ENVIRONMENTAL METRICS FOR SOLAR ENERGY

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ABSTRACT: Two metrics are discussed that exploit the greenhouse gas emission and water use advantages of solar energy technology. Furthermore, these metrics are generalized to be used for any environmental, cost or renewable resource consumption decision making. Future work is required on appropriate metrics for non-renewable resources.
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1 INTRODUCTION

Solar energy technologies are developed for their potential advantages over traditional fossil fuel energy generation. These advantages, however, are specifically seen during the use phase where the fuel is free, no onsite emissions are released, and water consumption is low.

While these advantages to solar are real, they must be balanced against the potential emissions and environmental impacts of mining, processing, manufacturing, transportation, installation, maintenance, and end of life. To address this, previous researchers have studied the life-cycle (LC) impacts of solar and found them to generally be an improvement upon fossil fuel technologies [1] [2] [3]. However, the metrics used for these assessments have not fully reflected the advantages of installing solar energy to a specific site. In this paper two metrics are discussed that exploit the greenhouse gas emission and water use advantages of solar, and the potential generalization of these two metrics to other areas are outlined for decision making.

2 ENERGY

Energy usage over a solar technologies lifetime has been traditionally expressed in terms of Energy Payback Time (EPT). This indicator of the years it takes a solar technology to output the equivalent energy required over its life-cycle is a useful metric of a technologies' efficiency and has been previously discussed in detail by Reich-Weiser et al. [3], Alsema et al. [2], and Fthenakis et al. [1].

3 GREENHOUSE GASES (GHG)

Although, the EPT is a useful metric of a technologies' efficiency, energy metrics fail to acknowledge the importance of mitigating climate change, a primary goal of solar technology. Because of this, previous researchers have used a GHG intensity metric, GHG/kWh, which is calculated as the life-cycle measured GHG emissions divided by the lifetime electricity production.

All metrics have their place, and the GHG intensity metric is useful for comparing technologies, assuming common assumptions about insolation and transit are used; however this metric is not particularly useful for decision making about how to most effectively mitigate climate change through the installation of solar energy technology. Towards this goal, the greenhouse gas return on investment (*GROI*) metric is suggested [4, 5], which indicates greenhouse gas savings due to solar energy replacing business as usual (BAU) relative to the life-cycle determined greenhouse gas emissions of the solar technology (Investment). This calculation is shown in equation 1. A positive *GROI* indicates that the technology and the specific installation scenario are a net greenhouse gas saver.

$$GROI = \frac{GHG_{BAU} - GHG_{Investment}}{GHG_{Investment}} \qquad (1)$$

4 WATER

Energy use and greenhouse gas emission related metrics are of particular relevance to societies' current energy and climate change concerns [9]; however an additional key concern of climate change is water scarcity (Fig. 1). In the United States, 48% of water withdrawals are by the electricity industry [6] primarily for cooling nuclear and fossil fuel power plants. Solar has the distinct advantage of low water consumption during its use-phase [7], making it ideal for installation in locations that have a highly variable or scarce fresh-water supply.

While a return on investment metric like that seen for greenhouse gases could be used for water, it can be argued that the LC determined water use of the system is not as important as regional water use relative to the available water in the region. To address this, the water consumption factor (*WCF*) metric is suggested [5] (equation 2), where water use is compared to the water available in the region. The "renewable supply" is the amount of water that is predicted to flow through the region annually; this does not include static stocks of water that can only be used once. A WCF that is greater than 1 indicates that the behavior is unsustainable.

$$WCF = \frac{WaterUse_{LocalInvestment}}{RenewableSupply_{Local} - WaterUse_{Local}} \qquad (2)$$

In equation 3, the water consumption factor is used to reflect water savings from a solar installation replacing an alternative energy technology. Water savings are calculated as the electricity produced by the new technology multiplied by the water usage per kWh of the replaced technology (C_{Water}). The offset factor, C_{Water}, can be determined from previous studies of water usage, such as that done by Hill et al. [7].

$$WCF = \frac{-Lifetime * Elec_{AnnualUseful} * C_{Water}}{RenewableSupply_{Local} - WaterUse_{Local}} \quad (3)$$

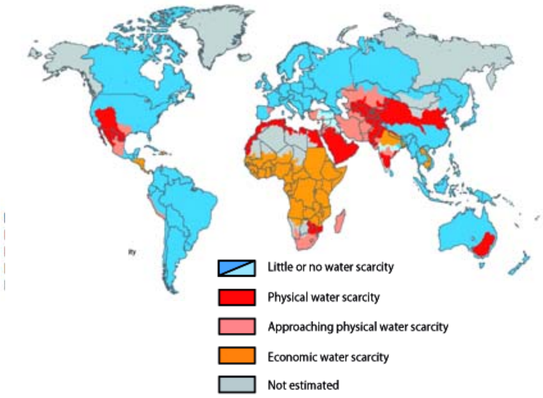

Figure 1: Area of Physical and Economic Water Scarcity [8].

5 GENERALIZED METRICS AND APPLICATION

The logic behind the development of GROI and WCF can be extended to any environmental or financial concern being addressed – the choice of metric is up to the user depending on the goal of the assessment. Table 1 summarizes these metrics in a generalized form. Note that the Intensity and ROI metrics are equivalent to financial cost metrics, whereas the Consumption factor is really an indicator of the inherent sustainability of a particular behavior (use relative to available). The missing piece of these metrics is how to account for the use of non-renewable resources. In general we can understand global use relative to global consumption as the number of years remaining before the resource is completely gone. However, extending this to a meaningful metric that can be used for decision making at a granular level requires future work.

When using these metrics for decision making, it is important to understand that not only are there the multiple metric types discussed, but there are different ways to apply the metrics. For a fundamental technological comparison of solar technology, it is appropriate to assume that all parts of the final good are manufactured and installed in a consistent location. Current studies of solar technologies use databases from differing locations and assume differing installations, making the results uncomparable. A standardized method is needed for studies that will be used to make general comparisons between technological capabilities. However, for engineering decisions within the company, specifics of electricity mix variations by location, transportation requirements, insolation available in the specific site considered, and offset electricity mix may be critical to meeting company goals [3]. It is up to the user of these metrics to make appropriate decisions about how to use and implement them.

Table 1: Metric Types [5]

Name	Formulation	Examples	Desire
Intensity	$\frac{\text{Indicator}}{\text{Functional Unit}}$	$/Watt	Minimum
Return on Investment	$\frac{\text{Savings}}{\text{Investment}}$	GROI	Maximum
Consumption	$\frac{\text{Use}}{\text{Available}}$	WCF	Minimum

6 CONCLUSIONS

- Choice of Metric is important for appropriate decision making depending on the goal of the assessment.
- Only a metric that accounts for the availability of a resource actually indicates sustainability.
- There is a difference between using a metric for a fundamental technological comparison and for decision making within a company

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