Does the $20 Million Carbon XPRIZE Exclude Solar Technologies?

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Rethinking CO_2 as a potential valuable feedstock, as promoted by the $20 million NRG COSIA Carbon XPRIZE (http://carbon.xprize.org), is laudable. The prize challenges innovators to reimagine what they can do with CO_2 emissions. The prize objective is to incentivize and accelerate the development of technologies that convert CO_2 into valuable products, with the premise that such technologies would have the potential to transform how the world approaches CO_2 waste, and thereby reduce costs involved in managing CO_2 by turning a liability into revenue. While it is not our intention to detract from this commendable objective, we express here some concerns regarding potential unintended consequences. For example, the rules of the competition do not explicitly consider the full life cycle or net emissions. In addition, the rules limit the innovation space by introducing an artificial land-area constraint. Ignoring life-cycle emissions risks opening the door to technologies that could produce more CO_2 equivalents than they consume. The land-area constraint risks closing the door to solar-driven technologies that potentially can avoid more CO_2 emissions than those technologies that are able to meet the land constraint. Thus, we ask:

Was the deck for the Carbon XPRIZE competition for converting CO_2 into high-value products unintentionally stacked against approaches in which solar is the sole source of energy?

We ask this question because converting CO_2 into useful products, such as fuels, chemicals, or plastics, is going to require energy, and lots of it. Unless the energy resource is renewable (e.g., solar), the conversion process might emit more CO_2 than it consumes or offset much less CO_2 than hoped. Nevertheless, the Carbon XPRIZE requires that competitors utilize a maximum land area of 2300 m^2 to partially convert 2 metric tons of CO_2 per day; the more that is converted the higher the score but at least 50 % should be converted to score any points. Seeing this constraint, we asked ourselves: Would meeting it with a solar-driven process imply the violation of the first law of thermodynamics: the conservation of energy? We find that the answer is theoretically "no" but practically very much "yes" given even the most optimistic considerations. First, solar technologies depend on location as the solar irradiation varies from site to site. For argument's sake we will consider a sun-rich location in the summer, with an average 8 kWh per square meter per day. Thus, the solar radiative energy available over 2300 m^2 is equivalent to approximately 66 GJ per ton or 2.9 MJ per mole CO_2 converted per day. For some technologies this amount will be enough energy, especially if there is another energy-rich input, although the life-cycle emissions in acquiring that energy-rich input must be a consideration in determining the sustainability of the process. Nevertheless, if a technology uses only solar energy, this land-area metric poses an arduous constraint. A reasonable, albeit tough target would be 15 % efficiency, thus products whose energy density is more than 437 $kJ\,mol^{-1}$ carbon would be excluded, such as gasoline, diesel, kerosene, methanol, methane, and most plastics. Carbonates make up one notable exception, as they are in principle downhill thermodynamically from CO_2. We note that many of the semifinalists require an energetic feedstock in addition to the CO_2. In most cases, if these innovators had to acquire the energy to produce their energetic feedstock within the restricted land area, it would be unfeasible.

To expand upon our premise, let's perform a back-of-the-envelope calculation for the conversion of CO_2 and water to methanol using solar energy. Let's assume for the purpose of illustrating the best-possible-case scenario that our solar-driven device effecting such conversion has an overall solar-to-fuel energy conversion efficiency of 95 %, the best that can expected for a blackbody source with a temperature of 5780 K. For a typical clear-sky day in a very sunny location, with a substantial solar irradiation of 8 $kWh\,m^{-2}$ per day, our perfect solar device would then be producing daily 7.6 kWh of fuel over 1 m^2, or the equivalent of 1.52 L of methanol, while consuming 1.66 kg of CO_2. Thus, a perfect solar process that converts 1 metric ton of CO_2 would require at least 603 m^2. We conclude that the Carbon XPRIZE restriction of 2300 m^2 does not violate the first law of thermodynamics, but it implicitly demands the demonstration of a solar device with an overall solar-to-fuel energy conversion efficiency of

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at least 26% for methanol, or greater for more-energetic carbon-based products.

Using solar electricity to convert CO_2 to fuels, for example by H_2O electrolysis followed by H_2/CO_2 processing, involves various irreversible steps that result in overall solar-to-fuel energy efficiencies well below 26%. The direct approaches such as solar photo/thermochemical, although of high promise, currently report efficiencies in the single digits. Additionally, solar concentrating systems cannot use every square meter of land since they track the sun and, as such, suffer from blocking and shading constraints, which result in the utilization of only a quarter to half of the land being irradiated. It would be unrealistic to expect overall efficiencies of at least 26% for any solely solar-driven device for converting CO_2 to fuels, chemicals, or plastics at the demonstration scale.

The bottom line is that the performance threshold of the Carbon XPRIZE on the land footprint effectively eliminates any competitors that use sunlight as the sole source of energy. Those competitors who use photosynthetic biomass-based processes, which typically have a larger land footprint than direct solar-based processes, are eliminated as well. Hence, innovators working on developing technologies for producing direct solar- or photosynthesis-based products from CO_2 are unable to participate in this competition, as they cannot fulfill one of the eligibility metrics.

It has been claimed in discussions with the organizers of the Carbon XPRIZE that the competition was designed to be as solution-agnostic as possible, to be open to the full spectrum of potential solutions. From what we conclude above, it is not agnostic enough to include solar-only approaches. We find that, in order to compete for the prize, it is necessary to bring energy into the system from an external source outside of the land footprint, most likely in the form of electricity. Ultimately, CO_2 utilization will have to account for CO_2 generated in the life cycle of the technology. If we look to the semi-finalists as representative of CO_2 utilization pathways, a number of promising solar-driven approaches are notably absent, presumably resulting from the artificial land footprint constraint.

Furthermore, nowhere in the guidelines of the Carbon XPRIZE is there any reference to how the judges are going to account for the concomitant CO_2 emissions derived from the energy—heat or electricity—consumed in the CO_2 conversion process. Clearly, no one wants to encourage CO_2 conversion processes that add more CO_2 to the atmosphere upon considering the whole life cycle. Those competitors using grid electricity have embedded CO_2 emissions; admittedly as the grid decarbonizes this will decrease over time. We therefore propose to introduce a trivial mass balance: the amount of CO_2 emissions associated with resources consumed should be subtracted from the amount of CO_2 converted in the process.

Our final point has to do with the source of CO_2 and who should claim the burden of the emissions. We note that if we convert CO_2 into transportation fuels, a high-volume opportunity for waste CO_2 emissions, eventually that fuel will end up as added CO_2 to the atmosphere. The Carbon XPRIZE targets converting CO_2 contained in flue gases derived from fossil-fuel-fired power plants. Power utilities with CO_2 capture would understandably want to claim that their electricity is low-CO_2 because much less is discharged directly into the atmosphere, while the operators of CO_2 conversion factories would be equally eager to claim that their product is CO_2 neutral because it consumes the same amount that it releases at the end of its lifetime. For both to derive the benefit would, however, be double-counting. We trust the judges of the Carbon XPRIZE will scrutinize the legitimacy of claims and make sure that words such as “clean”, “CO_2 neutral”, “sustainability”, and others of this appealing lexicon do not lead to misunderstandings about how much CO_2 emissions is avoided.

We are of the opinion that practitioners of the solar-driven conversion of CO_2 to value-added chemicals, materials, and fuels, who are making progress toward meaningful technological solutions at reasonable cost, would have wanted to participate in the Carbon XPRIZE competition, and perhaps could have if the scoring criteria had been modified as follows:

1) The land footprint criterion was dropped; and

2) The carbon footprint criterion was evaluated as the net value of CO_2 captured and converted in the process after subtracting the additional CO_2 emissions associated with the energy consumed in the process.

The implementation of these two changes into the scoring criteria would have been straightforward. Furthermore, these are consistent with the commendable spirit and objective of the Carbon XPRIZE, “INCENTIVIZING A CLEANER ENERGY FUTURE”. Solar scientists and engineers would look forward to the opportunity to participate in a follow-up Carbon XPRIZE, should there be one, with modified scoring criteria, which would be a win–win situation for all.

A representative of the Carbon XPRIZE did not respond to an invitation to publish a response to this letter.