment through air pollution during Te processing and PV manufacturing (Qin et al., 2017; Fthenakis and Zweibel, 2003). The Te released into the atmosphere reacts with oxygen to form Te oxyanions (Qin et al., 2017). These oxyanions can undergo the reactions shown in Fig. 3, which includes precipitation reactions (i.e. reaction 1, Fig. 3), acid/base reactions (i.e. reaction 2, Fig. 3), and formation of ionic compounds (i.e. reaction 3, Fig. 3). An electrochemical potential table is provided including reactions for which data was available (Table C.1). Positive electrochemical potential values indicate a spontaneous reaction as written (in the direction of the larger arrow). Two additional transformations that Te undergoes in the hydrosphere include: 1) bacterial reduction or oxidation of Te species to Te^0, which is a solid that precipitates out of the hydrosphere; 2) sorption to sediments/coprecipitation of Te to metal hydroxides in the water, such as iron hydroxide (which removes Te from the hydrosphere); and 3) adsorption of Te species to organic matter, including uptake into plants (i.e. crops). See Appendix D for more information.

Most notably, in Fig. 3, the formation of tellurium dioxide (TeO_2) is a thermodynamic sink. The reactions for the formation of TeO_2 have the highest electrochemical potential values in

Table C.1 and are all spontaneous. Additionally, the compound is considered insoluble in water. These two characteristics suggest that once Te enters the water, it tends to form TeO_2, which settles out in the soil.

Ultimately, Te is often found as a contaminant in the soil, rather than the hydrosphere (Qin et al., 2017). Te species become structurally incorporated inside metal hydroxides (sediments) and will remain there until changes in conditions that cause Te species to dissolve. This means Te species are generally less of a concern for drinking water, but pose other risks, such as Te contamination of crops.

1.4. Effects of conventional water treatment technologies on CdTe and Cd and Te species

Certain common steps in conventional water treatment processes including coagulation, flocculation, filtration, and disinfection contribute to removal of heavy metals and metalloids from drinking water. These processes represent the known widely applied techniques for removing these species from drinking water and provide possible opportunities for innovation. The fact that these techniques remove some quantities of heavy metals is useful, but conventional drinking water treatment techniques were not put into place specifically to remove heavy metals. This is why developing and optimizing innovative technology to specifically remove heavy metals is crucial.

The main mechanisms of heavy metal removal during coagulation include complexation, adsorption, and coprecipitation (Tang et al., 2016). A promising type of coagulation that has shown some success in trials and pilot studies is electrocoagulation (Parga et al., 2005; Krystynik et al., 2019; Filatova, 2016). It has been shown to be a simple, fast, and effective alternative to traditional coagulation, and it is especially effective for removing heavy metal and metalloid ions (Bazrafshan et al., 2015). However, Al-Qodah and Al-Shannag (2017) highlight drawbacks that limit the applicability of electrocoagulation, such as current dependence on fossil fuel generated electricity (which could be overcome with increasing penetration of renewable energy sources such as CdTe PV), the need to replace the electrode due to its oxidation, and a current lack of management practices for the solid waste produced. Flocculation is the aggregation of destabilized particles into flocs that can be removed from water more easily than the original suspended particles. Insoluble heavy metals, such as solids like TeO_2, are finer particles and colloids, which can be trapped in flocs. As a result, formation of larger flocs ensures more effective heavy metal removal.

During membrane filtration, feed water is pumped under pressure across a semipermeable membrane, which separates clean water, known as permeate, from contaminants in the feed water. The smallest membrane pores exist in nanofilters, which have pores of about 0.001 μm (Crittenden et al., 2012). Nanofiltration and reverse osmosis filters have appropriate pore sizes to remove soluble Cd^{2+} and all common Te ions from water. Unfortunately, membrane filtration has a relatively high energy demand, especially as pore size decreases, therefore it may not be a viable treatment practice in all scenarios (Crittenden et al., 2012).

Disinfection, another step in conventional water treatment, has the unintended side effect of potentially transforming heavy metals and metalloids into different species. Disinfection is the partial destruction and inactivation of disease-causing organisms from exposure to chemical agents (e.g. chlorine) or physical processes (e.g. UV radiation) (Crittenden et al., 2012). In the case of Cd^{2+} species, disinfection will likely not have an impact because Cd^{2+} cannot easily be oxidized. In the case of Te, disinfection will likely not impact species found in water because they will be in the 6+ oxidation state. However, Te species adsorbed to residuals in the water, such as soil or NOM, can be oxidized by chlorine and other chemical oxidizing agents to Te^{4+} and Te^{6+} (Qin et al., 2017).

1.5. Health hazards associated with CdTe and Cd and Te species in water

In general, Cd and Te species have the potential to bioaccumulate and persist in the environment. Cd is carcinogenic and mutagenic, while both Cd and Te can cause harm to reproduction and development and have acute and chronic toxicity in the aquatic environment (See Table E.1). Therefore, to protect human health, it is necessary to intervene in the life cycle of CdTe thin film PV cells to prevent contamination of drinking water.

In the case of Cd, all species are carcinogenic, persistent, bioaccumulative, and show acute mammalian and aquatic toxicity. Many species are also mutagens, genotoxic, endocrine disruptive, harmful if inhaled or swallowed, and cause chronic cardiovascular, renal, and musculoskeletal effects (Godt et al., 2006). Additionally, Cd(0) dust and powder are flammable as well as explosive and may ignite spontaneously in air or under heating conditions. The serious acute and chronic effects of Cd on human health show the importance of humans consuming no Cd whatsoever. Cd is very toxic to aquatic life with long lasting effects; interventions to prevent the leaching of Cd from anthropogenic activity into the environment need to be implemented.

The hazards associated with Cd and Cd species to humans and the environment are well documented in the scientific literature. How water systems are being polluted and how to intervene is less clear. Studies investigating Cd pollution in certain regions do show however the negative impact Cd pollution has on communities, as stated in the case study on China discussed in section 1.4.1. In addition to significant challenges in China, Savic et al. (2014) report excessive Cd concentrations measured in drainage channels along areas of agricultural land in Vojvodina, Serbia, exposing food production to Cd contamination. This study highlights the importance of water quality measurements in agroecosystems near complex pollution sources (Savic et al., 2014). The contamination of agricultural lands leads to food contamination which, particularly with global trade of staple foods such as rice, affects all communities, not only communities located near pollution sources. Communities without effective water treatment systems to remove heavy metals will also be drinking Cd contaminated water in polluted regions, compounding the effects of eating contaminated food.

In the case of Te, a preliminary study suggests that the soluble TeO_4^{2-} and TeO_3^{2-} anions are the most harmful in contaminated drinking water (Deutsche Forschungsgemeinschaft, 2006). These oxyanions can cause both chronic and acute effects to humans if consumed or inhaled (Deutsche Forschungsgemeinschaft, 2006). They also tend to persist in the environment and bioaccumulate (Deutsche Forschungsgemeinschaft, 2006). The toxicity of solid Te species in drinking water may be less of a concern than soluble compounds because solid species tend to settle out of solution or adsorb to metal oxides in the water (Qin et al., 2017). Adsorption to the sediment may create a concern for crops growing out of contaminated soil; however, the European Chemicals Agency (2019) suggests that toxicity risk from contaminated soils is low because direct and indirect exposure to contaminants in soil is unlikely. This may be because Te species tend to become structurally incorporated into soil particles (Qin et al., 2017). This is reflected by the fact that there currently is no maximum recommended safe level of Te species in the water, but there is an OSHA level for particles in the air (Qin et al., 2017).

1.6. Current regulation of CdTe PV technology

Regulation concerning CdTe thin film PV technology varies by location. While policy can be effective, its success is dependent on context and how well it is enforced. Since 2005 the European Union (EU) has enforced the Waste from Electrical and Electronic

Equipment (WEEE) directive, which promotes the reuse, recovery, recycling, and proper disposal of electronic waste, including the requirement to recycle end-of-life CdTe PVs (Sinha, 2016). Since 2006 the EU has enforced the Restriction of Hazardous Substances (RoHS) directive, which bans the use of cadmium, lead, mercury, and other hazardous substances in new electrical and electronic equipment (Sinha et al., 2008). While common PV consumer products such as solar calculators and watches fall under the WEEE and RoHS directives, thin film PV cells do not and thus there are no restrictions placed on CdTe PV applications under EU policies (Sinha et al., 2008). The WEEE directive does make it compulsory for PV manufacturers to take-back and recycle at least 85% of PV modules with no charge to the user of the PV modules (Wirth, 2019). The EU RoHS directive exempts CdTe PV technology from its scope because of its relation to climate change policy; CdTe PV can decrease greenhouse gas concentrations in the atmosphere and reduce fossil fuel dependency (Sinha et al., 2008). Each kilowatt-hour of electricity generation from a CdTe thin film PV cell offsets one kilogram of carbon dioxide from coal-based electricity production emissions (Sinha et al., 2008). Likewise, each gigawatt-hour of electricity generated from CdTe thin film PV cells can prevent 8.8 g of Cd emissions from fossil-fuel based electricity production (Sinha et al., 2008).

In 2006 the People's Republic of China implemented a similar policy to the EU RoHS directive: the Management Methods for Controlling Pollution by Electronic Information Products (Sinha et al., 2008). This regulation intends to control and reduce pollution from disposal of electronic products with the purpose of safeguarding the environment and human health; one limitation is that products destined solely for export are exempt (Sinha et al., 2008). In contrast to the EU RoHS directive, this regulation specifically lists every product within its scope instead of outlining exemptions from a broad perspective, which can lead to case-specific loopholes. Originally, thin film PV cells were a product destined for export and were not marketable in China (Sinha et al., 2008). However, thin film PV cells have been on the Chinese market since at least 2011 (ASP Story-Advanced Solar Power (Hangzhou) Inc., 2019; Weng et al., 2017). Korea and Japan have both created policies similar to the EU RoHS directives as well: Korea's Act for Recycling of Electrical/Electronic Products and Automobiles, and Japan's Law for Promotion of Effective Utilization of Resources, respectively (Sinha et al., 2008). Thin film PV cells are not included in either Korea's or Japan's regulation (Sinha et al., 2008). Current regulations in the United States surrounding photovoltaics are focused on incentives for PV adoption such as tariffs and subsidies, and not on end-of-life collection or resource recovery (Goe and Gaustad, 2014). The widespread use of CdTe thin film PV cells globally with the exception of China calls for regulation surrounding recycling and end-of-life practices.

2. Reviewed Interventions

From our knowledge of the role of CdTe in thin film PV cells, the adverse terrestrial and aquatic effects of Cd and Te species on humans and the environment, the transformation of Cd and Te species in water, and the policies currently in place governing CdTe and Cd and Te species in water, we reviewed three interventions to protect drinking water contamination. We define interventions as policies, regulations, behaviour changes, technologies, and processes that minimize hazards to humans through the consumption of Cd and Te species in drinking water, as well as minimize hazards to humans and the environment.

2.1. Regulation for recycling and end-of-life practices

Considering the increase in photovoltaic installations globally in spite of some regulations limiting CdTe PV adoption, end-of-life regulations are crucial in preparing not only for future waste disposal but also for material scarcity, sustainable energy production, and production cost (Mahmoudi et al., 2019). Regulations are needed in two areas related to end-of-life management and disposal of CdTe PV modules. These two areas include increasing the incidence of recycling and sustainable end-of-life practices. We focus our recommendations on approaches that will make recycling more logistically viable.

Again, we reiterate the importance of integrating CdTe thin film PV cells into energy production. As stated previously, each kilowatt-hour of electricity generation from a CdTe thin film PV cell offsets one kilogram of carbon dioxide from coal-based electricity production emissions (Sinha et al., 2008). Likewise, each gigawatt-hour of electricity generated from CdTe thin film PV cells can prevent 8.8 g of Cd emissions from fossil-fuel based electricity production (Sinha et al., 2008). In order for an overall positive impact on the environment, from cradle to grave, regulation to enforce recycling would address the end-of-life hazards associated with CdTe PV technologies.

The scientific literature shows the numerous advantages to recycling PV modules. Recycling reduces materials going into landfills, saves considerable energy and costs as compared to manufacturing entire thin film PV cells from scratch, and decreases the energy payback time of PV technologies (Goe and Gaustad, 2014). Additionally, recycling may alleviate future material scarcities as the demand for CdTe thin film PVs grows. As mentioned, Cd and Te are currently available in excess as by-products of other mining, but decoupling costs from other industries has benefits for long-term market stability.

Recycling is hampered by the limited geographic distribution of properly equipped facilities (Goe and Gaustad, 2014). Additionally, Goe and Gaustad (2014) make note of potential obstacles for recycling CdTe thin film PVs in unregulated areas. In these areas, it is likely that there will be more incentive to recover materials that already have well-developed recycling infrastructure and technology, rather than newer devices that require research and development to optimize recycling processes (Goe and Gaustad, 2014). Furthermore, Goe and Gaustad (2014) suggest that devices with small quantities of recoverable materials, even if they are expensive and energy-intensive to acquire as raw materials, will likely not be recycled.

The world's leading manufacturer of PV modules, First Solar, has only recently implemented a take-back policy, paving the way for recycling at scale and encouraging other competing companies to follow suit (Raugei and Fthenakis, 2010). Global and local regulation is required to ensure that enough facilities are technologically and logistically equipped to manage PV module resource recovery, and that these facilities are accessible to industry and the public. To implement this sort of regulation would require significant industry and government buy-in, and therefore require both awareness of the importance of recycling and incentives for compliance. Awareness relates to education of stakeholders on the impacts of contamination; the impacts on drinking water specifically may increase access to government resources to prevent or mitigate a public health crisis.

Implementation could take several forms: having manufacturers reclaim used PV cells, potentially with a government incentive for doing so or penalty for failure to do so; equipping existing recycling depots or eco stations to collect PV cells; or having a separate entity charged with collecting and recycling PV cells. If technically feasible, a requirement that new PV manufacturing contain a certain percentage of recycled material might be leveraged to create a stable recycled materials supply chain. Furthermore, regulation and enforcement is required to make recycling mandatory up until the material components can no longer be restored to the required purity for PV module production. Once components can no longer

be recycled, regulation and the resources for implementation are required to ensure the hazardous components are disposed of in controlled hazardous waste landfills.

Recycling is a large industry that consists of a complex web of operational and material-specific systems. Components of this web include collection, drop-off and buy-back centres, commercial recycling centres, and material recovery facilities (Fthenakis et al., 1996). The recycling of CdTe thin film solar cells is made even more complex by the decades-long interval between installation and disposal. Moreover, the geographic dispersion of PV modules means there will not always be an appropriate recycling facility in the vicinity (Fthenakis et al., 1996). Fthenakis et al. (1996) propose that PV modules be collected for recycling by manufacturers or contracted recycling centres, similar to telecommunications and electronics recycling. Reasons are two-fold: simplified logistics around recycling, and avoiding triggering waste treatment regulations in some locations (Fthenakis et al., 1996). As mentioned in section 1.6, the WEEE directive was enforced in 2012 and had to be implemented in all EU states by the end of February 2014. WEEE made compulsory the take-back and recycling of at least 85% of PV modules by the manufacturer free of charge (Wirth, 2019). In the United States, the Resource Recovery and Conservation Act (RRCA) sets legislation regulating disposal of solar products and other waste (Cyrs et al., 2014). WEEE provides precedent for a mandatory recycling model that could be adapted for CdTe thin film solar cells, although the regulatory context of the EU is fundamentally different from other parts of the world.

Alternatively, if economically viable either through market or regulatory forces, companies could adopt a leasing policy similar to SolarCity, a Tesla, Inc. subsidiary specializing in solar energy services headquartered in San Mateo, California. SolarCity markets, manufactures, and installs residential and commercial PVs across the United States (Litvak, 2014). Solar leasing is available in both the residential and commercial sectors from SolarCity (EnergySage, 2019). In 2013, SolarCity was the leading residential installer of PVs in the United States occupying 26% of the residential market (Litvak, 2014). Solar leasing is gaining momentum in the United States: in the residential market over 70% of PV installations in California, Arizona, and Colorado are leased (Wang, 2013). In the European market, solar leasing is available through the German company PV^2 Energie, which develops ground and roof-mounted photovoltaic systems in agricultural, public, and commercial markets (PV2 Energie, 2019). Furthermore, PV^2 Energie opened business operations in 2017 in the Philippines with a new branch entitled PV^2 Energie Solar Philippines, offering their services across the Philippines, including solar leasing (PV2 Energie Solar Philippines, 2019). Leasing PVs has many advantages to the consumer: it mitigates a large initial expenditure that may require financing, it alleviates the complexities surrounding owning PVs, and customers are not responsible for maintenance, repairs, or disposal (Mauritzen, 2016). All these advantages serve to broaden the customer demographic (Mauritzen, 2016). Other recycling strategy options suggested in the literature include municipalities collecting PV modules, and the PV industry providing arms-length guidance to the municipalities on best-practice recycling methods, or multi-material recyclers, such as recyclers for telecommunications and electronics, evolving to accommodate PV module recycling (Fthenakis et al., 1996). In summary, the recycling of CdTe thin film solar cells is a complex issue that requires careful attention to global, federal, and local regulations, materials economics, and experiences of comparable industries.

As stated earlier, most PV cells are disposed in municipal landfills. This poses serious hazards to terrestrial and aquatic ecosystems as the Cd and Te may leach out of the landfills and contaminate soils, groundwater, and surface water. This is especially a concern as the global use of PV modules increases. Global and local regulation is required to ensure that the hazardous materials in PV modules, including Cd and Te, be extracted and disposed of in a controlled hazardous waste landfill. The most effective way to enforce this regulation would be to implement a mandatory recycling framework and provide necessary resources to make it feasible. When materials are being separated for recycling purposes, the components that are hazardous and cannot be recycled are disposed in controlled hazardous waste landfills instead of municipal landfills. This increases disposal cost, but instead of externalizing the cost of disposal in the form of environmental degradation, the cost is internalized in a form that is easier to mitigate.

2.2. Utilizing biochemical reactors to safely and efficiently extract and recycle Te

In order to increase the viability of implementing and enforcing concrete regulation surrounding recycling of CdTe thin film PVs, there is room for technical innovations regarding extraction and recycling of Te in particular. Te is one of the least common metals/metalloids on earth (United States Geological Survey (USGS), 2015). The DOE classifies Te as a 'near critical' resource in respect to its necessity for future innovations in the energy sector, and to acknowledge the inevitable shortage faced if extraction and recycling methods are not improved (Bonificio and Clarke, 2014; Hunt et al., 2015). As mentioned above, current methods require high temperatures and hazardous chemicals to separate and purify (Bonificio and Clarke, 2014). Using existing processes, common recovery efficiencies are only about 30–40% (USGS, 2015). Based on the drawbacks of current processes for extracting and recycling Te species, it is crucial to design safer, more efficient, and less energy intensive processes.

Innovative technology has been applied to extract and recycle heavy metals and metalloids, however, most has not been tested specifically on CdTe. One innovative approach is biosorption, during which a non-living bio-derived material (biosorbent), such as algae, fungi, or spent coffee grounds, captures heavy and precious metals via adsorption to remove them from solution. Following adsorption, the heavy metal must be desorbed, which regenerates the biosorbent. The preferred method at this time is using an acid wash (Dodson et al., 2015). This process has been used for remediation, however, it requires further research to optimize it for harvesting the biosorbed metals (Dodson et al., 2015). Another promising approach that is spawned from phytoextraction is "phytomining". In "phytomining" plants remove heavy and precious metals from solution in the form of metallic nanoparticles, which can be harvested and used. Similar to biosorption, phytoextraction has been used for remediation, however, "phytomining" requires future research to optimize techniques for harvesting "phytomined" metals (Hunt et al., 2014). Additionally, both of these alternative processes currently lack metal specificity (Dodson et al., 2015; Timofeeva et al., 2017).

Based on the success of these novel, green, bio-inspired alternatives in relatively uncontrolled environments, it should be technically feasible to develop and scale biochemical reactors for specifically recovering and recycling Te. In contrast to open-environment phytoextraction processes, biochemical reactors create highly controlled environments in which heavy metals can be extracted and purified for use in new PV cells and other devices. Indeed, this innovative technology has already been tested for extracting Te from mining by-products and from recycled devices containing Te (Bonificio and Clarke, 2014, Ramos-Ruiz et al., 2017). Currently, research ranges from small-scale solid and liquid media precipitation and volatilization assays (Bonificio and Clarke, 2014) to bench-scale tests, such as a 1.2 L upflow anaerobic granular sludge reactor (Mal et al., 2017) and a 2 L continuous stirred

tank reactor (Rajwade and Paknikar, 2003). Further research and development will need to occur before large-scale applications are realistic.

Identification of appropriate bacteria for biochemical reactors is a limiting challenge in this research. Certain biochemical reactors, such as sulfate-reducing bioreactors, contain bacteria that consume oxygen in the reactor, creating an anaerobic and reducing environment (Baldwin et al., 2015). In this environment, bacteria can interact with and possibly transform heavy metal and metalloid species in order to detoxify the environment (Igiri et al., 2013). One transformation method is the reduction of oxides into metallic species via enzymatic activity (Baldwin et al., 2015; Igiri et al., 2013). Metallic species are immobilized, thus they are less bioavailable and less hazardous. Research is underway to optimize biochemical reactors for the removal and disposal of Cd from mining waste and recycled devices (i.e. Neculita et al., 2008; Nielsen et al., 2018). However, research on extraction and recycling of Te is limited to the few examples given above because of specific challenges of Te biochemistry. It is difficult to design a biochemical reactor to specifically extract Te because Te species, especially the dissolved tellurite ion, which oxidizes thiols and produces reactive oxygen species, tend to be toxic to many bacterial strains (Bonificio and Clarke, 2014). It is therefore necessary to select bacteria to populate a biochemical reactor that are resistant to Te, and thus able to reduce Te species to metallic Te, which could be harvested and used to build new PV cells and other devices.

Bacteria located on geothermal vents deep in the ocean show promise because vent chimneys have high concentrations of Te, thus bacteria there would need to be resistant to Te (Bonificio and Clarke, 2014). Bonificio and Clarke (2014) tested the efficacy of vent bacteria in the genus *Pseudoalteromonas* at reducing Te from various sources including cadmium telluride, bismuth telluride, autoclave slime, and tellurium dioxide. Their research suggests that *Pseudoalteromonas* can reduce Te species to metallic Te. These results show promise for using *Pseudoalteromonas* species to more efficiently and safely extract Te, providing a supplemental material stream for this relatively rare element.

In addition to the reduction of metals to metallic species, bacteria in biochemical reactors can form volatile methylated metals and metalloids (i.e. dimethyl telluride, $(CH_3)_2Te$) (Baldwin et al., 2015; Bonificio and Clarke, 2014). These volatile methylated species pose hazards to human health and the environment; therefore they pose a danger if released from the system (Bonificio and Clarke, 2014). A method must be developed to deal with these volatile methylated metals. Some solutions that show promise pending future development include: implementation of scrubbers to remove volatile species (Neculita et al., 2008; Zhang et al., 2015); a series of bioreactors to transform volatilized species into metallic Te (Sahu et al., 2009; Mohanty and Das, 2006; Hiras et al., 2004); genetically engineering bacteria to only produce metallic Te, rather than producing both metallic Te and volatile Te (i.e. Zhang et al., 2015); and lastly, altering the conditions in the biochemical reactor to favor the formation of metallic species (Compeau and Bartha, 1984).

Ultimately, a safer, more effective, and less energy intensive method must be designed to extract Te from mining by-products and from recycled devices in order to meet the rising demand for Te. Biochemical reactors show promise as a method for extracting and recycling Te, however, future research is needed to optimize the method. The quickest solution to implement would be a train of biochemical reactors, although, this solution would likely be costly. As we learn more about the processes that occur in biochemical reactors, we may be able to optimize a single bioreactor to form only metallic Te, negating the need for a train of reactors.

2.3. Dye-sensitized solar cells as an eco-friendly and accessible alternative PV technology

While recycling and recovery are keys to making the current industry more sustainable, it is worthwhile to consider alternative technologies that achieve the same function, namely solar energy harvesting, via potentially greener techniques. Similar to CdTe thin film PV cells, dye-sensitized solar cells (DSSC), which are also thin film, produce electricity from sunlight and can be produced by similar low-cost manufacturing techniques. DSSCs are not currently being commercially produced, rather, companies are researching improvements in DSSC design and performance and creating small demonstration projects (Market Watch, 2019b).

DSSCs have a photoanode consisting of a wide-band semiconductor material (commonly titanium dioxide) coated in a photosensitized dye (i.e. ruthenium-polypyridine) and a platinum cathode (Rawal et al., 2015; Varanasi et al., 2018). The dye increases the surface area for absorption compared to the semiconductor material alone, and increases the amount of visible light that can be absorbed by the photoanode. The entire system is bathed in an electrolyte solution, such as the liquid iodide/triiodide (I^-/I_3^-) electrolyte. When sunlight strikes the PV, electrons in the dye become excited and pass through the semiconductor layer. The electrons flow through the external circuit toward the cathode, along the way producing electricity. The excited electrons in the cathode reduce the triiodide electrolyte to iodide. The triiodide then gets oxidized in the process of reducing the dye at the anode (Rawal et al., 2015).

DSSCs have some advantages over CdTe thin film PV cells. DSSC's have a relatively simple design, evidenced by the existence of do-it-yourself DSSC protocols available for purchase (Powers, 2019), and potential dye materials are readily available across the globe, such as chlorophyll (Rawal et al., 2015). Titanium dioxide, the common semiconductor material in DSSCs, is considered biologically inert in humans and animals when greater than 100 nm in size, making it a potentially more ecofriendly, non-toxic semiconductor material (Skocaj et al., 2011). The design of DSSC's allows the devices to absorb an increased amount of light across the visible spectrum compared to a semiconductor alone, allowing DSSCs to absorb more light on cloudy days than silicon PVs (Rawal et al., 2015). Additionally, impurities in the semiconductor layer are insignificant due to the role of the semiconductor, which is transporting charge, not absorbing sunlight (Rawal et al., 2015). DSSCs are also able to radiate heat more easily and quickly than CdTe thin film PVs, resulting in a lower loss in efficiency due to heat (Rawal et al., 2015). Lastly, DSSCs also have efficiencies of up to 11–13%; although this gives a lower cost to efficiency ratio than CdTe thin film PV cells, it does have a favorable cost to efficiency ratio compared to fossil fuels (Tiwari and Mishra, 2012).

However, DSSCs also have disadvantages compared to CdTe thin film PV cells. As mentioned, their cost-to-efficiency ratio is not optimal, which is an important characteristic for large-scale applications (Rawal et al., 2015). The applicability of DSSCs is also limited because a liquid electrolyte is commonly used, which is not stable in varying temperatures. At low temperatures the aqueous electrolyte can freeze, damaging hardware and preventing the panel from continuing to produce electricity, and at extremely high temperatures the liquid electrolyte can expand, which makes it difficult to seal the solar cell during manufacturing and maintenance and also can damage the structure of the solar cell (Rawal et al., 2015). Research is ongoing to employ solid electrolytes to decrease this limitation while maintaining efficiencies (Rawal et al., 2015). The integrity of the current design is impacted by the iodide/triiodide electrolyte, which can be corrosive to the sealing materials, limiting the lifespan of the PV (Rawal et al., 2015). Additionally, ruthenium dye, which is commonly used in DSSCs, is potentially

hazardous and expensive (Reddy, 2014). However, research is ongoing to design and employ more eco-friendly and efficient dyes for DSSCs. Unfortunately, most low cost natural dyes have efficiencies lower than 2% (Shalini et al., 2016). Lastly, more modern DSSCs commonly use nano-sized particles of titanium dioxide, which have increased associated health concerns compared to larger particles (Heringa et al., 2016). If these issues are addressed and the efficiency is improved, DSSCs represent a potentially greener, more accessible PV design compared to CdTe thin film PVs.

3. Results

We have identified and described three interventions to protect drinking water from contamination by CdTe and Cd and Te species: regulations to promote better recycling and disposal practices; biochemical reactors for extracting and recycling Te; and dye-sensitized solar panels as a greener alternative technology. The goals of these interventions are to mitigate the externalized negative human and environmental health hazards associated with CdTe PV. The scope of our case study is focused specifically on CdTe and Cd and Te species as they impact drinking water quality.

A multiple criteria decision analysis (MCDA) provides a framework through which to evaluate the three reviewed interventions using performance criteria defined below. We perform a case study illustrating the use of the MCDA by analyzing the three interventions discussed in this Critical Review.

3.1. Multiple Criteria decision analysis (MCDA)

We have identified six performance criteria to evaluate the potential for improving protection of drinking water and the environment, as well as increasing renewable energy availability of alternative technologies and interventions. Each criterion is assigned a score of 1, 2, or 3 according to the guidelines in Table 2: 3 is better than 2 and 2 is better than 1. The interventions are assigned a score in each category in Table 3. A cost analysis is not included in the MCDA due to lack of data.

A summation is performed to determine the total score for each intervention. In the example analysis provided here, we assume every performance criteria holds equal importance; these weightings could be changed to reflect needs and priorities of a decision-maker in a more specific context. The higher the score, the more desirable the intervention. We demonstrate this framework in Table 3 where we analyze the three interventions discussed in this Critical Review. Please note, the scores given are at our own discretion, and do not reflect a consensus from experts in the field.

Table 2
Scoring guidelines of performance criteria.

Performance Criteria	Score		
	1	2	3
Ease of implementation and enforcement	Not easy	Moderately easy	Easy
Infrastructure, technology, and logistics are currently in place	Not in place; require major development	In place; require minor development for use	In place; ready to be used today
More research is required before this intervention can be implemented	Significant lack of knowledge	Some holes in knowledge	All required knowledge available
Replaces a current technology with one that will increase electricity production and efficiency of the solar cell	Does not replace a technology	Replaces a technology; minimal increase in efficiency	Replaces a technology; major increase in efficiency
Reduces CdTe and Cd and Te species in drinking water	Does not decrease contamination	Minor decrease in contamination	Substantial decrease in contamination
Reduces hazards to human health and environment	Does not reduce hazards	Minor decrease in hazards	Substantial decrease in hazards

Table 3
Comparison of interventions.

Performance Criteria	Intervention 1 Regulation of Recycling and Disposal	Intervention 2 Biochemical Reactor	Intervention 3 Dye-Sensitized Solar Cells
Ease of implementation and enforcement	1	1	1
Infrastructure, technology, and logistics are currently in place	1	1	1
More research is required before this intervention can be implemented	2	1	1
Replaces a current technology with one that will increase electricity production and efficiency of the solar cell	1	2	1
Reduces CdTe and Cd and Te species in drinking water	3	2	3
Reduces hazards to human health and environment	3	2	2
SUMMATION	**11**	**9**	**9**

In our example analysis, the highest score is given to the intervention: "Regulation of Recycling and Disposal". The most notable advantages of this intervention are the lack of technological barriers and that, if implemented and enforced appropriately for the context, it will likely lead to a reduction in water contamination and hazards to human health and the environment. The difficulties for this intervention are the implementation and enforcement of the regulations and creating the infrastructure required to implement and enforce the regulations. Additionally, careful analysis of trade-offs is necessary to avoid over-regulation that disincentives PV adoption in favour of fossil fuel-based energy and exacerbates Cd contamination as noted in Section 1.6 (Sinha et al., 2008). The amount of research required before this intervention can be implemented is moderate (2): while there is a lack of precedent for regulation of CdTe thin film PVs, other industries with comparable issues may be referred to in order to find solutions; a parallel knowledge base exists. Because regulation is needed on a local scale as well as federal and global, more research is required to design context-appropriate regulation, justifying a score of 2 and not 3.

"Biochemical Reactors" and "Dye-Sensitized Solar Cells" have different strengths in the example analysis. Biochemical reactors could potentially decrease the life cycle impacts of CdTe thin film PV cells, while dye-sensitized solar cells offer a less-efficient replacement for CdTe thin film PV cells at the current state that could mitigate some hazards. However, both Interventions ranked lower than "Regulation" because they are higher risk interventions that require significant technological research and optimisation before either can be implemented; however, in the long term they could positively impact the nexus between clean energy and water & sanitation.

This example analysis suggests that from a technical perspective, regulation is the most realistic intervention to pursue in the immediate term. This is largely due to gaps in knowledge and technology related to bioreactors and dye-sensitized PVs, meaning that long R&D timelines precede widespread market-readiness of

bioreactors for metals recovery or dye-sensitized PVs. This does not account for the myriad challenges of designing, implementing, and enforcing effective regulations. However, it does emphasize the importance of parallel development of technical and policy solutions. Ultimately, as CdTe PV technology increases in popularity, forethought should be used to produce a well-rounded product. This means regulating production and recycling and disposal, as well as finding the most eco-friendly way to produce the technology. We recommend further research on location-specific regulation for recycling that is appropriate for the context, enforcement routes, available infrastructure for implementing and enforcing regulation, and recycling strategies in industries with comparable issues.

4. Conclusion

The use of clean renewable energy technologies such as CdTe thin film PV cells can effectively promote the Sustainable Development Goals of "Clean Water and Sanitation" and "Affordable and Clean Energy", making the PVs an important part of the emerging renewable energy landscape. They are competitive with silicon PV cells, having achieved a laboratory efficiency of 21.1% (Market Watch, 2019a). Additionally, being thin film PV cells, they require less material than conventional solar panels, are relatively inexpensive, and are flexible. CdTe thin film PVs also make use of Cd and Te, diverting hazardous materials into beneficial use that would otherwise be disposed of as waste by-products of mining, potentially leading to contamination of terrestrial and aquatic ecosystems. CdTe is also a more stable and insoluble compound compared to other Cd and Te species, thus hazardous and bioavailable Cd and Te species are less likely to enter the environment once transformed into CdTe.

There are, however, some risks of contamination associated with processing the raw metals/metalloids and manufacturing the thin film technologies. Specifically, risks associated with stockpiling of Cd and Te in the form of mining by-products, during recycling, and during disposal. The three suggested interventions are intended to prevent, or at the least decrease, the risk of contamination of drinking water by CdTe and Cd and Te species. We propose a framework for analyzing the environmental benefits of an alternative technology or innovation which encompasses uncertainty and data gaps. The Multi-Criteria Decision Analysis is illustrated with a case study.

We recommend the Multi-Criteria Decision Analysis as a tool to help business and political leaders in decision making with regards to green technologies and interventions. The role of informed decision making in the nexus between alternative technologies and/or interventions and clean water is integral for achieving water security and growing green, affordable energy.

CRediT authorship contribution statement

A.M. Curtin: Conceptualization, Methodology, Investigation, Writing - original draft, Visualization. **C.A. Vail:** Conceptualization, Methodology, Investigation, Writing - original draft, Visualization. **H.L. Buckley:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wen.2020.03.007.

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