Assessing the life cycle cost of decoupling electricity generation from greenhouse gas emissions

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Abstract—The aim of decoupling business growth from environmental impacts has led to corporate commitments to renewable energy. A greenhouse gas (GHG) avoidance cost metric ($ per kg CO₂-eq avoided) based on levelized cost of energy (LCOE) and life cycle GHG emissions is used to assess the life cycle cost of decoupling. Both conventional (nuclear, natural gas) and renewable (solar, wind, geothermal) electricity generation technologies are evaluated, assuming displacement of coal generation as an upper bound on emissions avoidance potential. With a combination of low LCOE and low life cycle GHG emissions, wind and utility-scale solar PV have the lowest life cycle cost for decoupling electricity generation from GHG emissions ($0.03-0.06 per kg CO₂-eq avoided). Because GHG emissions are only one of many inter-related environmental indicators, multi-criteria life cycle approaches to decoupling may be needed, as exemplified in the NSF 457 sustainability leadership standard for photovoltaic modules and inverters.

Keywords—product life cycle management, cost benefit analysis, environmental economics, global warming, power industry

I. INTRODUCTION

Decoupling refers to producing greater economic value out of fewer resource inputs (both material and energy) per unit of value [1]. Corporate interest in renewable energy has been driven by the objective of affordably decoupling business growth from environmental impacts. As of 2020, over 230 companies are signatories to the RE100 program, in which companies commit to sourcing 100% renewable electricity by 2050 at the latest [2]. These commitments are expected to drive long-term growth in renewable energy needed to meet the projected 2030 renewable energy shortfall of 210 TWh for the current RE100 signatories [3]. In 2019, the commercial and industrial (C&I) sector drove 19.5 GW of power purchase agreements (PPA’s) globally [3] and 19% of all new solar procurement in the U.S. [4]. A leading environmental indicator behind this trend is greenhouse gas (GHG) emissions and the aim to mitigate global climate change.

Assessing the potential for decoupling should be done on a life cycle basis in order to account for the full range of costs and environmental impacts over a technology life cycle. In this study, a GHG avoidance cost metric is used to compare the potential for affordable decoupling across different electricity generating technologies. In addition to these comparisons, potential constraints on decoupling are discussed based on a framework developed by the European Environmental Bureau (EEB).

II. METHODS

The potential for affordable decoupling of GHG emissions from business growth on a life cycle basis is assessed with the quotient of two life cycle metrics, levelized cost of energy (LCOE; $/MWh) and life cycle assessment (LCA) of GHG emissions avoidance potential (LCA_{GHG avoidance}; kg CO₂-eq avoided/MWh) (Eq. 1).

\[ \text{LCOE} \div \text{LCA}_{GHG \text{ avoidance}} = \text{GHG avoidance cost} \]  

where: GHG avoidance cost has units of $ per kg CO₂-eq avoided.

The levelized cost of energy is obtained for conventional (coal, nuclear, natural gas) and renewable (solar, wind, geothermal) electricity generation technologies from Lazard (V. 13.0) [5]. Life cycle GHG emissions for the same electricity generation technologies are obtained from the U.S. National Renewable Energy Laboratory (NREL) LCA harmonization study [6]. These life cycle GHG emissions are converted to life cycle GHG emissions avoidance potential by assuming the displacement of electricity generated with coal, which is the generation technology with the highest life cycle GHG emissions (Table I).

III. RESULTS

The life cycle costs of decoupling electricity from GHG emissions are derived in Table I and summarized in Fig. 1. The costs for different technologies range from a low value of $0.03 per kg CO₂-eq avoided for wind and thin-film utility-scale solar photovoltaics (PV), to >$1 per kg CO₂-eq avoided for natural gas peaking, assuming displacement of coal generation.

The comparisons in Fig. 1 help explain why wind and utility-scale solar PV are decoupling options commonly chosen by the C&I sector. Their combination of low LCOE and low life cycle GHG emissions results in low GHG emissions avoidance cost ($0.03-0.06 per kg CO₂-eq avoided). Another renewable...
Table I: Derivation of Life Cycle Cost of Decoupling Electricity Generation from Greenhouse Gas Emissions

<table>
<thead>
<tr>
<th>Technology</th>
<th>LCOE unsubsidized ($/MWh) [5]</th>
<th>LCA$<em>{GHG</em>{emissions}}$ (kgCO$_2$eq/MWh) ² [6]</th>
<th>LCA$<em>{GHG</em>{avoidance}}$ (kgCO$_2$eq/MWh) upper bound assuming displacement of coal</th>
<th>GHG avoidance cost ($/kg CO$_2$eq avoided; Eq. 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV Rooftop Residential</td>
<td>Low 151 High 242 Low 39 High 49</td>
<td>Low 881 High 1011 Low 0.15 High 0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar PV Rooftop C&amp;I</td>
<td>Low 75 High 154 Low 39 High 49</td>
<td>Low 881 High 1011 Low 0.07 High 0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar PV Community</td>
<td>Low 64 High 148 Low 39 High 49</td>
<td>Low 881 High 1011 Low 0.06 High 0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar PV c-Si Utility Scale</td>
<td>Low 36 High 44 Low 39 High 49</td>
<td>Low 881 High 1011 Low 0.04 High 0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar PV Thin Film Utility Scale</td>
<td>Low 32 High 42 Low 14 High 36</td>
<td>Low 894 High 1036 Low 0.03 High 0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Thermal Tower with Storage</td>
<td>Low 126 High 156 Low 14 High 27</td>
<td>Low 903 High 1036 Low 0.12 High 0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geothermal</td>
<td>Low 69 High 112 Low 22 High 52</td>
<td>Low 878 High 1028 Low 0.07 High 0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>Low 28 High 54 Low 8 High 18</td>
<td>Low 912 High 1042 Low 0.03 High 0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Peaking</td>
<td>Low 150 High 199 Low 570 High 750</td>
<td>Low 180 High 480 Low 0.31 High 1.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Combined Cycle</td>
<td>Low 44 High 68 Low 420 High 480</td>
<td>Low 450 High 630 Low 0.07 High 0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear a</td>
<td>Low 118 High 192 Low 7 High 24</td>
<td>Low 906 High 1043 Low 0.11 High 0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>Low 66 High 152 Low 930 High 1050</td>
<td>Low 0.17 High 0.27</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

⁡ Low and high values for LCA GHG emissions represent the 25th and 75th percentile, respectively

a. LCA GHG emissions for nuclear are for light water reactor (LWR) technology

The table above shows the life cycle cost of decoupling electricity generation from greenhouse gas emissions for various technologies. The technologies include solar PV, geothermal, wind, gas peaking, gas combined cycle, nuclear, and coal. The table includes the levelized cost of energy (LCOE) unsubsidized, life cycle assessment (LCA) for greenhouse gas emissions, and the life cycle assessment for greenhouse gas avoidance, upper bound assuming displacement of coal. The GHG avoidance cost per kg of CO$_2$eq avoided is also provided.

As a related benchmark, the global economy has a GHG intensity of approximately 500 g CO$_2$-eq per $ [7]$, or roughly 1 kg of CO$_2$-eq is emitted for every $2 increase in gross domestic product (GDP). As shown in Table I and Fig. 1, it is possible to avoid GHG emissions by 1 kg of CO$_2$-eq for a fraction of this cost using renewable energy. Depending on the current and future market price for conventional grid electricity, the GHG emissions avoidance may also be achieved with a net negative cost (net savings) using virtual PPAs with low LCOE technologies such as utility-scale solar PV and wind [8].

Moreover, the monetization of external costs through a carbon tax or other financial instrument would provide additional motivation for use of low carbon technologies. The U.S. government estimated the 2010-2050 social cost of carbon to range from approximately $30-70 in 2017 dollars per metric ton of CO$_2$ [9], or approximately $0.03-0.07 per kg CO$_2$. Since this value is comparable to the GHG avoidance cost for utility-scale solar PV and wind ($0.03-0.06 per kg CO$_2$-eq avoided), monetization of external costs increases the likelihood of net savings from use of these technologies.

For simplicity and as a common upper bound benchmark for the other generation technologies, the GHG emissions avoidance potential has been derived by assuming the displacement of electricity generated with coal. However, project-specific analysis could be undertaken which incorporates the generation mix of a particular electricity grid, and considers whether displacement of baseload or non-baseload generation should be assumed. For example, assuming the displacement of combined cycle natural gas instead of coal generation would result in an approximate doubling of the GHG avoidance cost values in Table I and Fig. 1, since combined cycle natural gas generation has approximately half the life cycle GHG emissions per MWh compared to coal generation (Table I).

The U.S. Environmental Protection Agency (USEPA) provides regional grid GHG emissions factors for both baseload and non-baseload electricity generation that could be used in project-specific analysis [10]. The non-profit organization WattTime has estimated avoided emissions of renewable energy projects using both grid-specific and time-varying marginal GHG emissions factors [11].

For simplicity and consistency, all LCOE and LCA values in Table I have been taken from the same sources (Lazard and NREL, respectively) but more current LCA values are available for specific technologies. For example, life cycle GHG emissions for PV technologies are available in recent literature [12-14] and through the International Energy Agency PV LCA web service (ENVI-PV) [15].
While GHG emissions are a priority issue behind corporate interest in decoupling, there are numerous other life cycle environmental impact indicators covering topics such as ecosystems, health, and natural resources, which can also be factored into a decoupling assessment. A more holistic analysis increases confidence that optimizing one environmental indicator does not significantly affect other indicators. For example, multi-criteria life cycle environmental impact assessment has been recently undertaken by the United Nations Environment Programme (UNEP) [16] and the European Union Product Environmental Footprint (EU PEF) Pilot Program [17].

IV. DISCUSSION

The concept of decoupling has come under scrutiny and skepticism in relation to the idea of green growth, that sustaining the Earth’s ecosystems can be accomplished while accommodating rapid economic growth. EEB identified seven potential constraints which would need to be addressed to satisfactorily achieve decoupling [18]. These constraints are depicted in Fig. 2 in relation to the electricity generation technologies in this study, and discussed below.

- “Rising energy expenditures” refers to how each additional unit of resource extracted requires more energy. The non-renewable generation technologies have the disadvantage that extraction of remaining resource stocks becomes a more resource- and energy-intensive process.
- “Rebound effects” refers to saving with efficiency improvements but then reallocating the savings to more consumption. This constraint is more relevant to consumer-level decoupling than at the C&I or utility-scale level.
- “Problem shifting” is addressing one environmental problem but aggravating another one. This constraint is relevant to all technologies as each relies on finite resources in the supply chain and/or during operation and has environmental impacts during construction and/or operation. This constraint can be alleviated by multi-criteria life cycle environmental impact assessment as described previously.
- “The underestimated impact of services” refers to how shifting to a service economy adds to, rather than substitutes, impacts of a material economy. This constraint has limited relevance to the decoupling considered in this study.
- “Limited potential of recycling” refers to low recovery rates and net benefits from recycling. This constraint is a major challenge for achieving sustainable energy transitions. The non-renewable technologies have the disadvantage of consuming resources during operation, which cannot be recycled. The renewable energy technologies have the challenge of implementing circularity in their supply chains and commercializing and scaling recycling technologies. For example, thin film CdTe PV solar technology has had a commercial recycling program in operation since 2005 [19].
- “Insufficient and inappropriate technological change” means the technology is too little, too late to be disruptive. This constraint is currently more applicable to distributed (e.g., rooftop PV) generation which requires more numerous and costly installations to achieve the capacity of utility-scale projects. However, the potential for disruptive distributed generation remains part of future energy transition scenarios [20].
- “Cost shifting” is shifting impacts across borders by international trade. This constraint is broadly applicable to all technologies whether it involves international trade in non-renewable fuels or components of renewable energy supply chains. As climate change is a global issue, GHG emissions need to be accounted for across borders.

As illustrated in Fig. 2, most of the constraints to decoupling identified by EEB are relevant to the generation technologies considered in this study. Multi-criteria life cycle approaches may be needed to address tradeoffs associated with decoupling. Current ecolabel and proposed eco-design initiatives provide a potential path forward for achieving decoupling while managing these tradeoffs [17][21]. For example, the new NSF 457 sustainability leadership standard provides a framework and standardized set of performance objectives for manufacturers and the supply chain in the design and manufacture of PV
modules and inverters [22]. It covers multiple product attributes such as management of materials, life cycle assessment, energy efficiency and water use, end-of-life management and recycling, and corporate responsibility. The standard is being used as the basis for new photovoltaics and inverter product categories in the EPEAT registry of green electronics [23].

Fig. 2. Potential constraints to decoupling based on a framework developed by EEB [18] as applied to the generation technologies in this study. Green, yellow, or red denote that a technology is favorable, uncertain, or unfavorable, respectively, at addressing the potential constraint.

V. CONCLUSION

With a combination of low LCOE and low life cycle GHG emissions, wind and utility-scale solar PV have the lowest life cycle cost for decoupling electricity generation from GHG emissions ($0.03-0.06 per kg CO₂-eq avoided, assuming displacement of coal generation). Because GHG emissions are only one of many inter-related environmental indicators, multi-criteria life cycle approaches to decoupling may be needed, as exemplified in the NSF 457 sustainability leadership standard for photovoltaic modules and inverters.

REFERENCES
