NATIONAL RENEWABLE ENERGY LABORATORY

Feasibility Study of Economics and Performance of Solar Photovoltaics at Massachusetts Military Reservation

A Study Prepared in Partnership with the Environmental Protection Agency for the RE-Powering America's Land Initiative: Siting Renewable Energy on Potentially Contaminated Land and Mine Sites

Byron Stafford, Robi Robichaud, and Gail Mosey

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-6A20-49417
July 2011

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Executive Summary

The U.S. Environmental Protection Agency (EPA), in accordance with the RE-Powering America's Land initiative, selected the Massachusetts Military Reservation (MMR) to receive technical assistance from the National Renewable Energy Laboratory (NREL) for a feasibility study to be conducted on a superfund site located within MMR. The purpose of this report is to assess sites within the landfill area at MMR for suitability for possible solar photovoltaic (PV) installations and estimate the cost, performance, and site impacts of the different PV mounting options. In addition to this, the report recommends future actions that could assist in the procurement and implementation of a PV system.

Four sites were considered and found suitable to incorporate PV systems at MMR—three landfill caps and a borrow pit. See Figure ES-1 for an aerial view of the four potential sites. The economics of the potential PV systems were analyzed using an electric rate of $0.159/kWh and incentives offered in the Commonwealth of Massachusetts, such as the solar renewable energy certificates (SRECs). Table ES-1 summarizes the system performance and economics of a typical potential system at MMR. Crystalline silicon PV modules were used in the calculations. Using PV modules with higher or lower efficiencies will result in significantly different results. In addition, different types of PV mounting systems—fixed tilt, single-axis tracking, and two-axis tracking—were analyzed. A fixed-tilt PV system is a more likely outcome because of lower operations and maintenance (O&M) and ease of meeting wind-loading requirements. However, proposals with single-axis and two-axis PV system mounting could be considered if all of the MMR requirements are met and the overall project costs are reasonable.

Any procurement should include all types of PV modules and all types of PV mounting systems. Table ES-1 represents reasonably sized 30-degree fixed-tilt PV systems in the range of 8 MW for MMR. Portions of these PV systems could be installed depending on the needs, available funds, and interest. Table ES-1 also summarizes job creation if the MMR sites were used for PV.

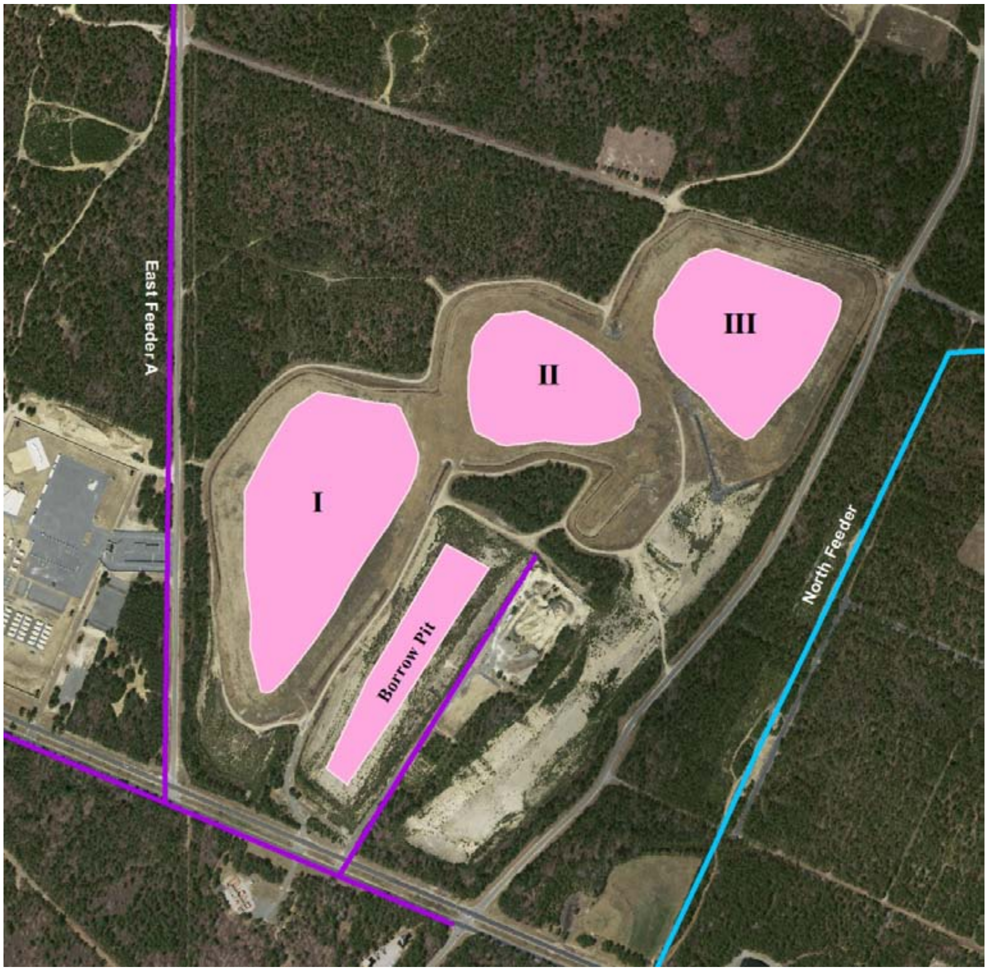

Figure ES-1. Aerial view of potential PV system sites at MMR

Credit: AFCEE, 2011 MMR-AFCEE Data Warehouse with 2009 Aerial Photography from MassGIS

Table ES-1. PV System Performance and Economics by Site[a]

Site	PV System Size (kW)	Installed Cost ($/W)	Annual Output (kWh/year)	Annual O&M ($/year)	System Cost ($)	Simple Payback Period (years)	Jobs[b] Created	Jobs[c] Sustained
I	3,633	$5.00	4,112,548	$30,880	$18,165,000	9.4	197	0.34
II	1,356	$5.00	1,535,060	$11,527	$6,780,000	9.4	74	0.13
III	1,888	$5.00	2,137,612	$16,051	$9,442,000	9.4	103	0.17
Pit	857	$5.00	970,492	$7,287	$4,287,000	9.4	47	0.08
Total	**7,735**	**$5.00**	**8,755,712**	**$65,745**	**$38,674,000**	**9.4**	**420**	**0.71**

[a] Data assume a usable area of 2,062,596 ft^2 and a fixed-tilt system at 30 degrees.
[b] Job-years created as a result of project capital investment including direct, indirect, and induced jobs.
[c] Jobs (direct, indirect, and induced) sustained as a result of O&M of the system.

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1 Study Location

The U.S. Environmental Protection Agency (EPA), in accordance with the RE-Powering America's Land initiative, selected the Massachusetts Military Reservation (MMR) to receive technical assistance from the National Renewable Energy Laboratory (NREL) for a feasibility study to be conducted on a superfund site located within MMR.

MMR, a military training facility, is located on the upper western portion of Cape Cod, immediately south of the Cape Cod Canal in Barnstable County, Massachusetts. It includes parts of the towns of Bourne, Mashpee, and Sandwich and abuts the town of Falmouth. MMR covers nearly 21,000 acres—approximately 30 mi^2.[1]

The Air National Guard, located at the Otis Air National Guard Base (ANGB) [102 Intelligence Wing (102 IW)] on MMR, is interested in exploring opportunities for on-site generated renewable energy to offset the high energy costs ($0.159/kWh) and to help meet the federal mandate under Executive Order 135142 to achieve greater energy efficiency and use of renewable energy at federal facilities. The main base landfill was selected as a preferred location for solar photovoltaics (PV).

The ANGB property includes the main base landfill; however, the landfill is managed by the Air Force Center for Engineering and the Environment (AFCEE) as a superfund site under the Installation Restoration Program. The landfill is 100 acres, of which 60 acres consist of three landfill caps managed under the Resource Conservation and Recovery Act (RCRA) Subtitle C program. The adjacent borrow pit is 5.3 acres. This report estimates the feasibility of PV systems on the landfill caps and in the borrow pit.

[1] Massachusetts Military Reservation. http://www.mmr.org. Accessed September 2010.
[2] Executive Order 13514. *Federal Register*. http://edocket.access.gpo.gov/2009/pdf/E9-24518.pdf. Accessed March 2011.

2 PV Systems

Solar PVs are semiconductor devices that convert sunlight directly into electricity. They do so without any moving parts and without generating any noise or pollution. They must be mounted in an unshaded location; rooftops, carports, and ground-mounted arrays are common mounting locations. PV systems would be appropriate at MMR, where the average global horizontal annual solar resource is 3.63 kWh/m^2/day.[3] This number, however, is not the amount of energy that can be produced by a PV system. The amount of energy produced by a PV system depends on several factors. These factors include the type of modules, the tilt and azimuth of the modules, the tracking of the modules, the temperature, and the level of sunlight and weather conditions. An inverter is required to convert the direct current (DC) to alternating current (AC) of the desired voltage compatible with building and utility power systems. The balance of the system consists of conductors/conduit, switches, disconnects, and fuses. Grid-connected PV systems feed power into the facility's electrical system and do not include batteries.

Figure 1 shows the major components of a grid-connected PV system and illustrates how these components are interconnected.

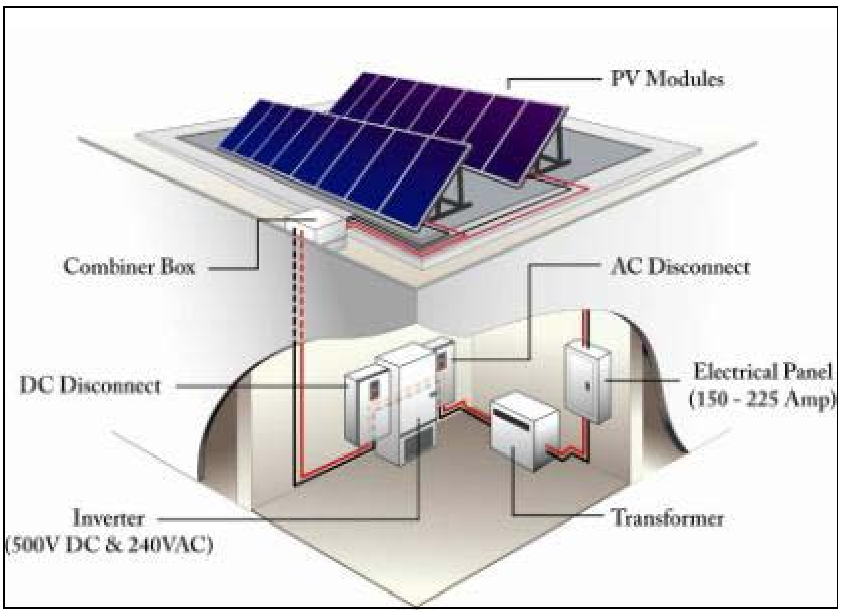

Figure 1. Major components of grid-connected PV system

Credit: NREL

PV modules are made up of many individual cells that all produce a small amount of current and voltage. These individual cells are connected in series to produce a larger current. PV modules are very sensitive to shading. When shade falls on a module, that portion of the module is no longer able to collect the high-energy beam radiation from the sun. If an individual cell is shaded, it will act as a resistance to the whole series circuit, impeding current flow and

[3] Typical meteorological year 3 (TMY3) data for Otis ANGB available from NREL, http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/. NREL's System Advisor Model (SAM), version 2010.11.9, summarized the annual global horizontal solar resource as 1,325.2 kWh/m^2/year, or 3.63 kWh /m^2/day. SAM is available at https://www.nrel.gov/analysis/sam/.

dissipating power rather than producing it. By determining solar access—the unimpeded ability of sunlight to reach a solar module—one can determine whether an area is appropriate for solar panels.

If a site is found to have good potential for a PV system, then the next step is to determine the size of that system, which highly depends on the average energy use of the on-site facilities. Providing more power than a site would use is generally not advisable due to the economics of most net-metering agreements. The system size would thus be determined by the economics of the project along with the applicable net-metering regulations or by how much land area is available. The PV systems will be broken down by site so the total system size can be adjusted based on what the utility requests, requirements by MMR, and financial incentives.

PV module efficiencies range from high efficiency crystalline silicon PV modules with 18% efficiency to thin-film amorphous silicon PV modules with 6% efficiency. An efficiency of 13.5% was used in the analysis, which is typical for crystalline silicon PV modules. For a first approximation, if a higher efficiency module of 18% efficiency is assumed, then the power of the PV system would be proportionally higher by the ratio of 18/13.5, or the area of the PV system would be reduced proportionally by the ratio of 13.5/18.

2.1 PV System Performance and Solar Resource

In general, a PV module facing south and tilted from the horizontal about the same number of degrees as the latitude of the PV module will produce the maximum annual energy output. The azimuth is the descriptor for the orientation of the PV module's face with respect to the compass degrees. A PV module with an azimuth of 180 degrees faces south. For most installations, PV modules cannot be oriented or tilted for maximum annual energy production and compromises between energy production, total system cost, and future operation and maintenance (O&M) costs are made.

Most PV systems are described by the sum of the DC power ratings of all of the PV modules in a system. NREL has developed a Web-based software program called PVWATTS[4] to estimate the monthly and annual energy output of a PV system based on the system size, location, tilt, and azimuth. NREL has also developed a software program called System Advisor Model (SAM)[5] Version 2010.11.9 that incorporates PVWATTS. Solar resource data for Otis ANGB was used.[6] The resource data used are from a typical meteorological year (TMY3) from 1991–2005.

Using SAM, the annual energy production of a 1 kW PV system was calculated for various tilts with an azimuth of 180 degrees. The energy production numbers are linearly scalable for larger PV systems—a 100 kW PV system produces 100 times more energy than a 1 kW PV system. Figure 2 shows the energy output as a function of the tilt. In addition, the ratio between energy produced and power is useful for estimating the energy production from any size PV system. For example, if for a given location, the tilt and azimuth ratio of kWh/W is 1.2, then a 2 MW PV system would produce 2,400 MWh of energy per year.

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[4] PVWATTS. www.nrel.gov/rredc/pvwatts. Accessed March 4, 2011.
[5] SAM. www.nrel.gov/analysis/sam. Accessed March 4, 2011.
[6] See http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/ for a listing of all sites and a description of the data.

At high latitude, such as at MMR, the maximum energy production does not occur at a PV module tilted at latitude—41.7 degrees. Instead, the maximum energy production occurs at a tilt of 35 degrees. Christensen and Barker[7] suggest four reasons why this occurs: (1) clearer summer days when the sun is higher in the sky; (2) more diffuse scattered light on lower tilted modules; (3) less atmospheric attenuation when the sun is higher in the sky; and (4) lower tilt angles reduce the number of hours when the sun rises or sets north of east and north of west. A tilt of 30 degrees was selected for this analysis since a lower tilt will reduce the wind loading, which will require less ballast weight while only reducing the performance less than 0.5%.

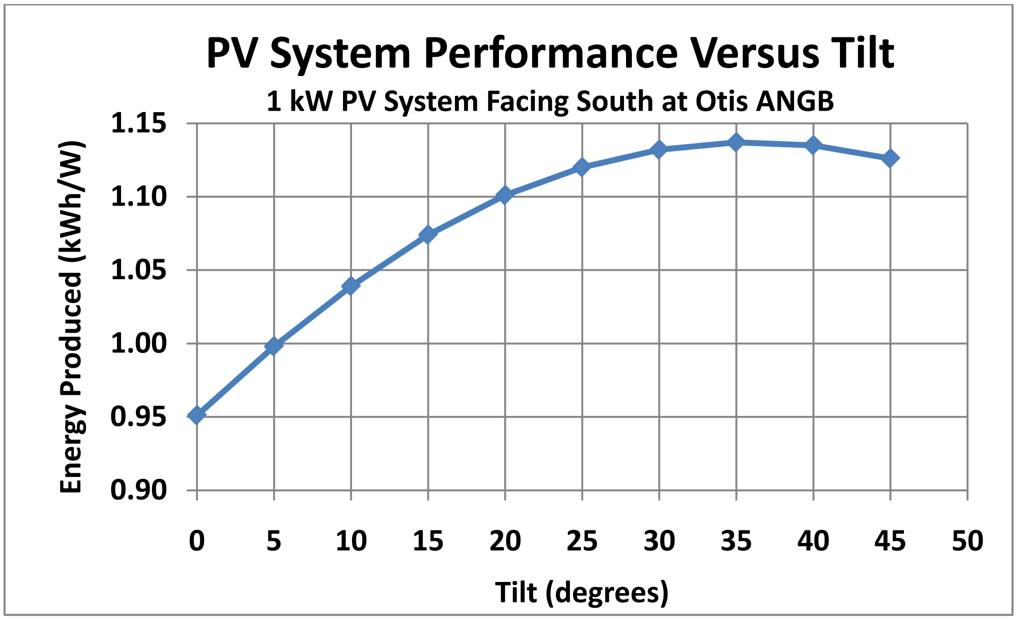

Figure 2. Comparison of energy production for 1 kW PV system at Otis ANGB as a function of tilt

Data from SAM Version 2010.11.9 using PVWATTS and Otis ANGB TMY3 solar resource data

Using SAM, the monthly energy production of a 1 MW PV system was calculated for a fixed 30-degree tilt with an azimuth of 180 degrees. See Figure 3 for a chart of the data.

[7] Christensen, C.B.; Barker, G.M. (2001). “Effects of Tilt and Azimuth on Annual Incident Solar Radiation for United States Locations.” Kleis, S.J.; Bingham, C.E., eds. *Solar Engineering 2001: Proceedings of the International Solar Energy Conference Presented at FORUM 2001, April 21-25, 2001, Washington, D.C.* NREL Report No. CP-550-32966. New York: The American Society of Mechanical Engineers (ASME); pp. 225-232.

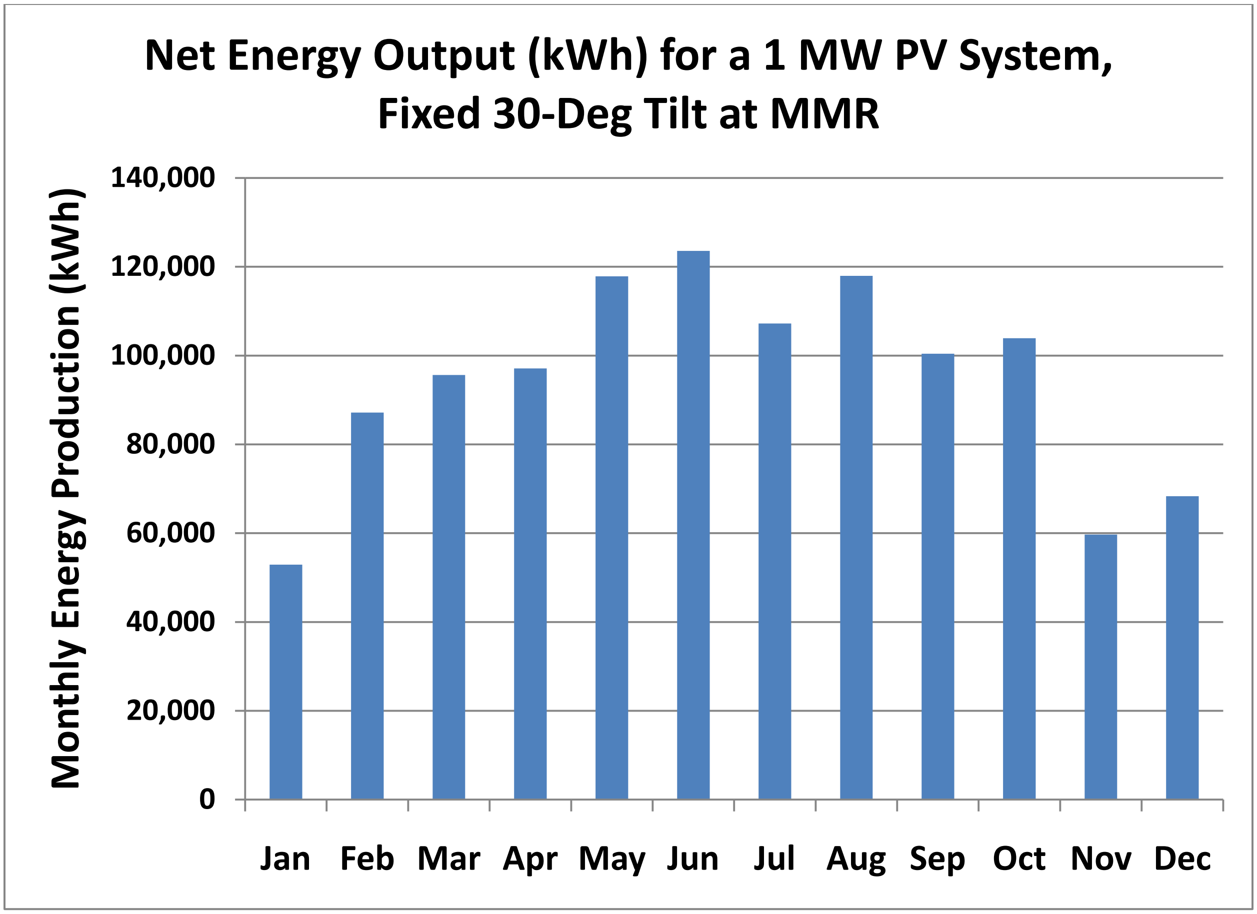

Figure 3. Estimate of monthly energy production for a 1 MW PV system at MMR

Data from SAM Version 2010.11.9 using PVWATTS and Otis ANGB TMY3 solar resource data.

For a PV system with a tilt of 0 degrees, there is no azimuth and the energy production is the same at all azimuths. A PV system with a 0-degree tilt is not practical on the ground. All PV systems need some slope to facilitate rainwater runoff. Most PV module manufacturers recommend a minimum of 10 degrees. In a snowy climate, such as MMR, a steeper tilt is desirable to encourage any accumulated snow to slide off. A distance of 3 ft from the bottom edge of the PV modules is a sufficient distance for snow to slide off the PV modules without blocking the modules. Steep module slopes necessary for snow to slide off require more ballast weight since the PV system would have a higher wind profile. A tilt of 30 degrees is used in this analysis compared to an optimal 35 degrees based solely on energy production. Commercial mounting hardware options are more readily available for ballast weighted systems tilted 30 degrees or less.

The labor cost to clear snow from PV systems is usually more than the increased production revenue. The PV system operator needs to determine when it would be cost effective to clear snow from the PV modules. As an example, it may take 32 man hours (two people, 2 days, 8 hrs/day) at $30/hr, or a total of $960, to clear the snow from a 1 MW PV system. However, the sun could melt it off the PV modules in 4 days. If the energy production increase is only 20% for 4 days in winter, the increased energy production is 1,360 kWh (1,700 kWh/day production in January for a 1 MW PV system at MMR), which is valued only at $231 if electricity is

$0.17/kWh. Rainfall is adequate in this location so PV module cleaning is generally not considered.

As depicted in Figure 4, when PV module A is tilted at a given angle, then PV module B placed behind it—to the north—must be spaced so that the shadow from the top of PV module A in front does not shadow the bottom of PV module B in back. Usually PV modules or groups of PV modules are placed in rows, so this spacing is called row spacing, which can be generalized to a non-dimensional term called packing factor. The worst solar day occurs at the winter solstice, which is typically December 22. A 6-hr window of no shade on the back row is used in this analysis. The critical angle for MMR is a sun altitude angle of 12.75 degrees above the horizon 3 hrs before and after solar noon on December 22. This critical sun elevation determines the row spacing for the latitude of MMR.

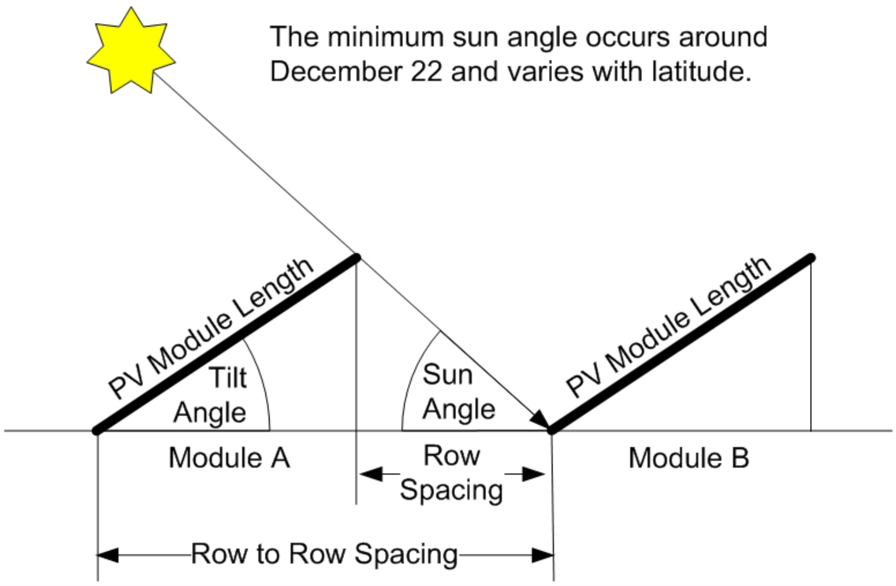

Figure 4. Row spacing depends on the latitude and tilt of the PV modules

Packing factor is the ratio of the row spacing divided by the row-to-row spacing. Figure 5 illustrates different packing factors as a function of tilt. A packing factor of 0.30 was used in this analysis to determine the total PV system size for a given area. The total PV system size is the area times the packing factor times the PV module's power per unit area. A system designer can increase the packing factoring to place more PV modules in a smaller area at the expense of some PV production in the winter months. The majority of PV energy is produced in the spring and summer months so some reduction in winter months could be acceptable.

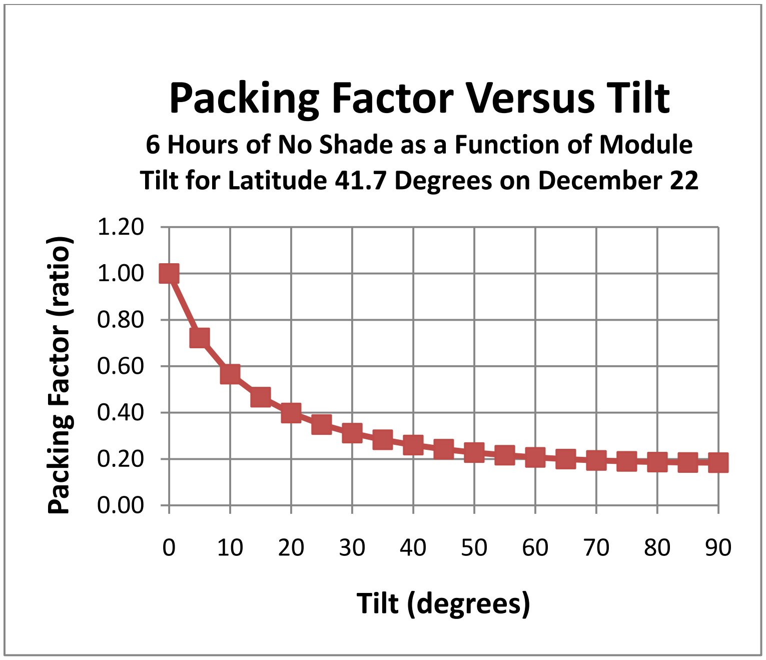

Figure 5. Packing factor estimate versus tilt

Based on location, the available area, the packing factor, the tilt and azimuth of the PV modules, the size, and the energy production of the PV system can be estimated. It is generally not advisable to provide more energy than the site will use on an annual basis due to the economics of most net-metering agreements. Based on meter data, the base grid at MMR uses about 2 million kWh of energy per month. In addition, another 800,000 kWh of energy per month was used from independent utility feeders. From July 2009 to June 2010, a 12-month period, the base grid at MMR used 24,792,501 kWh.[8] This is almost twice the energy that a PV system on the landfill caps and borrow pit could produce on an annual basis. The PV system size can be adjusted based on what the utility requests, financial incentives, and what MMR requires.

In addition to the estimated energy production, the electrical infrastructure at MMR needs to be able to absorb the peak power production from the PV system. An 8 MW (DC rating) PV system could produce peak power around 6.2 MW (AC rating). Typically, this peak power production occurs during the months of May, June, July, and August. The PV system could be segmented such that the peak power is split between different feeders. An interconnection study is needed to determine the best way to interconnect any PV system on MMR.

2.2 Ground-Mounted PV Systems

A ground-mounted PV system can be an in-ground system using poured concrete foundations or metal piers driven into the ground. This is not an acceptable mounting method for a PV system on top of a landfill cap. However, ballast-weighted ground-mounted PV systems are possible. This is a common mounting method for PV systems on roofs where roof penetrations are not permitted or desired. Only ballast-weighted mounting methods are considered in this analysis for the landfill cap sites at MMR. The borrow pit site at MMR could have either an in-ground

[8] Base energy data supplied by Rose Forbes, AFCEE.

mounting system or a ballast-weighted mounting system as there are no landfill materials underneath that may be penetrated by an in-ground mounting system.

Ballast-weighted mounting methods rely on the weight of the PV modules, the mounting racks, and extra ballast to meet wind-loading design considerations. Three wind-loading conditions—overturning, uplifting, and sliding—need to be considered. In most systems, sliding is the more critical design requirement since the friction between the ground and the ballast has to be estimated under all weather conditions. A steeper module tilt increases the wind loading and, consequently, the total ballast weight. The ballast weight can increase or decrease the point load depending on the area of the ballast weight in contact with the ground. The maximum total dead weight and individual point loads need to be determined and approved for the landfill caps.

An engineering analysis was completed for a hypothetical ballast-weighted PV system—the Greenfield PV system in Greenfield, Massachusetts.[9] The calculated contact bearing pressure for this hypothetical PV system was always less than the landfill cap maximum load of 1,008 lb/ft^2. The engineering analysis included a poured concrete ballast weight of 3 ft (W) x 8 ft (L) x 1.5 ft (H), buried 0.5 ft in the ground. Concrete slabs for transformers and inverters were also considered. Although the slope of the landfill cap is in the range of 2.0–3.5 degrees, the downhill sliding of the ballast weight was considered. The maximum bearing pressure for the MMR landfill caps needs to be determined for that specific cover system. The range of maximum bearing pressure for landfill caps in Massachusetts is in the range of 720–1,008 psf.[10] In summary, most any commercially available ballast-weighted PV system will be less than the maximum weight-loading requirements of the MMR landfill caps.

Vehicle access on the landfill caps during the assembly needs to be considered. Typical delivery vehicles for a PV system of this size include standard tractor-trailers. Equipment is off-loaded by an overhead crane or by forklifts. Overhead cranes could be separate truck-mounted cranes or cranes mounted on the delivery vehicle. Forklifts could be either construction-type (extending booms) or fixed-mast forklifts. Equipment could be reloaded at MMR onto smaller vehicles more suitable for travel on the landfill caps. Andrews designed a temporary 18-in thick gravel road that could be installed and used on the landfill caps.[11] Alternately, portable roadways could be installed. An example is a product, MegaDeck,[12] that could reduce the point loading to less than 1,008 lb/ft^2. The portable roadway is moved around a landfill cap as the PV system is installed. The dynamic loading of the temporary or the portable roadway when using a crane still needs to be evaluated. Vehicle access on the landfill caps during maintenance can be accomplished with low-ground-pressure vehicles such as all-terrain vehicles.

The design of the ballast and PV module mounting frame needs to consider storm water runoff, snow load, potential local settling of the landfill cap, and the slope of the ground so that the PV

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[9] Andrews, D. *Calculations of Contract Bearing Pressure and Estimated Settlement of Foundation Footings for Axio Greenfield Solar.* Internal report of Massachusetts Department of Environmental Protection (MassDEP), June 11, 2010.

[10] Dakers, M. Email. MassDEP, Boston, MA, 31 March 2011.

[11] Andrews, D. *Calculations of Contract Bearing Pressure and Estimated Settlement of Foundation Footings for Axio Greenfield Solar.* Internal report of MassDEP, June 11, 2010.

[12] Signature Flooring, MegaDeck product. www.eventdeck.com/MegaDeck.shtml. Accessed March 4, 2011.

system does not gradually slide downhill. This is manageable, but it is site and manufacturer specific.

A Weston & Sampson report estimates the expected settlement of the nearby Falmouth landfill cap.[13] Similar settlement may be possible at MMR but needs to be evaluated. Settlement is normal and expected. The following is a brief summary based on the Falmouth landfill study. Primary settlement of a landfill cap usually occurs in the first 1–3 months and should have happened years ago. Secondary settlement occurs over the life of the landfill. Weston & Sampson estimate a uniform secondary settlement of 0.25–0.55 ft over a 30-year period. There can also be differential settlement from a localized subsidence at the landfill. Two cases were modeled. The first case considers a refrigerator collapsing that causes a 2-ft drop on the top surface over an area of 6 ft x 8 ft. The second case considers a single cell or trench that was poorly compacted or settled faster than nearby cells or trenches. In the second case, a drop of 8 ft on the top surface could occur over an area 50 ft wide by the length of that landfill trench. Based on expected settling, the PV system design for the landfill caps should consist of separate units with dimensions in the range of 50 ft or less that can be separately adjusted. The separate units should not be physically interconnected along with some reasonable physical separation. It is possible to design a PV-mounting structure that will accommodate future secondary settlement. Settlement is not expected at the borrow pit, so the range of PV-mounting systems is expanded. Annual or semiannual inspections are required to check on the physical structure of any PV system.

For this report, three types of ground-mounted systems are considered. Fixed-tilt systems are installed at a specified tilt and are fixed at that tilt for the life of the system. Single-axis tracking systems have a fixed north-south axis and a variable tilt in the east-west direction. Two-axis tracking systems continually adjust the azimuth and tilt so that the PV modules always face the sun. Typically, two-axis tracking systems are mounted on a single pole, which requires extensive concrete or piers deep into the ground. While the typical two-axis tracking system should be okay for the borrow pit, it is unacceptable for the landfill caps. Although large-scale ballast-weighted two-axis tracking systems have not been deployed, it is possible to conceive of a two-axis tracking system similar to a fixed-tilt PV system where the individual PV modules track the sun.[14] In addition to fixed-tilt PV systems, single-axis and two-axis tracking systems could be considered for the landfill caps and for the borrow pit and should not be excluded from any procurement. Proposers need to meet the point-loading requirements along with the wind-loading requirements. In addition, all proposers should include an estimate of the O&M costs for the weather and ground conditions at the MMR sites.

Based on the solar resource for the MMR area, a single-axis tracking system and a two-axis tracking system can produce nearly 12% and 31% more energy, respectively, than a flat 30-degree fixed-tilt system. The drawbacks to single-axis and two-axis tracking systems include increased O&M costs, increased ballast weight, and increased installed costs. Nonetheless, single-axis and two-axis tracking systems should be included in any procurement since the gain

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[13] "Design Summary Report and Technical Specifications, Landfill Closure Design, Thomas Landers Road Landfill." Weston & Sampson report to Town of Falmouth, MA, 1998.

[14] Some examples are http://kdmegatech.en.ec21.com/Rooftop_Solar_Tracker_Dual_Axis--4607559_4612259.html and http://www.sedonaenergylabs.com/storage/white-papers/SEL_ProductSheet_final5.pdf. NREL presents these systems as concepts and has no knowledge as to their suitability for MMR.

in energy production could balance out any drawbacks. If there is a power (kW) limitation on the MMR electrical distribution system, a single-axis or two-axis tracking system can produce more energy (kWh) for no change in the power rating (kW).

When considering a ground-mounted system, an electrical tie-in location should be identified to determine how the energy will be fed back into the grid. Two different electrical feeders—East Feeder A and North Feeder—are in close proximity to the landfill site. An electrical engineering study is needed to determine the power capabilities of these two feeders. The PV system could be segmented to feed separate feeders to alleviate power limitations on a single feeder.

2.3 PV System Components

The PV system considered here has these components:

- PV arrays, which convert light energy to DC electricity
- Inverters, which convert DC to AC and provide important safety, monitoring, and control functions
- Various wiring, mounting hardware, and combiner boxes
- Monitoring equipment

2.3.1 PV Array

The primary component of a PV system, the PV array, converts sunlight to electrical energy; all other components simply condition or control energy use. Most PV arrays consist of interconnected PV modules that range in size from 50 peak DC-Watts to 300 peak DC-Watts. Peak watts are the rated output of PV modules at standard operating conditions of 25°C (77°F) and insolation of 1,000 W/m². Because these standard operating conditions are nearly ideal, the actual output will be less under typical environmental conditions. PV modules are the most reliable components in any PV system. They have been engineered to withstand extreme temperatures, severe winds, and impacts. ASTM E1038-0515 subjects modules to impacts from 1-in hail balls at terminal velocity (52 mph) at various parts of the module. PV modules have a life expectancy of 20–30 years, and manufacturers warranty them against excessive power degradation for 25 years. The array is usually the most expensive component of a PV system; it accounts for approximately two-thirds of the cost of a grid-connected system. A large choice of PV manufacturers is available.[16]

2.3.2 Inverters

Inverters are required to change the DC output of the PV modules into AC electricity. The DC input range of the inverter is selected to match the DC output of the PV modules. The AC output is selected to match the voltage of the distribution wiring where the inverter will be interconnected. A typical AC output is 480 V, three-phase. Transformers are used if a higher output voltage is required.

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[15] ASTM International. "E1038-05 Standard Test Method for Determining Resistance of Photovoltaic Modules to Hail by Impact with Propelled Ice Balls," West Conshohocken, PA, 2005, DOI: 10.1520/E1038-05. http://www.astm.org/Standards/E1038.htm. Accessed August 2010.

[16] Go Solar California, a joint effort of the California Energy Commission and the California Public Utilities Commission, provides consumer information for solar energy systems. See http://www.gosolarcalifornia.org/equipment/pv_modules.php.

Large inverters are commercially available in the 100–1,000 kW AC sizes. The inverters synchronize to the utility so multiple inverters can be used for megawatt-sized PV systems. For example, a 1 MW PV system would require four 250-kW inverters or ten 100-kW inverters. All inverters should meet "UL Standard 1741, Standard for Static Inverters and Charge Controllers for Use in Photovoltaic Power Systems."[17] This standard is universally recognized by most electric utilities in the United States for interconnecting a PV system.

Warranties on inverters range 5–10 years with some manufacturers offering extended warranties to 20 years. While most inverters are weather proof, they should be shielded from direct sunlight to reduce possible thermal limiting within the inverter and help lengthen the service lifetime. Typical efficiencies of these inverters are 95%–98%. The California Energy Commission has a comprehensive listing of inverters, sizes, and weighted efficiencies.[18]

2.3.3 Monitoring Equipment

Monitoring equipment is a requirement for any PV system. Inverters may include or have options for some metering and data-logging capability.

2.3.4 Operation and Maintenance

PV panels come with a 25-year performance warranty. A typical PV module performance warranty states that modules will produce 80% of the initial module power rating after 25 years. The decrease in power can be linear over the warranty time period or can be specified by the year, such as 90% in the first 10 years and 80% in the remaining years. The module warranties are manufacturer and module specific.

The inverters, which come standard with a 5–10-year warranty (extended warranties are available), would be expected to last 10–15 years. System performance should be verified on a vendor-provided website. Wire and rack connections should be checked at least annually and more frequently if specified by an equipment manufacturer. For this economic analysis, an annual O&M cost of 0.17% of total installed cost is used based on the O&M cost of other fixed-tilt grid-tied PV systems. For the case of single-axis tracking, an annual O&M cost of 0.35% of total installed cost is used based on O&M costs of existing single-axis tracking systems. Two-axis tracking systems would have a higher O&M cost than single-axis tracking systems. The exact O&M cost is system specific and should be specific by the system integrator or designer.

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[17] UL 1741. "Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources." http://ulstandardsinfonet.ul.com/scopes/1741.html. Accessed July 2010.

[18] Go Solar California. "List of Eligible Inverters per SB1 Guidelines." http://www.gosolarcalifornia.org/equipment/inverters.php. Accessed February 2011.

3 MMR Ground-Mounted PV Site Locations

An NREL solar assessment site visit occurred on February 25, 2010.[19] Sampson analyzed PV systems on landfills, and the report was used in consideration of PV systems at MMR.[20]

MMR has three landfill caps and a borrow pit that are suitable for ground-mounted PV systems. For this report, the caps are numbered I, II, and III, from west to east (Figure 6). These caps have short vegetation without any trees. There are no significant shading issues on these caps—see Figure 7. The caps are relatively flat on top with slopes ranging from 2.0, 3.5, and 2.7 degrees from the top of the landfill caps numbered I, II, and III, respectively. The slopes are uniform in all directions based on the NREL analysis of the contour map in the Appendix—Figure A-1. As seen on the contour maps, the caps are relatively flat with significant slopes only at the edges of the caps. Only the relatively flat areas were considered for PV systems. The remaining areas of the landfill caps were not considered for a PV system because of significant slopes near the edges.

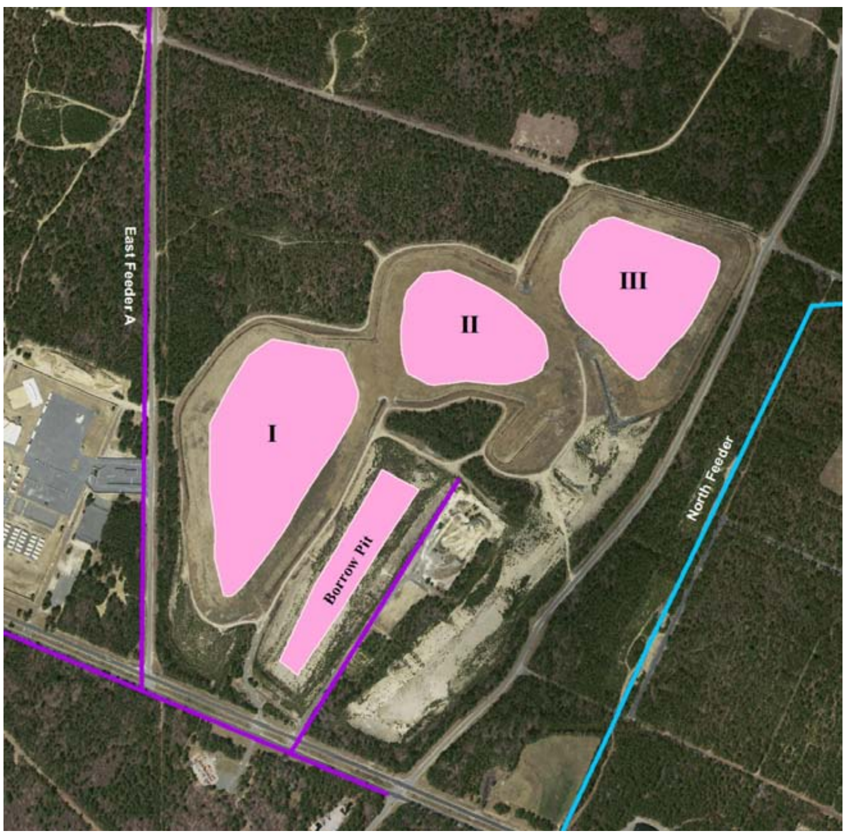

Figure 6. Aerial view of potential PV system sites at MMR

Credit: AFCEE, 2011 MMR-AFCEE Data Warehouse with 2009 Aerial Photography from MassGIS

[19] Mosey, G,; Robichaud, R. “Site Visit Report for Solar Assessment Activities at the Massachusetts Military Reserve, Falmouth, MA.” Golden, CO: National Renewable Energy Laboratory, May 7, 2010.
[20] Sampson, G. *Solar Power Installations on Closed Landfills: Technical and Regulatory Considerations.*” Bren School of Environmental Science and Management, Santa Barbara, CA: University of California, 2009.

Figure 7. Landfill cap with relatively shallow slope

Credit: AFCEE/MMR

At the request of AFCEE, the borrow pit was also included. The borrow pit is a depression that has a relatively flat bottom of compressed aggregate—see Figure 8. The existing vegetation, consisting of primarily scrub pines, could be removed if necessary. The borrow pit has good drainage and is not known to hold water after a rain storm. There is no active equipment for draining the borrow pit. While the borrow pit is an easy site for a PV system, a back-up sump pump should be considered for extreme rain events or other flooding possibilities.

Figure 8. View of the bottom of the borrow pit

Credit: AFCEE/MMR

The PV system envisioned for this analysis consists of many east-west rows of PV modules that cross over the crowns of the landfill caps or cover the flat area of the borrow pit. There should be significant space to drive a vehicle (all-terrain vehicle or pickup truck) in between the rows for maintenance. The rows should have gaps so that any settling of the cap will have only a limited impact on the PV-mounting structure.

Only ballast-weighted PV-mounting systems should be considered for the landfill caps. These systems usually require no ground penetrations. Typically, ballast-weighted PV-mounting systems are placed on top of the existing soil. If allowed, the ballast weights could be partially buried in the top soil of the landfill caps.[21]

The range of PV-mounting systems for the borrow pit can be expanded to include driven or poured concrete piers.

3.1 Wind Loading

MMR operates under the Unified Facility Criteria (UFC) system for most design and construction projects where appropriate.[22] The most recent UFC Structural Engineering, UFC 3-301-01, addresses wind-loading criteria.[23] Table E-1, Structural Climatic Loading Data – United States, Its Territories and Possessions, in UFC 3-301-01 lists 115 mph basic wind speed for Otis ANGB/Falmouth. Dr. Robert Dinan states that depending on the configuration of the PV arrays,

[21] Andrews, D. *Calculations of Contract Bearing Pressure and Estimated Settlement of Foundation Footings for Axio Greenfield Solar.* Internal report of MassDEP, June 11, 2010.

[22] Unified Facilities Criteria (UFC). Available from Whole Building Design Guide. http://www.wbdg.org/ccb/browse_cat.php?o=29&c=4. Accessed April 2, 2011.

[23] UFC. Structural Engineering, with Change 2, 31 January 2011, http://www.wbdg.org/ccb/DOD/UFC/ufc_3_301_01.pdf. Accessed April 2, 2011.

the design wind load on the PV arrays would be calculated using ASCE 7-05 Section 6.5.13, Equation 6-25.[24,25] Dinan states that even though this is not a building, the PV array would respond to wind in the same manner as an open building with a monoslope roof.

3.2 Typical PV-Mounting Systems

This analysis presents two different types of fixed, ballast-weighted PV-mounting systems for a basic wind speed of 90 mph.[26] PV system designs, including ballast-weighted systems, are possible with design wind speeds up to 115 mph.

The first example considers a PV-mounting system similar to Unirac's ISYS Ground Mount system,[27] which uses ballast weights instead of buried supports to install the PV system to the ground. This system is similar to the system analyzed in Andrews's structural report.[28] Assuming 20 PV modules (BP3225T) in a 4 module by 5 module landscape arrangement will result in a sub-array of 4.5 kW, which is about 30 ft long by 14 ft deep. Furthermore, assume only two poles will hold this sub-array at an effective angle of 30 degrees with respect to level, not necessarily the ground.

Two precast concrete ballast weights are estimated at 9,000 lbs each for this location.[29] Exact structural calculations are required. Snow load was the critical factor since the sub-array is supported in the middle and not at the corners or edges. Typical dimensions of the ballast could be 2 ft (W) x 10 ft (L) x 3 ft (H). This results in a contact bearing pressure of 450 lb/ft^2, which should be acceptable for the landfill cap. Total weight of the sub-array would be around 20,000 lbs, including the framing and the PV modules. Over the sub-array area of 30 ft by 14 ft, this averages to a net 50 lb/ft^2. The UFC Structural Engineering document lists the snow loading for Otis ANGB/Falmouth as 25 lb/ft^2 in Table E-1.[30] Meeting the combined system weight loading and the snow loading is very doable for both the landfill caps and the borrow pit.

See Figure 9 for a typical sub-array using two ballast weights. This type of PV-mounting system has access benefits—it will be easy to walk around the system to perform maintenance and to realign the PV sub-array if localized settlement occurs.

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[24] Dinan, R. E-mail correspondence. Air Force Civil Engineer Support Agency, 5 May 2011.
[25] American Society of Civil Engineers (www.asce.org) publishes standards, including ASCE 7-05, which covers wind loads.
[26] While two particular mounting systems were used, these are representative and not an endorsement of any particular company. Non-concentrating flat-plate tracking systems are not covered in this report, but could be used at MMR.
[27] Unirac. ISYS Ground. http://www.unirac.com/?q=commercial/commercial-products/isys-ground-commercial. Accessed July 17, 2011.
[28] Andrews, D. *Calculations of Contract Bearing Pressure and Estimated Settlement of Foundation Footings for Axio Greenfield Solar.* Internal report of MassDEP, June 11, 2010.
[29] Lonetti, D. Telephone conversation. Unirac, 9 August 2010.
[30] UFC. Structural Engineering, with Change 2, 31 January 2011, http://www.wbdg.org/ccb/DOD/UFC/ufc_3_301_01.pdf. Accessed April 2, 2011.

Figure 9. A ballast-weighted system using two precast concrete weights

Credit: Unirac

Another option is using a ballast-weighted PV-mounting system similar to those used on rooftops (see Figure 10). These types of PV-mounting systems spread the weight over a wide area by using structural beams. On a roof, the lower edge of the PV modules can be relatively close to the roof membrane. For a ground-mounted system, the lower edge, hence the whole structure, needs to be elevated to reduce the potential of the vegetation growing high and shading the modules. In addition, a higher height allows room for snow to slide off the PV modules. This type of sub-array PV-mounting system is good if there is any localized settlement and if the sub-arrays are not physically connected.

The net loading of this system will be around 4 lb/ft^2.[31] Concrete blocks can be placed under the mounting system to elevate the whole system so that the lower edge of the PV modules is about 36 in off the ground. The contact bearing pressure could be in the range of 500 lb/ft^2 if there are four support blocks, each 4 ft^2 in surface area.

Figure 10. A ballast system similar to that used on rooftops can be adapted for a ground-mounted PV system

Credit: Unirac

[31] Lonetti, D. Telephone conversation. Unirac, 9 August 2010.

3.3 Usable Land Area

Using Google Earth, polygons were drawn similar to the possible areas for PV systems at MMR on a map similar to the one shown in Figure 6. The sum of the Google Earth polygons is 2,062,594 ft^2—see Table 1. For the PV-sizing analysis in this report, the areas from Google Earth were used in Table A-1 since the areas could be broken out for each landfill cap. The saddles between the caps could be used as well but were neither highlighted in Figure 6, nor estimated in Table 1.

Table 1. Usable Area of Four Different Sites

Location	Usable Area (ft^2)
I	968,798
II	361,616
III	503,560
Pit	228,620
Total	**2,062,594**

3.4 MMR Electrical Distribution System

MMR is fed by a 25 kV distribution line from a local electric utility company, NSTAR.[32] The Main West Substation distributes the power around MMR through various feeders. A separate engineering report is required to determine the best options to interconnect a PV system onto the NSTAR system, the MMR distribution system, or a combination of both.

3.5 Environmental Considerations

There are several environmental considerations that need to be addressed during the design, construction, maintenance, and eventual end-of-life decisions for the PV systems. An Environmental Assessment or Environmental Impact Statements may be required depending on the local, state, or federal regulations.

Landfill gas is an environmental consideration that needs to be considered. Landfill gas can pose a risk to public health (toxic compounds in ambient air), safety (explosion, fire, and asphyxiation), and welfare (nuisance odors). One concern associated with the installation of a PV system at almost every landfill will be worker exposure to landfill gas during installation and O&M. An Occupational Safety and Health Administration (OSHA) health and safety plan needs to be provided for installation and O&M.

Depending on the PV modules selected and the orientation (tilt and azimuth), there may be some glare—that is, sunlight reflection. Typically, the glare is comparable to glare from buildings or lakes. At various times during the day and throughout the year, there may be some unwanted sunlight reflection. This may pose a risk for aircraft pilots. However, given the speed of the aircraft, any reflection in a pilot's eye is short in duration. While a complete ray tracing can be done to determine when and where these reflections occur, it is easier to mitigate the problem after installation if there is one. Mitigation may be as simple as placing a sun screen to block a specific reflection. The Federal Aviation Administration (FAA) addresses glare in their recent

[32] Forbes, R. Telephone communication. AFCEE, Otis ANGB, MA, 16 August 2010.

document, "Technical Guidance for Evaluating Selected Solar Technologies on Airports."[33] The FAA does not have specific standards for potential glare. Consultation with the FAA early in the PV system design is recommended.

At some point, the PV system will be decommissioned or repopulated with different PV modules. Recycling programs are still under development for PV modules. The general problem is that the disposal requirements of PV modules are module specific and disposal-method dependent. One state or county may permit PV modules to be tossed in a landfill as construction waste, while other jurisdictions prohibit it. What is permitted this year may not be permitted next year or 20 years from now. When there is a broken PV module, the decision regarding disposal needs to be made sooner than at the PV system's end of life. A landfill operator can determine if the PV modules are considered non-hazardous based on data or results from the toxic characteristic leaching procedure. Also, recycling should be considered for broken PV modules and during the decommissioning of the PV system. At least one company, First Solar, has a bonded recycling program for their cadmium-telluride (CdTe) PV modules.[34] First Solar's program is a prefunded, extended, producer-responsibility program that is paid from a portion of the initial purchase price of the PV modules. Most of the PV module manufacturers have a voluntary program to take back broken or old PV modules for recycling. The inverters and other electronics have standard disposal requirements. Disposal and recycling options should be presented by the PV system vendor, or the options could be made a part of the evaluation criteria if there is a competitive solicitation.

With PV modules tilted at any angle, the rainwater runoff needs to be managed to prevent soil erosion. The use of gutters and piping to channel rainwater to the bottom of PV modules is never used due to cost considerations—mostly maintenance costs. Within the first several months, a survey of the PV system is made and corrective actions are taken on the ground, such as adding gravel to major drip points or regrading the soil in critical areas. The initial corrective actions should be part of the installation contract and in the O&M contract if third-party owned.

The row spacing described earlier is ideal for PV annual performance. The rows could be placed closer together, improving the summer production at the expense of winter production when more of the rows would be shaded by the rows in front. There are other factors to consider in row spacing unrelated to PV performance but of importance to landfill management by MMR.

Storm water runoff associated with the site drainage system must be analyzed as well as any extra erosion mitigation measures that might be necessary due to the PV system. The landfill cap, as it stands now, has an impervious membrane covered by topsoil that is currently fully vegetated with native grasses, small vegetation, and weeds. This layer of vegetated topsoil serves as an effective absorber for heavy rain conditions thereby preventing drainage overload conditions. Heavy storms are currently able to be fully absorbed with no areas of standing water

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[33] Federal Aviation Administration (FAA). "Technical Guidance for Evaluating Selected Solar Technologies on Airports." November 2010. http://www.faa.gov/airports/environmental/policy_guidance/media/airport_solar_guide.pdf. Accessed March 31, 2011.

[34] First Solar. "First Solar Module Collection and Recycling Program." http://www.firstsolar.com/Downloads/pdf/Brochure_CollectionRecyclingProgram_NA.pdf. Accessed April 5, 2011.

accumulating due to the well-designed erosion mitigation system in place. Soft saturated soil conditions often exist during “mud season,” which occurs most springs after there has been a period of freezing temperatures and precipitation.

The PV modules themselves are impervious and contribute to accelerated runoff streams coming off of every module during rainstorm conditions. They also significantly reduce aspect ratio of absorbable land versus impervious land. The landfill surface essentially has an imperviousness ratio of zero. That is, there are no impervious surfaces across the entire landfill surface.

Installing the PV system will result in a significant addition to the numerator of that ratio. The smaller the ratio the better in terms of accelerating runoff streams. The steeper the modules, the smaller the ratio and the better for water runoff management. This is the opposite of the wind-loading consideration for MMR. Consideration for both cost and performance for each system is necessary.

Also of interest/concern is the vegetation—its growth and required maintenance activities. These two primary factors need to be included in the final row spacing analysis. Left unchecked, most wild grassy panels with wildflowers turn into bush habitat within a few years followed by trees. Regular maintenance of the vegetation will be required. It is already being done periodically. The issue to investigate is if the maintenance activities can be accomplished as well and as easily as they currently are or if the row spacing requires a new method of vegetation control be developed.

PV systems generate practically zero greenhouse gases (GHGs) over the lifetime of the system. During manufacturing, installing, and decommissioning, some GHGs are produced. During operation, no GHGs are produced except by vehicles used for maintenance. For the most part, PV systems, on a life cycle basis of 20–25 years, do not produce GHGs. An estimate of the GHGs reduced can be determined by locating the GHG emissions data of the electric power that the PV system replaces. The exact GHG reduction is dependent on the fuel mix (coal, hydro, and natural gas), time of day (peaking plant or base load), and season (hydro) for the electric utility power that is being displaced. An estimate of the GHGs avoided in the New England area is 890 lbs/MWh of PV energy produced.[35]

Installing ground-mounted PV systems will have some, but not a significant, impact on the flora and fauna. The vegetation under the PV modules will be shaded and different types of grasses or vegetation will flourish better. Similarly, the shade will provide a different type of habitat for animals. Overall, the impact on the flora and fauna will be minor. There will be some disturbance during construction. A site survey before construction and at intervals during operation is always recommended. Vegetation that routinely gets taller than 36 in should be pulled. This is not a concern on the landfill caps but is a concern in the borrow pit based on Figure 6.

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[35] ISO New England. “2008 New England Electric Generator Air Emissions Report.” http://www.iso-ne.com/genrtion_resrcs/reports/emission/2008_emissions_report.pdf. Accessed February 2011.

4 Economics and Performance

4.1 Summary of the Sites

MMR was found suitable to incorporate PV systems. The economics of the potential systems were analyzed using an electric rate of $0.159/kWh and incentives offered in the State of Massachusetts, most notably the solar renewable energy certificate (SREC) of $300–$550/MWh for 10 years. The 30% federal investment tax credit (ITC) could also potentially be captured. The calculations reflect the solar potential if the total area is utilized from Locations I, II, and III and the borrow pit. The results are summarized in Table 2 for a 30-degree fixed-tilt PV system with a conservative SREC market estimate of $300/MWh. Additional information is summarized in Table A-1.

Table 2. PV System Performance and Economics by Site[a]

	PV System Size (kW)	Installed Cost ($/W)	Annual Output (kWh/year)	Annual O&M ($/year)	System Cost ($)	Simple Payback Period (years)	Jobs[b] Created	Jobs[c] Sustained
I	3,633	$5.00	4,112,548	$30,880	$18,165,000	9.4	197	0.34
II	1,356	$5.00	1,535,060	$11,527	$6,780,000	9.4	74	0.13
III	1,888	$5.00	2,137,612	$16,051	$9,442,000	9.4	103	0.17
Pit	857	$5.00	970,492	$7,287	$4,287,000	9.4	47	0.08
Total	**7,735**	**$5.00**	**8,755,712**	**$65,745**	**$38,674,000**	**9.4**	**420**	**0.71**

[a] Data assume a usable area of 2,062,596 ft^2 and fixed tilt system at 30 degrees.
[b] Job-years created as a result of project capital investment including direct, indirect, and induced jobs.
[c] Jobs (direct, indirect, and induced) sustained as a result of O&M of the system.

4.2 Assumptions and Input Data for Analysis

SAM was used to estimate the levelized cost of energy (LCOE) for different systems with different financial assumptions. The state or the federal government could buy the system outright, foregoing many incentives available to tax-paying entities, such as depreciation and federal tax credit. SREC payments would still be available from the state. A more likely option is a power purchase agreement (PPA) where a third party (a tax-paying entity) owns the PV system on leased land with a guaranteed energy purchase agreement—usually the land owner. The PPA can include an option for the land owner to purchase the PV system at a fair market value at the end of the PPA or even at an intermediate time during the term of the PPA. The financial assumptions in Table 2 assume a PPA.

See Table 3 for a list of input data used in SAM. It is assumed that the installed cost of fixed-tilt ground-mounted systems will be $5/W. This price includes the PV array and the balance-of-system components for each system, including the inverter, electrical equipment, and installation. In July 2010, the average sales price for a PV module was $4,180/kW.[36] Typically, the PV modules are one-half to two-thirds of the total installed system price. Therefore, an installed price of $6/W is reasonable for small PV systems. Large PV systems usually have lower prices than small PV systems so a base installed cost of $5/W was used for fixed-tilt PV systems.

[36] Solarbuzz. "Solar Module Retail Price Environment." http://www.solarbuzz.com/Moduleprices.htm. Accessed August 2, 2010.

Slightly higher system costs of $5.50/W and $6.00/W were used for the single-axis and two-axis tracking systems. The actual installed price is dependent on many factors, such as installation difficulty, local labor prices, and equipment availability. The best price estimate is a response from a vendor to a request for a quote for a specific system.

Table 3. List of Parameters used in SAM for Financial Calculations

Parameter	Value(s). Values with a range were varied in the SAM statistical analysis
Energy price	$0.159/kWh
Size	1 MW
Cost	$5/W fixed, $5.5/W single-axis, $6/W two-axis (range $3.50–$7.00/W)
O&M costs	Fixed at $8.50/kW/year for all systems
Inverter replacement	$300,000 at year 12
PV system degradation	1%/year
Inflation rate	2% (range 1%–3%)
Debt fraction	50% (range 20%–60%)
Loan rate	8% (range 4%–12%)
Minimum required IRR	12% (range 9%–14%)
Real discount rate	12% (range 4%–12%)
DSCR	No minimum DSCR
PPA escalation rate	0.5%/year
Loan term	25 years
Analysis period	25 years
System lifetime	25 years
Financial incentives	Federal 30% ITC
State incentives	SREC, low case of $300/MWh/year and high case of $550/MWh for 10 years, taxable
Federal, state, property tax	35%/year, 8%/year, 2%/year
Depreciation	MACRS mid-quarter convention

The economics of grid-tied PV depend on incentives, financing, the cost of electricity, and the solar resource including panel tilt and orientation. For this analysis, it was assumed that the cost of electricity was $0.159/kWh. See Figure 11 for a statistical analysis of LCOE with varying PPA financial parameters of system cost, inflation rate, debt fraction, loan rate, minimum required internal rate of return (IRR), and real discount rate. The LCOE is strongly dependent on the system cost ($/W) and the debt fraction.[37] A linear regression line is shown. For a given system cost, there is a range of possible LCOE depending on the other financial assumptions. Depending on the present financial conditions, not all data points are necessarily possible but are instructive to show the importance of those parameters.

[37] See the SAM website for an explanation of the different financial terms. www.nrel.gov/analysis/sam.

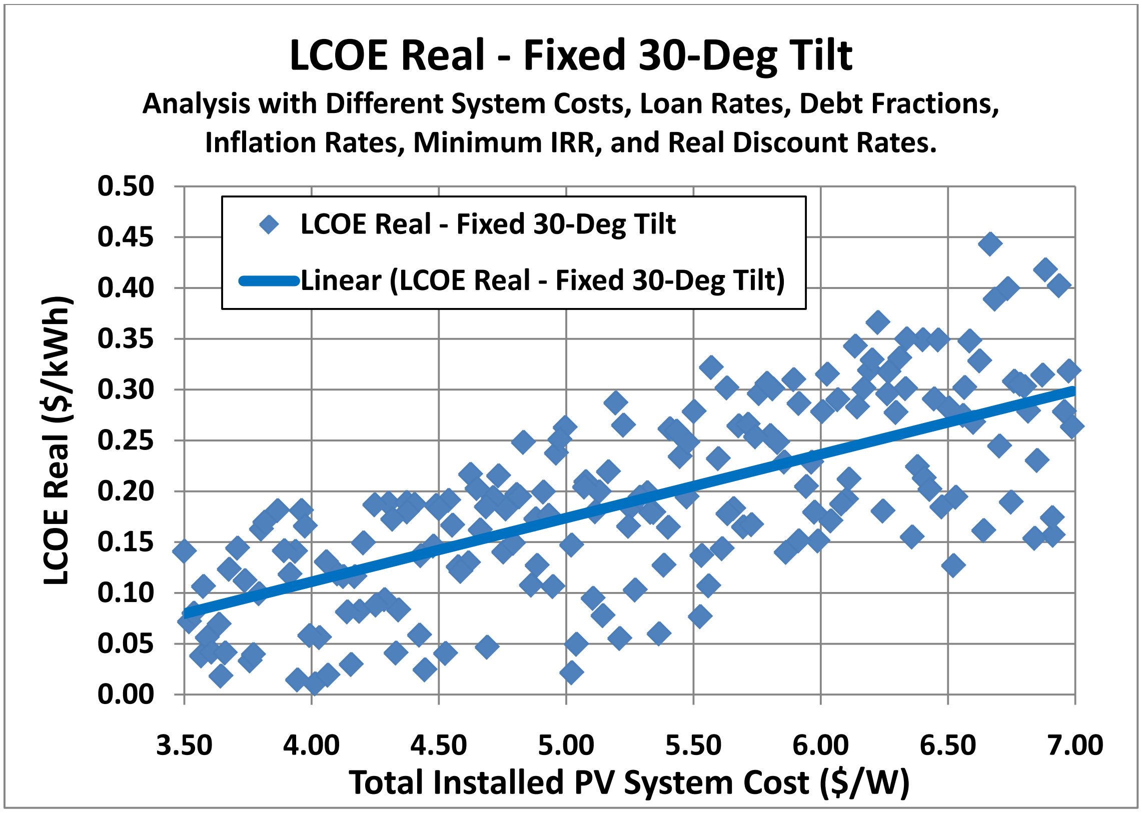

Figure 11. Statistical analysis of LCOE using ranges of values listed in Table 2

Similar analyses were made for 10-degree fixed-tilt, single-axis, and two-axis tracking systems. Another analysis was made for a 30-degree fixed-tilt PV system using a high estimate of $550/MWh for the SRECs. Figure 12 shows only the linear regression lines for all four PV system mounting types, plus a high estimate of $550/MWh for a fixed 30-degree tilt system.

Analysis of Figures 11 and 12 indicate that single-axis and two-axis tracking systems may be economically possible (based on assumptions in this analysis) if favorable system costs are available and if the systems can meet the point-loading and wind-loading requirements and weather conditions of the different MMR sites. Also, a 30-degree tilted system will be more economical than a 10-degree tilted system if both systems cost the same since there is more energy production with the higher tilt.

The value of the SREC clearly influences the LCOE as seen by the difference between the two curves for a fixed 30-degree tilt system with SRECs of $300/MWh (low case) and $550/MWh (high case). The SRECs favor energy production compared to other states' incentive programs based on the power rating of the system. Depending on the additional costs for tracking systems, which increase the energy production without increasing the system power rating, tracking systems could be economically more favorable in Massachusetts. However, the load-bearing pressure constraints of the landfill caps may preclude placing a tracking PV system on the landfill caps. A tracking PV system in the borrow pit is feasible.

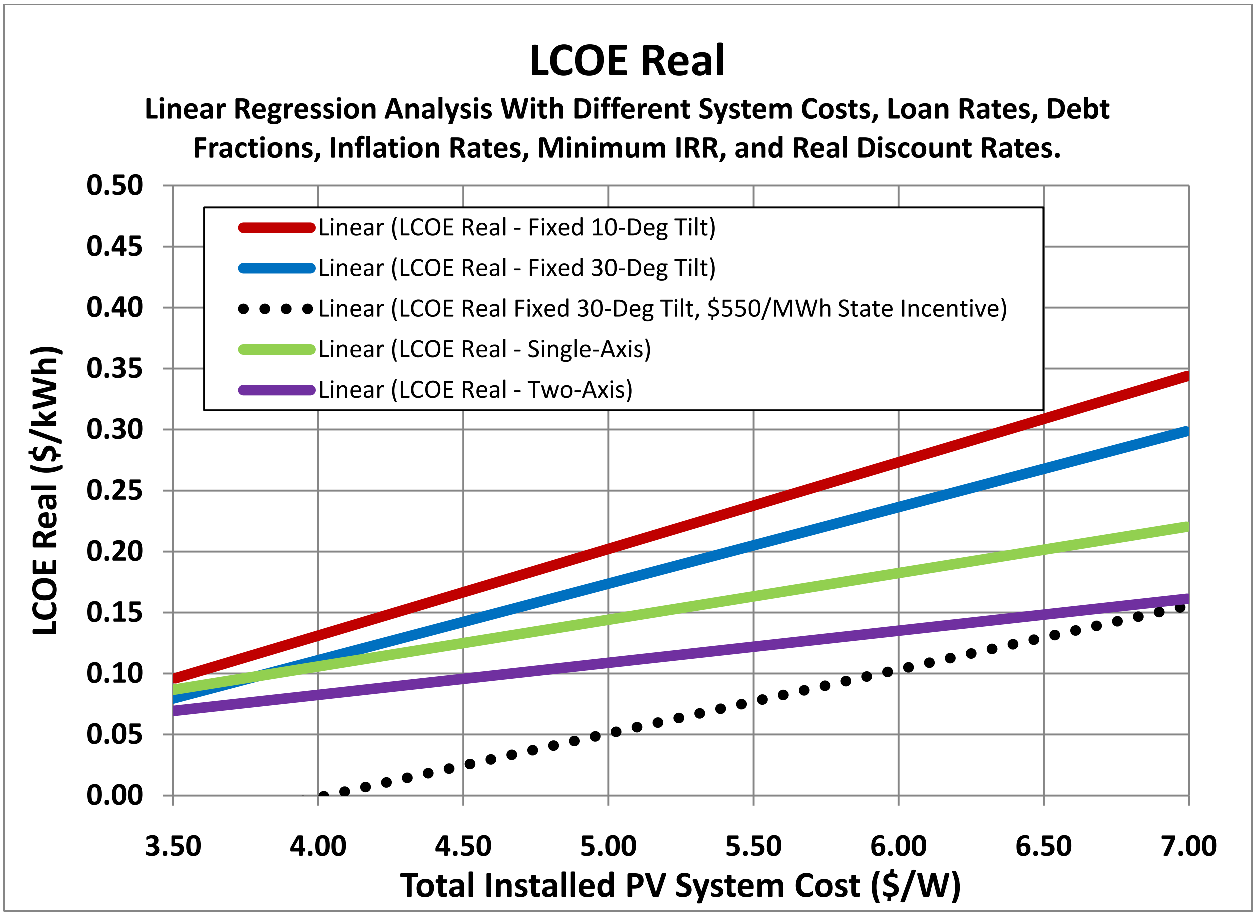

Figure 12. Linear regression analysis of statistical analysis of LCOE using ranges of values listed in Table 2 for four different types of PV mounting

Table 4 is a summary of the results for the four different 1 MW PV system mounting options, along with a high SREC case. See Table A-2 in the Appendix, which also includes the SREC income and the energy cost savings.

Table 4. Summary of Four Different PV Mounting Options

PV System Type (1 MW)	Annual Production (kWh/year)	Energy/ Power Ratio (kWh/W)	Capacity Factor (%)	Cost ($/W)	Total System Cost ($)	LCOE Real ($/kWh)	Simple Payback if Only SREC Income and Energy Cost Savings (years)
Fixed 10-deg tilt—low SREC $300/MWh	1,039,000	1.039	11.9	$5.00	$5,000,000	$0.202	10.7
Fixed 30-deg tilt—low SREC $300/MWh	1,132,000	1.132	12.9	$5.00	$5,000,000	$0.173	9.6
Single-axis tracking—low SREC $300/MWh	1,273,000	1.273	14.5	$5.50	$5,500,000	$0.163	9.4
Two-axis tracking—low SREC $300/MWh	1,484,000	1.484	16.9	$6.00	$6,000,000	$0.143	8.8
Fixed 30-deg tilt—high SREC $550/MWh	1,132,000	1.132	12.9	$5.00	$5,000,000	$0.050	6.2

Note: LCOE was determined from Figure 12 for the relevant system cost for each PV-mounting option.

A net system DC to AC conversion of 77% was assumed. This includes losses in inverter efficiency, wire losses, PV module losses, and losses due to temperature effects. A breakdown of the DC to AC conversion rate is available on the PVWATTS website.[38]

It is assumed for this analysis that federal incentives are received. It is important to find state incentives or grants to make PV cost effective. A private, tax-paying entity that owns PV systems can qualify for a 30% federal ITC and accelerated depreciation on the PV system. In lieu of the 30% ITC, companies can apply for a U.S. Treasury Department grant of 30% of the system cost under the 1603 program.[39] In addition, Massachusetts offers a SREC based on the energy produced. The price of the SREC is market-based and can vary from a floor price of $300/MWh to a ceiling of $600/MWh. The total potential tax benefits to the tax-paying entity are significant. A PPA with a third party could be an attractive contractual instrument for MMR to pursue. Given the changing credit markets and interest rates, a third-party financing estimate cannot be provided with any degree of certainty. A general recommendation is to issue a request for interest, qualifications, or quote to determine potential companies.

4.3 Incentives and Financing Opportunities

The Database for State Incentives for Renewable Energy (DSIRE) provides a summary of incentives and programs within Massachusetts and the federal government.[40] DSIRE provides a

[38] National Renewable Energy Laboratory. "PVWATTS™ Version 1 Calculator." http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/derate.cgi. Accessed February 2011.
[39] U.S. Treasury Department, Program 1603, Payments for Specified Energy Property in Lieu of Tax Credits, http://www.treasury.gov/initiatives/recovery/Pages/1603.aspx. Accessed April 6, 2011.
[40] Database for State Incentives for Renewable Energy (DSIRE). www.dsireusa.org. Accessed September 2010.

summary of net metering, interconnection rules, and incentives available to Massachusetts utility customers.[41] The power from the MMR system can be used directly at MMR.

Renewable energy systems, including commercial solar PV, are subject to interconnection rules promulgated at the state level. In Massachusetts, there is no set limit for the amount of PV power that can be interconnected. However, the 6 MW limit on the Massachusetts SREC program may effectively limit the PV system based on financial considerations.

4.4 Job Creation

The implementation of this project would represent a large amount of money entering the clean energy industry of the United States. The Council of Economic Advisors (CEA) calculated the number of jobs created due to federal spending using economic models developed with real-world data. CEA found that $92,000 in federal spending is equivalent to one job-year.[42] This means that for every $92,000 of federal money that is spent, there is a job created that can be sustained for 1 year. See Table 2 for an estimate of job creation if MMR installs solar PV. The jobs created column refers to the number of job-years that would be created as a result of the one-time project capital investment. This means that the jobs will be created and sustained for 1 year. The jobs sustained column refers to the number of jobs that would be sustained as a result of the O&M of the system. These jobs will be sustained for the life of the system, due to the annual costs to keep the system operating.

[41] DSIRE. http://www.dsireusa.org/incentives/index.cfm?re=1&ee=1&spv=0&st=0&srp=1&state=MA. Accessed September 2010.

[42] Council of Economic Advisors, Executive Office of the President. “Estimates of Job Creation from the American Recovery and Reinvestment Act of 2009.” May 2009, http://www.whitehouse.gov/sites/default/files/microsites/Estimate-of-Job-Creation.pdf. Accessed September 2010.

5 Conclusions and Recommendations

MMR is a promising area in which to implement a PV system. MMR can easily place 8 MW of ground-mounted PV systems on the crowns of the three landfill caps and the borrow pit with fixed PV modules tilted at 30 degrees. A fixed-tilt PV system is the more likely outcome, but proposals with single-axis and two-axis should be considered if all of the MMR requirements are met and the overall project costs are reasonable.

While the Massachusetts SREC program has a cap of 6 MW per system, MMR may be able to have multiple systems with different owners. Potential negative consequences such as settlement on the landfill caps will need to be addressed in the design of the PV system.

MMR should issue a request for proposal or qualifications for the purchase of PV systems and for third-party PPAs. While estimates of PV system size and price were made in this analysis, a vendor's proposal will be more accurate.

This site has existing transmission lines and road access in place for this renewable energy project. This site is an ideal candidate for a PV system and an ideal candidate to help the United States further its goal of increasing clean energy use and reducing environmental impact.

Appendix

Table A-1. Summary of PV System Calculations for a 30-Degree Fixed-Tilt PV System for All Four MMR Sites Using a Low SREC Estimate of $300/MWh

Location	Usable Area (ft^2)	PV System Size (kW)	Annual Production (kWh/year)	Total Installed Price ($1,000)	Annual Cost Savings ($/year)	SREC Credits ($/year)	Annual O&M ($/year)	Real LCOE ($/kWh)
I	968,798	3,633	4,112,548	$18,165	$699,133	$1,233,764	$30,880	$0.173
II	361,616	1,356	1,535,060	$6,780	$260,960	$460,518	$11,527	$0.173
III	503,560	1,888	2,137,612	$9,442	$363,394	$641,284	$16,051	$0.173
Pit	228,620	857	970,492	$4,287	$164,984	$291,148	$7,287	$0.173
Total	**2,062,594**	**7,735**	**8,755,712**	**$38,674**	**$1,488,471**	**$2,626,713**	**$65,745**	**$0.173**

Note: The usable area of 2,062,594 ft^2 is about 47.4 acres, resulting in 6 acres/MW of installed PV. This is consistent with other large-scale PV systems that range from 5–10 acres/MW of installed PV.

Table A-2. Summary of Financial Calculations for Four Different 1 MW PV Mounting Options

PV System Type (1 MW)	Annual Production (kWh/year)	Energy/ Power Ratio (kWh/W)	Capacity Factor (%)	Cost ($/W)	Total System Cost ($)	LCOE Real ($/kWh)	Annual SREC Income ($)	Annual Energy Cost Savings ($)	Simple Payback if Only SREC Income and Energy Cost Savings (years)
Fixed 10-deg tilt—low SREC $300/MWh	1,039,000	1.039	11.9	$5.00	$5,000,000	$0.202	$311,700	$165,201	10.7
Fixed 30-deg tilt—low SREC $300/MWh	1,132,000	1.132	12.9	$5.00	$5,000,000	$0.173	$339,600	$179,988	9.6
Single-axis tracking—low SREC $300/MWh	1,273,000	1.273	14.5	$5.50	$5,500,000	$0.163	$381,900	$202,407	9.4
Two-axis tracking—low SREC $300/MWh	1,484,000	1.484	16.9	$6.00	$6,000,000	$0.143	$445,200	$235,956	8.8
Fixed 30-deg tilt—high SREC $550/MWh	1,132,000	1.132	12.9	$5.00	$5,000,000	$0.050	$622,600	$179,988	6.2

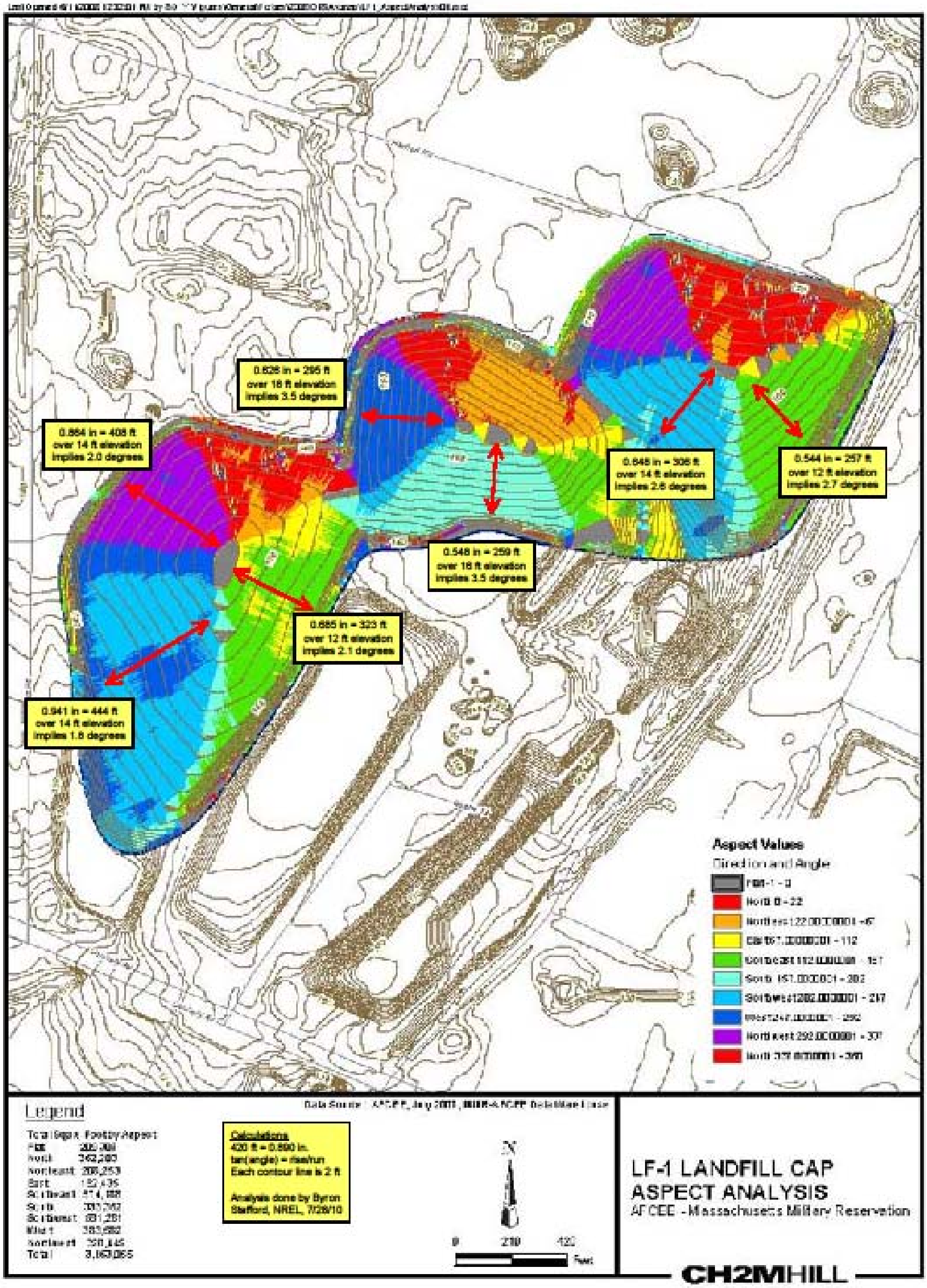

Figure A-1. Landfill cap aspect analysis

Note: The slopes of the landfill caps vary from 2.0–3.5 degrees.
Credit: Aspect analysis was performed by CH2M Hill and slope analysis was performed by NREL