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Greenhouse Gas Return on Investment: A New Metric for Energy Technology

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Abstract

The greenhouse gas return on investment (GROI) metric is introduced as a compliment to the energy return on investment (EROI). Unlike EROI, GROI accounts for the life cycle energy mix, the efficiency, circularity, and supply chain of energy distribution, and the energy offset by a new energy installation. The average greenhouse gas emissions of labor and electricity are calculated for multiple countries to be used in GROI calculations. GROI is applied to a case study of SolFocus Inc. solar panels, and the potential extension of GROI methodology to a modified EROI and to decision making beyond energy is discussed.

Keywords:
Energy; Return on Investment; Greenhouse Gas

1 INTRODUCTION

Alternative energy technologies such as solar, solar-thermal, hydro, and wind, are developed for their potential to replace traditional fossil fuel based energy sources. The main goal, currently, is the mitigation of climate change due to concerns over increasing levels of greenhouse gases in the atmosphere. For the development of these new technologies to be worthwhile, their net life cycle greenhouse gases (GHG) per kWh of electricity produced must be less than that of traditional fossil fuel generation, and they must produce more energy over their lifetime than is required for their entire life cycle from cradle to grave. Additionally, to most rapidly reduce global GHG emissions, new technology installations should preferentially replace the worst GHG emitting energy technologies.

Previous researchers have calculated the life cycle GHG/kWh and the energy payback time (EPBT) of energy technologies for comparison and to establish practicability [1] [2] [3]. Life cycle assessments (LCA) typically include an analysis of materials extraction, manufacturing, transportation, installation, maintenance, and end of life. EPBT is a metric of efficiency stating the number of operating years required to output the LCA determined energy demand of a technology.

Because an EPBT that is greater than the product lifetime is not worth pursuing, the Energy Return on Investment (EROI) metric is an important extension of EPBT (this has also been called the Energy Return Factor). EROI is calculated as the product lifetime divided by EPBT, and it indicates the amount of energy produced per unit of energy demanded by the technology. An EROI of less than 1 indicates that a technology is a net energy sink, and not worth pursuing without innovation.

EROI and GHG/kWh are both useful comparative metrics to establish feasibility, however each lack important components of a comprehensive metric. EROI fails to address one of the main motivations of alternative energy technologies: mitigating climate change. For example, EROI does not distinguish between a component manufactured using solar energy or one manufactured using fossil fuel energy. Additionally, GHG/kWh only acknowledges insolation installation differences; for example, GHG/kWh does not distinguish between a solar technology installed to replace a coal-fired power plant or a hydro-power facility. Unlike EROI and GHG/kWh, a return on investment metric based on greenhouse gases can account for the types of energy used during the technologies' lifetime, the efficiency of energy distribution, and the energy being offset at the point of use.

The greenhouse gas return on investment metric (GROI) metric is introduced in this paper as a compliment to EROI. GROI specifically addresses the goal of alternative energy technology – climate change mitigation – while enabling the quickest pathway to a reduction of greenhouse gas emissions globally by rewarding the replacement of high GHG/kWh technologies. As is appropriate for a comprehensive metric, GROI is most favourable when a technology is produced using low GHG/kWh electricity and installed to offset high GHG/kWh electricity.

In this paper the concept of GROI is presented. An explanation of how to calculate GROI is followed by a discussion of GROI sensitivity to supply chain and installation decisions; and GROI is applied to a case study of SolFocus Inc. concentrator photovoltaic systems. Finally, the extension of the GROI methodology to a modified EROI, climate change focused decision making, and public policy is addressed. Where GHG values are mentioned, they are given in terms of global warming potential in CO2 equivalents.

2 GHG RETURN ON INVESTMENT (GROI)

GROI is an indicator of the GHG emissions prevented for every GHG emitted by a technology. It is calculated as the technology lifetime (standard is 20 to 30 years for solar energy) divided by the GHG payback time (GPBT), where

$$GPBT[years] = \frac{GHG_{Emissions}}{GHG_{SavedPerYear}} \qquad (1)$$

$GHG_{Emissions}$ are the emissions of the technology determined through LCA. GHG_{Saved} are the emissions prevented by installing new electricity capacity, whether it is the marginal emissions from a power plant, or the life-cycle emissions of an alternative installation. GHG_{saved} accounts for installation location differences such as circularity, the electricity supply chain, distribution losses, consumer needs, and regional electricity capacity. The nuances of GHG_{saved} will be discussed in the next section.

3 INPUT VALUES TO THE GROI METRIC

3.1 Prevented GHG Emissions

Determining GHG_{Saved} requires an understanding of the consumer, the current electricity supply, and alternative new installations. There is a difference between a technology installed directly at the point of use and one installed to the grid; solar technology installed at the point of use offsets both the production and distribution losses, while a grid-tied option only offsets production. Additionally, there is a difference between providing electricity to new customers, who would require additional capacity in the grid regardless of technology, and providing electricity to customers who already have full access to the current electricity grid.

Each potential offset scenario will involve offsetting a subset of the following:

1. Electricity Production: The direct GHG emissions associated with the production of electricity. This depends on the specific electricity mix of a location.
2. Distribution Losses: Losses of electricity from production to consumption. This depends on the distribution efficiency and distances.
3. Circularity: An economic concept based on the amount of additional electricity consumed internally by the electricity sector when a kWh of electricity is produced. For example, production of a kWh of electricity requires additional electricity for lighting, pumping, and powering peripherals at the power plant.
4. Production Supply Chain: The GHG emissions associated with the mining, materials, transportation, and all other goods and services consumed directly or indirectly by the electricity industry to produce a kWh.
5. Technology Life cycle: The GHG emissions of materials extraction, transportation, manufacturing, installation, maintenance, and end of life for the entire power plant. The technology life cycle includes and goes beyond the GHG of electricity production, the supply chain, circularity, and distribution; and is only offset in a situation where a new energy technology is being installed in place of the complete installation of a different technology.

The relationship between production, distribution, circularity, and the supply chain is illustrated in Figure 1 with the US as an example. Every kWh of electricity demanded in the US requires the net production of 1.29 kWh, when losses and circularity are accounted for [6] [8]. Additionally, there are CO2 emissions associated with the supply chain necessary to support each kWh produced by the electricity industry. The three largest contributors to GHG/kWh of the USA electricity supply chain are coal mining, pipeline transportation, and oil and gas extraction activities [9].

To clarify the possible offset scenarios, consider three questions: (1) is the potential customer currently using electricity (2) will the new technology supply electricity to an established grid or directly to the customer (3) is new capacity required to satisfy the demands of the customer? These questions and the potential outcomes are outlined in Figure 2. The result is 4 possible scenarios:

1. The installation of a new technology to the grid electricity mix. This new technology will satisfy new electricity demand that could not be satisfied by the current grid capacity. In this case new capacity must be installed in any case ; therefore the new energy technology is preventing the entire life cycle GHG emissions of an alternate technology installation.

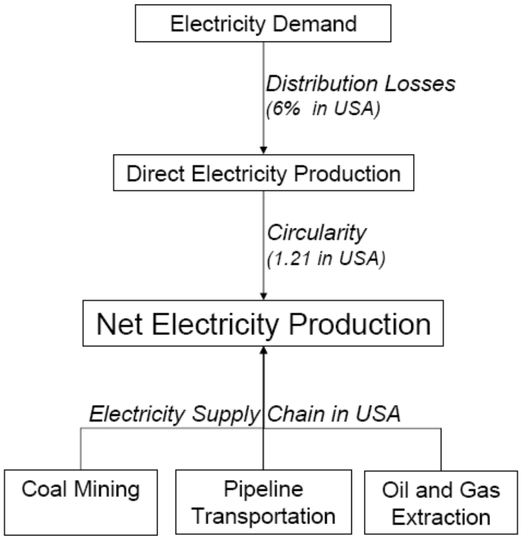

Figure 1: Contributors to Net GHG/kWh of Electricity – example based on USA.

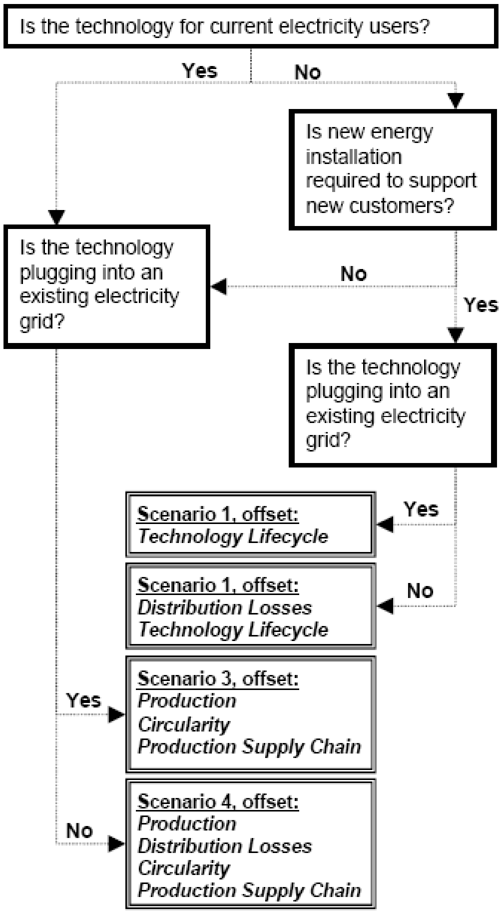

Figure 2: Decision tree for determining the appropriate offset scenario.

2. The installation of a new technology at the point of use. This installation is for a customer who previously did not consume electricity and who would require additional capacity from the grid if not for this direct point of use installation. Unlike scenario 1, this customer is offsetting both the entire life cycle of an alternate technology and distribution losses.
3. The installation of a new grid-tied technology for a customer who does not require additional capacity installed to meet demand, but who requests lower carbon intensive energy. Because an older technology has already been installed this customer only offsets marginal emissions of production, circularity, and the supply chain.
4. The installation of a new technology at the point-of-use for a customer who does not require additional capacity installed to meet demand and will receive electricity directly. This offset scenario is similar to scenario 3, except distribution losses are also offset.

An important difference between the first two and last two scenarios is whether the new energy technology is offsetting marginal or life cycle greenhouse gas emissions. However, the distinction may not always be obvious. For example, a utility company may desire to install a new technology that will supply electricity to both current and new customers. How does the utility calculate GROI in this situation? One solution might be to use a weighted average of the offset scenarios based on the number of customers in each category.

3.2 Electricity Life Cycle GHG/kWh

In scenarios 1 and 2 presented above, there is an inherent choice being made between alternate electricity installations. In this case, the entire life cycle of a new energy installation is compared with the installation of an alternate one. GHG_{Saved} is then the life cycle GHG/kWh emissions of the alternate technology. Previous researchers have analyzed the life cycle GHG/kWh of energy [1] [2], with their results summarized in Figure 3. This data does not account for distribution losses for a particular location, which will be discussed in the next section. Note that this data is presented as CO2 rather than net GHG emissions due to data availability; however it provides a reasonable comparison between technologies. Nuclear (Europe) and nuclear (USA) are different only in the electricity mix assumed throughout their manufacture.

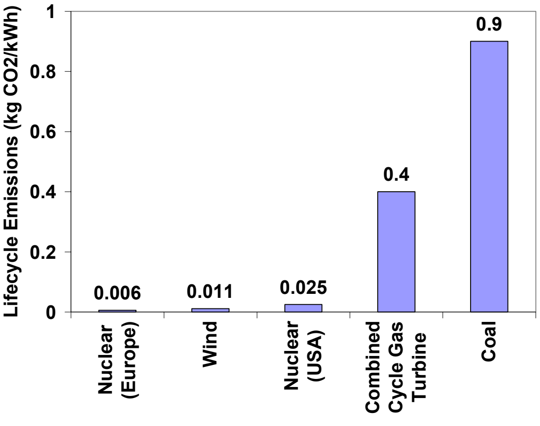

Figure 3: Life cycle CO2 emissions for energy technologies [1] [2].

3.3 Electricity Marginal GHG/kWh

Offset scenarios 3 and 4 assume electricity exists and is available, but its use is being replaced by a new energy installation. In this case, the installation of the old electricity has already occurred, and only marginal GHG/kWh emissions are prevented by the new installation. For these scenarios, information on the regional electricity mix in GHG/kWh is needed. This is investigated here for countries with available data. The GHG/kWh of a particular electricity mix is also useful for determining optimal manufacturing locations within the supply chain [4].

Determining the GHG/kWh of the current mix requires an understanding of the direct GHG emissions per kWh of production, the distribution losses from production to consumption, the circularity of electricity, and the supply chain of electricity, as discussed in section 3.1.

The first step is to understand the emissions associated with a kWh of produced electricity. Multiple data sources provide information on the emissions of electricity production, with varying results. Ecoinvent, a popular LCA database, provides life cycle GHG/kWh data, but only for European countries [5]. The International Energy Agency (IEA) provides data on CO2/kWh; however this data only accounts for the CO2 emissions associated with fuel combustion, not of the entire electricity mix.

For this discussion, IEA data from 2004 on both the CO2 emissions of all electricity & heat production in a given year, and the total production of electricity & heat within a country is used [6]. IEA also provides electricity consumption data, allowing for the calculation of distribution losses. Although the IEA data is in CO2 rather than total GHG emissions, it is seen in the Ecoinvent data that CO2 data is accurate to within 5% of GHG data for electricity production, making the IEA data a reasonable approximation.

The CO2 emissions of electricity and heat are provided as a single value by the IEA; however the electricity and heat production are provided separately. To calculate the GHG/kWh of just electricity, heat production is converted to an equivalent electricity value; it is assumed that fossil fuels are used to first generate heat and then electricity; therefore, because heat does not go through the secondary conversion it has a lower CO2 per kWh than electricity. It is unknown how much of this comes from cogeneration facilities, which adds further complication, and is ignored here. Also, the possibility that heat is produced from electricity is ignored here. Aggregation into a single value is done by approximating the heat to electricity conversion efficiency; heat to electricity conversion efficiency is a widely variable value, depending on method of conversion, and is here assumed to be 40% [7]. Equation 2 summarizes the calculation of GHG/kWh, where η is the assumed heat to electricity conversion efficiency.

$$GHG_{ElectricityMix} = \frac{GHG_{Heat,Electricity}}{Electricity + \eta * Heat} \quad (2)$$

Circularity is determined from economic input-output tables provided by the organization for economic cooperation and development (OECD) [8]. These tables are based on 41 industry sectors within each country, and they indicate the flow of money between industries in a given year; the year of each dataset varies between 1992 and 1998. The sector of importance here is utilities, described as “electricity, gas, and water supply.” The circularity of utilities is assumed equivalent to the circularity of electricity and is calculated as the ratio of demand for utilities by the utilities sector divided by the total demand for utilities.

Supply chain data is not readily available for countries other than the USA. In the United States, an online database of industry level environmental impacts is provided by Carnegie

Mellon University (EIOLCA) [9]. Within the power generation industrial sector, EIOLCA data is used to determine the ratio between the GHG/$ of power generation and the GHG/$ of the rest of the supply chain. The supply chain is found to add an additional 6% to the direct GHG/kWh within the USA.

The CO2/kWh results are shown in Figure 4. France has the lowest CO2 per kWh because 78% of their electricity is nuclear and 12% from renewables such as wind, solar, and hydro electricity [10]. The US, on the other hand gets 20% of its electricity from nuclear power and only 9% from renewables, with the remainder from fossil fuels [11].

Supply chain data for each country is not included in Figure 4, due to data limitations, but remains important. For example, France has the lowest CO2/kWh due to their large percentage of nuclear energy facilities; however, the nuclear energy supply chain may be significant considering the mining and transportation required to supply fuel on a regular basis. An additional factor not considered by this assessment is the end of life; this may be particularly important for nuclear due to decommissioning and long term fuel storage demands such as cooling, lighting, safety systems, labor, and construction.

It should be understood that this aggregated country level analysis, when used for offsetting in GROI, overlooks the differences between offsetting base versus peak load electricity. For example, solar energy in the USA likely offsets peak demand, which may be provided by natural gas; whereas wind energy offsets base demand in the evening, which is primarily coal based in the USA. Additionally, the analysis assumes an average mix that is homogenous across a country, whereas regional differences have been previously shown important by Reich-Weiser et al. [4].

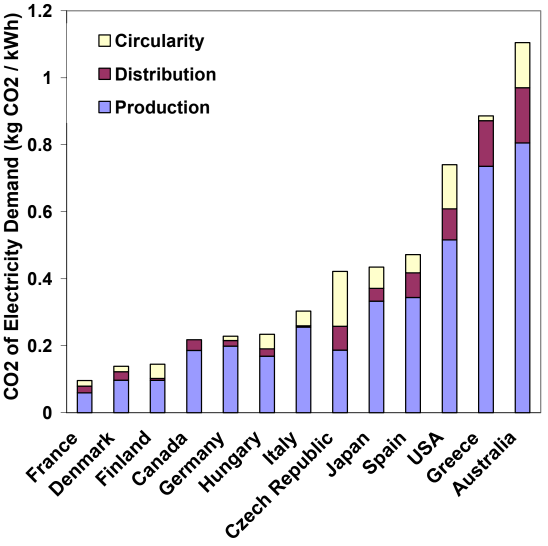

Figure 4: CO2 emissions of electricity generation; supply chain not yet included [6] [8].

3.4 Labor GHG

The incorporation of labor into LCA has been suggested by Zhang et al. [12], and is relevant to this discussion of how installation and supply chain decisions impact GROI. Labor should be included in LCA to ensure a comprehensive analysis and allow for fair comparisons between products that are manufactured in a primarily automated setting and those that are handmade. Zhang's energy per worker-hour incorporates the energy demands of infrastructure (water, electricity, roadways, public transportation) on a per capita hourly basis. Zhang includes infrastructure in the labor calculation because it is necessary for each person to operate efficiently in society.

Energy per worker-hour, as defined by Zhang, is calculated as the net energy demand of a country minus industrial energy demand (to avoid double counting) all divided by the working population (equation 3). The working population is used rather than the entire population for the same reason that the LCA of a machine tool is included in LCA: a person has both a beginning and end of life, which are relevant to their function as a working adult.

$$E_{Labor} = \frac{E_{Country} - E_{Industry}}{Population_{Working}} \qquad (3)$$

Just as the energy per worker-hour is necessary for comprehensive energy LCA, the GHG per worker-hour is calculated here to be used in GROI assessments. Unfortunately, data on industrial GHG emissions is poorly defined and widely unavailable. In some cases industrial GHG emissions are defined as all emissions associated with the flaring of fossil fuels, which includes residential natural gas emissions. In other cases, industrial GHG emissions are only available for a particular company [13]. For these reasons, the GHG of labor is calculated here as the net GHG emissions [14] divided by the working population [15]. This is an overestimate and has the downside of misrepresenting labor forces in countries that primarily produce goods for consumption by other nations.

Figure 5 shows the GHG of labor values calculated for some typical manufacturing countries. GHG of labor is as much a function of the energy mix of that country as the standard of living and efficiency.

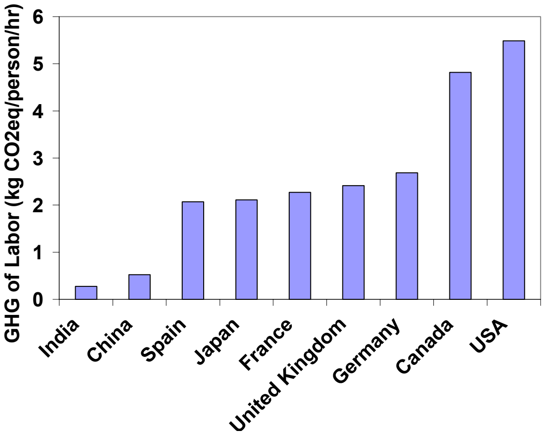

Figure 5: GHG of Labor.

4 CASE STUDY – CONCENTRATED SOLAR POWER

SolFocus Inc. has been working with researchers at UC Berkeley to assess the environmental impact of their concentrator solar energy technology. In this section, GROI sensitivity to installation choice is investigated for SolFocus solar panels.

SolFocus panels are designed specifically to minimize the levelized cost of energy (LCOE) in cents/kWh [16]. Environmental impact is also a key design concern for the SolFocus panels. By concentrating solar energy 500 times, the area of photovoltaic material, often considered the most environmentally harmful and costly component of solar energy, is minimized without unreasonably increasing tolerances and tracking costs.

These design efforts are critical to reduce the GHG/kWh of SolFocus panels; however the installation location will also impact GROI through the following parameters:

1. Offset GHG/kWh: a percentage change in offset GHG/kWh results in the same percentage change in GROI.
2. Insolation: a percentage change in insolation nearly results in the same percentage change in GROI (tracker losses that are constant location to location make this a non-linear association). Because SolFocus panels are concentrating, the direct normal irradiance (DNI) is used.
3. Labor: required for installing and maintaining the panels, installation labor has an impact on GROI that is proportional to the man-hours demanded.

To observe GROI sensitivity to these parameters, five potential installation sites are investigated for SolFocus: Paris, France; Vancouver, Canada; Madrid, Spain; Phoenix, AZ; and Sydney, Australia. Assuming that the SolFocus panels will be grid-tied utility scale installations, the offset electricity mix presented in Figure 4 is utilized, where Australia has a GHG/kWh that is 11 times greater than France. However, the DNI less than doubles within these locations: Phoenix has the highest DNI (5.5 kWh/m2/day), and Paris has the lowest DNI (3.3 kWh/m^2/day) [17]. Because the offset GHG/kWh is seen to have a larger variability than insolation, the offset GHG/kWh has the greatest opportunity to impact GROI.

Figure 6 illustrates the preliminary GROI results for each location, assuming a 30 year lifetime. The choice of installation location is seen to greatly affect the feasibility of pursuing this technology. The best GROI is obtained in Australia, where 3 tons of GHG emissions are prevented for every ton of GHG emitted throughout the SolFocus life cycle. This analysis does not consider transportation differences to each location, and considers everything except installation location to be constant.

5 EXTENSIONS AND FUTURE WORK

5.1 Modified EROI

The logic presented thus far for GROI can be similarly applied to create a modified EROI. EROI is defined as the technology lifetime divided by the EPBT (equation 4).

$$EPBT = \frac{E_{Input}}{Electricity_{AnnualOutput}}\eta_{electricity} \tag{4}$$

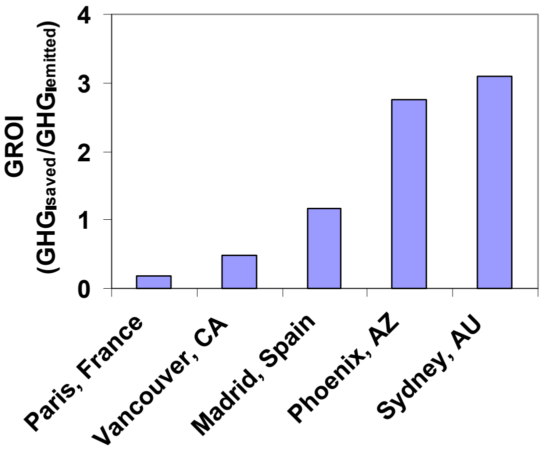

Figure 6: Preliminary results of GROI sensitivity to installation location for SolFocus Concentrator.[*]

In previous EPBT analyses, a standard conversion efficiency is often utilized rather than the appropriate local value, which ignores installation location differences. Additionally, $\eta_{electricity}$ has not previously accounted for circularity, supply chain, or distribution losses. A modified EPBT requires modifying $\eta_{electricity}$ to reflect the particular installation scenario and appropriate offset components as given in Figure 1.

A modified $\eta_{electricity}$ will require data on the primary energy to electricity conversion efficiency of countries and energy technologies. Incorporating the supply chain will also require additional research. Circularity data from input output tables [8] and distribution losses [6] can be used here as it was for GROI.

5.2 Beyond Energy

The logic of GROI can be used outside the context of energy technologies to inform product tradeoffs. Used in this way, $GHG_{Emissions}$ are still the life cycle GHG emissions of a product, and GHG_{Saved} are the emissions associated with an alternate purchase. For example, deciding to purchase new aircraft for a commercial airline fleet could be decided based on the life cycle GHG/mile of a new plane relative to the marginal GHG/mile emissions of the plane to be replaced. A GROI of less than 1 indicates that the new plane is not worth the investment in terms of greenhouse gas emissions. The logic of Figure 1 still applies to determine whether the life cycle or marginal emissions of an alternate technology are offset.

Additionally, this metric can be used by policy makers to establish incentives that will promote the fastest path to climate change mitigation.

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[*] Note that the SolFocus GROI value may improve dramatically as supply chain and end of life considerations are included in the offset GHG/kWh of each location.

5.3 Discounting Environmental Impact

In this discussion of greenhouse gas emissions and energy consumption, an assumption has been made that greenhouse gas emissions in the future are equivalent to greenhouse gas emissions today. A discounting method, such as is used for net present value calculations in economics, may also make sense for energy, greenhouse gases, and other environmental impacts. For example, energy may increase in value due to efficiency improvements that make it possible to do more with a kWh than can be done today; or, energy may decrease in value due to increased production. GHG emissions in the future rather than today may be favorable if technology develops to mitigate emissions or to slow the onset of climate change today. Work is needed to understand the appropriate way to account for future impacts and consumption in EROI and GROI type metrics.

6 CONCLUSIONS

The GHG return on investment metric is presented in this paper to address the drawbacks of decision making solely using EROI and GHG/kWh for new energy technologies. Specifically, EROI does not address climate change concerns, the primary goal of alternative energy; and GHG/kWh only accounts for insolation differences of alternative installation sites. GROI accounts for the types of energy used during the technologies' life cycle, the efficiency, circularity, and supply chain of energy distribution, and the type of energy being offset at the point of use.

The complicated nature of determining the offset emissions of a new technology is an important feature of this metric. It allows for dynamic location based decision making by inherently acknowledging that a choice to install a technology is a choice to not install or utilize an alternate technology. GROI encourages the quickest pathway to a reduction of greenhouse gas emissions globally, by rewarding the replacement of high GHG/kWh technologies. Furthermore, the GROI metric can be used by policy makers to establish incentives and is applicable to decision making beyond energy technology.

7 ACKNOWLEDGMENTS

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