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Equivalent Breakeven Installed Cost

A Tradeoff-Informed Measure for Technoeconomic Analysis of Candidate Heliostat Improvements

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Abstract. Technoeconomic analysis (TEA) is commonly used to determine economic viability of power-generating technologies, including concentrating solar power (CSP) and thermal (CST) production plants. Levelized cost of electricity (LCOE) and analogous measures provide an estimate of long-term costs for operating power plants over their designed lifetimes by accounting for revenues and costs in a time-discounted manner. While these measures are effective when assessing a technology's total lifecycle costs and productivity under various designs, TEA of candidate incremental technology improvements from the lens of LCOE can be limited when required investment and LCOE impacts are small. In this work, we propose a novel metric for TEA of a plant component technology that recasts relative changes in levelized system costs into component-specific capital cost budgets. This measure, which we refer to as the equivalent breakeven installed cost, is the maximum budget for the technology component that leads to improved levelized costs. We illustrate the usefulness of this metric using the example of candidate heliostat improvements for a CSP tower plant. Here, the results suggest that a reduction in mirror washing costs yield a total plant O&M cost of $37/kWe-yr, which is a breakeven proposition if the average reflectance is reduced from 0.90 to 0.85 as a result of the cost savings.

Keywords: Technoeconomic Analysis, Concentrating Solar Power, Heliostat Design

1. Introduction

TEA is commonly used to determine the economic viability of power-generating technologies from pilot to industrial scales [1], including that of CSP plants. A common metric used to compare the benefits of different candidate technologies and/or locations for a CSP plant is the LCOE, which accounts for time-weighted revenues and costs according to parameter-specific discount rates [2]. Plants designed to produce industrial process heat or fuels use analogous measures of levelized cost of heat (LCOH) [3] or levelized cost of fuel [4], respectively. These measures are effective when assessing a technology's total lifecycle costs and productivity under various design or process options and conditions for the total system; however, they assume certainty in both costs and production.

Parametric analysis that varies one or more inputs along a user-specified range, such as that available in TEA tools like System Advisor Model (SAM) [5], can provide perspective on the impact of changes in costs or production as compared to a baseline case. However, the use of LCOE or net present value of a plant does not fully capture the projected return on investment for a candidate technology for which the costs and/or production impacts are either not fully known or specific to a subsystem rather than the entire plant.

In this work, we propose a novel metric for technoeconomic analysis of a plant component technology that recasts relative changes in levelized systemwide costs into a relative change in the capital cost of a component, which we refer to as the equivalent breakeven installed cost. While we use the case study of a collection of candidate heliostat technology improvements to illustrate the use of this metric, the method is general enough to use when comparing candidate improvements of components within a CSP system.

2. Methodology

This section summarizes the methodology we use to obtain the equivalent breakeven installed cost metric. Specifically, we present the calculation of our chosen levelized cost metric, LCOH, using thermal energy delivered to the receiver as our chosen heat measure. Then, we present the method we use to obtain equivalent breakeven installed cost, when comparing performance to a baseline case.

2.1. Cost Metric: Levelized Cost of Heat

To recast a technology improvement as a change in installation costs, we begin by determining the relationship between capital cost and the new levelized cost metric for this case study's baseline inputs. For the results that follow, we use LCOH as heliostat improvements may have an impact on receiver and tower characteristics (e.g., fewer, better heliostats may yield a smaller tower and receiver surface) but are unlikely to influence the size of the power cycle for an electricity-generating plant. In this case study, we define heat production as the thermal energy delivered to the receiver from the solar field, which accounts for optical losses (e.g., image intercept, attenuation, cosine) but not reflection and reradiation at the receiver. We adopt this measure in our calculation of LCOH to focus on (a) the heliostat field, which is the focus of potential technology changes in our application, and (b) interactions between heliostats and the tower and receiver, which impacts the heat entering the collection system. We calculate LCOH by starting with the LCOE estimate produced in SAM and performing the following adjustment in equation (1):

$$LCOH = LCOE * (P_E / P_R) * (C_{RS} / C_P), \tag{1}$$

in which P_E and P_R denote the electrical energy produced and the thermal energy delivered to the receiver, respectively, while C_{RS} and C_P denote the capital cost of the receiver and solar field and the capital cost of the entire plant, respectively. The electrical and thermal energy estimates come from SAM's Year 1 estimate for a given system design. This estimate of LCOH removes the costs of the power cycle and thermal energy storage and assumes that operating expenses are proportional to the capital costs of each subsystem in the plant.

2.2. TEA Metric: Equivalent Breakeven Installed Cost

By running a parametric analysis in SAM, in which heliostat installation costs change, we can use the resulting installation cost inputs and LCOH outputs to derive the affine relationship in equation (2):

$$L = a \cdot C + b, \tag{2}$$

in which L is the LCOH associated with the baseline plant design, C is the per-square-meter installation cost of the heliostat, and a and b are constants derived via linear regression. We assume that (a) the fixed design's heat production does not change, and (b) the variable (i.e., operations and maintenance [O&M]) costs for the heliostats do not change in this analysis. If a new case is created in which another parameter besides heliostat installed cost is varied, we can determine the heliostat installation capital cost, C', that would give an equivalent LCOH via equation (3):

$$C' = (L' - L) / a + C, \tag{3}$$

in which C and L are the baseline installation cost and LCOH, and C' and L' are analogous measures for the new case, i.e., C is the capital cost that achieves the same LCOH as the new case if the only measure to change is installation cost. Finally, to determine the equivalent breakeven installed cost, C^*, that would offset the change in LCOH from the parameter varied in the new case to match the baseline value of L, we invert the change between C' and C as shown in equation (4):

$$C^* = 2 \cdot C - C'. \tag{4}$$

Another way to think of the equivalent breakeven heliostat installed cost is as a budget for implementing a change in the cost or performance of a system component without changing the overall cost of energy (i.e., LCOH) for the system. For example, assume a proposed increase in mirror reflectance results in an equivalent breakeven heliostat installed cost \$5/m^2 above the baseline case. This means that if the actual cost to increase the mirror reflectance, for example by paying for a higher quality mirror, is less than \$5/m^2 then the LCOH would be lower and that investment is worthwhile. In contrast to a detailed cost analysis similar to the work by von Reeken et al. [6] that directly recalculates LCOE after incorporating the cost of the technology upgrade, the equivalent breakeven installed cost allows the user to consider the expected benefits from a change in heliostat design or maintenance relative to the cost of implementing that change in a heliostat. We propose this new measure in Equation (4) due to its flexibility in assessing either positive or negative changes to the heliostat's performance, as the measure can also be used directly to assess cost improvements that reduce performance. In either case, the measure consistently produces a budget for any contrived heliostat design with the performance and plant information is known.

3. Results

This section presents a description and results of our case study of a CSP tower plant that we generate in SAM. We consider changes to (a) optical error, (b) installation cost, (c) heliostat reflectance, and (d) O&M costs in our study. We present a parametric analysis in which we vary one or more of these to assess the impact of each measure on the LCOH measure in equation (1), and then recast the results under the equivalent breakeven installed cost metric via equations (2)–(4).

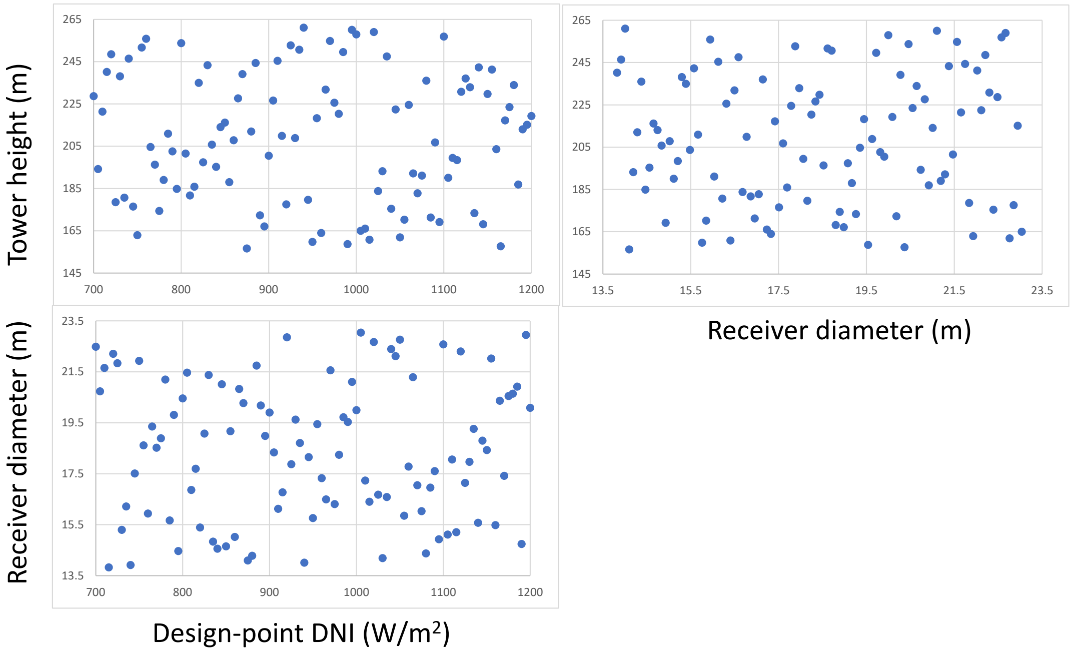

Figure 1. Summary of design parameters generated via Latin hypercube (n=101), subdivided into three plots that show pairs of parameter values.

3.1. Case Descriptions

The baseline case study we adopt is adapted from the large electric plant baseline in the U.S. Department of Energy's Heliostat Consortium (HelioCon) roadmap report, the details of which are discussed in [7]. However, in a second scenario, we assume that the heliostat's installation cost is reduced from \$140/m^2 to \$50/m^2 to mirror the cost target of the 2030 SunShot study [8]. The parameters we vary are consistent with those of the HelioCon roadmap report [7], but unlike the predecessor paper, which uses the native optimization method in SAM to obtain designs, our approach generates a Latin hypercube of potential designs, in which we vary (a) the tower height, (b) the receiver dimensions, and (c) the direct normal irradiance (DNI) assumed to size the field to deliver the designed thermal power incident to the receiver surface. Parameters (a) and (b) are consistent with the optimization variables in SAM's graphical user interface, while (c) is included to assess the impact of adding or subtracting heliostats relative to a baseline design layout. This is equivalent to simulating an oversized or undersized solar field relative to the thermal power rating of the receiver. We generate a Latin hypercube [9] of 101 candidate designs to ensure adequate coverage of the possible design space and choose the design that yields the lowest LCOH in each case. Figure 1 plots the candidate designs that we assess for each pair of parameters. For each candidate solution, SolarPILOT [10] is used to obtain the solar field design, using a solar angle of the summer solstice, which is consistent with the default in SAM.

3.2. Parametric Study

Our parametric study adopts similar metrics and ranges to those in a recent heliostat technology roadmap study [7] and evaluates the impact of changes to (a) optical error, (b) installation cost, (c) field reflectance, and (d) O&M costs on LCOH. Figure 2 displays the LCOH estimates as each of these parameters vary for the two case studies we adopt. In each case, the baseline assumption is at the centerline of the horizontal axis. Parameter sensitivity is assessed from 50% lower than the baseline, to 50% higher than the baseline, using reflectance losses from an ideal image as a proxy for field reflectance when determining the range for that parameter. While this is consistent with the relative ranges in [7], reasonable ranges for each parameter are likely to vary by project and location. The results in Figure 2 show that for the range of values assessed, LCOH tends to be more sensitive to increases in optical error than decreases; unlike the finding in the HelioCon roadmap report [7], LCOH is more sensitive to installation costs as compared to optical error. This is likely due to the ability to add more heliostats in response to increased optical error, reducing the overall impact to LCOH.

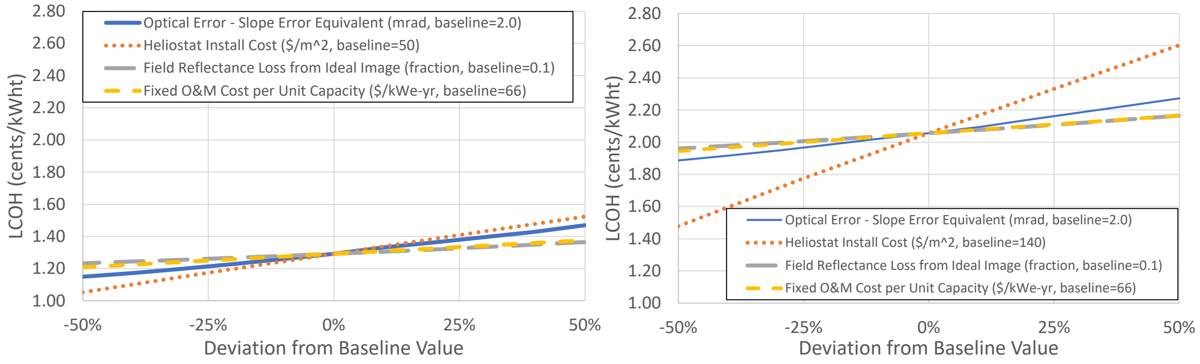

Figure 2. Parametric analysis on impact to LCOH for a large-scale electric plant case study, using baseline installed capital costs of \$50/m^2 and \$140/m^2 on the left and right plots, respectively. Baseline values of 1.29 and 2.05 cents/kWht are located on the centerline of the horizontal axis for each case.

3.3. Equivalent Breakeven Installed Cost

Figure 3 displays the equivalent breakeven installed cost for the same collection of model instances used for the parametric analysis that is summarized in Figure 2. The results recast changes in LCOH to a budget-friendly format when selecting candidate improvements. For example, in the $140/m^2 case, a heliostat with a 25% reduction (improvement) in optical error can sustain the same LCOH if the change only increases installed heliostat costs by $10/m^2. If it costs more than $10/m^2 to improve heliostat optics, the benefits are outweighed by the heliostat installed cost increase and the investment is not worthwhile for this project.

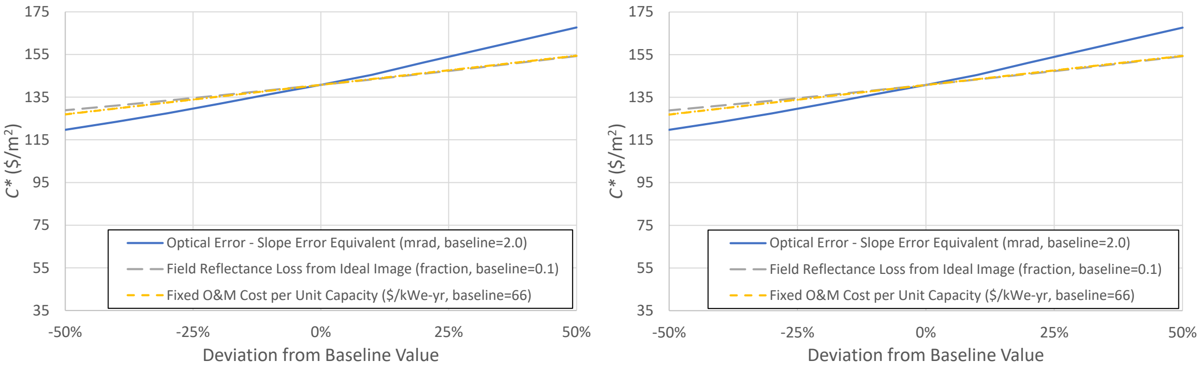

Figure 3. LCOH parametric analysis on impact to equivalent breakeven installed heliostat cost, *C**, for a large-scale electric plant case study, using baseline installed capital costs of $50/m^2 and $140/m^2 on the left and right plots, respectively. Baseline values of 1.29 and 2.05 cents/kWht are located on the centerline of the horizontal axis for each case.

Figure 4 extends the parametric LCOH analysis of the $50/m^2 case to include changes to both reflectance losses and O&M costs, then recasts the analysis using the equivalent breakeven capital cost metric. This then determines the installation cost required to obtain the same LCOH as the baseline case under the new performance and cost values. For example, to obtain a reduction in O&M cost to $45/kWe-year and an improvement in field reflectance from 0.90 to 0.95, an increase in installation cost from $50/m^2 to approximately $60/m^2 yields the same LCOH as a plant with the baseline cost, reflectance, and O&M cost, whereas a 50% increase in reflectance losses and O&M costs cannot achieve the same LCOH, unless the heliostat installed cost was reduced to $30/m^2. The vertical jumps in some of the iso-lines is likely to due to the resolultion of the runs performed in the sensitivity analysis. This graph can inform O&M policies, as well; for example, a reduction in mirror washing costs to yield a total plant O&M cost of $37/kWe-yr is a breakeven proposition if the average reflectance is reduced to 0.85 as a result of the cost savings.

4. Conclusions

We present a novel CSP heliostat TEA metric to compare the benefits of a new component technology by recasting relative benefits into an equivalent installed capital cost required to obtain the same plant-wide levelized cost. We illustrate the usefulness of the metric using an example case study of a large-scale CSP tower plant, focusing on changes to heliostat technology and performance.

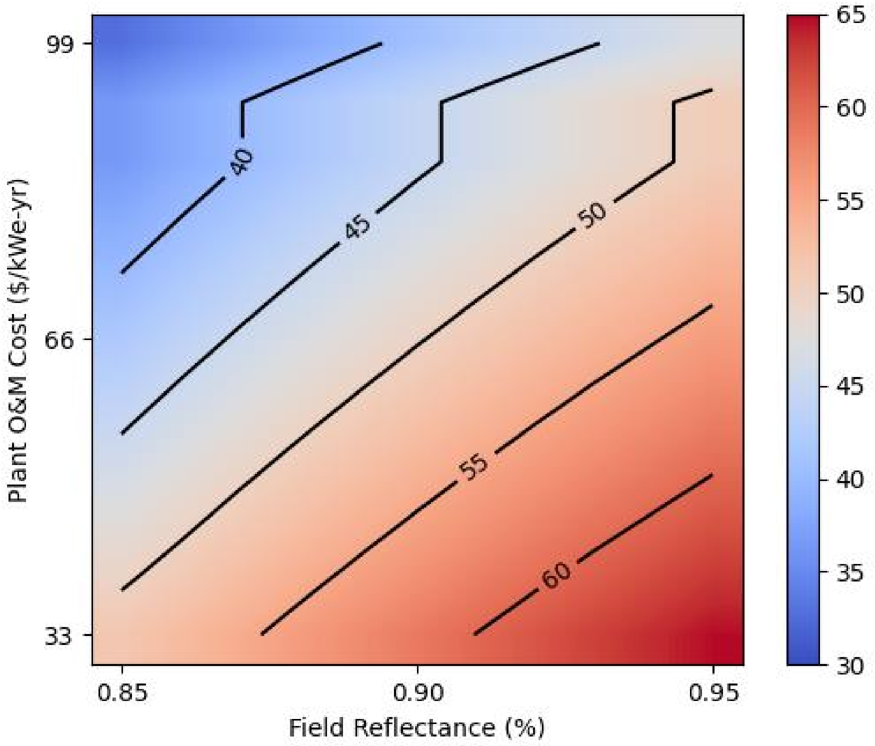

Figure 4. Heat map depicting equivalent breakeven installed cost as reflectance and O&M costs vary. Contour lines indicate capital cost levels. Baseline cost of $50/m2 is located at the center of the graph.

The equivalent breakeven installed cost can be paired with other levelized costs or net-present-value metrics, and it can be expanded to other components or technologies supporting large-scale production plant projects in or out of the energy sector. Future work by this group will develop O&M models of higher fidelity to allow for analyses like these to have more specificity, such as comparisons of pairing different mirror-washing technologies with the solar field. Finally, the Latin hypercube method may be adapted to perform random sampling [11] to incorporate uncertainty in cost and performance parameters and obtain confidence intervals on LCOH or performance metrics [12], which the authors will investigate in future work.

Data availability statement

The assumptions for the SAM models we develop for this case study, with the exceptions listed above in the Results section, are detailed in [7]. The SAM models and scripts are currently housed in a private repository with plans to be published in a larger database at a future date.

Underlying and related material

The case that we adopt is adapted from the baseline large electric plant instance from the HelioCon roadmap [7], which contains a similar parametric analysis. Our extensions include an in-depth explanation of our methodology, a new case study, and the two-dimensional parametric analysis shown in the results.

Author contributions

Alexander Zolan: Writing – Original Draft; Writing – Review and Editing; Methodology; Visualization; Formal Analysis; Software. **Chad Augustine:** Supervision; Writing – Review and

Editing; Methodology; Project Administration; Conceptualization. **Kenneth Armijo:** Supervision; Writing – Review and Editing; Methodology.

Competing interests

The authors declare no competing interests.

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