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 CO_2-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 CO_2-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 CO_2-eq avoided/MWh) (Eq. 1).

$$LCOE \div LCA_{GHG\_avoidance} = GHG\ avoidance\ cost \qquad (1)$$

where: GHG avoidance cost has units of $ per kg CO_2-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 CO_2-eq avoided for wind and thin-film utility-scale solar photovoltaics (PV), to >$1 per kg CO_2-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 CO_2-eq avoided). Another renewable

TABLE I. DERIVATION OF LIFE CYCLE COST OF DECOUPLING ELECTRICITY GENERATION FROM GREENHOUSE GAS EMISSIONS

	LCOE unsubsidized ($/MWh) [5]		**$LCA_{GHG\_emissions}$ ($kgCO_2eq/MWh$)[a] [6]**		**$LCA_{GHG\_avoidance}$ ($kgCO_2eq/MWh$) upper bound assuming displacement of coal**		**GHG avoidance cost (\$/kg CO_2-eq avoided; Eq. 1)**	
	Low	***High***	***Low***	***High***	***Low***	***High***	***Low***	***High***
Solar PV Rooftop Residential	151	242	39	49	881	1011	$ 0.15	$ 0.27
Solar PV Rooftop C&I	75	154	39	49	881	1011	$ 0.07	$ 0.17
Solar PV Community	64	148	39	49	881	1011	$ 0.06	$ 0.17
Solar PV c-Si Utility Scale	36	44	39	49	881	1011	$ 0.04	$ 0.05
Solar PV Thin Film Utility Scale	32	42	14	36	894	1036	$ 0.03	$ 0.05
Solar Thermal Tower with Storage	126	156	14	27	903	1036	$ 0.12	$ 0.17
Geothermal	69	112	22	52	878	1028	$ 0.07	$ 0.13
Wind	28	54	8	18	912	1042	$ 0.03	$ 0.06
Gas Peaking	150	199	570	750	180	480	$ 0.31	$ 1.11
Gas Combined Cycle	44	68	420	480	450	630	$ 0.07	$ 0.15
Nuclear[b]	118	192	7	24	906	1043	$ 0.11	$ 0.21
Coal	66	152	930	1050	-	-	-	-

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

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

technology available to the C&I sector is commercial rooftop solar PV (\$0.07-0.17 per kg CO_2-eq avoided), which has GHG emissions avoidance cost similar to geothermal and natural gas combined cycle (\$0.07-0.15 per kg CO_2-eq avoided). Solar thermal tower with storage (\$0.12-0.17 per kg CO_2-eq avoided) has GHG emissions avoidance cost similar to nuclear (\$0.11-0.21 per kg CO_2-eq avoided).

As a related benchmark, the global economy has a GHG intensity of approximately 500 g CO2-eq per $ [7], or roughly 1 kg of CO2-eq is emitted for every $2 increase in gross domestic product (GDP). As shown in Table 1 and Fig. 1, it is possible to avoid GHG emissions by 1 kg of CO2-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].

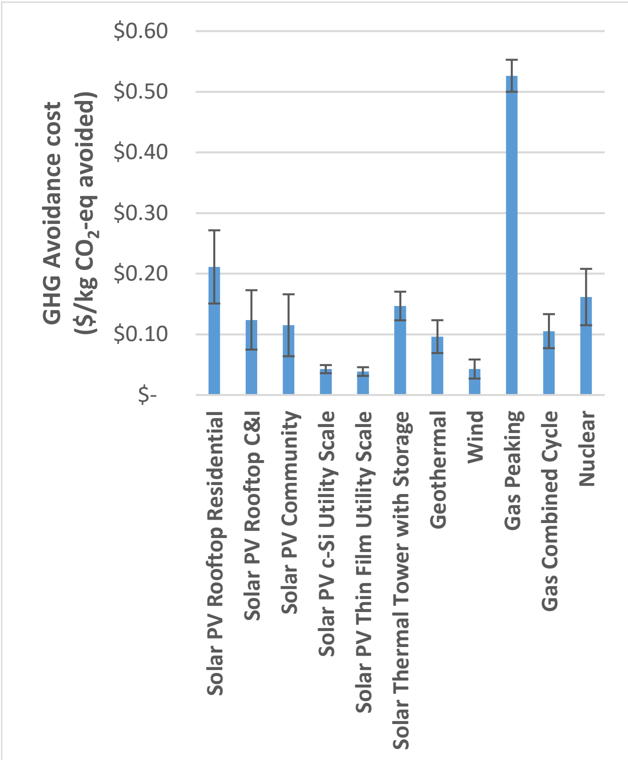

Fig. 1. Comparative life cycle cost of decoupling electricity generation from greenhouse gas emissions. GHG avoidance assumes displacement of coal generation.

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].

	Rising energy expenditures	Rebound effects	Problem shifting	Underestimated impact of services	Limited potential of recycling	Insufficient and inappropriate technological change	Cost shifting
Solar PV Rooftop Residential	1	0	0	0	0	0	0
Solar PV Rooftop C&I	1	1	0	0	0	0	0
Solar PV Community	1	0	0	0	0	1	0
Solar PV c-Si Utility Scale	1	1	0	0	0	1	0
Solar PV Thin Film Utility Scale	1	1	0	0	0	1	0
Solar Thermal Tower with Storage	1	1	0	0	0	1	0
Geothermal	1	1	0	0	0	1	0
Wind	1	1	0	0	0	1	0
Gas Peaking	-1	1	0	0	-1	0	0
Gas Combined Cycle	-1	1	0	0	-1	1	0
Nuclear	-1	1	0	0	-1	1	0

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 CO_2-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

[1] E.U. von Weizsäcker, J. de Larderel, K. Hargroves, C. Hudson, M. Smith, and M. Rodrigues, “Decoupling 2: technologies, opportunities and policy options,” UNEP, 2014.

[2] RE100, “Companies,” available at: http://there100.org/companies

[3] Bloomberg New Energy Finance, “1H 2020 Corporate Energy Market Outlook,” 2020.

[4] SEIA/Wood Mackenzie, “Solar market insight report 2019 year in review,” 2020.

[5] Lazard, “Lazard’s levelized cost of energy analysis version 13.0,” 2019.

[6] U.S. National Renewable Energy Laboratory (NREL), “Life cycle assessment harmonization,” available at: https://www.nrel.gov/analysis/life-cycle-assessment.html

[7] T. Jackson and P. A. Victor, “Unraveling the claims for (and against) green growth,” Science, vol. 366(6468), pp. 950-951, 2019.

[8] R. Zanchi and R. Kansal, “Choosing off-site renewable PPAs for Environmental and Social Impact: A Case Study on Cummins’ Virtual Power Purchase Agreement in Indiana,” Rocky Mountain Institute Business Renewables Center, 2018.

[9] U.S. Interagency Working Group on the Social Cost of Carbon, “Technical support document: technical update of the social cost of carbon for regulatory impact analysis under executive order 12866,” Washington, DC, 2016.

[10] U.S. Environmental Protection Agency (USEPA), “Emissions & generation resource integrated database (eGRID2016),” 2018.

[11] H. Richardson, “Lifecycle and avoided emissions of solar technologies,” WattTime, Oakland, CA, 2020.

[12] E. Lecissi, M. Raugei, and V. Fthenakis, “The energy and environmental performance of ground-mounted photovoltaic systems—a timely update,” Energies, vol. 9(8), 622, 2016.

[13] A. Louwen, R.E.I. Schropp, W.G.J.H.M. van Sark, and A.P.C. Faaij, “Geospatial analysis of the energy yield and environmental footprint of different photovoltaic module technologies,” Solar Energy, vol. 155, pp. 1339-1353, 2017.

[14] F. Liu and J. C.J.M. van den Bergh, “Differences in CO_2 emissions of solar PV production among technologies and regions: Application to China, EU and USA,” Energy Policy, vol. 138, pp. 111234, 2020.

[15] International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) Task 12, “ENVI-PV: Environmental performance tool for PV systems,” available at: http://www.iea-pvps.org/index.php?id=463

[16] E.G. Hertwich, J. Aloisi de Larderel, A. Arvesen, P. Bayer, J. Bergesen, E. Bouman, T. Gibon, G. Heath, C. Peña, P. Purohit, A. Ramirez, and S. Suh, “Green Energy Choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity production,” United Nations Environment Programme (UNEP), 2016.

[17] A. Wade, P. Stolz, R. Frischknecht, G. Heath, and P. Sinha, “The product environmental footprint (PEF) of photovoltaic modules—Lessons learned from the environmental footprint pilot phase on the way to a single market for green products in the European Union,” Prog Photovolt Res Appl., vol. 26(8), pp. 553-564, 2018.

[18] European Environment Bureau, “Decoupling Debunked: Evidence and arguments against green growth as a sole strategy for sustainability,” 2019.

[19] P. Sinha, S. Raju, K. Drozdiak, and A. Wade, “Life cycle management and recycling of PV systems,” PV-Tech Power, Vol. 13, pp. 47-50, 2017.

[20] T. Huld, K. Bodis, I. P. Pascua, E. Dunlop, N. Taylor, and A. Jäger-Waldau, “The rooftop potential for PV systems in the European Union to deliver the Paris Agreement,” European Commission Joint Research Center (JRC), 2018.

[21] European Commission Joint Research Center (JRC), “Preparatory study for solar photovoltaic modules, inverters,” 2019.

[22] NSF International, “NSF/ANSI 457-2019 sustainability leadership standard for photovoltaic modules and photovoltaic inverters,” 2019.

[23] N. Gillis, “Overview of green electronics council PV modules and inverters product category,” 36th EU PVSEC, Marseille, France, 2019.

TITLE OF PAPER/ARTICLE/REPORT: Assessing the life cycle cost of decoupling electricity generation from greenhouse gas emissions
COMPLETE LIST OF AUTHORS: Sinha, Parikhit; Wade, Andreas
IEEE PUBLICATION TITLE (Journal, Magazine, Conference, Book): 47th IEEE Photovoltaic Specialists Conference
LINK TO FINAL PUBLICATION: http://ieeexplore.ieee.org/Xplore/home.jsp