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End of Life decommissioning and recycling of Solar Panels in the United States. A real options analysis.

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Abstract

It is estimated that hundreds of thousands of tons of solar panel waste are going to be produced yearly just in the United States from the year 2035 on, most of which could be recycled. This paper estimates the amount of scrap material to be produced from solar photovoltaic panels decommissioning and determines the optimal date and location to establish centralized or regional recycling centers to better deal with this issue on its early stages, between the years 2024 and 2042. Solar panel recycling could become a multi-billion USD industry over that time, however the main challenge today is to keep its overall costs down while allowing for the mayority of panels to be recycled. Real Options Analysis is deployed to assess the optimal solution to face this challenge. This approach allows determining the optimal time and location to invest in recycling centers and the best strategy to undertake among different alternatives. The goal of this paper is to set a cornerstone for dealing with solar panel decommissioning and recycling at the end of their useful life in the United States, and we also determine a model that accounts for optimal location of the recycling facilities, which is a novel approach. This paper also offers a new application of the ROA modeling for estimating the optimal investment date for solar panel recycling plants from the investor perspective of the U.S. government in Washington D.C. Further applications of the model proposed in this work could allow for a similar analysis at an international level.

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1 Introduction

Solar energy is one of the most common forms of renewable energy, and it is typically classified as green energy. Economic and environmental benefits resulting from the production of energy from photovoltaic (PV) panels or modules are widely studied and its convenience is hard to question. This affirmation regards only the operation of panels but sets aside the rest of their life-cycle. Solar photovoltaic energy, like any other energy production form, has its downsides, and it can yield a significant amount of waste. In particular, solar energy offers important environmental advantages while producing energy, but triggers salient impacts resulting from the production and transportation of the PV panels, and at the end of life (EoL)[1] of those same panels. All this tenders important opportunities for reuse and recycling of materials that significantly improve the life-cycle performance of the panels environmentally and financially. This work explores alternatives regarding the best disposal management of the panels and explores whether or not it poses a noteworthy investment opportunity.

Recycling PV panels is necessary for environmental and financial reasons. Crystalline Silicon Panels are the most common PV panels installed to date. According to experts, they represent 85 to 90% of the market[2]. They are mostly manufactured with aluminum, glass, silicon, copper, and plastics (DAdamo et al., 2017), which can be recovered at very high rates, and in most cases convey significant economic value. The recycling process for PV panels includes chemical and physical treatment approaches, which have been successfully implemented by other industries, i.e. consumer electronics recycling. We believe that the technical part of the process has been well determined and studied by experts in the field, and we center our approach to determining the financial viability of these processes. PV panels also contain other hazardous components, i.e. heavy metals and other toxic elements, that require special treatment and are typically encapsulated inside plastic elements in the panels. Processing those plastics results in an additional cost to the overall process and deteriorates the quality of plastics to be recovered from the panels, which is recognized financially in our approach.

Solar panels also tend to be big and heavy, and so they frequently exceed the allowance for conventional waste management centers in different locations. In addition to that, Crystalline Silicon Panels do not typically pose interesting profits to recyclers as they do not contain significant precious or scarce metals, however, the equipment to produce 1 MW of energy with this technology can weight around 75 tons on average (DAdamo et al., 2017). In many cases, recycling the panels can be very efficient, and reach between 78% to almost 100% efficiency of recovering for some components (DAdamo et al., 2017). After the panels are processed, glass, silicon, plastics, and copper recovered can be used to manufacture new panels. Solar PV panels have a useful life that can range from 25 to 30 years in most cases. The ques-

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[1] End of life is a term used to describe that the useful life of a product has been exhausted.

[2] Our numbers show an even higher proportion, as it can be seen in section 1.1 of this work.

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tion here is what should happen to the panels after their operational life has been exhausted. There certainly could be a problem to handle the equipment is treated like trash, as they would annually represent more than: “3 million tons [of waste] in 2035 to 9.5 million tons in 2050” (Bakhiyi et al., 2014), but also for the hazardous components present in the panels, that cannot be dumped to the landfill.

Recycling the panels could result in an interesting financial opportunity. In a 2016 report by IRENA[3] (Weckend et al., 2016) it was detailed that recovered materials from the panels alone could be worth $450 million USD by 2030 and exceed $15 billion USD by 2050. We know with relative good certainty where a lot of those panels are located within the U.S. We cannot know, however, the exact time of deployment, provided different investors may have specific capital requirements for their projects, and we can expect some exogenous events to occur,[4] affecting the expected useful life of the panels, but we can estimate the time of deployment stochastically, as described in Section 3, provided that data regarding their installation and useful life is readily available and some of such events can be estimated.

1.1 Solar energy in the United States

In the United States, PV panels started to ground in the 1970s but did not become a hot topic until the 2000s. It was only until two decades ago that renewable energy was targeted to reduce emissions and to diminish our reliance on fossil fuels. Between 1999 and 2017, 26.6 thousand Megawatts of PV were installed in the U.S., 69.8% alone over the period of 2013 to 2017, and 11.4% of which corresponds to the year 2017. Solar panel installations between the years 1999 and 2017 have grown by 184.4% on average for that period (Barbose et al., 2017).

Installed solar PV capacity in the United States represents an estimated 2 million tons of solar panel scrap to be produced between 2024 and 2042, under general assumptions, further detail can be observed in table 1. Actually, the factors explained in section 1.3 below, could result in accelerated decommissioning of the panels and higher estimates. With these numbers, the United States could be the second market by potential solar PV waste production, behind China and ahead of Germany and India.

Of the total installed PV panels in the U.S. between 1999 and 2017, only 6 states concentrated 94.81% of that capacity. Arizona and California were the states with most PV panels in kW, respectively with 52.20% and 25.77%. Meanwhile, Massachusetts, Utah, New York, and Colorado accounted for an aggregated 16.85%. Finally, other 19 states[5] aggregated together with the remaining 5.19% of the national total. The rest of the states did not report installed capacity to this dataset. Further detail on installed PV capacity by the state can be found in table 2. The six states with

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[3] International Renewable Energy Agency.

[4] Examples of such events are described in subsection 1.3.

[5] Arkansas, Connecticut, Delaware, Florida, Illinois, Kansas, Maine, Maryland, Minnesota, Missouri, New Hampshire, New Mexico, Ohio, Oregon, Pennsylvania, Texas, Vermont, Washington D.C., and Wisconsin.

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Table 1: Installed Solar PV Capacity in the United States.

Year Installed	Installed Capacity (in kW)	Estimated Scrap (in tons)
1999	953.21	71.49
2000	696.32	52.22
2001	4,666.67	349.97
2002	22,633.93	1,697.41
2003	24,294.76	1,821.96
2004	37,078.48	2,780.66
2005	42,943.72	3,220.52
2006	65,715.64	4,928.28
2007	116,387.72	8,728.38
2008	204,232.00	15,316.17
2009	929,568.88	69,712.09
2010	3,003,921.70	225,276.17
2011	2,223,006.21	166,712.13
2012	1,362,354.12	102,168.39
2013	5,721,665.06	429,090.55
2014	1,821,191.13	136,578.41
2015	2,252,238.89	168,904.40
2016	5,767,794.60	432,549.99
2017	3,033,668.86	227,506.96
Total	26,635,011.89	1,997,466.09

Source: Based on data from Barbose et al. (2017)

the most panels are located all over the United States geography. While California is localized in the west very close to Arizona, New York, and Massachusetts are in the east. Colorado and Utah can be found in the center part of the country.

1.2 Solar panel recycling

Solar PV recycling seems to be a relatively unexplored field internationally. Some areas such as the European Union have specific directives regarding it, such as Waste Electrical and Electronic Equipment Directive (also known as WEEE Directive) which was originally established to deal with general electronic recycling, but also includes provisions for solar panels. By the time this paper was written, the United States had not passed significant regulation regarding this issue, except for California that attempted to establish rules to manage solar panel waste, i.e. ”Proposed Standards for the Management of Hazardous Waste Solar Modules” in 2010. Although that piece of legislation was limited and did not seem to cover implementation thoroughly, also was not in effect at the time that this article was written. Other pieces of regulation, i.e. the ”Universal Waste Management Regulations” have been recently passed by

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Table 2: Installed Solar PV Capacity by the state in the U.S.

State	Percentage of total installed panels
Arizona	52.20%
California	25.77%
Massachusetts	7.87%
Utah	4.03%
New York	3.65%
Colorado	1.30%
Other 19 states[5]	5.19%

Source: Based on data from Barbose et al. (2017)

the state regarding this topic, and are yet to be implemented, but the scope of these regulations to solve this issue is not completely clear at this point in time.

Perhaps the best approach could come directly from the industry, i.e. First Solar, the biggest American solar panel supplier, and organizations such as PV Cycle[6], that specializes in PV recycling, as they self describe "waste management and legal compliance services for companies and waste holders around the world." They offer recycling services throughout a decentralized network of collection points in certain geographies aiming to breach the gap between end-consumers of the panels and the recycling process. According to Reuters[7], a joint effort between Veolia and PV Cycle France resulted in the first European solar panel recycling plant in France just in 2018. The facility was set to recycle 1,300 tons of solar panels in 2018 is expected to be able to reach 4,000 tons by 2022.

1.3 Factors affecting the useful life of the panels

As above mentioned, the useful life of the panels is typically 25 years but can reach 30 years in some extraordinary cases. The estimated useful life includes an expected decay of the equipment by regular use. As mentioned above, sometimes panels can exceed that expectation, but in some cases, they are also deployed early for different reasons, i.e. due to some of the following factors:

1.3.1 Accelerated degradation and defects

Regardless of their expected useful life, solar panels sometimes incur in early failures. Warranties in most cases cover defects, however, it is difficult to ship back the defective panels to the producer, and while the equipment gets replaced, the responsibility of disposal of the defective equipment remains with the end-consumer. Also

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[6] See: www.pvcycle.org

[7] See: https://www.reuters.com/article/us-solar-recycling/europes-first-solar-panel-recycling-plant-opens-in-france-idUSKBN1JL28Z

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during their lifetime, PV panels can develop defects and experience performance degradation due to local stresses. The defect type and rate of degradation depend on several factors, i.e. cell technology, manufacturing quality control, installer workmanship, and the installed environment, etc. Defects can be diverse, from purely cosmetic, to sometimes causing safety risks (Jordan and Kurtz, 2011).

Also, according to Jordan and Kurtz (2011) ”for monocrystalline silicon, the most commonly used panel for commercial and residential PV, the degradation rate is less than 0.5% for panels made before 2000 and less than 0.4% for panels made after 2000.” This is just the normal degradation of the panels and does not account for increase degradation resulting from the above-mentioned factors. It is typical to consider a 20% decline on the production capacity of the panels to be considered failure, but it does not seem to be clear a consensus on it.

1.3.2 Natural phenomena

Some panels get damaged for weather events or other eventualities. But where are those panels going now? According to experts, to the landfill, since ”there is no dedicated national program or requirement to safely dispose of the panels, and some, unfortunately, find their way into the landfill” Pickerel (2018). The question then is, who should be responsible for the disposal of those panels in the U.S.? We have on one side the producer that is sometimes regarded liable for what they offer to the market in some geographies, i.e. in Europe with the WEEE Directive, or on the other side, the end consumer who is acquiring the equipment and this case should assure that it gets properly disposed of. Perhaps, we could also appoint waste managers and ultimately local, state and federal governments responsible to deal with health and safety of civil society. Some liberals may even argue that the market itself should be allowed to self regulate into dealing with the issue. The truth of the matter is that there is no answer yet, at least not in the United States. This, in fact, goes against the promise of solar energy to be clean an renewable source of energy. Pickerel (2018) also presents a comprehensive report on claims for solar PV panels in North America. According to it, weather-related events were the most common reason for claims, approximately 49.8% followed by fire with 36.1% and electrical breakdown with 9%. Other causes roughly reach 5% of the claims and include mechanical breakdown, lightning, and theft. And it seems that provided increased weather-related events and wildfires in the United States, an increase in claims can be expected. According to Kelly Pickerel, innovation could be an alternative to make more resistant panels, but still, the challenge results from already existent panels.

1.3.3 Investor preference

In addition to the typical external scenarios of deployment, we can also observe, that in some cases, older projects were installed in the best locations. This motivated by the added effort needed to achieve profitability at the state of technology when that happened originally. Those locations also resulted interesting for renewed invest-

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ment today and can be incorporated in a further application of the present work, provided the current state and a projected state of technology. Innovations tend to pose opportunities are a great set point for real options. As it is well known, innovation is not a recent phenomenon. Modern industries deal with innovation on a regular basis, and while innovation usually implies a certain investment that can eventually be recovered or not, it does promise potential benefits. In such case, it is just a rational expected response from investors to opt to refurbish or completely rebuild their solar capacity as new technologies reach a certain level of improvement, to take advantage of the best locations, as it would be more profitable in the long run. In our setting, this would accelerate the expected end of life of the panels. Other factors affecting the expected life-cycle of the panels exist, and could be analyzed, although not enough documentation can be found at the time, and therefore further research is needed.

1.4 Real Options

Real option assessment (ROA) models are a great fit to identify optimal stopping problems, such as the problem stated in this paper where we try to anticipate the optimal investment date for a recycling facility. These models are used in order to check whether investment decisions should be taken and when is the optimal time to do so. Besides these models, the standard tool used in this setting before was time value of money, and particularly, Net Present Value (NPV). This methodology, an investment should be triggered if and only if its NPV, i.e. the difference between its expected discounted payoffs and costs is positive.

The criteria for NPV is then static to the extent to which the choice is between realizing the investment at the date when the NPV is calculated, or never. This is a significant drawback of the NPV criterion. NPV also assumes that cash flows and cost are known, in other words, as long as there is certainty in the amount and frequency of the cashflows an estimation can be made in NPV. In the case that cashflows are uncertain, ROA is found to be a more useful tool to value investments. ROA is also useful to assess value when an investment can be delayed.

1.5 Sections

This paper is organized as follows: Section 1 gives an overview of the current status of end of life management of solar PV panels installed in the United States and describes the problem that we address in our research. Section 2 gives an overview of the existing literature regarding this issue and also describes some of the previous efforts to apply ROA in particular for electronics decommissioning, end of life management and recycling. Section 3 outlines the model and the numerical methods used to solve it and the choice of parameters deployed. Section 4 introduces the case of the United States and the variables used for the setting defined and our model assumptions. Section 5 gives the main results and the key findings in the sensitivity analyses of our results. Section 6 concludes.

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2 Literature Review

Renewable energy is a frequent topic to academic work, and so it is to the field of Real Options Analysis. As it would be expected most exertion regarding renewable energy can be found regarding investment, financing, feed-in-tariff schemes, but recycling and end-of-life assessment of solar PV panels is a relatively new topic. Our article contributes to the literature by developing a dynamic real options model that allows determining the optimal time to invest in the best strategy to undertake among distinct possible alternatives.

Seminal work on End-of-life management and recycling of PV panels started with Fthenakis (2000). In this work, the author highlights the environmental advantages of PV technology and presents a feasibility study for recycling thin-film solar cells and manufacturing waste, based on the current collection and recycling infrastructure, but also based on current and emerging technologies. Cucchiella et al. (2015) present a traditional Net Present Value financial analysis on End-of-Life of used photovoltaic panels, and they state that the scientific literature presents divergent technological solutions, and highlight the environmental benefits resulting from the PV panels recycling, but conclude that the economic arguments are more fragmented.

Technical aspects of PV recycling can be found in the work of Doi et al. (2001), Klugmann-Radziemska et al. (2010), and Berger et al. (2010). Klugmann-Radziemska and Ostrowski (2010) conclude that the disposal of PV systems will become a problem in view of the continually increasing production of PV panels. These can be recycled for about the same cost as their disposal. Fernández et al. (2011) even go further to present a study on the recycling of crystalline solar cells inside cement matrices. Rocchetti and Beolchini (2015) study how to manage valuable materials inside the panels through different recycling alternatives. Tao and Yu (2015) review the feasibility of recycling pathways and technologies of solar photovoltaic panels from three different pathways.

Latunussa et al. (2016) perform a Life Cycle Assessment (LCA) of an innovative recycling process for crystalline silicon photovoltaic panels. It is worth mentioning that LCA is also a favored methodology for assessing end of life management of solar panels provided the characteristic of this methodology to assess different impacts at the product level. Further reviews on innovative recycling methods for PV panels can also be found in the work of Shin et al. (2017) and Choi and Fthenakis (2010), that present the status of photovoltaic recycling planning and discuss a mathematical model of the economic feasibility and the environmental viability of several PV recycling infrastructure scenarios in Germany in 2010. An important paper that contributed significantly to the parameters used in this work was written by DAdamo et al. (2017), who describe in much detail the outcomes of the recycling of Si PV panels. The work of DAdamo et al. (2017), however only sets to analyze the global situation of PV recycling in a general way and describes a simplified NPV approach with linear price estimations that is enriched with the model presented in our work.

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China can be found in studies by Lee and Shih (2010) and Chi et al. (2014). Chi et al. (2014) study E-waste collection channels and household recycling behaviors in a region of China. McDonald and Pearce (2010) explore the responsibility of the producer in recycling solar photovoltaic panels. They even present detail on the cost of landfill disposal of different types of solar panels. One of the most comprehensive and earlier studies on the scale of the problem regarding the end of life management of solar panels is presented by Weckend et al. (2016). In this study, the authors determine panel waste volumes to 2050. Xu et al. (2018) establish a quantitative basis to support the recycling of PV panels, and suggests future options policy determinations.

Other Real Options Analysis work can be found in the field of climate change that could also be extrapolated to energy modeling. Chesney et al. (2017a) elaborate on more on this by introducing risk aversion in Real Options while assessing the optimal choices of a forest owner given his option to enter an irreversible scheme that provides uncertain cash flows under different risk aversion scenarios. Considerations of game theory and competition could also be included to asses competition once the market matures, and new entrants start to interest in this market, and such situation could by captured by a model such as the one proposed by Botteron et al. (2003). Besides the entry barriers already highlighted, intermittent production is the other key challenge to solve. Also, the model proposed by Rai and Robinson (2015) incorporates the integration of social, behavioral, economic, and environmental factors in a model of energy technology adoption. This could also be good to include in further research.

The financing gap that could result from the imminent interest in solar PV recycling could also result in a financing gap, such as the one that currently exists in solar PV investments and energy storage. Further research would be needed in that regard. Finally, research comparing different solar PV markets, i.e. the United States and Europe is also common, for an example, we can see Seel et al. (2014). Further work on recycling could also be done not only including those two markets, and China, India and other global players as presented by different authors (Chi et al., 2014; Zhang et al., 2016b; Lee and Shih, 2010; Ding et al., 2016; Weckend et al., 2016).

Although wind and solar seem to be the most persistent cases to be found in academic literature regarding applications of Real Options for Renewable Energy, since the early 2000s, it is also possible to find further academic work studying the different aspects of other forms of renewable energy. Typical examples include tidal, hydro, alternative fuels (ethanol, biomass, biogas, etc.), and renewable energy in general. Even further work can be found regarding nonrenewable forms of energy, i.e. Nuclear. Provided the scope of this work, that literature was not included in this summation.[8] Our work contributes to the existing literature by presenting a model that estimates the viability of distinct potential solutions for the PV recycling problem in the United States, accounting the uncertain timing of the life-cycle of

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[8] For further reference regarding research on Solar PV investments, please refer to Vargas and Chesney (2019), included as chapter 2 of this compendium.

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PV panels and provided multiple market factors. The value added of this paper is that it assesses the problem of PV recycling in the United States before it becomes a problematic situation resulting in hundreds of thousands of scrap to be improperly disposed of. This model also deals with real options regarding the optimal location which is a novel approach.

3 Model and Numerical Methods

The present study describes some basic properties of ROA aiming to determine an optimal allocation of resources and timing for an investment in one or two solar PV panel recycling plants. Provided that existing panels are located in different states, our model assumes a rational decision from the perspective of the U.S. federal government in Washington[9]. The general setting of this paper is based on the work of Chesney et al. (2017a,b); DAdamo et al. (2017); Vargas and Chesney (2019), but also establishes the benchmark of a ROA model that can describe the problem at hand. We also further detail the main assumptions regarding key model parameters and elucidate on their calibration.

3.1 Model Setup

For this work, we take the view of the U.S. Government in Washington that foresees a number of solutions to deal with hundreds of thousands of solar PV scrap from 2024. They understand that all solutions could become costly, but recognize that the inclusion of revenue making input into their solution, could potentially reduce their own expenditure and even become profitable. In our setting, there is a benchmark case, and four long-term decisions that they could evaluate:

(BM) To delay the investment in a recycling plant as long as possible, paying only for storage cost, and assuming the recycling of the panels would have to be done eventually.

(A) To install one recycling plant that deals with all national solar PV scrap.

(B) To install two regional facilities in order to distribute the recycling between them.

(C) To improve existing consumer electronics plants to deal with solar PV scrap, taking advantage of economies of scale.

(D) To send the panels to be recycled in Mexico in order to take advantage of reduced operational costs.

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[9] Regarding this assumption, the authors recognize that there could be practical and political implementation issues that arise, and we discuss them further in Section 6 below.

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The above options are very different, but the evaluation of their viability demands for a relatively similar decision process. We assume that the U.S. Government is a rational decision maker who would aim to reduce the cost of recycling panels whenever possible. We also assume that in case that the recycling is not performed storage cost is incurred (also described further as the benchmark case), which would be a costly alternative. We assume that the investment horizon of the U.S. Government is $[0; T]$; in our numerical solution, we consider $T = 19$ years[10] and a discount rate of 3% as suggested by DAdamo et al. (2017) and other experts[11]. ω_t^{BM} is the yearly cost to the U.S. Government under the benchmark corresponds to:

$$\omega_t^{BM} = \kappa_t^{st}(Q_t) \tag{1}$$

Equation 1 describes the factors that influence the potential yearly cost to the U.S. Government, where $\kappa_t^{st}(\cdot)$ is the cost to store the scrap PV panels, we believe that given that storage is a simple operation it can be handled locally. Q_t is the amount of panels (in tons) available for recycling during the years 2024 to 2042, assuming that panels are typically disposed after 25 years of useful life, and our data provides detail on the panels installed between the years 1999 and 2017.

We assume that all panels would have to be recycled sooner or later, and non-recycled panels from previous years would be recycled as capacity allows. With that aim in mind, but also trying to reduce their expenditure in the dealing with this issue, the U.S. Government has a set of long-term investment options they could undertake. We have identified 4 distinct options that are described below:

3.2 Option A

The first option in our model, also $Option\ A$, is to establish a national recycling facility. This one facility would deal with the whole volume of scrap PV panels generated nationwide and their yearly cost ω_t^A could be described by:

$$\begin{aligned} \omega_t^A = \kappa_t^p(Q_t, A) + \kappa_t^m \gamma^{Pl}(Q_t, A) + \kappa_t^{tr}(Q_t, \Phi, A) \\ -P_t^{Al}\gamma^{Al}(Q_t, A) - P_t^{Cu}\gamma^{Cu}(Q_t, A) - P_t^{Gl}\gamma^{Gl}(Q_t, A) - P_t^{Si}\gamma^{Si}(Q_t, A) \end{aligned} \tag{2}$$

$\kappa_t^p(\cdot)$ is the cost function of the recycling that depends on the amount available and the adaptation options already implemented[12]. Since plastics cannot be recycled, the yield of plastics obtained γ^{Pl} is adjusted by the cost to deal with conferred materials $\kappa_t^m(\cdot)$ and its product is an added cost to the recycling process. Finally, $\kappa_t^{tr}(\cdot)$ is the cost of transportation of the panels from one state to another, and it is a function Q_t but also Φ the average travel distance in between states[13]. This function also allows us to determine the optimal location for the recycling plant. We make the

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[10] Data for installed PV panels in the U.S. deployed for this analysis covers the years 1999 to 2017.

[11] See: https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf

[12] $\kappa_t^p(\cdot)$ includes the collection and processing of the panels.

[13] Intrastate transportation is already accounted for in the overall of $\kappa_t^p(\cdot)$

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general assumption that only interstate travel is to be accounted for, meaning that any transportation cost within the state's limits is assumed to be zero.

P_t^{Al} is the time t price of recovered aluminum, P_t^{Cu} is the time t price of recovered copper, P_t^{Gl} is the time t price of recovered glass and P_t^{Si} is the time t price of recovered silicon from the recycling process[14], γ^{Al}, γ^{Cu}, γ^{Gl}, and γ^{Si} are the yields in kg/ton of each corresponding material to be obtained per Ton of recycling scrap material. Each material recovered is a function of the amount of panels available for recycling or Q_t and the long-term adaptation $Option\ A$ that has been already implemented. The proceedings of these materials reduce the overall cost of operation. Copper and Aluminum are two of the main components to be recovered from Silicon based panels (Si Panels), their historical price performance can be seen in Appendix A. P^{Al} and P^{Cu} are assumed to be stochastic and follow a Geometric Brownian Motion as defined below:

$$\frac{dP_t^{Al}}{P_t^{Al}} = \alpha_1 dt + \sigma_1 dB_t^{Al} \tag{3}$$

$$\frac{dP_t^{Cu}}{P_t^{Cu}} = \alpha_2 dt + \sigma_2 dB_t^{Cu} \tag{4}$$

Where (B^{Al}, B^{Cu}) is a two-dimensional Brownian Motion with a correlation coefficient equal to 0. Glass and Silicon are not traded commodities and so, their base prices P_t^{Gl} and P_t^{Si} are adjusted by inflation to reflect an estimation. All costs overtime are also adjusted by inflation. Since the investment decision that the U.S. Government is evaluating is long-term, their expected total cost Ω_A is determined by the sum of yearly cost under the benchmark case and under the new option after the investment that they have made:

$$\Omega_A = \mathbb{E}\left[\sum_{t=0}^{\tau_A} \omega_t^{BM} e^{-rt} + I_{\tau_A} e^{-r\tau_A} + \sum_{t=\tau_A}^{T} \omega_t^{A} e^{-rt}\right] \tag{5}$$

Where I_{τ_A} is the one-time sunk cost to establish the recycling facility in option A. In equation 5, τ_A marks the time of the investment. Formally, τ_A is a stopping time, or the anticipated optimal investment date whereby the U.S. Government moves from the benchmark case to the post-investment one[15]. In other words, storage cost or BM is incurred as long as the recycling plant is not installed, but once it does the one-time investment cost I_{τ_A} to install the plant is triggered and the cost of recycling, or $Option\ A$, substitute those of BM. The U.S. Government will decide when to invest in $Option\ A$ by minimizing their total expected sum of future discounted cost:

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[14] Plastics (Pl) are also recovered during the recycling process, but cannot be directly recycled due to contamination, and generate a cost rather than income.

[15] Let $(\Omega, F, \{F_t\}_{t\in I}, \mathbb{P})$ be a filtered probability space, i.e. a probability space equipped with a filtration of σ-algebras. Then the random variable τ_A is a stopping time if $\{\omega \in \Omega : \tau(\omega) \leq t\} \in F_t$, i.e. the decision to stop waiting and to invest is only based on historical data.

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$$\min_{\tau_A} \Omega_A \tag{6}$$

3.3 Option B

Considering that a centralized location could also not be optimal to solve this issue, we allow the model for an alternative to installing two regional facilities to distribute the recycling *Option B*. For example, one in the west coast and the other in the east coast provided that a great number of panels are allocated in those states. Under this option, a facility is installed as long as excess investment is less than potential savings from logistics $\kappa_t^{tr}(Q_t, \Phi, B)$ that result from the distribution of the operation regionally. Now there could be up to two recycling facilities, each facility would deal with the whole volume of scrap PV panels generated for its corresponding region, and their yearly cost ω_t^B could be described by:

$$\begin{aligned}\omega_t^B = &+\kappa_t^p(Q_t^1, B) + \kappa_t^m \gamma^{Pl}(Q_t^1, B) + \kappa_t^{tr}(Q_t^1, \Phi, B) \\ -P_t^{Al}\gamma^{Al}(Q_t^1, B) - P_t^{Cu}\gamma^{Cu}(Q_t^1, B) &- P_t^{Gl}\gamma^{Gl}(Q_t^1, B) - P_t^{Si}\gamma^{Si}(Q_t^1, B) \\ &+\kappa_t^p(Q_t^2, B) + \kappa_t^m \gamma^{Pl}(Q_t^2, B) + \kappa_t^{tr}(Q_t^2, \Phi, B) \\ -P_t^{Al}\gamma^{Al}(Q_t^2, B) - P_t^{Cu}\gamma^{Cu}(Q_t^2, B) &- P_t^{Gl}\gamma^{Gl}(Q_t^2, B) - P_t^{Si}\gamma^{Si}(Q_t^2, B)\end{aligned} \tag{7}$$

Where Q_t^1 includes only the panels for the western states: Arizona, California, Colorado, and Utah. While Q_t^2 includes only the panels the eastern states, Massachusetts, and New York. The rest of the panels for states not listed above are distributed evenly between the two regions.

As it can be observed, two simultaneous options similar to *Option A* are considered in this setting. Once again, the government is evaluating the option to undertake a long-term investment in the future. Their expected total cost Ω_B is determined by the sum of yearly cost under the benchmark case and under the new option after the investment that they have made.

$$\Omega_B = \mathbb{E}\left[\sum_{t=0}^{\tau_B} \omega_t^{BM} e^{-rt} + I_{\tau_B} e^{-r\tau_B} + \sum_{t=\tau_B}^{T} \omega_t^B e^{-rt}\right] \tag{8}$$

Where $I_{\tau_B} > I_{\tau_A}$ to denote the redundancies and cost insufficiencies that could result from having two recycling plants running simultaneously.

The U.S. Government will decide when to invest in *Option B* by minimizing their total expected sum of future discounted cost. In equation 8. τ_B is a stopping time, or the anticipated optimal investment date whereby the U.S. Government moves from the benchmark regime to the post-investment one in *Option B*:

$$\min_{\tau_B} \Omega_B \tag{9}$$

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3.4 Option C

We can also consider a further option, where another existing facility, originally purposed to recycle other consumer electronics could be adapted to process PV panels as well. This alternative, presented in equation 10 and further denoted as *Option C* assumes a similar profit structure as the one presented in *Option A*, but adjusts the cost levels to a parameter λ_C, in order to account for potential efficiencies and cost savings in the recycling process. This one facility would deal again with the whole volume of scrap PV panels generated nationwide and their yearly cost ω_t^C could be described by:

$$\begin{aligned} \omega_t^C &= \lambda_C \kappa_t^p(Q_t, C) + \kappa_t^m \gamma^{Pl}(Q_t, C) + \kappa_t^{tr}(Q_t, \Phi, C) \\ -P_t^{Al}\gamma^{Al}(Q_t, C) - P_t^{Cu}\gamma^{Cu}(Q_t, C) &- P_t^{Gl}\gamma^{Gl}(Q_t, C) - P_t^{Si}\gamma^{Si}(Q_t, C) \end{aligned} \tag{10}$$

Where $\lambda_C < 1$

Since the U.S. Government is evaluating the option to undertake a long-term investment in the future, their expected total cost Ω_C is determined by the sum of yearly cost under the benchmark and under the new option after the investment that they have made:

$$\Omega_C = \mathbb{E}\left[\sum_{t=0}^{\tau_C} \omega_t^{BM} e^{-rt} + I_{\tau_C} e^{-r\tau_C} + \sum_{t=\tau_C}^{T} \omega_t^C e^{-rt}\right] \tag{11}$$

The U.S. Government will decide when to invest in *Option C* by minimizing their total expected sum of future discounted cost. In equation 11. τ_C is a stopping time, or the anticipated optimal investment date whereby the U.S. Government moves from the benchmark regime to the post-investment one in *Option C*:

$$\min_{\tau_C} \Omega_C \tag{12}$$

3.5 Option D

We also propose a modification of *Option C* where we consider further that cost efficiency could be obtained by installing a recycling plant in Mexico. This alternative, further denoted as *Option D* assumes a similar setting for the one proposed in *Option C*. This potential cost-saving tries to denote that investment and costs could even consider the use of recycling facilities in Mexico that geographically are convenient for southern states, i.e. California, but represent considerable financial efficiencies for this model in practical terms. However, in this setting we account the distance between Mexico and California, and add it up to any other travel distance in between states, i.e. $\Phi^{MX} = \Phi^{CA} + 700$, to establish the additional logistical cost to incorporate a hypothetical recycling plant in Mexico, located some 700 kilometers

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south of California.[16] Similar to $Option\ C$ we still account for potential cost-savings in operation, now defined by λ_D and their yearly cost ω_t^D could be described by:

$$\begin{aligned} \omega_t^D &= \lambda_D \kappa_t^p(Q_t, D) + \kappa_t^m \gamma^{Pl}(Q_t, D) + \kappa_t^{tr}(Q, \Phi^{MX}, D) \\ -P_t^{Al}\gamma^{Al}(Q_t, D) &- P_t^{Cu}\gamma^{Cu}(Q_t, D) - P_t^{Gl}\gamma^{Gl}(Q_t, D) - P_t^{Si}\gamma^{Si}(Q_t, D) \end{aligned} \tag{13}$$

Where $\lambda_D < 1$

Also, the government is evaluating the option to undertake a long-term investment in the future. Their expected total cost Ω_D is determined by the sum of yearly cost under the benchmark case and under the new option after the investment that they have made.

$$\Omega_D = \mathbb{E}\left[\sum_{t=0}^{\tau_D} \omega_t^{BM} e^{-rt} + I_{\tau_D} e^{-r\tau_D} + \sum_{t=\tau_D}^{T} \omega_t^D e^{-rt}\right] \tag{14}$$

The U.S. Government will decide when to invest in $Option\ D$ by minimizing their total expected sum of future discounted cost. In equation 14. τ_D is a stopping time, or the anticipated optimal investment date whereby the U.S. Government moves from the benchmark regime to the post-investment one in $Option\ D$:

$$\min_{\tau_D} \Omega_D \tag{15}$$

4 Model Calibration

The case study considered in this work is one of a typical rational investor, in this case, the U.S. government. They want to tackle their problem by recycling all solar PV scrap, while minimizing their cost. The investor is looking to minimize their expenses by setting up one or more recycling centers for PV panels nationwide. The detail on parameters used for the model calibration can be found in Table 3 below:

As it can be observed, some of the parameters related to the recycling process come from DAdamo et al. (2017). This work was very useful to determine the general costs and expected outputs of the recycling process in our assumptions. The price of materials, supply of panels and transportation cost were obtained from specialized datasets, namely IndexMundy (2019); Hooper and Murray (2018); Barbose et al. (2017). These sources provided detailed historical data that was very valuable to determine some of the main inputs of this model. Finally, storage cost was determined as a general proportion of processing cost, while installed capacity, discount rate and investment horizon were determined based on available data as explained in section 3 above.

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[16] The actual distance to travel from Los Angeles, California to Mexicali, Mexico is close to 700 km.

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Table 3: Model calibration parameters.

Parameter	Explanation	Value	Units	Sources
P^{Al}; P^{Cu}	Price of materials	Stochastic	USD	IndexMundy (2019)
γ	Yield of recovered materials	$\gamma^{Al} = 175; \gamma^{Gl} = 7.8; \gamma^{Cu} = 638.26; \gamma^{Si} = 24.65$	kg/ton	DAdamo et al. (2017)
κ_0^p	Unitary recycling cost	\$441.24	USD	DAdamo et al. (2017)
κ_0^m	Unitary cost of conferred materials	\$124.09	USD	DAdamo et al. (2017)
κ_0^{st}	Unitary storage cost	$0.10 \cdot \kappa^p$	USD	–
κ_0^{tr}	Unitary transportation cost	\$0.0050	ton/km	Hooper and Murray (2018)
Q_t	Available supply of panels	See table 1	tons	Barbose et al. (2017)
Q'	Installed PV capacity	330,030; 62,284; 400,853	tons	–
I	Investment cost	\$104,751,900	USD	DAdamo et al. (2017)
r	Discount rate	3%	–	–
t	Investment horizon	[2024; 2042]	–	–

5 Results

This section presents the results for our model. Our initial aim was to determine the optimal time to invest in this effort in order to deal with this issue for the period 2024 to 2042. As it will be described, all options aim to minimize the expected expense of the U.S. Government, who would have the option to delay the investment as long they are willing to pay for the storage cost of the panels generated every period. The analysis also focuses on determining the best state to localize the recycling facilities in each case, considering that the panels are already installed in specific locations, and transportation costs are determined as explained above. Finally, we also sensitize the results by varying important model parameters, in particular, investment and cost, and movements in commodities prices.

5.1 First Option

The first option is to invest in one national centralized facility. This sort of effort would require that plant to deal with as many panels as necessary to recycle all of them. We can simply observe that the maximum amount of panels scrap expected to be produced in a single year is 432,550 tons in 2041, would be a good reference, however, when running the model with this setting, we obtain a very inefficient outcome due to idle overcapacity for several periods. In our setting recycling after the maximum capacity required can be distributed between the period that it generates and the following periods, as long as capacity is still available for the current operation. We can then estimate that 330,030 tons of PV panels per year is a more reasonable level of installed capacity to deal busiest operation period for $Option\ A$. With that level of installed capacity, the investment in the recycling facility can be delayed up to 2036 (14 years).

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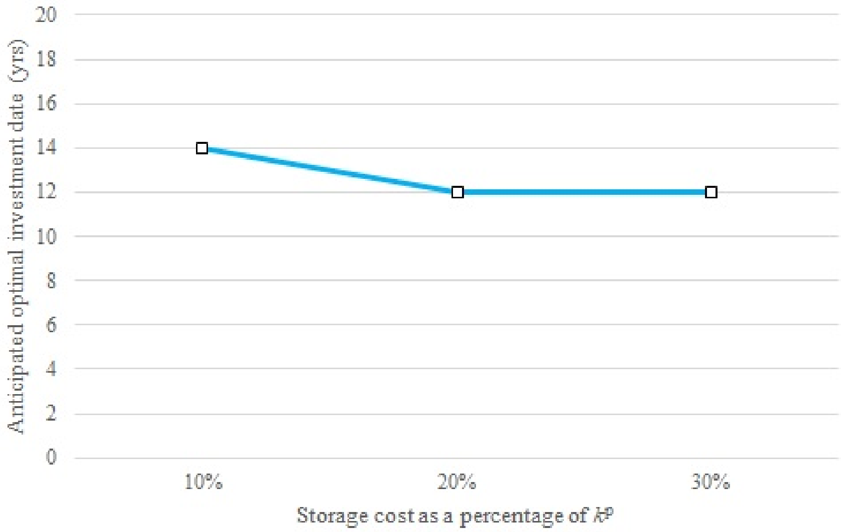

Figure 1. Option A for 330,030 tons of Installed capacity

As we can observe, an increased cost of storage results in an expected faster investment, this as a result of the increased cost that it implies for the overall operation. The reason for this is that storage cost is an imporant parameter for the BM case. As long as we do not invest in $Option\ A$ storage cost is incurred, and so the higher this cost, the more incentive there is to triger the investment.

Based on our setting we can also determine that the best locations to install a single recycling plant according to transportation cost efficiency would be:

Table 4: Order of priority to install a single recycling plant according to state location and transportation cost.

Order	State
1	Arizona
2	Colorado
3	Utah
4	California
5	New York
6	Massachusetts

In this table, we can see that Arizona is the best location for a sigle recycling plant, followed by Colorado, Utah, California, New York and finally Massachussetts. This can be determined by comparing the total expected sum of discounted costs to operate the recycling plant in each of those locations.

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5.2 Second Option

The second option is to invest in two regional recycling facilities, i.e. one on the east and the other on the west coast of the United States. As it can be observed in Appendix B, the longest distance in between states results from Massachusetts and New York to the rest. However, both states are 327.5 Km away from each other, and so setting a recycling plant to serve both states, and another on the west to serve the rest of states, seems to be the best strategy to minimize cost. This allocation could potentially reduce the transportation cost significantly when compared to the best alternative of *Option A*. Under this new setting, each recycling facility would have to deal with a recycling volume of 62,284 (east coast) and 400,853 (west coast) tons of PV panels yearly at their busiest operation periods, assuming each one of them also take half of the panels generated by other states. This amount depends on the maximum required capacity or each region and would determine the installed capacity in each case, but we can also optimize the installed capacity for the west coast to allow for the recycling to be distributed over the last 5 years and still allow for all panels to be recycled. Based on our setting we can also determine that the best locations to install two recycling plants according to cost efficiency would be the following:

Table 5: Order of priority to install two recycling plants according to the state and transportation cost.

Order	State
1	Arizona & Massachusetts
2	Arizona & New York
3	California & Massachusetts
4	California & New York
5	Colorado & Massachusetts
6	Colorado & Massachusetts
7	Utah & Massachusetts
8	Utah & New York

This option could allow for the facility on the west coast to delay its investment even more, until 2036 (year 16) and the one on the west coast to keep the delay until 2034 (year 14). In any case, the cost of this scenario would be approximately 5.4% more expensive than the best scenario in *Option A*.

5.3 Third Option

In the third option, we consider the potential of economies of scale by recycling the panels in existing recycling facilities that deal with other consumer electronics. This is a similar approach to the one currently conducted by the European Union.

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Provided that the operational cost of the recycling process seems to be high enough to exceed potential revenues, the third option considers the possibility to reduce the operational cost even to a point that it could become profitable. In this setting, we take the benchmark case and apply different levels of cost reduction to anticipate the optimal investment date.

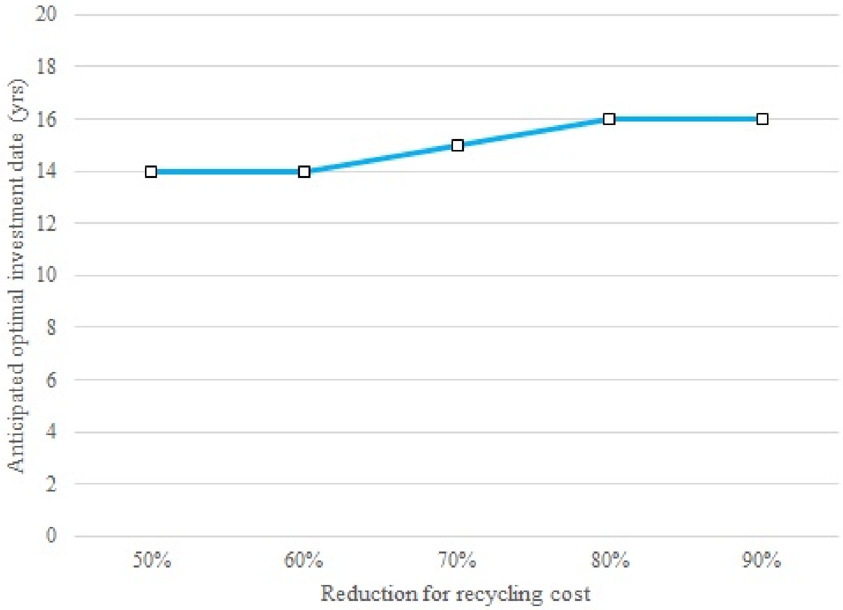

Figure 2. Option C for different levels of reduction for recycling cost.

After running different combinations of cost reduction, we determined that even aggressive cost reductions would not delay the investment. We observe that by reducing the recycling cost anywhere up to 60% we keep the anticipated optimal investment date at 14 years. However if we expect to reduce the cost even more, the anticipated optimal investment date starts to increase, and we can further delay the investment time to 15 years for a reduction of 70%, and to 16 years after a reduction of 80%.

5.4 Fourth Option

Similar to the previous option, it is possible to consider a further variation of $Option\ C$ that would allow the establishment of a single recycling plant in Mexico. In which case, the logistical cost would have to be adjusted accordingly.

Again the delay on the investment could reach 14 years, and we observe that there is no significant difference between the results of $Option\ C$ and D. In fact, the small difference in the results from both options comes from the increased transportation cost needed to take the panels to Mexico,[17] i.e. to transport the panels 700

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[17] This analysis does not account for import duties, quotas or other fees that could result from the

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km more.

5.5 Comparison of options

In order to better asses the findings of our study, we set a comparison of the total expected sum of future discounted cost of recycling the panels. We define the comparison as a percentage of cost reduction to the benchmark case, or to delay the investment on any of the options as much as possible, as described in table 6 below:

Table 6: Comparison of expected sums of future discounted costs resulting from the analysis of options.

Option	Description	Cost savings
BM	Delay the recycling as much as possible	–
C	Use existing recycling facilities (with κ^p at 50%)	-72.3%
D	Recycling in Mexico (with κ^p at 50%)	-71.5%
A	1 new recycling facility	-39.7%
B	2 new recycling facilities	-36.6%

We can observe that on average, *Option C* to improve existing consumer electronics plants to deal with solar PV scrap, taking advantage of economies of scale, is the single one option that results in the highest cost reduction, 72.3%. Followed by *Option D* to send the panels to be recycled in Mexico in order to take advantage of reduced operational costs with 71.5% cost reduction, *Option A* to install one recycling plant that deals with all national solar PV scrap represents a cost reduction of 39.7% and *Option B* to install two regional facilities in order to distribute the recycling between them with 36.6% cost reduction. These results only compare for the expected sums of future discounted costs between options, but do not consider additional complexities, such as the practicality of achieving such increased cost efficiencies or market and political constraints of implementation.

5.6 Further options

Besides the results shown in this work, further applications of this model could be developed. i.e. to assess the accelerated decommissioning of panels due to the potential efficiency increases resulting from the development of new technologies. In addition to that, the period between 2024 and 2042, included in the present analysis poses an interesting case that could allow for a diversity of potential solutions due to the increased volume of PV panel scrap to be generated.

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shipment of panels into a foreign country, but we could expect additional cost resulting from it could be caused.

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Assuming scalability would prevent financial losses from the recycling process, and different levels of cost reduction could result in the immediate implementation of the first recycling plant as soon as the critical volume of scrap material is reached. Other alternatives to accelerate implementation and minimize cost by increasing profitability could include:

1. Recycling thin-film panels together with crystalline Silicon panels, to extract more valuable metals from the process, in order to increase potential revenue.
2. Innovate the recycling process in order to reduce operational cost and/or increase valuable recovered materials (similar to $Option\ C$ and D above).

6 Conclusion

Regardless of the potential environmental benefits of crystalline Silicon panels recycling outlined in this work, solar PV panel recycling still represents an important challenge financially, operationally, technically and logistically. As we were able to show with our model, the cost and income structure proposed by DAdamo et al. (2017) results in financial losses and could ultimately result in improper handling of the panels. As a step forward of previous research, our approach implements a more realistic market price estimations for Commodity Prices (Copper and Aluminum) and estimates the availability of the panels for recycling based on real market data. We also sensitize for potential cost efficiencies. Although the location of the panels is known and most of them are concentrated in only 6 states nationwide, the panels are still heavy and complicated to handle and the exact time of deployment is still uncertain.

As challenging as it may seem, some components of the PV panels require proper management after the end of their useful life. They have to be properly handled, and we better find the most efficient and effective way to do so. The environmental risk resulting from improper management would just be too high to leave it unattended. In addition of establishing that potential environmental risk, there are important policy issues to solve in order to deal with this situation:

1. Regulation needs to be developed and implemented to establish guidelines for proper management of PV panels after deployment in the United States, and subsidies could be an important part of it.
2. Since the cost structure of recycling for silicon panels seems to be too expensive, subsidies are required to trigger seed investments, and the amounts required under different scenarios seem to be reasonable, as described by this work. This could allow for private investments to be started.
3. Besides subsidies, other market mechanisms, i.e. direct payments could be implemented to reduce the burden of cost on the U.S. Government. Some countries in Europe already have such schemes in place to deal with recycling of electronics.

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4. Waste management and recycling infrastructure will need to be developed accordingly. Early action results in less expensive implementation.

Different options allow for more efficient investment in the recycling plants, as shown in section 5 of this work. Current regulation regarding this issue fails short to address this problem properly, even in the states with the majority of panels, where the issue has been identified by authorities and initial efforts have been done. In any case, it seems that it could still be optimal to slightly delay the implementation, depending on the alternative chosen, as far as storage cost keeps low. In any case, recycling capacity will need to be developed to deal with the expected scrap material to be generated over the next decades, since traditional waste dumping off the panels is not an option, provided the environmental risk that it poses. The best alternative would be to locate a single recycling facility in Arizona, provided cost savings can be achieved, but other alternatives also pose interesting opportunities. This paper proposes several potential solutions to this problem, and many more could also be considered. Dealing with solar PV panels at the end of their useful life will be, in any case, a very costly endeavor and so early action could result in better alternatives for the authorities.

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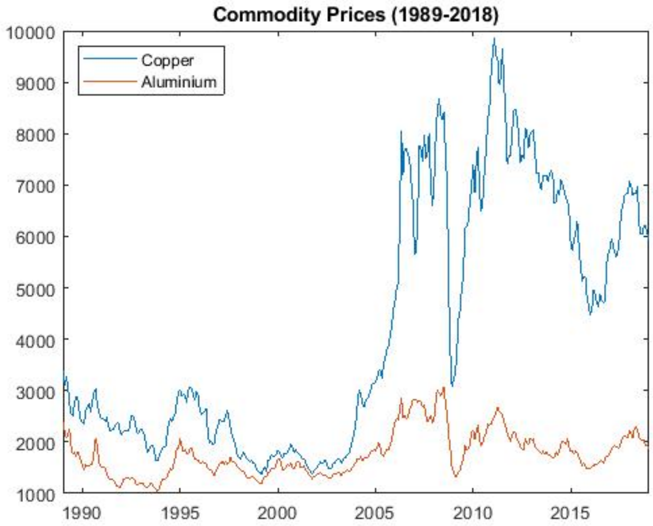
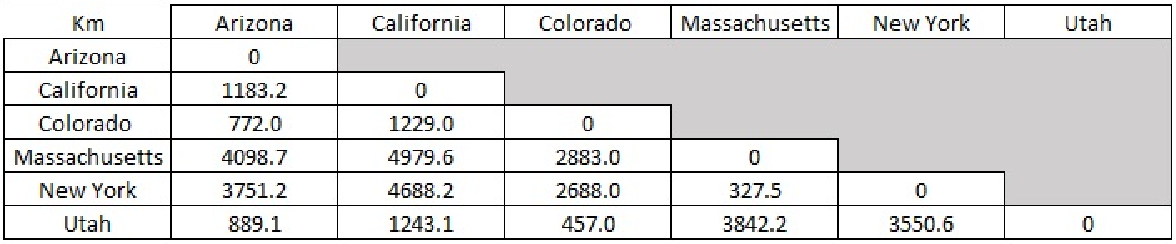
Appendix

Commodity prices 1989 - 2018 (in USD)



Source: Based on data from IndexMundy (2019)

Distance between states (in Km)



Km	Arizona	California	Colorado	Massachusetts	New York	Utah
Arizona	0					
California	1183.2	0				
Colorado	772.0	1229.0	0			
Massachusetts	4098.7	4979.6	2883.0	0		
New York	3751.2	4688.2	2688.0	327.5	0	
Utah	889.1	1243.1	457.0	3842.2	3550.6	0

Source: Based on data from Google Maps, 02.05.2019

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