AN INVESTIGATION TO USE TAILING PONDS AS SOLAR PHOTOVOLTAIC FARMS[1]

Moe Momayez[2], Terril Wilson, Alex Cronin, Srikant Annavarapu, and Bill Conant

Abstract. Fine-grinding of ores for the liberation of metal- or other valuable concentrates most often results in acreage dedicated to tailings impoundments. A determination of the post-mining land use of such acreage is then required. Tailings impoundments can be suitably utilized as sites for installation of solar photovoltaic (PV) panels. The electrical energy produced can be used initially for mining and concentrating operations, and subsequently for the utility grid after mine closure is complete. Since the extraction, processing and transport of minerals is energy-intensive, most mines already have a substantial electrical transmission-line infrastructure. This eliminates one of the major costs associated with PV energy farms. In this paper, we analyze the long-term economic benefit (i.e. payback period) of PV installation and energy production at mine sites. We also discuss integrating PV systems with erosion control and revegetation measures.

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[2] Moe Momayez is Associate Professor, Terril Wilson is Adjunct Professor and Srikant Annavarapu is Graduate Associate, Department of Mining & Geological Engineering, University of Arizona, Tucson AZ. Alex Cronin is Associate Professor, Department of Physics, University of Arizona. Bill Conant is Assistant Professor, Department of Atmospheric Sciences and Institute for Atmospheric Physics, University of Arizona.

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Introduction

Dual objectives of this paper are a discussion of 1) energy demands of mining and processing of minerals, and 2) an opportunity for energy production associated with the disposal of process tailings, namely, solar energy generation using vast expanses of already reclaimed land areas; this approach eliminates the need to expropriate public or private lands allowing the mining companies to reduce their dependency on the national grid and provide clean and renewable energy long after the mine shuts down.

Steps involved in the extraction, processing and transportation of coal, base and precious metals and industrial minerals require large amounts of energy (see Fig. 1). According to a report published by the US Department of Energy (US-DOE, 2008), the total energy consumption in the United States in 2005 was 1.017 x 10^{17} Btu, or slightly over 100 Quads. The mining industry alone consumed more than 1% of this amount or a sum equivalent to $3.2 billion on energy. This amount represents 21% of the total operating cost of mining, excluding labor and administration (US-DOC, 2005). Given the importance of the mining industry in the US economy, its energy requirements, and the rising cost of traditional sources of energy, any measures, processes or technologies that could generate savings will allow the mining companies to be more competitive. Moreover, the reduced dependency on the national grid will make more energy available for other uses and lower the environmental effect of burning fossil fuels.

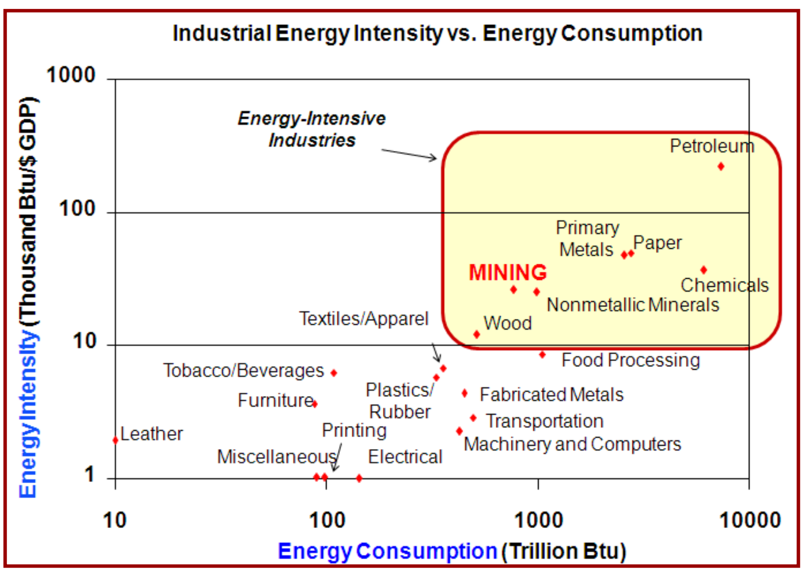

Figure 1: Energy requirement of mining and mineral processing industries compared to other manufacturing sectors (Scheihing, 2005)

Cost saving measures can be implemented in two ways: improve the efficiency of processes in order to use less energy, and wherever feasible, substitute the existing supply source with alternative forms of energy. In this paper, the authors discuss the latter option, more specifically the use of in-service and reclaimed tailing ponds as sites for solar photovoltaic energy production.

Tailing Ponds As Solar Farms

Critics argue that the footprint needed to generate energy from renewable sources is too large compared to conventional options. One could mention biomass, solar and wind as examples of alternative forms of energy that would expropriate large land areas that could otherwise be used for farming, recreational or residential purposes. Conflicting reports published by various researchers and agencies (Gagnon, 2002, Pimentel, 2002, Gates, 1985, Gipe, 1995, Ecoinvent, 2004) compare the estimated land use for solar, coal fuel and natural gas sources. A recent study (Fthenakis, 2009) attempts to normalize the land mass used by alternative sources of energy such as biomass, wind, solar, coal, nuclear, natural gas, and hydroelectric, and concluded that on average, the solar (photovoltaic) option has the smallest footprint among the renewable energy sources while the biomass option requires the largest amount of land. The authors considered a number of metrics in the life cycle of the electricity generation options, such as the length of time for the extraction of resources, the electricity generating capacity, disposal of the waste (if needed), and both direct and indirect land mass transformations.

Characteristics of Tailing Piles

Since the early 20th century, economic recovery of finely-divided ore minerals, particularly base and precious metals, has involved crushing and fine-grinding of the ore, and separation of ore minerals from gangue minerals by aqueous froth flotation using appropriate surfactant additives. Typically, the ore is reduced to nominally 0.25 mm (60 mesh) or finer particle topsize, to achieve liberation of mineral values and to enhance “floating” the valuable mineral grains by attached air bubbles. The flotation process remains widely used today. Additionally, fine-grinding of ores (particularly precious metal ores) prior to vat-leaching provides enhanced process kinetics, as compared to coarse ore leaching. The purpose of fine grinding is to create an aqueous stream of fine particles, often silica or feldspar minerals, which is then typically delivered to process thickeners for concentration of the solids as underflow, and separation of clarified water as overflow for immediate re-use in grinding and flotation. Thickener underflow (typically 50 to 60 weight percent solids) is most often pumped or delivered by gravity flow to a settling pond. Supernatant water from the settling pond is pumped backed for re-use in the process, and settled fine solids are allowed to dry (see Fig. 2). Hydraulic cyclones may be used to enhance solids-water separation; the cyclones are usually located at the perimeter of the settling pond, with the coarser partially-dewatered solids in the cyclone underflow being directed to the peripheral embankment and dilute cyclone overflow being directed to a central pond area (see Fig. 3).

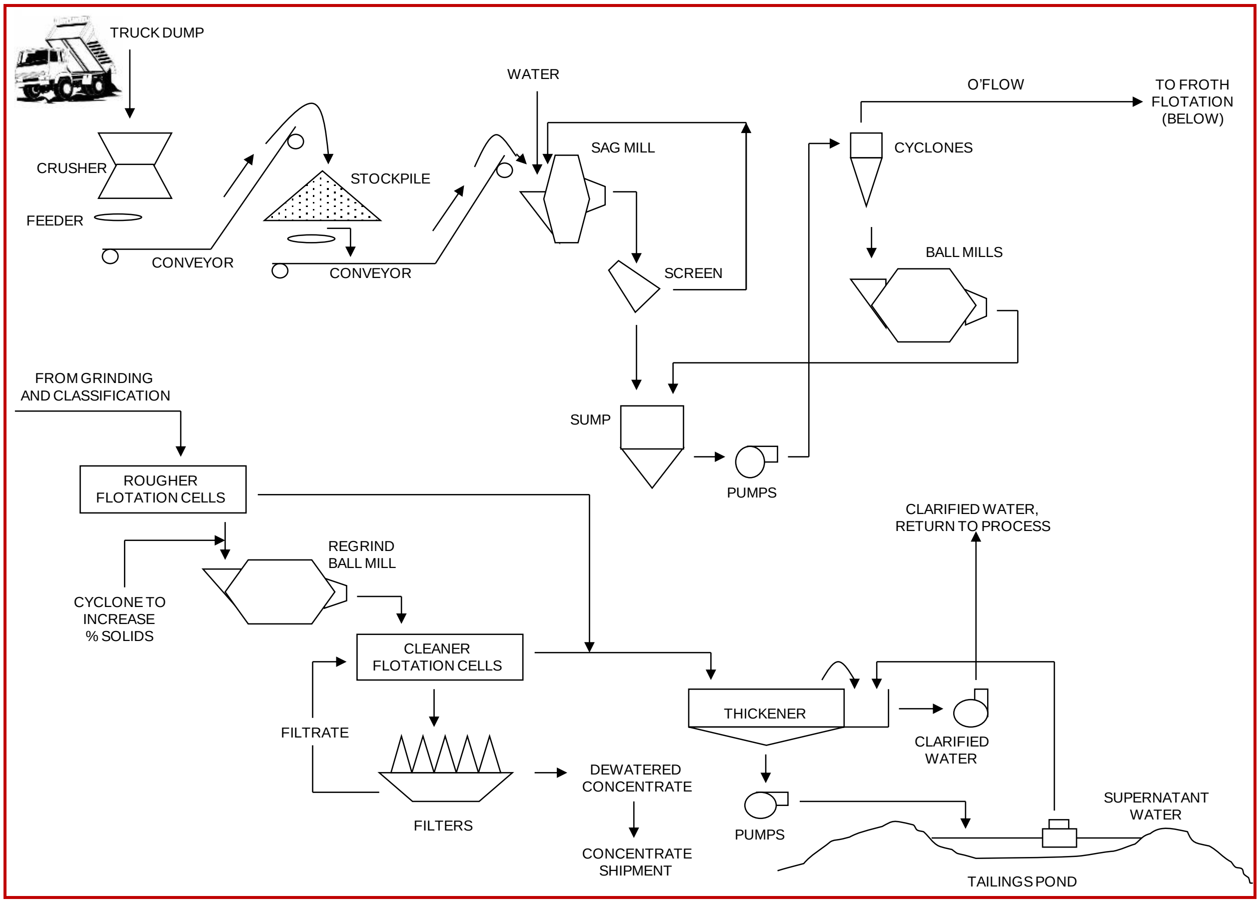

Figure 2: Flow Diagram for Concentration of Base Metals by Flotation

The process described above allows for a particle size distribution gradient to develop (even if hydraulic cyclones are not used for tailings dewatering), and coarser particles tending to be deposited at the tailings pile perimeter, with progressively finer particles being deposited toward the central pond area of the pile. The particle size gradient from the perimeter toward the central pond area has immediate implication with respect to the geotechnical characteristics and structural integrity of the pile (Annavarapu, 2009). If the perimeter of the pile is designed to be free-draining, and constructed at a relatively shallow slope, it will be less prone to shear failure, either under external load factors or under its own weight. By the same reckoning, the central pond area of the pile, which contains super-fine solids and relatively high water content, may be structurally weak (Bengson, 2008).

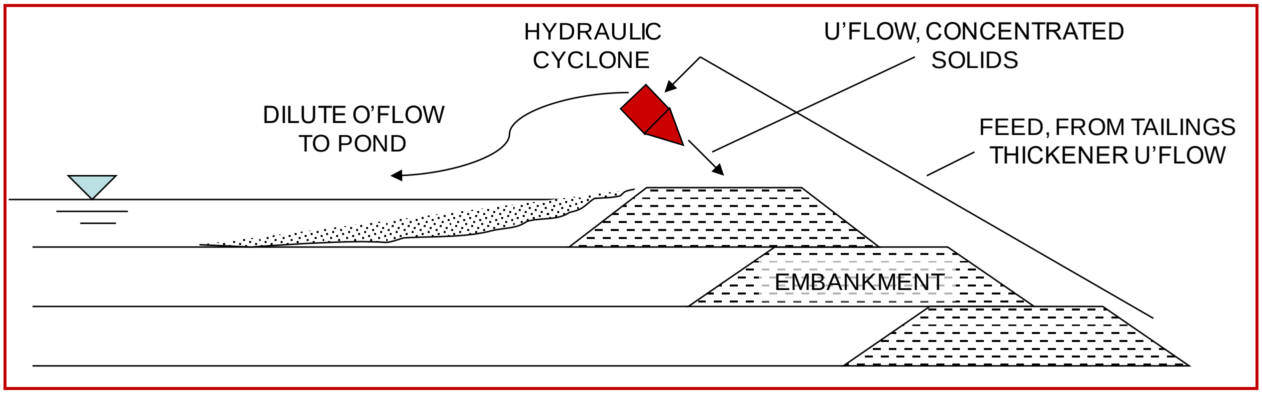

Figure 3: Slurry Dewatering at Tailings Pond by Hydrocyclone

In consideration of these factors, the delivery of thickened slurry to a settling pond, the placement of the slurry for decantation, and the configuration and construction of the pond and ensuing pile must be carefully planned activities. Permit issuance for a tailings pond deservedly requires scrutiny of size, configuration, structural integrity, fugitive elements (windblown dust, transmission or curtailment of tailings water to groundwater), and wildlife habitat during and after service of the facility, and ultimate land use. Currently, best management practices require substantial lining of the base of a proposed tailings pond, assurance of the long-term geotechnical stability of the pile, and eventual capping and restoration/revegetation of the pile surfaces following service. The authors propose that the use of active tailings areas and potentially longer-term use of closed tailings impoundments, for solar photovoltaic sites can serve a valuable purpose, near-term and long-term.

<u>Basic Principles of Photovoltaic Cells and Panels</u>

Various semiconductor materials including refined silicon (Si), Gallium Arsenide (GaAs), Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS) and others, are employed as individual or compound thin films, applied to a glass substrate and covered in sandwich fashion with an overlying glass protective sheet. These semiconductor materials have the property of absorbing photons and releasing mobile electrons under suitable incoming photon wavelength and intensity conditions, whereby electric current is created. Typical thickness of thin films is 0.1 mm for Si and 0.01 mm for CIGS. For Si, open circuit voltage per cell is approximately 0.5 volt under favorable operating conditions. Cells may be configured on a panel to provide various current / voltage outputs. Typical panel output for Si is 100 to 140 (max.) watts per square meter, and for CIGS, 45 watts per square meter

Figure 4: Typical Tailings Disposal Area in Southern Arizona (Google Earth)

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Solar Panel Configurations

A variety of options exist for solar panel configuration and layout. Flat panel arrays can be tilted upward from horizontal at an angle approximately equal to the site's latitude (32 deg. for southern Arizona) in rows similar to those shown in Fig. 5. In the northern hemisphere, the panels should face south in order to receive the maximum amount of exposure to sunlight. Alternatively, tracking mechanisms can be incorporated with panel arrays to continuously orient the panel normal to the sunlight. In either case, the layout should avoid partial shading from neighboring panels. Figure 5 shows rows of panels on fixed (static) mounts, located at latitude 32 degrees, where partial shading is completely avoided if 50% of the area is covered. Since the panels are tilted, the map-view would have 42% coverage. If the panels are too close together, then the energy-yield during morning and evening hours is significantly less, as shown in Fig. 6. The different modules are rated for different power, so comparing the maximum power is not significant. The morning (turn-on) and afternoon (turn-off) times for the systems are remarkably different from each other due to partial shading from neighboring panels. This shows how important the layout can be. The partial fill-factor also provides space for installation, maintenance, and electrical conductor access. The optimum distance between rows of panels is latitude specific. Figure 7 illustrate how this distance can be determined. The calculation is done for a 1-meter tall stick standing vertically above the origin (location 0,0) at a given latitude. For Tucson (latitude 32 degrees), it is recommended to space rows of photovoltaic modules at least twice as far away from each other as their height.

Based on the previous discussion, if typical (1.8 meter length x 1.2 meter width) Silicon panels are placed on static mounts over one hectare (100 m x 100 m) of Tailings area, then 5,000 square meters of modules could be deployed. Direct-current power output under favorable conditions (noontime sunlight on the equinox) would be 700 kilowatts. This is based on the irradiance (power per area) of sunlight times the conversion efficiency of the photovoltaic modules. Sunlight has an irradiance of 1000 Watts per square meter. Silicon photovoltaic modules have a conversion efficiency of approximately 14%.

Figure 5: Solar Panel Array – Tucson Electric Power Co. (Unisource, Inc.) test site, Tucson, AZ

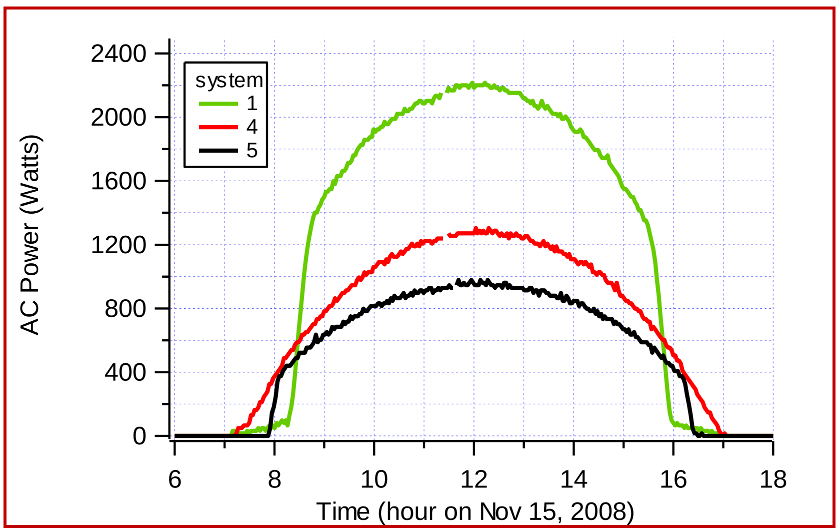

Figure 6: AC power generated in one day (Nov 18, 2008) by four different photovoltaic systems at the Tucson Electric Power solar test yard.

For a projected direct current/alternating current (DC/AC) inversion efficiency of 95 percent, the AC electrical power produced would then be 656 kilowatts. The conversion efficiency has been observed with test systems, as shown in Fig. 8. Using the peak power, system efficiency is calculated based on a model for annual energy-yields from photovoltaic installations that 1.18 megawatt-hours of energy can be obtained each year from this field.

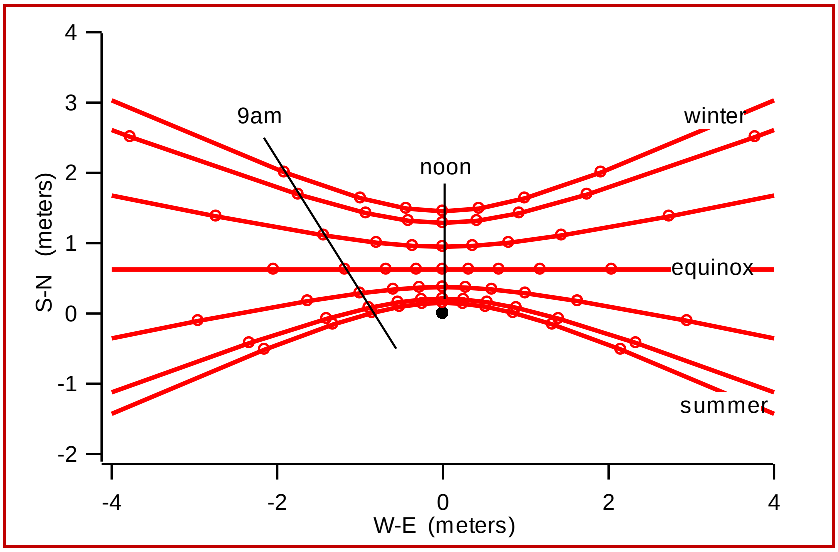

Figure 7: Shadow paths and lengths at latitude 32 degrees.

A tailings area solar panel array would include, in addition to small vehicle access roads, an electrical equipment station (enclosed) for inverter, metering, switches and circuit protective equipment, and an enclosure for general maintenance (Wies, 2009).

Depending on the distance from mine and plant operations to the solar panel array, power output (3-phase) of the array would either be transmitted directly to the main mine transformer station, or introduced into the main incoming power line via appropriate synchronizing switchgear.

Post-Mining Advantage of Solar Photovoltaic Installation on Tailings

From the public policy viewpoint of investment in alternative energy sources, one may state two key advantages in favor solar photovoltaic installation on active or recently-closed mine tailings areas. First, no public or private lands need to be expropriated as the tailings area is large enough to accommodate present and medium term future demands. Second, as the electric power transmission lines for the mine and plant already exist, the major cost of transmission infrastructure need not be incurred again.

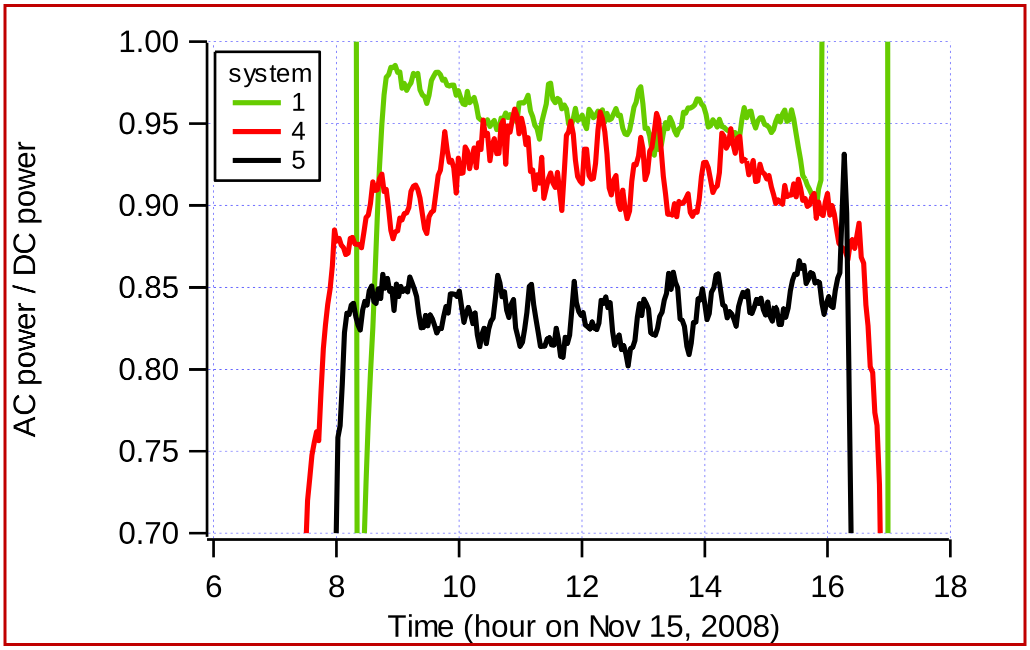

Figure 8: The measured ratio of AC power to DC power for four different systems on Nov 18, 2008 at the Tucson Electric Power solar test yard.

Other possible Beneficial Effects of Solar Photovoltaic Installation on Tailings

The orientation of solar panel arrays on mine tailings would be primarily for maximum capture of solar energy. Depending on prevailing wind direction, the supplementary benefit of reducing ground-level wind velocity and thereby reducing blowing dust could be achieved. This advantage would be site-specific. The incorporation of tailings revegetation with the solar panel arrays is a topic for further investigation. Typical solar panel mountings consist of lightweight stainless structural steel grade (e.g. 1 inch or 1 ½ inch angle), which may provide water-channeling, erosion-control and nutrient retention advantages. A necessary investigation would be systematic interspersing open areas with panel-shaded areas to provide improved growth conditions.

Long-term Considerations; Closure of Tailings Areas

If capping of a tailings area occupied by solar panel arrays is required under a Closure Plan, a systematic piece-wise removal of the panel arrays followed by reconstruction of the arrays atop the capped area would be required. Fortunately, relatively light-weight semi-portable panel modules, typically weighing less than 250 kilograms, can be designed. Handling requirements are comparable to double-pane windows. During closure, the capping activities would be coordinated with solar panel temporary removal and replacement.

Estimated Costs

Current solar panel costs are approximately $ 380 per square meter for Silicon panels. The total cost for the photovoltaic modules is therefore approximately $2,500 per kilowatt (peak) of AC electrical power. The balance of system components (inverter, mounting structure, wires, and installation) usually costs another $2,500. Hence the total installed cost for ground-mounted arrays is $5,000 per kilowatt output. The cost-benefit of adding tracking systems to the installation is currently under investigation. In the presented example of one hectare covered by 5,000 meters of photovoltaic modules, the modules alone would cost 1.9 million dollars, and the entire on-the-grid system would cost 3.8 million dollars.

The current annual energy yield model predicts only 1,800 kilowatt-hours per year per kilowatt (peak) of electrical power for non-tracking systems. This is equivalent to the panels operating only 5 hours a day at their peak power. The lost operating hours are accounted for by including losses due to sun-angle throughout the day and seasons, atmospheric attenuation which varies throughout the day, weather, and changes in module efficiency due to the ambient temperature.

Combining these factors with an estimated cost of electricity of 10-cents per kilowatt-hour suggests a payback period of 28 years, which may not be attractive for potential underwriters and investors. However, the technology is relatively young, and many advances are anticipated.

Most photovoltaic modules come with a 20 year warranty, and preliminary studies of aging indicate that modules only degrade at a rate of 0.3 % per year in a dry and hot environment such as Arizona. The degradation rate in different climates is currently under investigation. It is therefore possible that such installations could last for 100 years and maintain 70% of their annual energy yields in southern Arizona. The longevity of the inverters is less well known.

Advances in solar technology are likely to bring the cost of PV modules down to approach the benchmark price of $1.00 per watt (peak). Already, the manufacturer First Solar reports that their CdTe thin-film technology photovoltaic modules can be fabricated at a cost of $1.30 per Watt (peak) today. Progress is also being made with light-concentrator technology and bi-facial solar cells that can utilize reflected sunlight. If current efforts to lower the cost of the balance of system components are successful, then the price tag for the entire installation may drop to around $2,000 per kilowatt. Furthermore, tracking mounts can provide a 40% improvement in the annual energy yield predictions (although they are usually more expensive, and they usually require more map-view are per module). These improvements combined could reduce the payback period to 8 years.

Federal tax incentives are available to companies and individuals who invest in photovoltaic systems for the next 8 years. The initial capital cost can therefore be further reduced by providing an investment tax credit (ITC) of 30% of the base system. In some states, such as California and Arizona, a renewable portfolio standard (RPS) has also caused utility companies (such as Tucson Electric Power) to provide incentives for customers who build solar energy systems. Tucson Electric Power in effect will buy the rights to count the customer's photovoltaic system as part of their renewable portfolio. In addition, TEP does not purchase the photovoltaic system nor does it buy the energy. The utilities company simply buys the "credit" for having the photovoltaic system in their distribution and generation network. For this, TEP will provide a rebate as large as $3,000 per kilowatt (peak) or a performance based incentive (PBI) of up to 20-cents per kilowatt-hours for a 10 year duration.

The calculations presented above do not take into account the probability that the cost of electricity will increase over the lifetime of the photovoltaic system. Added to the post-mining benefit of a photovoltaic installation on a tailings area is the cost saving of not removing incoming power lines, transformers, and switchgear to comply with closure requirements, but of greater value will be the reduction in capital cost of the photovoltaic system because of the existence of this infrastructure. The value of the existing electric power infrastructure as a percentage of the total photovoltaic installation is currently being determined.

Taken together, the prospect for advanced (cheaper) technology, the current government-based economic incentives for installing photovoltaic systems, and the additional security to any industry gained by producing their own electricity, it is clearly within reason to consider utility-scale photovoltaic installations on mine-tailing locations.

Work in Progress

Recent test results, including wattage production under diurnal and seasonal variations in solar radiation, ambient temperature and atmospheric conditions, along with performance of various types of manufactured solar panels are presented in Table 1 (Cronin et al., 2008)

Table 1: Photovoltaic Hardware Operating at TEP Solar Test Yard.

System Number	PV Module Type	Power Modules	Number of Modules	Inverter Type	Total Power
1	Sharp	165 W	16	Aurora	2.64 kW
2	Kyocera	150 W	9	Xantrex TR	1.35 kW
3	BP 3150U	150 W	10	Xantrex TR	1.50 kW
4	Unisolar	64 W	24	Fronius	1.54 kW
5	Sanyo	167 W	8	Sunnyboy	1.34 kW
6	BP MST50	150 W	30	Xantrex TR	1.50 kW
7	ASE DGF17	300 W	6	Xantrex TR	1.80 kW
8	BP SX140	140 W	10	Xantrex TR	1.12 kW
9	ASE DGF50	300 W	6	Xantrex TR	1.80 kW
10	GSE	45 W	32	Xantrex TR	1.44 kW
11	Shell	40 W	38	Xantrex TR	1.52 kW
12	Sanyo	180 W	8	Fronius	1.44 kW
13	BPMST50	50 W	30	Sharp	1.50 kW
14	Solarex MST50	50 W	150	Beacon	7.50 kW
15	Shell	150 W	20	Xantrex TR	3.00 kW
16	Astro	164 W	9	Xantrex TR	1.48 kW
17	BP MST43	43 W	60	Solectra	2.58 kW
18	ASE DGF17	300 W	10	Xantrex OH4	3.00 kW
19	ASE DGF50	300 W	10	Xantrex OH3	3.00 kW
20	GSE	62 W	21	Xantrex TR	1.30 kW
21	BP 4170	170 W	10	Xantrex GT	1.70 kW
22	Kyocera	190 W	10	Fronius	1.90 kW
23	Sharp	305 W	144	3-phase	43.92 kW
Total	**19 Module Types**		**663 Panels**	**11**	**94 kW**

A detailed investigation of atmospheric parameters that may affect the efficiency and energy output of the panels has been undertaken by the authors. The issues considered are the following:

1. The effectiveness of the bright soils (or the water itself) acting as a "reflector", could increase the efficiency of the panels by collecting reflected radiation. At the selected site for this pilot project, the reflectivity of the soils is estimated to be as high as 50%. As discussed above, panels have a "cosine-weighted" sensitivity, which is why they are inclined with the latitude – to maximize the time-averaged cosine of the angle between the sun's direct beam and the panel's normal vector. This is merely a projected-area effect. This concept applies to diffuse radiation as well – the panel becomes increasingly less sensitive to radiation coming from angles large with respect to the normal to the

plane. Accounting for this, it is important to determine the contribution of radiation coming from the reflector below the horizon. The fraction of the cosine weighted diffuse field is equal to:

$$f = \frac{(1 - \cos(I)}{2}$$

where *I* is the angle of inclination, assumed to be 32°. At the selected tailings site, *f* is equal to 7%. If the surface is lambertian (light is scattered in all directions so that the apparent brightness would appear to be same irrespective of the observer's viewing angle) with an albedo (ratio of diffusely reflected light to the incident radiation) of 30% greater than a typical surface, then the enhancement will be 7% × cosine (solar zenith angle) × albedo difference ≈ 1% for the daily average and ≈ 2% for local solar noon. Experience has shown that when working with solar power a 2% enhancement is valuable. Water will be much less effective as a reflector, as only ≈2% to 20% of the sun's energy is glinted off the surface during useful production hours. It is possible that inclining the plane towards a bright surface will increase the efficiency – up to a point.

2. The concentration of aerosols at the site may affect the overall energy output of the system. More specifically, the fundamental saltation rate of the tailings and the attenuation of radiation due to particulate deposition onto the panels will be investigated.
3. As discussed in the previous sections, panels have an optimum operating temperature. It is interesting to explore the effect of wind-cooling of the panels; the lake-cooling of the wind; and the frequency of high wind conditions that lead to dust events.
4. Forecasting cloud coverage and surface solar radiation intensity will improve the management of energy production and delivery to the grid. The Department of Atmospheric Sciences makes regional weather predictions for southern Arizona using a mesoscale forecast model. This model is an improvement upon the NWS models for this region and a number of studies are currently under way to verify the accuracy of computer predictions. The data collected at several sites, including the tailings area, will be used to forecast surface solar radiation from WRF.

Conclusions

Given that the ultimate and long-term land use of mine tailings areas must satisfy regulatory agencies and public interest, the authors feel that a particularly good opportunity now exists to create clean and renewable energy from these sites. The energy can be used by mine operations while mining is in progress, and eventually by consumers after mining is completed.

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Appendix

The following is an excerpt from http://www.gosolarcalifornia.org/csi/tax_credit.html :

"On October 3, 2008 H.R.1424, the Emergency Economic Stabilization Act of 2008 was passed. Division B of this bill includes the Energy Improvement and Extension Act of 2008. This landmark legislation extends critical Federal Investment Tax Credits for solar customers and other renewable energy projects. This bill contains $18 billion in incentives for clean and renewable energy technologies, as well as for energy efficiency improvements.

See the entire bill, including Division B: Energy Improvement and Extension Act of 2008.

As part of this legislation, the solar investment tax credit (ITC) has been extended for 8 years through December 31, 2016. Here are the key provisions of the ITC:

- The 30% federal investment tax credit for both residential and commercial solar installations is extended for 8 years through December 31, 2016.
- Eliminates the $2,000 cap on the tax credit for the purchase and installations of solar electric on residential properties.
- Addition of small wind energy and geothermal heat pump projects as qualifying installations for tax credits
- Utilities may now benefit from the credit as eligible tax credit recipients.
- Extends through 2009 the authority to issue clean renewable energy bonds."