Supporting Information

Lackner et al. 10.1073/pnas.1108765109

SI Text A: The Cost of Avoiding Tailpipe CO_2 Emissions by Driving a Tesla

The introduction of the Tesla Roadster has reignited the electric car concept. Rather than accepting a low-performance approach with the goal of a gradual improvement, the Tesla is a high-performance vehicle that can absorb the elevated cost of a first-of-a-kind implementation integrated into an offering that is unique and provides many other advantages to its owner. The business model of the company has indeed been to introduce an expensive electric car, take advantage of the strengths of an electric engine, and absorb the high cost of electricity storage into the generally high cost of a luxury car.

One of the advantages of the Tesla is that it effectively eliminates the emissions of carbon dioxide from the tailpipe. One can therefore ask the question: How much does it cost to eliminate these emissions from the tail pipe and push them back to an electric power plant? At the power plant, there are several options for mitigating or avoiding emissions, even though they have not yet been implemented today.

Because the Tesla Roadster is a high-performance car, we compare it with a Porsche 911 Turbo. The Porsche exceeds the Tesla in size, price, and performance, which should result in higher emissions from the Porsche than one might expect from a more carefully matched analog. The replacement cost of a Tesla Roadster battery system has been stated by the CEO of the company as $36,000. The battery pack holds a nominal charge of 53 kWh, allowing for a range of 244 miles. The stated cost for the battery represents advances, as it is only half the cost reported in a recent Sandia National Laboratory study for stationary battery systems (1). The battery life is estimated by Tesla at 100,000 miles or 7 y, which results in 410 full discharges or 6.2 d per discharge. The electricity cost per charge is only $5 at $0.10/kWh, whereas the cost of the battery adds $88 per charge. At a 5% rate of return on investment one would need to add another $31 to account for the cost of capital. This results in a total cost of $124 per tank. The Porsche's fuel mileage is given by the Environmental Protection Agency as 19 miles/gallon, for combined city/highway driving, which requires 12 gallons of gasoline to match the Tesla's range. Such results suggest an effective fuel price of $10/gallon equivalent for the Tesla Roadster or $600 per metric ton of CO_2 (t CO_2), equal to the cost estimate for air capture of the American Physical Society (APS).

We note that the Tesla Roadster is the first entry into a new electric car market. Therefore, it is not surprising that the cost of the system is still very high and there is every expectation that the costs will come down dramatically over time. Indeed, although we were unable to obtain exact numbers for the new Nissan Leaf, it is clear that its performance is significantly better, mainly because the number of charges one can get out of a battery has been significantly increased. However, the reason we point to the Tesla is to show that in engineering other forms of carbon mitigation proponents are willing to enter the field at a price point that has been considered prohibitively high in the APS study.

SI Text B: A Lower Bound on the Cost of Removing CO_2 from Air

Motivation. One cannot argue that long-term cost estimates of nascent technologies are virtually impossible, as we do in the main text, and then claim to produce an accurate cost estimate of a future air capture system. However, one needs to show that nearly unavoidable costs do not render any attempt at air capture futile. For example, energy consumption will always exceed the thermodynamic limit. Thus, there is a minimum energy demand that is built into the process. The use of raw materials provides another set of constraints. The cost of common raw materials like steel is not likely to come down because of demand for steel from air capture, so the anticipated future cost of such materials will help put a floor under the cost of air capture, assuming that one can put a reasonable lower bound on the total requirement. If these costs add up to much more than what is affordable, even under optimistic assumptions, then with current concepts, it is not possible to arrive at an economic implementation. We emphasize that the lack of such limits does not prove that an economic implementation can be achieved, but it should remove objections to further investigations of the concept. In the end, the only cost estimates that are reasonably accurate are derived from specific practical designs, ideally ones that actually have been built. Experience has shown that initial cost estimates on nascent technologies can change by orders of magnitude over time.

In trying to establish a lower bound, it is not necessary to look at all components of the system. A single component on the critical path could already exceed the available budget. Here, we look at the unavoidable cost of contacting the air and absorbing CO_2 on a sorbent material. We focus on this component of the system because it is the only part of the system that is directly affected by the low concentration of CO_2 in the air. Its size and shape are defined by the concentration of CO_2 in the air, and it is reasonable to assume that its cost scales essentially linearly with the dilution of CO_2 in air. Thus, the criticism by House et al. (2), which implicitly assumes that this term is too expensive, is answered by showing that the only contribution to the cost that naturally scales linearly in the initial dilution is not unavoidably too expensive. Once CO_2 is bound on a sorbent, the subsequent separation problem is characterized by the dilution of CO_2 on the sorbent, rather than the dilution in air.

Rather than trying to obtain an estimate that applies to any air-contacting system, here we are looking at a specific system. By showing that this system has no intrinsically high costs associated with it, we in effect have countered the argument that any system of any type must be expensive. We assume that the air contactor considered here is passive; i.e., it operates with available natural air motion. Furthermore, we assume a solid sorbent, which must be moved from the contactor to the regenerator. These assumptions match our own approach to the problem, but could easily be generalized to different approaches. Our goal is to find one example that could be low in cost, to counter the argument that low-cost implementations are simply impossible.

Defining a Collector System and Setting Cost Targets. By definition, the CO_2 contactor comprises sorbent material put in the shape of air filters sufficient to collect CO_2 at a rate of 1 t CO_2/d and a structure to hold the air filters into the wind. The complete air capture device will contain additional sorbent material, because the sorbent will spend a fraction of its time in regeneration. In the system we have studied, this roughly doubles the sorbent in the system. In assigning costs to collection and generation, however, we account only for an amount of sorbent that at any given time is in the contactor. The cost of the additional sorbent is attributed to the cost of regeneration.

We assume the flow of air to be about 1 m/s through the filter and the collection efficiency to be 33%. The system we envision is passive with a very low cost of operation, and nearly all of its cost is upfront in building the system or in replacement of units that wear out, corrode, or otherwise cease to function. In the following we assume a 10-y lifetime, but keep some of the budget for contingencies.

We argue that with relatively minor improvements of currently available technology, the cost of such a subsystem could readily be covered at \$5/t CO_2. We note that this cost does not cover other steps in the operation, like the transfer of the sorbent to a regeneration system, or the cost of building, operating, and maintaining a regeneration system. We expect these costs to be larger. For example, if regeneration takes the same amount of time as contacting the air, regeneration costs would effectively include twice the amount of sorbent material, as only 50% of it would be in the contactor at any given time.

Revenue of \$5/t CO_2 would result in annual revenue of \$1,825. Assuming an equipment lifetime of 10 y and an internal rate of return of 10%, such annual revenue would allow for a capital expenditure of a little more than \$12,000. Assuming financing half of the cost with a utility-type loan at 5% and the other half from investors who demand a return of 15%, the budget would again be \$12,000. We take this scale of investment as our budget for constructing a 1 t/d capture unit.

Specific Design and Its Cost. We begin with a design of a capture system that is based on a particular approach we discussed previously (3). In this design, the sorbent is a solid material over which air flows. The sorbent material has been produced with a specific surface area of 4 m^2/kg and a time-averaged uptake rate of 25 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Assuming an airflow rate through the collector of 1 m/s and 33% capture efficiency, such a collector operating at 1 t CO_2/d requires a frontal area of 50 m^2 and 2,500 kg of sorbent material in the collector. In this example, the time it takes to swing the resin loading by about 30% of its capacity would take on the order of 1 h. For purposes of this discussion, we consider the sorbent material in the form of a honeycomb structure. Wall thicknesses would be about 0.5 mm and diameter of the honeycomb openings can be chosen such that the thickness of the filter is on the order of 10–50 cm.

The material described in ref. 3 was originally produced for entirely different applications, and it has in no way been optimized for air capture. Assuming some progress in the material design, one might aim for a 10-fold improvement in the total sorbent mass requirement for the CO_2 collector. Quite likely, most of the improvement would come from making thinner materials, which reduce the holding capacity without improving uptake rates. Some of the improvement may also result from enhancements in the uptake rate, which may represent improvements in the underlying reaction kinetics, in the rate of transport of CO_2 away from the sorbent surface, or in creating a rougher surface that results in a larger effective surface area for a given nominal surface area.

Here we assume a fivefold reduction in the sorbent mass of the system. This would require reducing the wall thickness of the sorbent material to about 0.1 mm, which has certainly been done with other similar materials. After such an improvement, the sorbent requirement would be 500 kg or about 10 kg/m^2 of frontal wind area. The anionic exchange resins suitable for this task in the design by Lackner (3) can today be purchased in bulk at about \$3/kg. Shaping these materials into filters may double the cost. Thus, a future price of such a filter could be as low as \$60/m^2. These numbers are not unreasonable, compared with current manufacturing processes. For example, individual drinking straws of comparable diameters and lengths aggregated into a honeycomb structure as required for a filter would result in a product that costs about \$6/kg. Honeycomb-structured polypropylene panels can be purchased at about \$5/kg. These costs are not atypical compared with other mass-manufactured systems. For example, furnace filters five inches thick can be purchased retail at about \$60/m^2. Wholesale costs are likely to be significantly smaller. At \$6/kg, the cost of the sorbent filters amounts to \$3,000 for a 1 t CO_2/d system.

Additional to this cost is the cost of the structure to hold the filter panels into the airflow in a manner that allows for easy removal for regeneration. Here, we consider a system of 10 filter panels, 2 m wide, 2.5 m tall, and each containing 50 kg of resin material. To sketch out such a system, we put up a center post and three posts 120° apart on a circle with a 10-m radius. The three outer posts are connected to the center post with horizontal bars that run from the top of each post to the center and hold the system together. The top bars act as a rail on which the panels can be hung. At any given time, two of the three horizontal bars are holding 10 panels each, and the third is empty. The freedom to choose which of the three rails remains empty provides a rudimentary way of pointing the structure into the wind.

A frame holding together a single panel including hardware is assumed to cost \$100. If the filter is thought of as a shallow box, the amount of plywood that would form the edges would cost less than \$30 at retail. Other materials may be more suitable, and the top also needs some hardware to attach to the scaffolding holding the system in place. Hence, we assume a higher cost.

The scaffolding, as described above, comprises four foundation pads of \$70 each (1 yard of concrete per pad), four posts 5 m tall, three cross beams 10 m long, and three steel rails to hang the filter panels on, plus associated hardware to hold all of this together. To get a feel for the cost, one might consider the cost of garage kits that contain structural elements to hold up roofs capable of holding snow loads far larger than the loads we intend to support here. The kits of structural steel tubing cost on the order of \$2,000. We obtain similar numbers by adding up the total steel in such a frame, assuming the frame is made from steel (30 m of light I beams, plus four pillars with a cross-section of 3.5 inches). So all totaled, we consider a system cost of \$6,500, which is commensurate with our budget. Leaving a safety factor of nearly 2 is not unreasonable. Real systems presumably have a lower capacity factor, and there will certainly be some maintenance cost, which has not been accounted for.

Considering these numbers, an ultimate cost of \$5/t of CO_2 for the air contactor of a passive system cannot be dismissed on first principles. Implicitly, we have assumed that maintenance costs of these structures are small and that the material will not deteriorate. Although our assumption may not be true for the first implementation, additional research and development will likely make systems more robust.

Is Scaling up Feasible? Extending the concepts discussed above to the regeneration system, we are outlining a system that contains approximately 1 t of sorbent material, half in the collector and half of it in a regenerator. The estimate is based on the observation in Lackner (3) that loading and regeneration have similar durations. While this estimate alone would double the cost, one also would have to add additional machinery for moving filters around and for actually performing the regeneration task. Such a system would have a number of moving parts that would transfer resin filters from the collector to the regenerator and back. Thus, significant complexity exists for the overall structure, which, given its mass and the presence of moving parts, resembles the complexity and size of an automobile.

Although we are not trying to make a direct cost comparison on the basis of these assumptions, we are interested in the question of whether current industrial practice would allow one to produce enough air capture units to have an impact on the world's carbon dioxide budget. Solely for this purpose we follow the analogy of car-manufacturing as an analog to producing a 1 t/d unit. As explained in the main text, the large scale of automobile and light truck production suggests that global manufacturing capacity is not likely to limit the introduction of air capture at the requisite scale.

Finally, the simplest implementation of a regeneration system would put a loaded filter panel into a slow air stream that carries away the CO_2 from the wet panel at a CO_2 concentration of about 5%. Although maybe not the most efficient implementation, it graphically makes the point that air capture will cost more than flue gas capture but not very much more. The upfront collector cost has been shown to be small compared with the cost of flue gas scrubbing. The output of the simple regenerator would be a stream of air that has a CO_2 and an H_2O content not unlike the exhaust from a natural-gas-fired power plant. Hence scrubbing this stream should pose similar costs to flue gas scrubbing, which greatly exceeds the cost and complexity of this first concentration step.

1. Ton DT, Hanley CJ, Peek GH, Boyes JD (2008) *Solar Energy Grid Integration Systems – Energy Storage (SEGIS-ES)* (Sandia National Labs, Albuquerque, NM), Report SAND2008-4247.
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3. Lackner KS (2009) Capture of carbon dioxide from ambient air. *Eur Phys J Spec Top* 176: 93–106.