

# A Trillion Tons

*Hal Harvey, Franklin M. Orr, Jr. & Clara Vondrich*

*Abstract: There is a consensus among scientists that stark dangers await in a world where the global mean temperature rises by more than about 2 degrees Celsius. That threshold corresponds to a collective human carbon emissions “budget” of around a trillion tons, of which half has been spent. This paper uses a new simulation model to look at strategies to stay within that budget, specifically assessing the impact of improvements in energy efficiency, aggressive deployment of renewables, and energy technology innovation. The simulations examine the timing of investments, turnover of capital stock, and the effect of learning on costs, among other factors. The results indicate that efficiency, renewables, and technology innovation are all required to keep humanity within the trillion-ton budget. Even so, these measures are not by themselves sufficient: changes in land use and a price on carbon emissions are also needed.*

HAL HARVEY is CEO of Energy Innovation: Policy and Technology LLC and Senior Fellow for Energy and the Environment at the Paulson Institute at the University of Chicago.

FRANKLIN M. ORR, JR., is the Keleen and Carlton Beal Professor in the Department of Energy Resources Engineering and Director of the Precourt Institute for Energy at Stanford University.

CLARA VONDRICH is Director of Leadership Initiatives at the ClimateWorks Foundation.

(\*See endnotes for complete contributor biographies.)

How much carbon can humans safely emit into the atmosphere? Climate scientists argue that a 2 degree Celsius (about 4 degree Fahrenheit) increase in global mean temperature is a threshold above which the probability of highly adverse consequences grows significantly. Such an increase would correspond to roughly a trillion tons of total human-caused carbon emissions over time.<sup>1</sup> If one trillion tons is humanity’s carbon budget, how much have we used so far? How fast will we emit the remainder under current trends? And what can we do to make sure that we don’t bust the budget?

To consider the relative contributions of different variables, ClimateWorks, a foundation that supports public policies that mitigate climate change, and its partners at Climate Interactive developed the system-dynamics computer model En-ROADS (Energy–Rapid Overview and Decision-Support simulator). En-ROADS is a global model that assesses how changes in energy supply and demand might affect emissions and, in turn, climate outcomes.<sup>2</sup> It is designed to rapidly assess the impact of various policy scenarios on cumulative emissions by manipulating variables as diverse as global GDP, energy efficiency, innovation, carbon price, and fuel mix.

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The simulations underlying this essay emphasize the dynamics of the transition to clean energy. Changes in energy systems take time because energy production relies on large, expensive infrastructure that is slow to turn over. The oil economy, for example, entails a vast network for exploration, drilling, transport, refining, production, automobile manufacture, highway construction, and even human-settlement patterns. Each of these elements cost hundreds of billions of dollars and took decades to build. The same is true for coal production and use. To transform these systems will take decades.

The world has spent more than half of the trillion-ton carbon budget. Current trends suggest that, absent policy action, we will exhaust the remaining half by about 2050.<sup>3</sup> The reality of infrastructure “lock-in” and inertia in the global energy supply mix further underscores how vital it is to consider *cumulative* carbon emissions over time, rather than assessing them solely on an annual basis. For instance, Figure 1 compares a business-as-usual (BAU) trajectory with a scenario in which future emissions remain flat. The figure depicts both cumulative emissions and annual emissions.

In the BAU case, emissions increase annually and sail by the trillionth ton as early as about 2050. Conversely, one might expect that if emissions remain at current levels and do not rise, the duration before we exhaust the budget would increase significantly. Yet the flat-emissions scenario crosses the trillion-ton line just about a decade later! In other words, *even if all future demand growth from this point forward were met by zero-carbon sources, we would still grossly overshoot the budget.* This finding highlights the reality that it is not enough for us to ramp down emissions or keep them flat: we must bring them to very low levels over the next few decades.

En-ROADS allows us to investigate different options for remaining below the trillionth ton and gives a sense of how long it will take for different actions, investments, and policies to reduce emissions. The model accounts for the system-wide interactions among different energy options. For example, how would the aggressive pursuit of energy efficiency affect the growth of renewable energy? How do technology learning curves change the suite of options? Underlying the model is an extensive study of factors such as construction delay times, progress ratios, price sensitivities, historic growth rates of specific energy resources, and energy-efficiency potential.

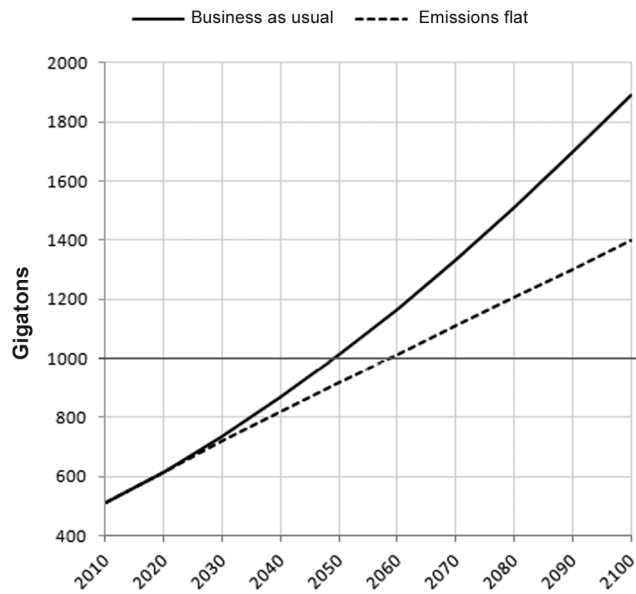
Note that En-ROADS is not a predictive model; its “results” – which, in this essay, are primarily a calculation of the year in which carbon emissions from a given test scenario cross the trillion-ton line – are approximations only, accompanied by a range of uncertainty. Instead, the model is a scenario-builder that tests assumptions about how prospective changes in the global energy supply mix might affect climate outcomes.<sup>4</sup>

If we remain on a BAU trajectory, we will surpass the trillionth ton and the 2 degree Celsius benchmark – the threshold that scientists suggest is a dangerous one to cross – around the middle of this century. The good news is that emissions in many parts of the industrialized world have begun to flatten and even decline. The bad news is that surging carbon emissions in China, India, and other rapidly industrializing countries do not yet show signs of abating. By 2030, China’s annual carbon emissions are projected to be around 5 billion tons, compared to around 2.8 billion in 2010. Left unchecked, and in light of prevailing growth rates, China’s emissions alone could overwhelm the carbon budget by the end of the twenty-first century.

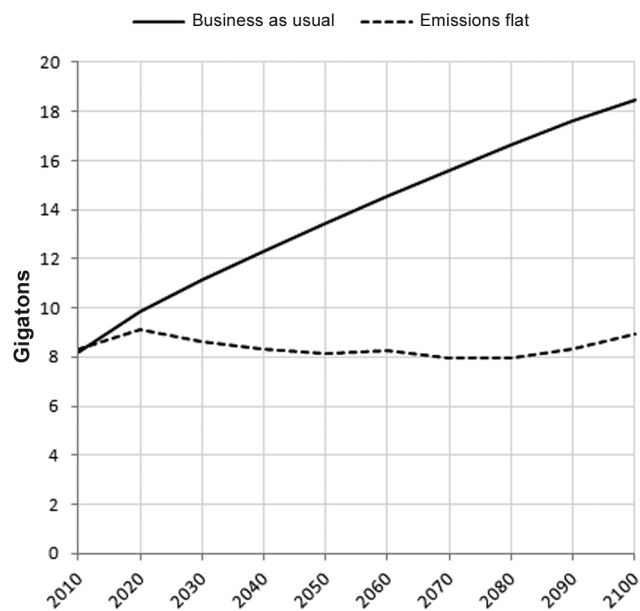
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Franklin M.  
Orr, Jr. &  
Clara  
Vondrich

A Trillion Tons Figure 1  
Two Carbon-Emissions Trajectories, 2010 – 2100

### Cumulative Carbon Emissions



### Annual Carbon Emissions



Source: All figures created by authors.

Locking in carbon-emitting infrastructure is among the more serious threats of a BAU world. Commercial and residential buildings have useful lives of several decades or more. Coal-fired power plants remain online for up to sixty years.<sup>5</sup> New oil and natural gas pipelines could operate for a half-century. Once these investments are made, the economic imperative is to use them. Any new zero-carbon energy source must contend with this embedded capital stock. After coal plants are built, their marginal costs of operation are relatively small, so the competitive bar for new technologies is high.

The current flood of urban migration in the developing world offers a useful case study of lock-in. China is experiencing the greatest urban population boom in human history. The United Nations estimates that Chinese cities will add 231 million people by 2025 and another 186 million by 2050<sup>6</sup> – numbers roughly equal to the populations of Indonesia and Brazil, respectively. To prepare for this growth, Chinese leaders plan to build at least one thousand new cities.

Well-designed cities can slash waste, reduce air and water pollution, and provide appealing spaces for people to work, shop, and socialize. Poorly designed cities sprawl across the landscape, locking in unsustainable patterns of energy use for decades. Without policy interventions, including tough building standards and regulations favoring compact development and low-carbon public transit, BAU development is likely to embed a high-consumption profile that will be virtually impossible to repair. Indeed, the International Energy Agency (IEA) has warned that without further action, by 2017 all CO<sub>2</sub> emissions permitted in its 450 Scenario – in which the atmospheric concentration of carbon dioxide equivalents (CO<sub>2</sub>e) stabilizes at 450 parts per million (ppm), resulting in an average warming

of 2 degrees Celsius – will be “locked in” by existing power plants, factories, buildings, and other long-lived infrastructure.<sup>7</sup> Today’s infrastructure decisions are thus of crucial importance to long-term climate change. Society sets structural patterns for future emissions every time a highway, power plant, factory, or house is built. That capital stock lasts fifty to one hundred years or more – and every year, contributes carbon to the atmosphere. Furthermore, it is far more costly to repair or retrofit any of these investments than to get them right in the first place. The duration of those investments, in light of the unforgiving mathematics of carbon accumulation, means that the window for making business-as-usual choices is closing fast. The IEA’s point is that doing this even for another half-decade locks in a future nobody wants to see.

However mundane it may seem, energy efficiency is a vital bridge to a low-carbon future. Efficiency improvements across the transportation, power, and industry sectors would slow or flatten the rise in energy demand in the coming decades, thereby making the climate problem more solvable. Aggressive pursuit of energy-efficiency solutions on the cutting edge of engineering, technology innovation, and thermodynamics would yield significant energy savings. Consider one example: If a coal plant is 33 percent efficient (the average in the United States), and an incandescent lightbulb is 5 percent efficient, then the *net conversion of energy to light* is about 1.65 percent. By contrast, a compact fluorescent lightbulb (CFL, roughly 25 percent efficient), powered by a combined-cycle natural gas turbine (about 60 percent efficient, using a lower-carbon fuel), converts 15 percent of the energy to light – almost a tenfold increase. The corresponding reduction in CO<sub>2</sub> emissions per hour of lighting is approximately 90 percent.

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Clara  
Vondrich

A Trillion  
Tons

The next generation of light-emitting diode lamps (LEDs) will garner even greater energy savings.<sup>8</sup> Indeed, the Department of Energy estimates that replacing regular lightbulbs with LEDs could potentially save 190 terawatt-hours annually, the equivalent of lighting more than 95 million homes or roughly 5 percent of total U.S. electricity consumption in 2010.<sup>9</sup>

Similar opportunities exist in virtually every sector of the economy. Not surprisingly, a number of major studies have found that energy efficiency measures are a powerful tool for slashing emissions. According to a study from the National Academy of Sciences and the National Academy of Engineering, the technical abatement potential for energy efficiency in the United States is large; moreover, its cost would be low – or negative, as energy savings would outweigh the costs of new technologies over time.<sup>10</sup> The study found that U.S. energy use could fall below BAU projections by 17 to 20 percent in 2020, and by 25 to 31 percent in 2030, provided that “energy prices are high enough to motivate investment in energy efficiency, or if public policies are put in place that have the same effect.”<sup>11</sup>

Globally, the prospects for energy efficiency are bright. A report published by McKinsey & Company suggests that, with reasonable investments in energy efficiency, the projected growth in global energy demand could be halved by 2020.<sup>12</sup> The necessary investments of roughly \$170 billion annually would generate an average internal rate of return of 17 percent, with total energy savings estimated at \$900 billion annually by 2020. The investment strategy would target only cost-effective opportunities, seeking efficiency improvements across systems such as lighting, cooling, and heating in particular, as well as vehicles and industrial machinery.

The authors of the report caution that their investment strategy would face a

number of significant challenges. For instance, “two-thirds of the investment opportunity lies in developing countries, where consumers and businesses face a variety of competing demands for their scarce investment dollars.” In many sectors, efficiency standards may have to be implemented to overcome market failures. Nevertheless, the global potential of energy efficiency to cut carbon at a low cost is tremendous.

What does En-ROADS tell us about the effect of aggressively pursuing energy efficiency? With regard to the global economy, the model’s BAU scenario assumes an average annual decrease in energy intensity (energy used per unit of GDP) of 1.1 percent from 2010 to 2050.<sup>13</sup> The globally aggregated En-ROADS model does not allow for a manipulation of efficiency improvements across individual sectors or regions. Instead, by varying the energy intensity of GDP, the model allows us to assess the impact of a highly efficient energy economy on the carbon budget.

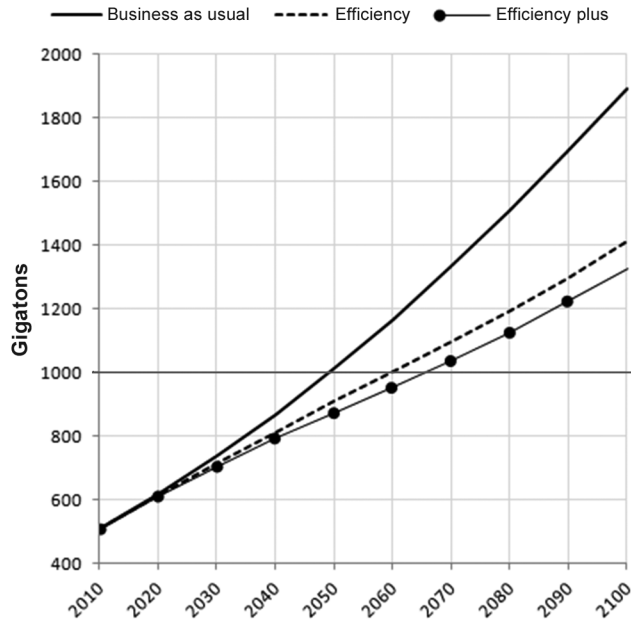
Figure 2 compares two energy-efficiency scenarios with a BAU world: “efficiency” (EE) and “efficiency plus” (EE+). The EE scenario assumes an average annual improvement in energy intensity of roughly 2.5 percent between 2010 and 2050; EE+ assumes an average annual improvement of roughly 3 percent. Sustained 2 to 3 percent improvements are plausible given a BAU energy-intensity improvement rate of about 1.1 percent between 2010 and 2050; further, they are consistent with mitigation scenarios examined by other models.

In both scenarios, cumulative carbon emissions still increase but do so more slowly relative to BAU. In the EE scenario, for example, annual emissions in 2050 are about 42 percent less than in the reference case. Although annual emissions bend downward in both test scenarios, they ultimately flatten and rise again. Why?

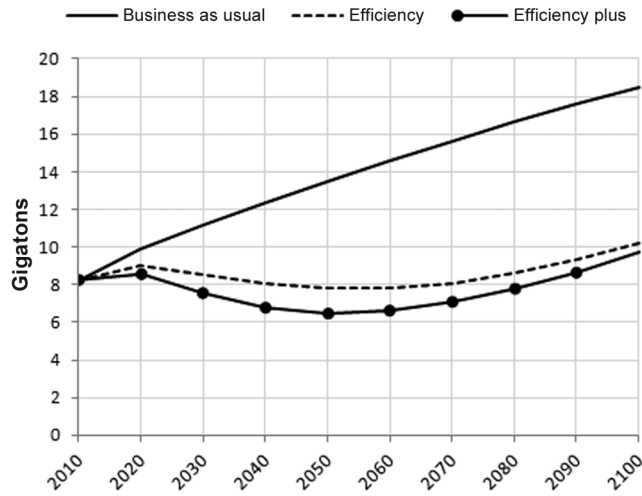
Figure 2  
Efficiency Test Scenarios, 2010 – 2100

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Clara  
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Cumulative Carbon Emissions



Annual Carbon Emissions





A Trillion  
Tons Efficiency measures provide large energy savings in the near term, but these gains are overwhelmed over time if population and GDP growth continue unabated.

The greatest reward in achieving either of the high-efficiency scenarios is that they cut the burden for new zero-carbon energy sources almost in half. Nevertheless, efficiency improvements alone are not enough to avoid exceeding the budget. The EE scenario reaches the trillionth ton in approximately 2060; EE+ crosses that line about five years later. While arguably modest, a ten- to fifteen-year grace period provides needed flexibility in the low-carbon transition and is especially significant because it can be attained at low cost.

How much can existing and near-term renewable energy sources, such as solar and wind, help? Renewable energy, excluding hydropower, is the fastest-growing source of electricity generation and is projected to account for up to a quarter of global electricity generation by 2035 (compared to less than 5 percent today).<sup>14</sup> The EIA predicts annual growth rates averaging 3.1 percent between now and 2035. By contrast, coal-fired electricity generation is expected to grow at an average rate of 1.9 percent per year over the same period.<sup>15</sup>

Recent growth rates are stunning: over the five-year period from 2005 through 2009, global renewable energy capacity grew at rates of 10 to 60 percent annually for many technologies.<sup>16</sup> While percentage increases of this magnitude cannot be expected to last as the base for renewables expands, the forward momentum is undeniable. In 2008, for the first time, more renewable energy than conventional power capacity was added in both the European Union and the United States.<sup>17</sup> In 2010, renewables represented half of all newly installed electric capacity worldwide.<sup>18</sup>

To further put these numbers in context, total global power-generating capacity in 2011 was estimated at 5,360 GW. By the end of 2011, total renewable power capacity worldwide exceeded 1,360 GW, up 8 percent over 2010. Renewables thus comprised more than 25 percent of total global power-generating capacity and supplied an estimated 20.3 percent of global electricity. Non-hydroelectric renewables exceeded 390 GW, a 24 percent capacity increase over 2010. Total installed capacity of non-hydroelectric renewables in 2010 was around 312 GW, just over 6 percent of the global total. Note that intermittent renewable energy resources are available only a fraction of the time, so nameplate capacity does not directly translate into energy. Energy production is equal to nameplate capacity multiplied by the capacity factor (the fraction of time plants or installations are in operation), which can vary from about 15 percent for solar photovoltaics in climates that do not receive much sunlight to up to 40 percent for offshore wind installations. Nevertheless, by 2035, renewables are expected to account for about a third of global installed capacity and to generate between 15 and 23 percent of the world's electricity.<sup>19</sup>

Some renewable energy technologies are close to commercially competitive, including wind. Solar photovoltaics (PV) are approaching the mark, while concentrated solar thermal power has some distance yet to go. Aggressive deployment of renewables can make a big difference relative to the carbon budget. Nevertheless, with the possible exception of onshore wind, these technologies still need to make substantial progress along the learning curve – dropping in price as their volume grows – to compete with incumbent fossil fuel sources.

Evolving technologies, including most renewable applications, have a high learn-

ing rate compared to mature technologies like coal.<sup>20</sup> Solar PV has traditionally exhibited an average learning rate of 20 percent, meaning that price drops by a fifth for every doubling of production.<sup>21</sup> If these rates persist, a few more doublings of production capacity could result in cost parity with fossil sources. Industry insiders suggest that solar PV is on track to be the cheapest energy source for many parts of the world by the end of the decade.<sup>22</sup> There are two caveats, however: solar learning curves may be flattening<sup>23</sup>; and the cost of solar cells is only half of the equation. The enclosure, glass cover, mounting racks, junction boxes, and wiring – together called the *balance of system* – are now about half the cost of solar electricity, and their price decline may be slower.<sup>24</sup>

Nevertheless, both wind and solar prices continue to decline. The solar industry has achieved manufacturing economies of scale, and more efficient cells are being developed. The cost of wind energy is already close to competitive with new gas and coal. According to REN21's 2011 *Global Status Report*, the cost per kilowatt-hour for onshore wind ranges from 5¢ to 9¢, for an average of 7¢/kWh.<sup>25</sup>

To examine the effect that an accelerated deployment of renewable technologies could have on the carbon budget, we modeled the following two scenarios:

- Renewables (REN). The cost of energy from new renewables was assumed to be 60 percent below its 2012 price, beginning in the same year. Such a dramatic decrease in price might come from an imagined technological breakthrough in R&D.<sup>26</sup>
- Renewables Plus (REN+). A 70 percent drop in cost was assumed beginning in 2012. We also added a 2 percent per year reduction in the barriers to electrifying the transport sector.<sup>27</sup>

Figure 3 compares emissions in these test cases to BAU, revealing a substantial divergence – at least in annual emissions. In 2050, annual REN emissions are 20 percent below BAU emissions; REN+ emissions are 31 percent lower. The difference is less striking in the cumulative emissions view, where REN+ crosses the trillionth ton less than a decade after BAU.

This delay is slight because the displacement of fossil fuels by renewables is minimal in the near decades. Scaling renewable technologies to meet global energy needs remains a challenge even when prices become competitive. When renewables enter the market at or below the price of new coal (as they do in both test cases), demand for coal declines only marginally – a result of the embedded infrastructure of fossil-fuel generating sources. Turning over the capital stock of coal plants takes time. Moreover, cost is not the only factor determining penetration rates of a young technology. Scalability and regional differences in wind and solar resources, as well as intermittency and the corresponding firming requirements,<sup>28</sup> also play a role.

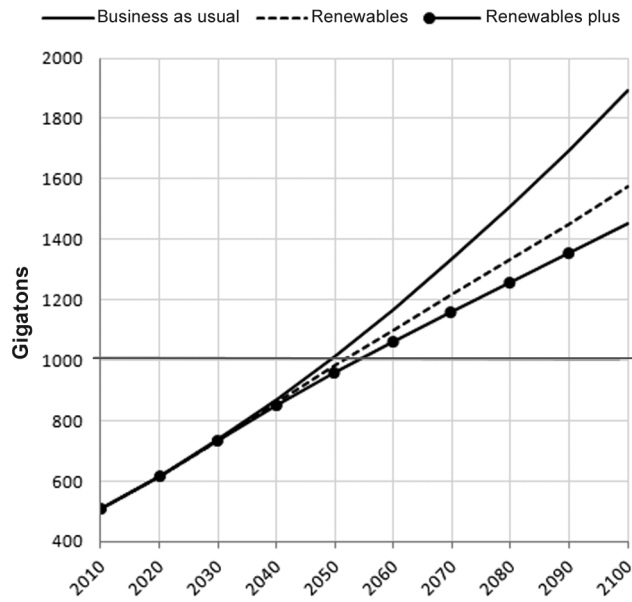
What other technology breakthroughs might play a significant role in the energy transition ahead? Carbon capture and storage (CCS) figures prominently in many mitigation scenarios as virtually a *sine qua non* of remaining on a 450 ppm pathway. However, progress has been slow in building the large-scale and capital-intensive demonstration projects needed to test the viability of the technology over its life cycle: that is, from combustion of the fossil fuel to the capture and storage of related emissions. In its 2012 report to the Clean Energy Ministerial, the IEA notes that we can expect to see about ten CCS plants operating by the middle of this decade. But we will need about 110 more by 2020, the agency argues, in order

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Vondrich

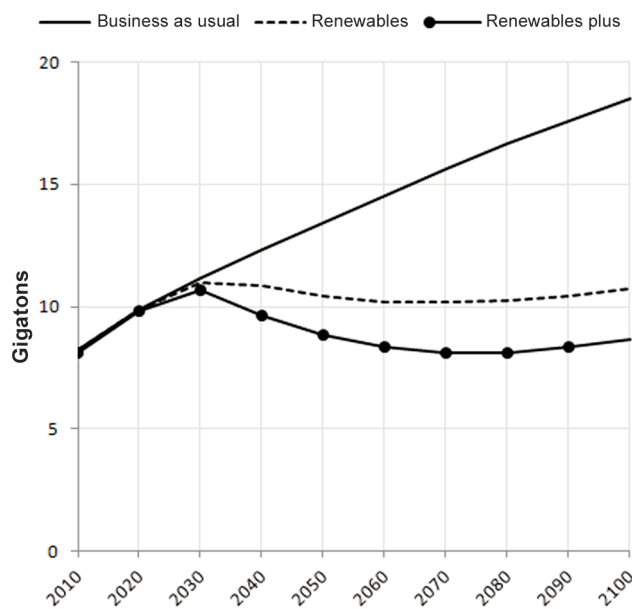


A Trillion Tons Figure 3  
Renewable Energy Scenarios, 2010–2100

### Cumulative Carbon Emissions



### Annual Carbon Emissions



to keep global temperature rise below 2 degrees Celsius.<sup>29</sup>

Public financing for CCS peaked in 2008 and 2009, when the technology received a boost as part of broader economic stimulus programs.<sup>30</sup> Nevertheless, much of the promised funding remains unallocated. As of 2012, only 60 percent of the approximately \$21.4 billion available to support large-scale demonstration projects had been assigned to specific ventures.<sup>31</sup> Ongoing upheaval in the global market will undoubtedly continue to squeeze CCS budgets. Moreover, CCS is likely to remain underfunded in the absence of strong and reliable policy signals, such as a price on carbon.

CCS provides just one example of the potential challenges facing any new breakthrough technology. Our decades-long experience with solar PV further confirms that, even after invention and initial deployment, a technology often needs additional help to progress along its learning curve. Despite being commercialized in the 1970s, and notwithstanding its recent and striking price reductions, solar PV has yet to achieve global penetration rates of 1 percent. Certainly, a few more doublings of production capacity and concomitant price reductions could revolutionize the outlook for solar, but the sheer scale of the transition means that this will take time.

Our discussion is by no means a condemnation of renewables and other new energy-supply innovations. The above examples merely underscore the intense pressure that innovations face as they try to gain a foothold in the market. In the case of renewables, this challenge is largely attributable to the fact that cheap fossil fuels are an entrenched and ubiquitous part of our energy economy. Further complicating matters is the uneven playing field that results from the failure to

price externalities associated with fossil fuels, including impacts on air quality, human health, and national security, among many other factors. Additionally, renewables are likely to have higher capital costs (but lower operating costs) than conventional resources, which cost less up front but require lifetime fuel purchase. Higher capital costs can limit financing for renewables. Financing also comprises the biggest fraction of the levelized cost of renewable energy, further undercutting competitiveness with established fossil sources. Any other new zero-carbon technology will likely face similar hurdles.

But let us adopt a techno-optimist's view and assume that a new energy game-changer arrives on the scene. This path-breaking technology circumvents the problems noted above because innovations have resulted in an energy source so cheap that the new technology enters the market at half the price of coal. It is deployable at scale and available for mass penetration around the globe. What is the impact of this game-changer on the carbon budget?

Specifically, we defined our New Technology (NT) scenario by the following assumptions:

- R&D efforts produce a zero-carbon prototype in 2020;
- Global deployment takes twelve years; and
- The technology enters the market at half the price of new coal.

The NT case assumes that a new zero-carbon energy source, not yet conceived, achieves mass global penetration slightly more than twenty years from now. This ambitious scenario exceeds by a wide margin the commercialization trajectories of any large-scale energy technology existing today. For instance, in the renewables sector, wind power has only recently achieved significant rates of penetration

*Hal Harvey,  
Franklin M.  
Orr, Jr. &  
Clara  
Vondrich*

in some countries (Denmark, Spain, and Germany) where it has received heavy public support – more than a half-century after the first grid-connected wind turbine was manufactured in 1951. Nevertheless, startling innovations are possible.

The NT scenario circumvents the most obvious hurdle to competitiveness – namely, cost – by stipulating that the new zero-carbon energy source enters the market at half the price of coal. While this strains credulity, it could be possible if a carbon price were imposed or if deployment of the new technology were declared a national or international priority. Again, our intent was to test assumptions at the outer bounds of technical or political feasibility to gauge the impact on the carbon budget. We found that the carbon emissions accumulated to date renders the budget relatively insensitive to even very aggressive assumptions on an energy game-changer.

Figure 4 shows that annual NT emissions are 11 percent below BAU emissions in 2050, but crossing the trillionth ton is delayed by less than a year (though the test case diverges more substantially from BAU as time passes beyond the trillionth ton). At first glance, the meager benefits of the NT scenario are hard to understand. The assumptions are so radical that one would expect the needle to move much more sharply. In the long run, if a new technology is cheaper, we would expect it to take over, partly because of the learning curve dynamics, which amplify any initial cost advantage (cheaper equals more sales, which leads to more learning and continued price reductions). However, this cycle is tempered by capital turnover; even if the new technology is dominant as a share of investment in new capacity, replacing existing capital and achieving dominance overall takes a long time.

For En-ROADS simulations, the fractional investment in various types of

energy supply over the course of each time period is determined by the relative attractiveness of each supply type. Relative attractiveness is a function of the cost of each technology, which in turn is influenced by learning, cost of nonrenewable resources, suitability of remaining sites for renewable energy installations, and capacity for construction of new supply.<sup>32</sup> As a result of this structure, market shares of a new technology may not correspond in the short term with what one might expect on the basis of cost alone.

These assumptions about the energy system imply that coal, oil, and gas will continue to be burned for energy throughout the century. Even in scenarios where renewable energy or new technologies grow significantly, drop in price, and dominate the market, fossil fuel energy continues to be inexpensive (recall that there is no price on carbon) and sufficiently available to attract investment and use. Although reliance on fossil fuels is much less than in the BAU scenario, it is still enough to prolong the increase of cumulative emissions.

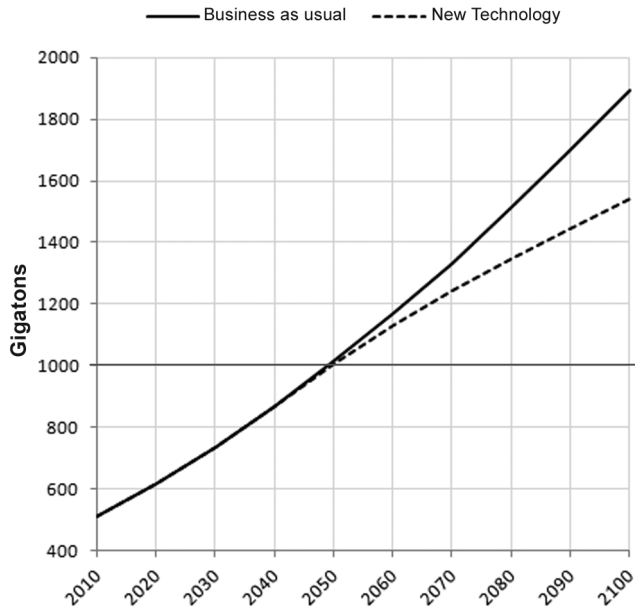
The En-ROADS simulations discussed in this essay indicate the value of a diversified portfolio of emissions-reducing tools. No one tool suffices. Efficiency alone, while curtailing demand, cannot stand in for a low-carbon energy source. Renewables are not powerful enough to displace coal in the near term; we need sustained investments and efficiency measures to give them time to descend the learning curve. A new technology breakthrough, though a crucial long-term solution for global energy needs, requires several decades before it can achieve sufficient market penetration to make a difference.

Estimated annual emissions do drop sharply in the individual scenarios. For ex-

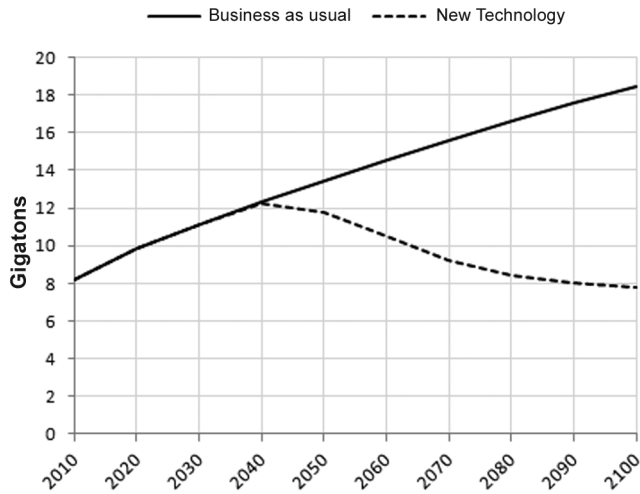
Figure 4  
New Technology Scenario, 2010 – 2100

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Clara  
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Cumulative Carbon Emissions



Annual Carbon Emissions



ample, in 2050, EE+ emissions are 47 percent below BAU, and REN+ emissions are 31 percent below. Nevertheless, the impact on the cumulative budget is limited. The aggressive renewables test case buys only a few additional years before we cross the trillion-ton line. The NT scenario is also marginal, buying less than five years beyond BAU. The impact discrepancy between annual and cumulative emissions underscores the inadequacy of national emissions reduction schemes based on the “targets and timetables” approach. For instance, the United States has committed to 80 percent reductions relative to baseline emissions in 2050. However, unless this target is placed in the context of cumulative emissions, the numbers are fairly meaningless: “[D]espite making reference to being guided by the ‘science’, the [Copenhagen] Accord makes no mention of cumulative emissions as the scientifically credible framing of mitigation. [Thus] the Accord still falls short of acknowledging what the science makes absolutely clear – it is cumulative emissions that matter.”<sup>33</sup> In other words, we cannot emit willy-nilly until 2049 and then slash emissions abruptly in 2050 and expect to be fine. Only cumulative emissions matter.

Nevertheless, we can delay emission of the trillionth ton much further by deploying a portfolio of actions. For instance, a serious ramp-up of renewables capacity coupled with an aggressive efficiency portfolio buys more than twenty years relative to BAU. Annual emissions in 2050 are 57 percent less than BAU, and the trillionth ton is not emitted until sometime around 2073. Combining the three most aggressive scenarios – EE+, REN+, and NT – is marginally better (see Figure 5).<sup>34</sup>

The combined scenario delays crossing the trillion-ton line by about a quarter-century – a good start, but not sufficient. Land-use changes are also an essential

piece of the puzzle. Terrestrial sinks, forests, and plants have sequestered about a quarter of human-driven carbon emissions over time.<sup>35</sup> Thus, deforestation in the Amazon, Indonesia, and the Congo Basin is a major threat, converting a massive carbon-storage sink into a massive carbon source. The draining and burning of peat bogs is another major global source of CO<sub>2</sub> emissions – indeed, the third largest after burning fossil fuels and deforestation. Unsustainable farming practices are also to blame. For instance, the carbon-rich grasslands and forests in temperate zones have been replaced by crops with a much lower capacity to sequester carbon. Aggressive policies are needed to arrest these developments and further forestall the trillionth ton.

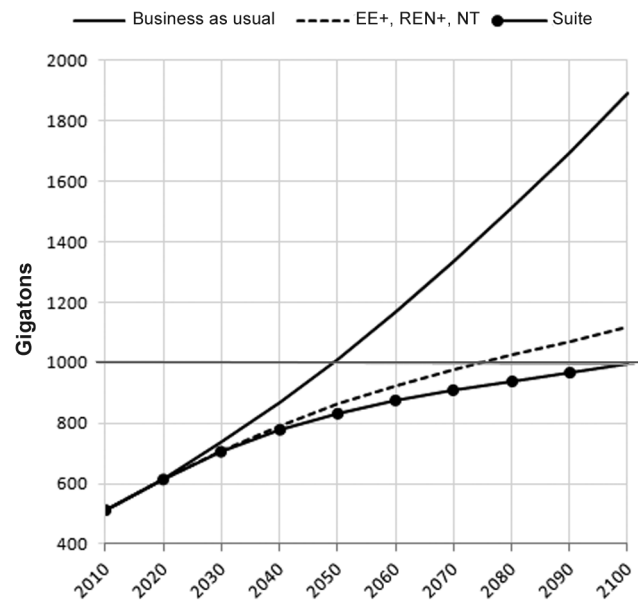
The last missing piece is the interaction of economic growth and coal. The scenarios modeled in this essay reflect this relationship in the second half of the century, when carbon emissions begin to grow after a period of steady decline. In the EE+ and REN+ scenarios, for example, annual emissions decline through the middle of the century only to rise again. Why does this happen? Quite simply, the clean energy supply is overwhelmed by growth, absent additional downward pressure on coal. If GDP continues to grow by 2 to 3 percent a year and coal remains cheap, efficiency gains and renewables will not keep pace with demand.<sup>36</sup> A price on carbon or an international deal on emissions reductions could alter this picture. Though policy options to achieve an ordered reduction of coal are manifold, we use the proxy of a carbon price in our final scenario below.

Our final scenario combines EE+, REN+, and NT with two new actions or policies: a CO<sub>2</sub> price of \$35 per ton starting in 2025, and a 50 percent reduction in emissions from land-use sectors and other more short-lived greenhouse gases.

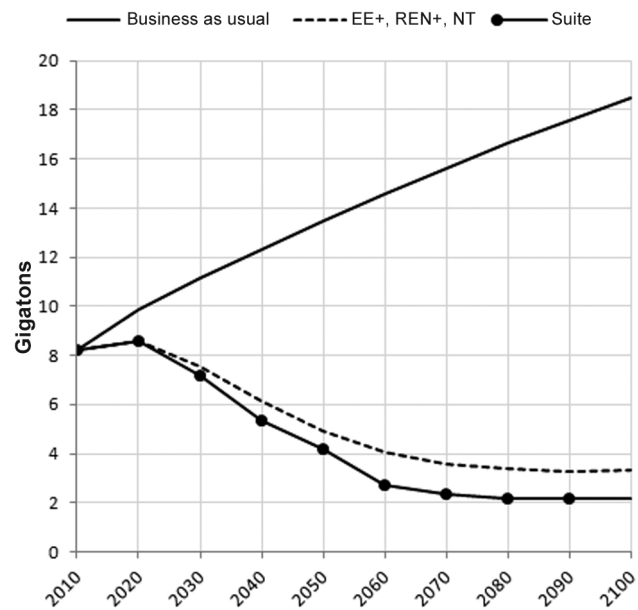
Figure 5  
Combination Scenarios, 2010 – 2100

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Clara  
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Cumulative Carbon Emissions



Annual Carbon Emissions





As Figure 5 shows, this scenario (“the Suite”) holds cumulative emissions below the trillionth ton throughout this century. In 2050, annual emissions are 67 percent below BAU. Specific components of the Suite could be adjusted, of course. Use of nuclear power (in place of coal) could reduce emissions associated with base-load electric power generation, and recent changes in the availability of natural gas could also be explored. A more stringent land-use policy might be traded for a carbon price. This thought experiment simply highlights that there is no single solution: multiple measures are needed to keep humanity on a reasonable climate trajectory.

The En-ROADS modeling exercise shows how rapid deployment of efficiency improvements, renewables, and new technologies might impact the carbon budget over this century. Specifically, it confirms that each component is necessary and none is sufficient alone. Combined with a carbon price and effective land-use policy, these three tools offer a challenging but credible path that stays within the

carbon budget. We do not have time to waste if we are to avoid dangerous, irreversible climate changes for which modern civilization is ill-suited to adapt. Indeed, the IEA warns that we have five years to get off the BAU path. After that point, the energy infrastructure we build will start to lock in emissions-generating infrastructure that will push global warming beyond 2 degrees Celsius.

Starting today, we can use existing tools to begin a steady decline in emissions at low cost. In coming years, renewable power will grow cheaper, while fossil fuel prices will adjust to future supplies and competition from other resources. A breakthrough innovation may well revolutionize the energy sector in ways we can now only dream about. Programs and policies to foster advances can be pursued on a national, state, or local level; policymakers and businesses at every level are empowered to take action now. The scenarios examined here suggest that with an aggressive and sustained effort, we can push back the timetable for expending our carbon budget and thus sharply reduce the risks of surpassing the trillionth ton.

#### ENDNOTES

\* Contributor Biographies: HAL HARVEY is CEO of Energy Innovation: Policy and Technology LLC and Senior Fellow for Energy and the Environment at the Paulson Institute at the University of Chicago. He is the founder of the ClimateWorks Foundation, where he previously served as CEO. He is former Environment Program Director at The William and Flora Hewlett Foundation and founder and past President of the Energy Foundation. An energy engineer, he has worked on energy policy in a dozen countries.

FRANKLIN M. ORR, JR., is the Keleen and Carlton Beal Professor in the Department of Energy Resources Engineering and Director of the Precourt Institute for Energy at Stanford University. He is also a Senior Fellow at the Woods Institute for the Environment. His research focuses on understanding the physical mechanisms that control displacement performance in gas injection processes for oil recovery and storage of greenhouse gases. His work has appeared in the *Journal of Fluid Mechanics*, *Energy Conversion and Management*, and the *International Journal of Greenhouse Gas Control*, among other publications.

CLARA VONDRICH is Director of Leadership Initiatives at the ClimateWorks Foundation. She is an attorney with a background in international arbitration and energy policy. Previously, she served as Counsel to the President’s Commission on the BP Deepwater Horizon Oil Spill, focusing on ecological restoration and environmental justice. She also helped pre-

pare amicus briefs in support of state plaintiffs in the landmark U.S. Supreme Court case *American Electric Power v. Connecticut*, which sought to hold major electric utilities liable for their contribution to climate change.

Hal Harvey,  
Franklin M.  
Orr, Jr. &  
Clara  
Vondrich

Acknowledgments: We would like to thank Andrew Jones and Elizabeth Sawin of Climate Interactive for their unfailing support and collaboration at all stages of producing this paper.

<sup>1</sup> Myles Allen et al., “Warming Caused by Cumulative Carbon Emissions Towards the Trillionth Tonne,” *Nature* 458 (April 30, 2009): 1163–1166. Other carbon budgets have been proposed, depending on the “acceptable risk” stipulated for crossing the 2 degree Celsius threshold. For instance, Malte Meinshausen and colleagues propose a carbon budget of roughly 830 billion tons to assure a 50 percent chance of staying under 2 degrees Celsius. See Meinshausen et al., “Greenhouse-Gas Emission Targets for Limiting Global Warming to 2° C,” *Nature* 458 (April 30, 2009): 1158–1162. Despite these differences, the “need in principle for a cumulative limit near or below one trillion tonnes is generally accepted”; see Myles Allen et al., “The Case for Mandatory Sequestration,” *Nature Geoscience* 2 (2009): 813–814.

<sup>2</sup> En-ROADS was created by Climate Interactive, Ventana Systems, MIT Sloan School of Management, and the ClimateWorks Foundation global research team. It is designed to complement, not supplant, other more disaggregated models addressing similar questions, such as those in the Energy Modeling Forum’s EMF-22 suite. En-ROADS relies on other models and Energy Information Administration (EIA) projections for testing and data. It is based on the Ph.D. dissertations of John Sterman, Professor in the MIT Sloan School of Management, and Tom Fiddaman of Ventana Systems. We wish to distinguish En-ROADS from the MIT Emissions Prediction and Policy Analysis model (EPPA), another simulation related to climate and energy. EPPA was developed as part of MIT’s Joint Program on the Science and Policy of Global Change. En-ROADS is a system-dynamics (high-order nonlinear differential equation) simulation; a more detailed description of En-ROADS methodology and assumptions is available at <http://climateinteractive.org/simulations/en-roads/en-roads>.

<sup>3</sup> Allen et al., “Warming Caused by Cumulative Carbon Emissions Towards the Trillionth Tonne.” See also Catherine Brahic, “Humanity’s Carbon Budget Set at One Trillion Tonnes,” *New Scientist*, April 29, 2009. But compare Meinshausen et al., “Greenhouse-Gas Emission Targets for Limiting Global Warming to 2° C.”

<sup>4</sup> The En-ROADS model does not include full economic feedbacks. For example, it does not capture the effect of energy prices on the aggregate economy’s growth rate, or the effect of climate impacts on economic growth. The model is not suitable, therefore, for exploring optimal trade-offs between mitigation and climate adaptation. Further, the current version of En-ROADS does not explicitly include carbon capture and storage, the dynamics of investment in and payoff from research and development, energy storage technologies, population, or labor. But it does include surrogates for each of these variables – namely, in its ability to model generic new clean-energy technologies, technology learning curves, and GDP growth.

<sup>5</sup> Estimates of the “useful life” of a coal plant vary from thirty to sixty years. Concerns about the conventional pollutants emitted by coal-fired power plants (sulfur and nitrogen oxides, particulate matter, and mercury) have led to increasing pressure in some countries to shut down the worst offenders. Still, the large base of coal plants and the low marginal cost of operation mean that many will run for a long time.

<sup>6</sup> United Nations Department of Economic and Social Affairs/Population Division, *World Urbanization Prospects: The 2009 Revision* (New York: United Nations, 2010), 12.

<sup>7</sup> *World Energy Outlook 2011* (Paris: International Energy Agency, 2011).

<sup>8</sup> At the moment, CFLs are more efficient than LEDs. Current LED efficacy is around 50 lumens per watt (60 lm/W max for some high-end Japanese products), whereas CFLs reach, at the most, 60 to 70 lm/W. CFLs will likely remain the better choice for general lighting for another five to ten years; LEDs are more likely to be used for specialty applications at first.

- A Trillion Tons<sup>9</sup> America's Energy Future Panel on Energy Efficiency Technologies, *Real Prospects for Energy Efficiency in the United States* (Washington, D.C.: National Academies Press, 2010).
- <sup>10</sup> Ibid.
- <sup>11</sup> Ibid.
- <sup>12</sup> Diana Farrell and Jaana K. Remes, "How the World Should Invest in Energy Efficiency," *McKinsey Quarterly* (July 2008).
- <sup>13</sup> The BAU scenario includes an annual improvement in primary energy intensity of 1.1 percent per year from 2010 to 2050. This estimate is somewhat lower than the reference scenarios developed by the IEA (approximately 1.8 percent per year from 2010 to 2050) and the EIA (1.7 percent per year from 2007 to 2035); but it falls in the range of EMF-22 reference scenarios (0.4 to 1.5 percent per year). See *World Energy Outlook 2011*; Energy Information Administration, *International Energy Outlook 2010* (Washington, D.C.: U.S. Department of Energy, 2010), Appendix J, "Kaya Identity Projections"; Leon Clarke et al., "International Climate Policy Architectures: Overview of the EMF 22 International Scenarios," *Energy Economics* 31 (2009): S64 – S81.
- <sup>14</sup> Energy Information Administration, *International Energy Outlook 2011* (Washington, D.C.: U.S. Department of Energy, 2011), 86, Table 11. When hydropower is included, renewable sources already supply nearly 20 percent of global electricity generation. See REN21, *Renewables 2011: Global Status Report* (Paris: REN21 Secretariat, 2011).
- <sup>15</sup> *International Energy Outlook 2011*, 86. Note that coal-fired generation, which starts from a far higher base than renewables, still experiences cumulative growth of 67 percent during that time: from 7.7 trillion kilowatt-hours in 2008 to 12.9 trillion kWh in 2035.
- <sup>16</sup> REN21, *Renewables 2010: Global Status Report* (Paris: REN21 Secretariat, 2010), 15.
- <sup>17</sup> REN21, *Renewables Global Status Report: 2009 Update* (Paris: REN21 Secretariat, 2009), 8.
- <sup>18</sup> REN21, *Renewables 2011: Global Status Report*.
- <sup>19</sup> Compare *World Energy Outlook 2011*, 178. The IEA's report forecasts the share of generation from non-hydroelectric renewables to be 15 percent in 2035, under its "New Policies Scenario." Also compare *International Energy Outlook 2011*, 86, Table 11. The EIA's report forecasts net electricity generation of renewables to be more than 23 percent.
- <sup>20</sup> Tooraj Jamasb, "Technical Change Theory and Learning Curves: Patterns of Progress in Energy Technologies," *The Energy Journal* 28 (3) (2007): 51 – 71.
- <sup>21</sup> See, for example, *Technology Roadmap: Solar Photovoltaic Energy* (Paris: International Energy Agency, 2010), 18. The IEA notes that PV module costs have decreased at historical learning rates of 15 to 22 percent and, further, that balance-of-system cost reductions have kept pace. The IEA assumes a prospective learning rate of 18 percent for the whole PV system on that basis.
- <sup>22</sup> Kees van der Leun, "Solar PV Rapidly Becoming the Cheapest Option to Generate Electricity," *Grist*, October 11, 2011, <http://www.grist.org/solar-power/2011-10-11-solar-pv-rapidly-becoming-cheapest-option-generate-electricity>.
- <sup>23</sup> David Keith and Juan Moreno-Cruz, "Is the Solar Photovoltaic Learning Curve Flattening?" Near Zero Technical Note, June 15, 2011, <http://nearzero.org>.
- <sup>24</sup> The extent to which balance-of-system costs are falling is an open question, with some parties quite optimistic. For instance, the IEA maintained that balance-of-system cost reductions have kept pace with the historical solar panel learning rates of roughly 20 percent. See *Technology Roadmap: Solar Photovoltaic Energy*, 18.
- <sup>25</sup> REN21, *Renewables 2011: Global Status Report*, 33 at Table 1. ("All costs in this table are indicative economic costs, levelized, and exclusive of subsidies or policy incentives. Typical energy costs are under best conditions, including system design, siting, and resource availability.

Optimal conditions can yield lower costs, and less favorable conditions can yield substantially higher costs.”)

Hal Harvey,  
Franklin M.  
Orr, Jr. &  
Clara  
Vondrich

- <sup>26</sup> A 60 percent cost reduction in renewable energy is clearly extreme. We sought to push the limits of technical feasibility for each test case to explore the ultimate impact on the carbon budget. That even extreme assumptions, individually or in partial combination, failed to prevent crossing of the trillionth ton is sobering.
- <sup>27</sup> Changes in investment and policy that would make it easier to electrify transportation were modeled by removing barriers to smarter grids, better electric vehicles, and complementary infrastructure such as fueling, parts, and maintenance.
- <sup>28</sup> Firming refers to use of a dispatchable backup resource (hydroelectric power or natural gas) to supplement an intermittent resource in order to ensure that energy supply is sufficient to meet demand.
- <sup>29</sup> *Tracking Clean Energy Progress: Energy Technology Perspectives 2012: Excerpt as IEA Input to the Clean Energy Ministerial* (Paris: International Energy Agency, 2010). The IEA scenario suggests that we need to capture about 270 million tons (Mt) CO<sub>2</sub> from the power and industry sectors in 2020. Meanwhile, the Global CCS Institute notes that the CO<sub>2</sub> storage capacity of the fourteen large-scale projects currently in operation or under construction is only about 33 Mt CO<sub>2</sub> per year.
- <sup>30</sup> For instance, President Obama allocated \$3.4 billion to CCS research development and deployment programs as part of the American Recovery and Reinvestment Act in 2009. Meanwhile, Europe established a financing program under the Emissions Trading Scheme to support large-scale demonstration projects for CCS and other low-carbon energy technologies (the “NER 300” program, so called because it allocates 300 million allowances in the New Entrants’ Reserve of the EU Emissions Trading Scheme).
- <sup>31</sup> *The Global Status of CCS: 2011* (Canberra, Australia: Global CCS Institute, 2011).
- <sup>32</sup> For details, see <http://climateinteractive.org/simulations/en-roads/en-roads>.
- <sup>33</sup> Kevin Anderson and Alice Bows, “Beyond ‘Dangerous’ Climate Change: Emissions Scenarios for a New World,” *Philosophical Transactions of the Royal Society A* 369 (1934) (January 13, 2011): 20–44.
- <sup>34</sup> This result is partially explained by market competition. A driving force in the scale-up of technologies is the “learning by doing” effect, whereby prices fall and investment becomes more attractive as installed capacity increases. When new technology and renewables grow simultaneously, neither accumulates an installed total as quickly.
- <sup>35</sup> Yude Pan et al., “A Large and Persistent Carbon Sink in the World’s Forests,” *Science* 333 (6045) (2011): 988–993.
- <sup>36</sup> These growth rates are used in En-ROADS simulations (and those in the EMF-22 suite, for example). Whether they are realistic for the end of the century is an open question.