Global Priorities for Zero-Emission Energy Innovation

AN EXPERT ELICITATION AND DISCUSSION

LED BY NEAR ZERO

Please refer to this document as:

Near Zero, Global Priorities for Zero-Emission Energy Innovation: An Expert Elicitation and Discussion

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March 2016

Global Priorites for Zero-Emission Energy Innovation

Summary of an expert elicitation and discussion led by Near Zero

Overview

In December 2015, world leaders from 20 countries announced Mission Innovation, an unprecedented increase in funds for accelerating affordable, zero-emission energy at global scale, doubling their respective clean energy research and development (R&D) investment over five years.

The Breakthrough Energy Coalition, a parallel private initiative led by Bill Gates, secured commitments from 28 significant private capital investors to support innovations coming out of this expanded public research pipeline.

Near Zero invited global experts in academia and industry to provide their perspectives on the opportunities and priorities for these R&D funds. Twenty-nine experts participated in this expert discussion (see Appendix A for a list of participants and Appendix B and C for a compilation of expert comments in full).

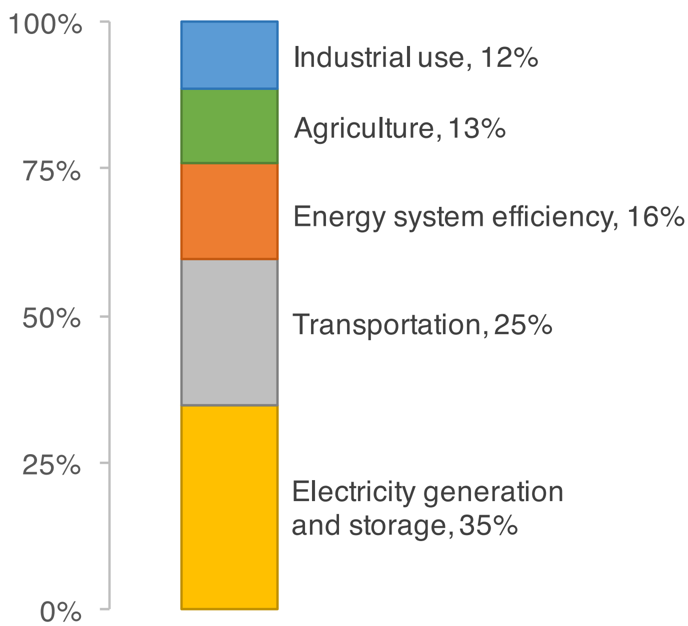


Figure 1: Experts' average allocation of a hypothetical $30 billion R&D budget across the categories identified by the Breakthrough Energy Coalition.

Key Takeaways

- Twenty-three experts allocated a hypothetical total global R&D budget of $30 billion per year across the five categories that the Breakthrough Energy Coalition has said it will invest in (Figure 1 and Figure A-1).
- On average, participants called for the largest share of funding to go to electricity generation and storage (35%), followed by transportation (25%).
- Most experts advocated a broad R&D portfolio, allocating a portion of the funds across all categories.
- Within these categories, experts recommended focusing on particular R&D priorities, the most favored being: Grid-scale energy storage, carbon capture and sequestration (CCS) for fossil generation, low-cost/high-density batteries for transportation, and carbon-neutral fuels for transportation that cannot be readily electrified.
- Many experts emphasized innovation for developing nations, which could have different priorities than developed nations and where technology transfer has sometimes failed in the past.
- Electrification of transportation should be a priority, most experts agreed. There was less agreement about whether energy efficiency R&D should be a lower priority than R&D in other sectors.

Allocation of R&D Budget

To transition the world to an energy future with near-zero emissions, the Breakthrough Energy Coalition has said it will invest broadly across five sectors: electricity generation and storage, transportation, industrial use, agriculture, and energy system efficiency. Experts were asked to allocate a hypothetical total global R&D budget of $30 billion per year across these sectors (averages in Figure 1, detailed breakdown in Figure 2).

Most experts advocated a broad R&D portfolio, allocating a percentage of funds to each of the five sectors. Electricity generation and storage received the highest level of allocation, with an average of 35%. All experts allocated funds to this sector, and several experts allocated in excess of 40%. This likely reflects agreement among experts that this sector will play a prominent role in decarbonization globally.

Transportation received the second highest level of allocation, with an average of 25%. This might reflect the view, suggested by several experts in written comments, that transportation is a relatively difficult sector to fully decarbonize.

The three remaining sectors received between 10-20% on average. Energy systems efficiency received an average of 16%, agriculture 13%, and industrial use 12%. This might reflect a desire by experts to design robust investment portfolios, as well as recognition that R&D opportunities exist in all five sectors.

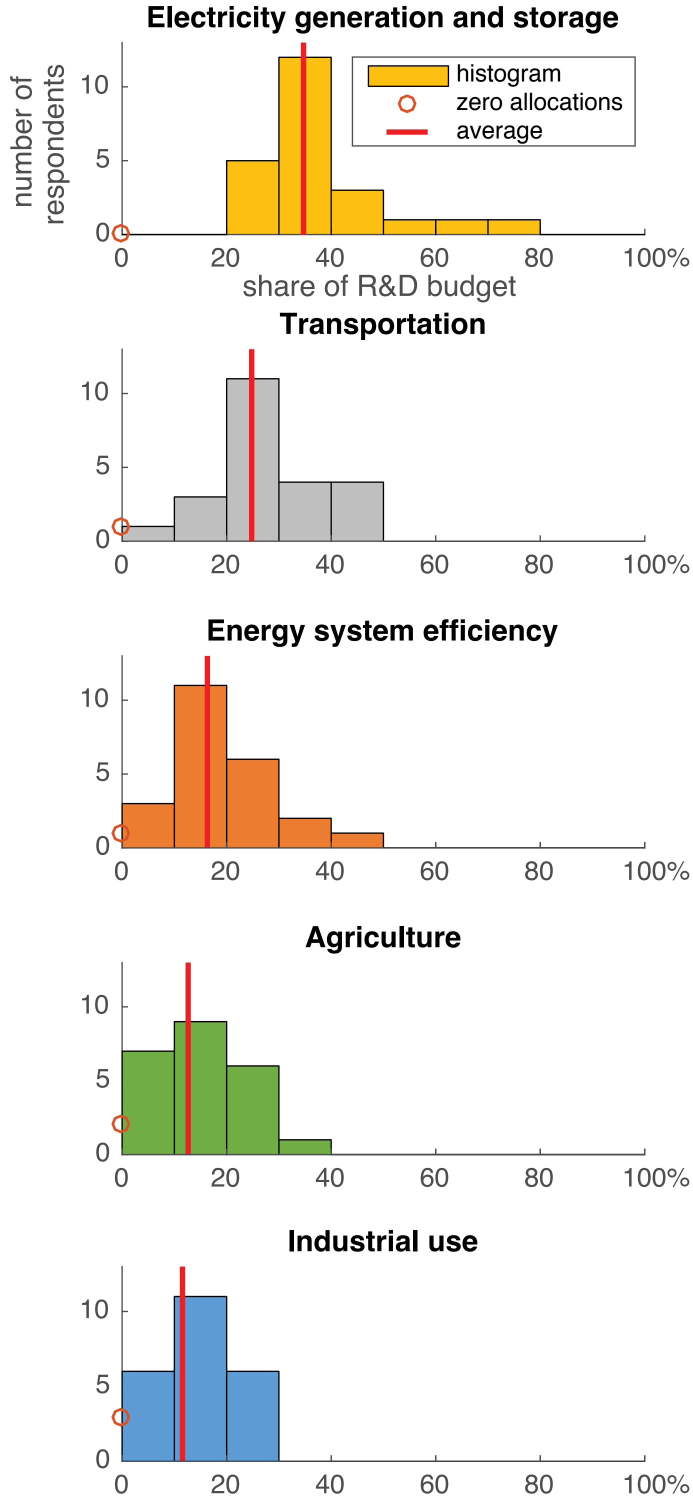


Figure 2: Share of the hypothetical $30 billion R&D budget that experts allocated for each category of spending—a breakdown of allocations summarized in Figure 1.

Specific Investment Priorities

During the early stages of the discussion, experts highlighted many specific R&D priorities that fell within the five broad Breakthrough Energy Coalition sectors. In addition, experts raised several overarching priorities relevant to R&D. All participants were then asked whether they agreed or disagreed with each of these items as top priorities (Figure 3). Recognizing that the list of topics was not constructed to be comprehensive, participants were also asked whether key topics were missing.

Within the electricity generation and storage and the transportation sectors, responses suggest some prioritization among options. Grid-scale energy storage, carbon capture and sequestration (CCS) for fossil generation, low-cost/high-density batteries, and carbon-neutral fuels garnered the largest support within these categories. Responses did not differentiate as strongly within the industrial use, agriculture, and energy system efficiency sectors, possibly due to fewer competing options.

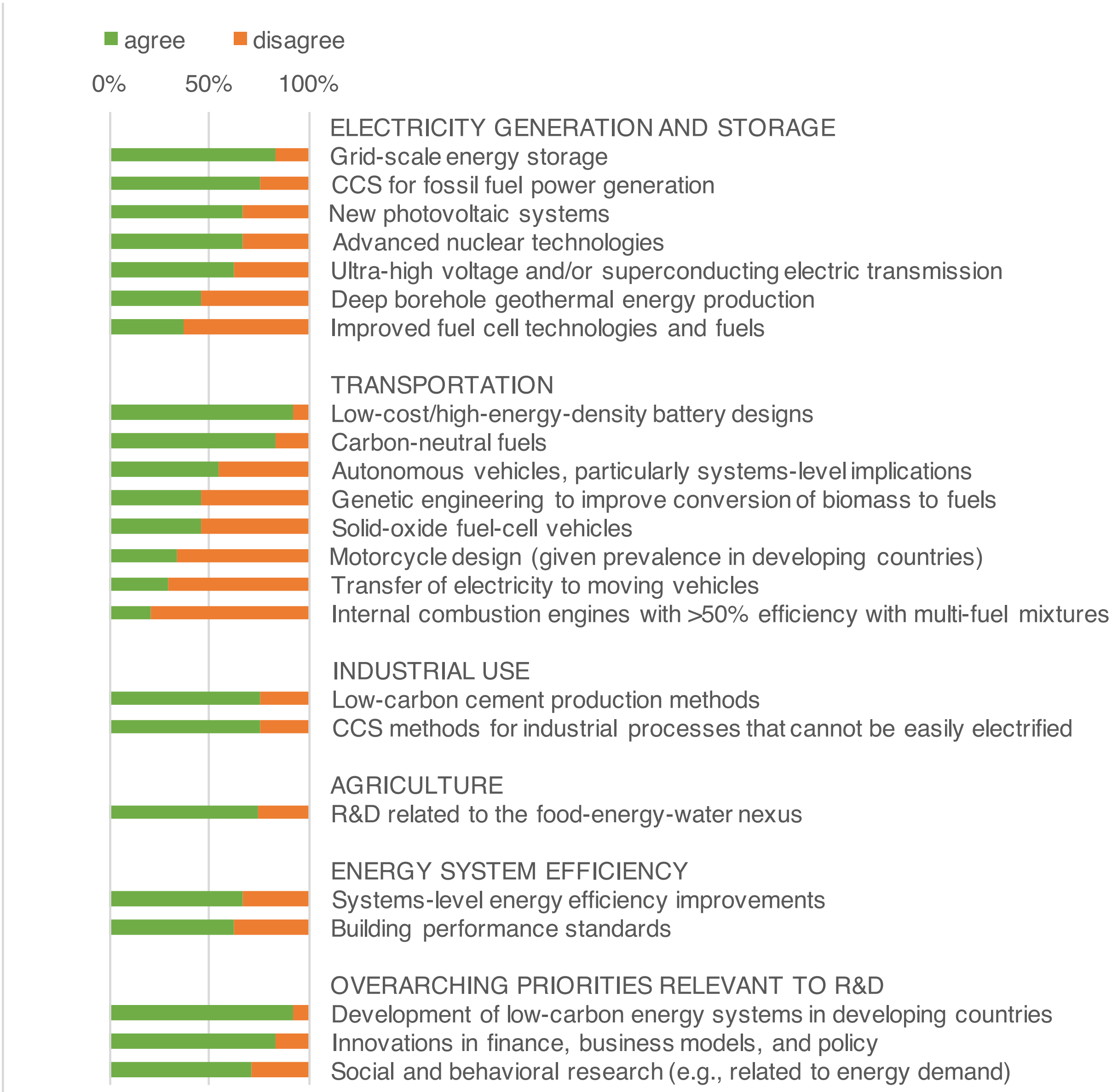


Figure 3: Percent of experts that agreed or disagreed that each listed investment possibility is a top priority. Possible investments are categorized within the five Breakthrough Energy Coalition sectors, as well as an additional category of "overarching priorities relevant to R&D" (24 participants).

Options categorized as "overarching priorities" received large support. These strategies are much broader than specific technology investments. For example, Arun Majumdar of Stanford University highlighted the importance of innovations in finance, business models and policy.

> **"[W]hat we need is coherence between innovations in technology, finance, business models, and policy, so that they are synergistically pulling each other (and not fighting each other)."**
> *Arun Majumdar, Stanford University*

Non-technical barriers were mentioned by many participants as a priority for future research.

Experts offered the following suggestions as missing from the list of specific investment priorities:

- Research on systems-level implications and analysis
- Process engineering research
- Research to understand new technology diffusion in development contexts
- Specific technologies relating to nuclear waste and next-generation nuclear design

Overall Investment Priorities

In the discussion and comments from experts, three important themes about overall global energy R&D investment priorities emerged:

1. Electricity, transportation, and coordination
2. Efficiency
3. Allocation strategies

See Appendix B and Appendix C for a full compilation of expert comments.

Electricity, transportation, and coordination

As highlighted in the quantitative data presented above, many experts felt that the electric power sector should be a focus for R&D efforts.

> **"Electrification of the transportation sector offers a great opportunity for reducing greenhouse gas emissions and other criteria air pollutants, as long as efforts to electrify the transportation sector are linked to progress in a cleaner electricity system."**
> *Paulina Jaramillo, Carnegie Mellon University*

> **"The electric power sector is the linchpin of global decarbonization efforts…"**
> *Jesse Jenkins, Massachusetts Institute of Technology (MIT)*

Many experts generally agreed that electrification of transportation was a top priority, but were divided about prioritization of energy efficiency R&D (Figure 4).

> **"Electrification of ground transportation has the best potential to reduce carbon and pollution emissions."**
> *Per Peterson, University of California, Berkeley*

> **"[T]he opportunities in electricity generation and utility-scale storage are consistently the largest in terms of both cost reductions and performance improvements and in terms of delivering the largest societal returns on investment."**
> *Laura Diaz Anadon, Harvard University and University College London*

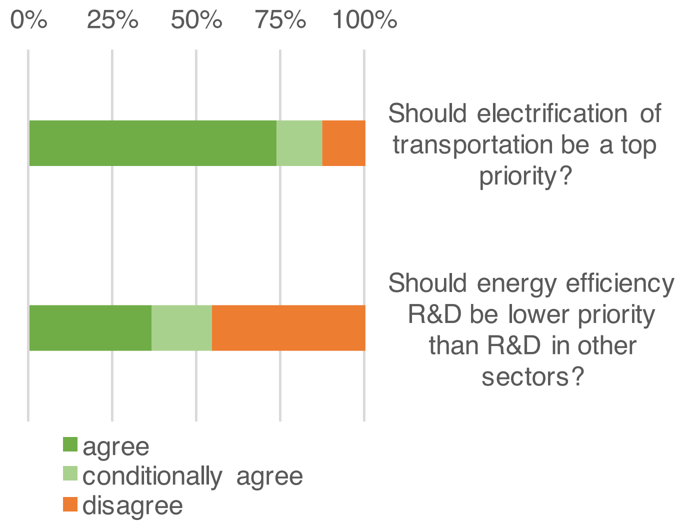


Figure 4: Expert opinion on relative priorities for R&D, showing the fraction of experts agreeing, conditionally agreeing (with caveats), or not agreeing with statements about global R&D priorities. Qualitative responses interpreted by authors (24 participants).

Coordination between transportation electrification and electricity system decarbonization was highlighted by some experts as critical to achieve large emissions cuts—however, some forms of transportation were seen as difficult to electrify.

"On-grid electrification of transportation will not significantly reduce CO_2 emissions in the near term because it depends on the CO_2 footprint of the grid."
Valerie Karplus, MIT

"High-energy-density, carbon-neutral fuels for transportation that cannot technologically readily be electrified (heavy-duty trucks, ships, and aircraft)."
Nathan Lewis, California Institute of Technology

Other experts reinforced and complemented these points, suggesting that carbon-neutral fuels, including advanced biofuels, might be a better opportunity for R&D and for decarbonizing transportation.

"[P]re-supposing that the solution is electrification (compared to zero-carbon-fuel based) cuts off a path with great potential."
John Woolard, Google

"Other more appealing options exist [than electrification], notably development of algal fuels. This option, which could take place incrementally, could preserve much of the existing fleet."
Lee Lane, Hudson Institute

And finally, some experts highlighted the different challenges and opportunities for transportation across countries at different levels of development.

"[T]he transport sector will see a massive growth particularly in developing countries because of their current low levels of vehicle ownership and rising incomes."
Leena Srivastava, The Energy and Resources Institute (TERI)

"Depending on the situation, [electrification] could be a top priority or not.… [E]lectrification should not happen in current mostly inefficient transport systems."
Youba Sokona, South Centre

Speaking more broadly about technology innovation and technology transfer, experts noted the importance of considering regional context.

"We have seen too many [examples] of technologies failing to thrive in developing country contexts; we also know that many of the needs of those populations are not being served with existing innovation efforts."
Laura Diaz Anadon, Harvard University and University College London

"If we do not properly design and operate low carbon electricity systems in developing countries, it is game over for climate change."
Paulina Jaramillo, Carnegie Mellon University

Efficiency

There was greater divergence among experts regarding whether energy efficiency R&D should be a lower priority than R&D in other sectors (Figure 4). Nearly half of participants said that efficiency R&D should not be trumped by other R&D efforts. But in general, there was divergence among experts about the scale and scope of efficiency improvements, and the relative roles of R&D, regulation, and prices in promoting efficiency.

Several experts highlighted the large role for efficiency in global decarbonization scenarios.

> **"[T]he ability to make existing global infrastructure efficient is key to reducing GHG emissions quickly."**
> *Steven Hamburg, Environmental Defense Fund*

> **"[A]spects of technologies and systems for demand-side management (writ large) are fundamental for the clean energy agenda."**
> *Morgan Bazilian, World Bank*

> **"[E]fficiency and conservation are likely the only major GHG mitigation options that reduce costs while also reducing energy use and life-cycle emissions."**
> *Dale Simbeck, SFA Pacific*

Some experts tried to clarify what efficiency R&D investments might be worthwhile, while others argued that efficiency is best advanced by other policy interventions.

> **"Device-level efficiency improvements may be driven largely by 'profit and cost-saving incentives' but system-level efficiency improvements will not be driven so simply by market forces."**
> *Ken Caldeira, Carnegie Institution for Science*

> **"[B]est available technologies are not uniformly widespread and the barriers to scale are many and not properly understood. [We need] to develop the right policy mechanisms and market conditions to ensure a rapid exploitation of all available technologies."**
> *Leena Srivastava, TERI*

Allocation strategies

Finally, several experts discussed strategies for allocation of an R&D budget.

> Portfolios should incorporate a long-term vision, prioritizing **"topics where almost every study about a clean-energy system has identified the major technology gaps at present."**
> *Nathan Lewis, California Institute of Technology*

> **"At this stage, we would be wise to invest broadly across all scalable low-carbon power-generation technologies, including solar, wind energy, nuclear energy, and carbon capture and storage."**
> *Jesse Jenkins, MIT*

Laura Diaz Anadon of Harvard and University College London described two concrete factors to incorporate in portfolio allocation: "(1) the potential for cost and performance improvements; and (2) the societal benefits (e.g., cost-effectiveness, reduction of GHG emissions, and improvement of human well-being)." However, she also emphasized how litte is known about portfolio analysis.

> **"In spite of a few groups (including mine) doing work on energy R&D portfolios over the past 10 years or so, more analysis remains to be done to provide holistic and systematic insights about tradeoffs involved in energy R&D portfolios to meet different goals. While individual experts thinking about the prospects of technology are absolutely essential, it is easy to miss important technologies and linkages without analysis that looks at optimal portfolios, [while] being transparent about metrics for assessment and assumptions."**
> *Laura Diaz Anadon, Harvard University and University College London*

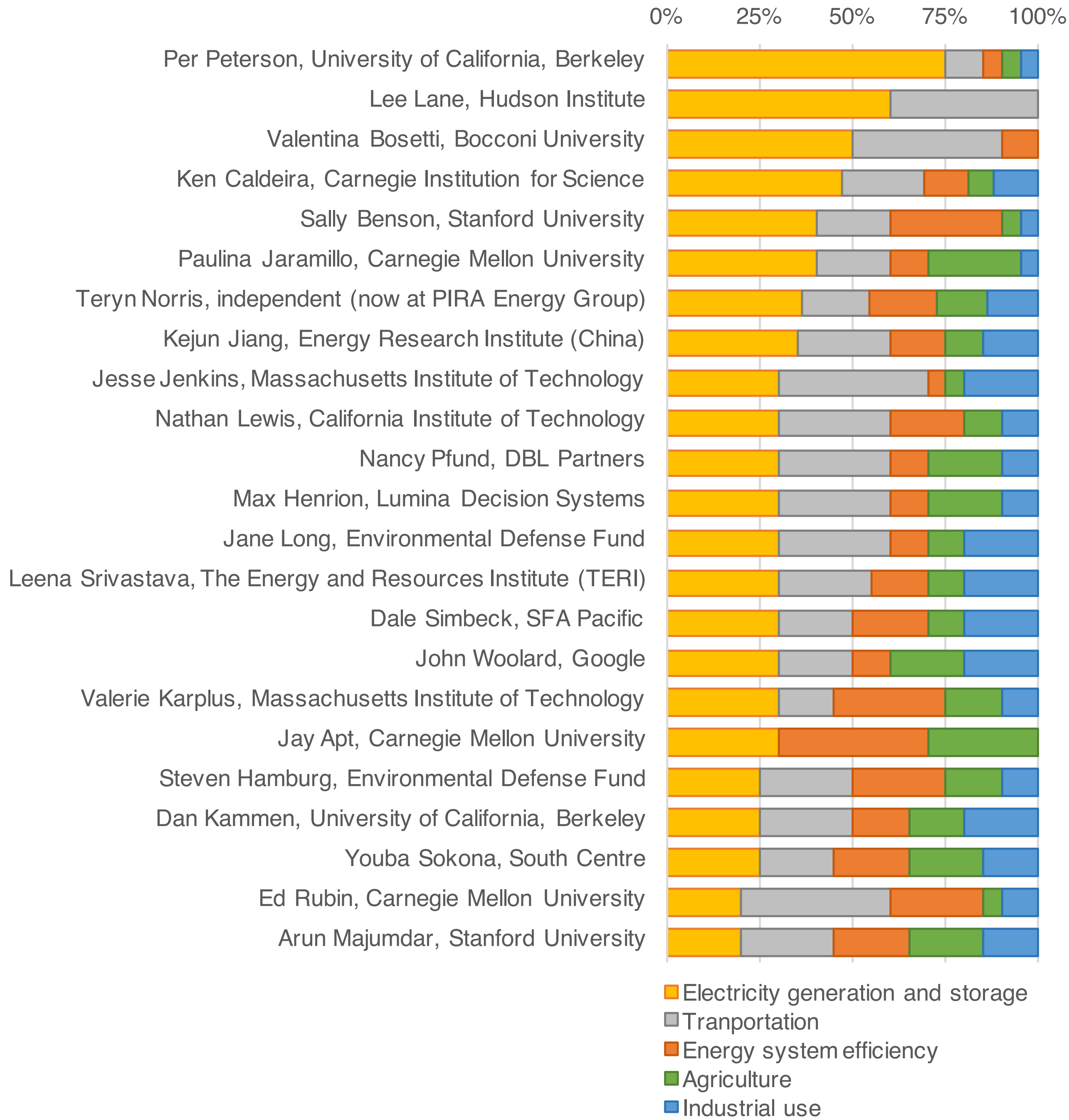
Next Steps

This discussion was an exploratory first step towards a broader and deeper assessment of global energy innovation priorities, building upon prior work, including a 2011 Near Zero report on U.S. Department of Energy (DOE) funding priorities. Given the magnitude of the energy challenge and the uncertainties inherent in technology innovation, the goal of this assessment is to reveal agreement and clearly articulate divergent views, rather than advocate any one view.

We are sharing this summary with participants in the Breakthrough Energy Coalition and Mission Innovation, inviting their input on priorities for follow-up work.

Appendix A: Participants and Allocations

Figure A-1. Individual experts' allocations of a hypothetical $30 billion R&D budget across Breakthrough Energy Coalition sectors (n=23).



Additional expert participants who did not provide an R&D allocation

- Morgan Bazilian, World Bank
- Laura Diaz Anadon, Harvard University and University College London
- Paul Ekins, University College London
- William Moomaw, Tufts University
- Greg Nemet, University of Wisconsin-Madison
- Neil Wilmshurst, Electric Power Research Institute

Appendix B: Discussion transcript

Near Zero launched its expert discussion of global innovation priorities on December 9, 2015. Participants were posed the topic of discussion below, as well as a quantitative question about how to allocate a hypothetical R&D budget (see Figure 1 and Figure 2). The discussion that followed is reprinted below in full. The discussion was officially closed on December 23, 2015.

To read the original version online, visit:

http://www.nearzero.org/observe/global-innovation

Topic of Discussion

With last week's announcements in Paris, governments and the private sector are poised to substantially increase investments in zero-emission energy innovation, with the goal of accelerating the decarbonization of the global energy system.

The question everyone is asking is: How should this money be spent?

We invite you to provide your unique perspective on the opportunities and priorities for these funds. The first step with this discussion is to get all ideas out on the table without too many constraints, to inform future steps that will be more targeted and quantitative.

What technology pathways present the biggest opportunities for achieving affordable, zero-emission energy at global scale? What factors should be considered when deciding whether or not to fund a given innovation? For example, the Breakthrough Energy Coalition has said they are looking for technologies with a credible pathway to scaling up rapidly.

Nate Lewis, California Institute of Technology

Dec 09, 2015 3:17 PM

In performing a qualitative "gap analysis," I preferentially allocated R&D expenditures to those topics where almost every study about a clean-energy system has identified the major technology gaps at present, which are:

- Massive grid-scale energy storage to compensate for the intermittency of renewables
- High-energy-density, carbon-neutral fuels for transportation that can not technologically readily be electrified (heavy duty trucks, ships, and aircraft)

There are also challenges in achieving transmission and in technologies for energy efficiency, but no "gaps" of the type that are listed above, which are so significant as to arguably preclude getting to a truly carbon-neutral and affordable clean energy system unless and until they are addressed and solved. Hence for R&D funding allocation purposes, I preferentially qualitatively down-rated such areas.

In this assessment, R&D would most beneficially and appropriately be used to enable two types of technologies: radically disruptive technologies that provide much lower costs to do otherwise what we know how to do now (solar paint for example vs solar panels), and to develop enabling technologies that are critically needed and gap bridging to provide optionality to allow us to do things that we simply don't know how to (affordably and/or scalably) do now.

For example, technologies that can directly produce fuel or scalably and effectively convert clean electricity into fuel would fall into both of the above categories and thus are obvious candidates for R&D funding that would allow them to be developed and enabled to be deployed when they are needed in a clean energy system, as opposed to funding that continues to move down the existing learning curve on existing technologies. Cost reduction is important to be sure but I see that as a secondary role for new R&D funding, which needs to complement deployment by providing optionality to do things that we simply don't know how to scalably and/or cost-effectively do now or in the foreseeable future otherwise.

Jesse Jenkins, Massachusetts Institute of Technology

Dec 10, 2015 12:24 PM

The electric power sector is the linchpin of global decarbonization efforts, expected to cut emissions fastest and furthest in virtually all global decarbonization scenarios consistent with stabilizing average global temperature increases to ~2C. The sector will need to be virtually entirely decarbonized by roughly mid-century, while expanding significantly to provide energy access to those in need and to electrify as much as possible industry, heating, and transportation sectors, which are comparatively harder to decarbonize.

At this stage, we would be wise to invest broadly across all scalable low-carbon power generation technologies, including solar, wind energy, nuclear energy, and carbon capture and storage. R&D efforts should focus on both next-generation designs and more incremental improvements to existing technologies. Next-generation work should be more significantly prioritized in the public R&D portfolio, as this is precisely where private sector investment will be least likely, but the public sector can also play an important and collaborative role in accelerating more incremental improvements, such as improved manufacturing methods, higher efficiencies, and accelerated testing and verification of improved designs.

While electricity may be the linchpin, we cannot afford to focus on electricity alone. Direct emissions from the electric power sector represent only about 1/3 of global GHG emissions, and industry and transport are equally important (followed by agriculture, putting aside net impacts of land-use changes for the moment, which if included, make agriculture a higher priority). While electrification can in many ways shift the decarbonization challenge to the power sector, we cannot count on electrification alone. In particular, several industrial processes, long-haul transport, and aviation are all not well suited to electrification. Zero-carbon, high-density fuels are essential, and thus a key RD&D priority. Carbon capture for industrial processes is also another critical component, as are low-carbon cement production methods. Finally, electrification of transport and industry itself must also be enabled by several innovation priorities, chiefly improvements in transportation batteries.

Research into energy efficient technologies should be a relatively low priority, in my view, for two reasons. First, profit and cost-saving incentives already provide strong incentives for incremental improvements in efficiency across the economy. A variety of non-R&D related market failures or policy implementation challenges slow the uptake of efficient technologies, as the literature on efficiency has long discussed, but better technology is not a key part of the solution to these challenges, and assuming these obstacles can be overcome, there is plenty of incentive for firms to steadily improve the efficiency of products and services. This is why global energy intensity has been steadily improving for decades, without any climate-related motivations. Second, where efficiency improvements yield improvements in total factor productivity, they will spur rebound effects, which reduce the efficacy of efficiency measures as a climate mitigation tool. While efficiency yields improvements in overall welfare -- the economy gets stronger, people get more value out of energy use, etc. -- and are worthwhile for these reasons, rebound effects do raise very important implications for the role of efficiency as a climate mitigation tool. Public-sector R&D should focus on radical or next-generation improvements in the efficiency of key industrial or end-use energy consuming processes, which are areas the private sector is likely to under-invest in. But this should be a relatively lower priority for climate-related R&D efforts.

In summary, here are a few discrete priorities:

- Accelerated demonstration and improvement of post-combustion CCS technologies
- Next-generation solar chemistries with the potential to achieve very low installed costs (on the order of $0.25/watt)
- Demonstration and improvement of engineered geothermal energy production methods
- Accelerated design and demonstration of next generation nuclear reactor designs
- Low-cost/high-energy-density battery chemistries/ designs for electrification of transportation
- Energy dense, very-low carbon liquid fuels for aviation and other difficult to electrify transportation sectors
- Carbon capture and storage methods for industrial processes that cannot be easily electrified
- Low-carbon cement production methods

Ken Caldeira, Carnegie Institution for Science
Dec 11, 2015 2:10 PM

> *Jesse Jenkins: Research into energy efficient technologies should be a relatively low priority…*

Device-level efficiency improvements may be driven largely by ‘profit and cost-saving incentives’ but system-level efficiency improvements will not be driven so simply by market forces. For example, mass transit systems, densification of urban centers with elimination of suburban sprawl, etc, could potentially come about through planning but not so much for market forces. So, it might be that R&D dollars into efficiency should be focused on system-level improvements rather than device-level.

I would not ignore device-level entirely however. For example, at Stanford recently a material was developed that, passively, can be 5 C cooler than ambient air even in direct sunlight because it is radiatively linked to the upper troposphere. A lab-developed material like this might not have an early investor if the material has substantial hurdles that prevent it from being a commercial product within a few years. This may be an example of ‘radical improvements’ mentioned by Jesse.

So, overall point well taken, but let’s understand that there are some efficiency R&D investments that could be worthwhile.

Ken Caldeira, Carnegie Institution for Science
Dec 11, 2015 2:15 PM

> *Jesse Jenkins: Demonstration and improvement of engineered geothermal energy production methods…*

I’m skeptical that geothermal will ever be a major power source for civilization, but some small amount of money might be well applied here.

Ken Caldeira, Carnegie Institution for Science
Dec 11, 2015 2:19 PM

> *Nate Lewis: There are also challenges in achieving transmission and in technologies for energy efficiency, but no “gaps” of the type that are listed above, which are so significant as to arguably preclude getting to a truly carbon-neutral and affordable clean energy system unless and until they are addressed and solved. Hence for R&D funding allocation purposes, I preferentially qualitatively down-rated such areas.*

If we could truly get an intercontinental superconducting grid, this could allow the world to be powered by solar energy alone. I don’t think I would put a huge fraction of overall resource into this, but the idea of a global electric grid should not be abandoned (cf. Hoffert et al., Science, 2002).

Nate Lewis, California Institute of Technology
Dec 11, 2015 2:45 PM

Seems like basically this whole thread is in violent mutual agreement

Around the edges one might tweak the numbers somewhat, but the underlying rationale seems to have uniform support from the commentaries below and nothing major seems of concern or controversy at least so far

Arun Majumdar, Stanford University
Dec 12, 2015 12:08 PM

I agree with Nate that the big breakthroughs that we are need are broadly on our electricity grid (which was never designed for high penetration renewables) and converting CO_2 into fuel at market competitive costs. That latter needs really inexpensive renewable energy as a feedstock, and we are now entering that era.

Let me add that while these two are important, there are many others as well. I generally present a Letterman-style list of Top 10 Game-Change Energy Technology Innovations, which you will find below. Why 10? Well, its not 1 and its probably not 100. It is on the order of 10, could be 12. I think others could add to this list as well because I probably have not captured them all.

Note that this does not include innovations in finance, business models and policy, which are critically important. The only exceptions I have noted are the need for building standards based on measured performance (beyond design code) and carbon price, which of course would be terrific in multiple dimensions, but there are others that I have not included (e.g. MLP Parity Act). In fact, what we need is the coherence between innovations in technology, finance, business models and policy, so that they are synergistically pulling each other (and not fighting each other), making the whole bigger than the sum of the parts.

1. Ultra-high voltage transmission lines and low-cost approaches (combination of storage, flexible loads, sensing, computation, control) to integration of intermittent renewables at greater-than 50% penetration
2. Use carbon-free energy to transform CO_2 into liquid hydrocarbon fuels at $2/gallon
3. Battery storage at capital cost less-than$100/kWh with greater-than 1000 cycles
4. Photovoltaic systems that are lighter and more efficient, enabling fully-installed capital cost of $0.5/W (levelized cost less-than 2.5 ¢/kWh)
5. Modular nuclear plant construction at capital cost less-than $3/W (levelized cost less-than 7 ¢/kWh)
6. Carbon capture from coal-fired power plants at cost less-than $30/t$CO_2$ with a carbon price greater-than $40/t$CO_2$
7. Genetic engineering that reduces cost and simplifies the conversion of biomass to useful chemicals and fuels
8. Internal combustion engines with greater-than 50% efficiency with multi-fuel mixtures
9. Building performance standards combined with designs, materials, sensors and control systems that significantly reduce building energy consumption
10. Deep borehole geothermal energy with levelized cost less-than 7-8 ¢/kWh

Leena Srivastava, The Energy and Resources Institute
Dec 12, 2015 10:37 PM

I made the highest allocation for storage technologies as economically attractive options here would pave the way for a massive upscaling of renewable energy. This is also important to provide a push to decentralised energy solutions that could benefit the energy poor beyond a basic provisioning and pave the way for an electrification of economies.

Beyond this, the transport sector will see a massive growth particularly in developing countries because of their current low levels of vehicle ownership and rising incomes. We urgently need to find economically attractive, stable fuel sources (beyond clean electricity) to meet these demands.

I agree with all others that we do not need major investments in energy efficiency technologies, however, it is as a fact that the best available technologies are not uniformly wide spread and the barriers to scale are many and not properly understood. Recognising this as a low hanging fruit also calls upon us to make the effort to develop the right policy mechanisms and market conditions to ensure a rapid exploitation of all available technologies.

I have provided a reasonable share of the allocation to the industrial sector with a clear focus on the small and medium enterprises that are an essential part of industrial growth but are technologically challenged. They provide the large part of employment in this sector but are also facing competitive disadvantages on account of high energy costs. There is an urgent need to develop as well as customise clean energy technologies for this sector, accompanied by major training and awareness programmes.

Paulina Jaramillo, Carnegie Mellon University
Dec 13, 2015 9:56 AM

I think the biggest challenge we face in the coming decades is the provision of electricity to the global poor. If we do not properly design and operate low carbon electricity systems in developing countries, it is game over for climate change. I thus gave the highest allocation to the electricity research. While there clearly is a need for research on novel technologies (I think advanced nuclear technologies deserve more attention), I think there is also a need to understand how to overcome non-technical barriers. There now seems to be agreement that universal energy access will not occur if we rely only on international aid. We thus need to better understand the mechanisms that have to be in place to spur private investment: What type of business models work? What are effective policy mechanisms to spur private investment? etc. Any research into electrification should also include social and behavioral research. For example, we don't have a lot of knowledge on how demand for electricity develops after first access.

We can't ignore transportation. In megacities of the developing world, transportation is a major driver of air quality so we need to figure out how to develop cleaner transportation systems. Obviously, future transportation systems could be extremely linked to the electricity sector. In the developing world, however, there is an opportunity to think beyond the personal vehicle. Motorcycles, for example, are a big part of the transportation fleet in many developing cities. These motorcycles are a safety hazard but are also a major source of air emissions. Is there any research we should pursue to make motorcycles better? Another potentially game changer technology for the transportation system is autonomous vehicles. There seems to be a lot of research on the technology aspects of these vehicles, but not as much on the system-level implications of the technology. Should these vehicles be electrified? What kind of infrastructure would be needed? How may they change travel behavior?

Finally, there is increasing awareness of the climate/environmental impacts of agriculture. NSF announced a couple of months ago that their new agency-wide focus area will be food-energy-water. I don't have great ideas about research questions on this issue, but it deserves attention.

Dale Simbeck, SFA Pacific
Dec 16, 2015 2:16 PM

A low priority for R&D of energy efficiency technologies is very typical, as this area does not have any "sex appeal," big ribbon cuttings, few radical breakthroughs and worst of all no great hypes of the "great clean, green, cheap technology of the future (forever)" favored for R&D funding. Nevertheless, efficiency and conservation are likely the only major GHG mitigation options that reduce costs while also reducing energy use and life-cycle emissions. Efficiency just keep giving and giving once instituted. Review of traditional historic energy projection documents by EIA and IEA shows efficiency improvements were greatly underestimated after the great energy price shocks in 1973 and especially 1980. High energy prices are efficiency improvements' best friend.

Another key issue in hurting improved efficiency are institutional barriers. The best example is that the big traditional regulated electric utilities consider purchasing large amounts of ultra-efficient cogeneration baseload electricity from energy intensive industries at a fair price their worst nightmare. The problem, this cogen electricity is too clean, too cheap, too large and worse of all, generated by others. Utilities very effectively marginalize cogen to just "small is beautiful" residential "distributed generation," knowing the small size and low annual load factors of residential thermal host make this cogen insignificant.

> *Jesse Jenkins: Accelerated demonstration and improvement of post-combustion CCS technologies*

I totally agree and specifically more effort on post-combustion CCS than pre-combustion (except if for hydrogen in fuel cell applications) and oxygen combustion. CCS development is critical for quick and large CO_2 reductions. Post-combustion CCS is ideal for big fossil fuel power generation, both coal and natural gas, as well as new or retrofit of existing power plants.

> *Jesse Jenkins: Next-generation solar chemistries with the potential to achieve very low installed costs (on the order of $0.25/watt)*

Also a good choice. Integration into roofing could further reduce installation costs, but the challenge continues to be wiring when new roofs are installed. Other solar challenges continue to be low annual load factors, inverters, surface cleaning and especially storage for peak time of day energy needs.

> *Jesse Jenkins: Demonstration and improvement of engineered geothermal energy production methods…*

Another good choice but a limited resource, thus would be near the bottom of my list.

> *Jesse Jenkins: Accelerated design and demonstration of next generation nuclear reactor designs…*

I totally agree, as nuclear is critical for any significant CO_2 mitigation because baseload electric power gen is the "big dog" CO_2 emissions source. I specifically like the small modular "cookie cutter" standardized nuclear designs and using ship manufacturing facilities to reduce capex and barge to final locations in developing nations with the high electric growth rates. Also need institutional changes in standardized, more effective permitting/licensing and especially R&D into advanced nuclear cycles with better fuel utilization and avoiding use for nuclear bomb materials.

> *Jesse Jenkins: Low-cost/high-energy-density battery chemistries/designs for electrification of transportation*

I am not certain that the future is electrification of transportation. That is unlikely until a major technology breakthrough in battery performance and costs, which could easily be the "great technology of the future (forever)." Better battery development is the holy grail of better electricity storage for all applications, especially storage for intermittent renewable electric power gen. However, the fact that the original Edison-invented lead acid battery still dominates after over 100 years and that fuel cells keep failing with improved performance suggests there may be some yet unknown limitations in advanced batteries performance. This is high risk R&D that may still be the "great energy technology of the future (forever)."

Jesse Jenkins: Energy dense, very-low carbon liquid fuels for aviation and other difficult to electrify transportation sectors

The key here is to make existing standardized jet fuel from zero CO_2 emissions hydrogen (renewables to hydrogen or fossil fuel to hydrogen with CCS) and any source of carbon, CO or CO_2 (but favoring from biomass). This usually involves H2 and CO reactions over catalysis via the classic Fischer-Tropsch (F-T) technology, which is very un-selective to just jet fuel. However, another more selective approach could be low carbon sources of H2 & CO via methanol and then methanol to jet fuel, similar to the ExxonMobil methanol to gasoline technology. A final approach is simply hydrotreating and hydrogen cracking any hydrocarbon carbon liquid (even from biomass) with lots of low carbon hydrogen. Like F-T this is complex and un-selective to jet fuel, but great fears of any oxygen left in the jet fuel is from biomass liquids. Finally, liquid hydrogen as a jet fuel has some interesting possibilities that cannot be totally ignored.

Jesse Jenkins: Carbon capture and storage methods for industrial processes that cannot be easily electrified

Almost any energy intensive industrial process can be electrified. However the fuel cost and overall life-cycle efficiency would be terrible. Nevertheless, electricity is the key growth end-use energy of the future, regardless of battery breakthroughs. Therefore both CCS for fossil fuel power generation (and energy intensive industrial processes) and nuclear electric power generation are essential for a carbon constrained world.

Jesse Jenkins: Low-carbon cement production methods

I totally agree and an excellent suggestion that most people overlook. Limestone based cement is a major source of world CO_2 emissions, especially in developing nations with high construction rates. I think there could be great potential for different chemistry plus more recycling of other existing solid waste like coal ash. I expect the key could be developing cement chemistry based on natural magnesium silicate in place of calcium carbonate (limestone). Keep in mind a key institutional limitation here is existing building material standards that would have to radically change to performance based standards, not existing chemistry standards.

Dale Simbeck, SFA Pacific
Dec 16, 2015 2:17 PM

Some other areas of potentially useful technology developments that I expect could have a major impact on CO_2 mitigation:

1. Improved higher temperature "superconductor" electric transmission development. This could effectively move excess renewable power in one region (like the US Midwest) to regions with higher costs and higher CO_2 emissions electric power generation (like the US Northeast). Effective use would also require political reforms toward a national electric transmission systems control with better grid connections. Sadly, this is currently controlled and opposed by State public utility regulators and the big politically powerful regional electric utilities.

2. Innovative transfer of electricity to moving vehicles on strategic high vehicle density roadways. One option is induced current transfer from wires in the roadway, already being tested in several countries. There are other likely better options. This

would greatly reduce the battery capacity required for electric vehicles (EV) and would be a great enabling technology improvement for more practical plug-in and all liquid fuel hybrid electric vehicles (HEV).

3. Development of improved fuel cell technologies and alternative fuel cell fuels. Solid oxide fuel cells (SOFC) likely have the biggest potential. For large scale electric power generation, SOFC can generate electricity from H2 & CO while in the same process producing a high purity CO_2 exhaust at moderate pressure. Thus, this would have much lower costs for CO_2 capture and storage (CCS) while at the same time much higher overall efficiency. SOFC using low carbon emission in manufacturing (like CO_2 free H2 reactions with CO_2 perhaps from CCS) of liquid methanol fuel is also very interesting for fuel cell vehicles. The greatest attribute of a transportation fuel is being a liquid at ambient temperature and pressure.

Per Peterson, University of California, Berkeley Jan 11, 2016 10:19 PM (Received after official close of discussion)

> *Arun Majumdar: Modular nuclear plant construction at capital cost less-than $3/W (levelized cost less-than 7 ¢/kWh)*

Nuclear energy is a complex technology, and Arun has accurately distilled the fundamental goal into a single sentence. Embedded in this economic goal is the requirements to comply with regulations for safety and physical security, and with international safeguards.

Today, Westinghouse charges ten times as much to convert steel, concrete, copper, and other materials into an AP1000 reactor built in the United States, as Vestas chargest to deliver wind turbines fabricated from the same materials.

The AP1000 is one of the most affordable reactors available today. There exist no physics that require reactors to be ten times more expensive to build than wind turbines. I predict that the innovation agenda that brings down these very high current nuclear construction costs will look a lot like the SpaceX model, which today charges $4600 per kg for launches that cost $60,000 per kg with the Space Shuttle.

Additional comments:

Morgan Bazilian, World Bank

A focus solely on technology R&D will not be as effective as one that is coupled with an associated research agenda in areas such as political and social sciences. Additionally, as some of the new technologies are finding their “first markets” in developing economies, there is also a need to allow for funding for development of financial innovations and market design. An explicit focus on the needs of developing markets at the early stages of R&D design would likely greatly improve the adoption of these technologies and systems for the billions of people that lack access to modern, reliable, and affordable energy services.

Max Henrion, Lumina Decision Systems

Allocation of R&D funds from the Breakthrough Coalition should not reflect simply the likely effectiveness of technology improvements in each area to reducing GHG emissions, but rather the likely effectiveness of R&D funds from this source, bearing in mind (a) there are R&D funds from other sources including private sector R&D and (b) the effect of current and likely “pull” policies (carbon taxes and other incentives) on R&D in each domain. For example, I proposed low allocation to energy efficiency not because it isn’’t critically important, but rather because I’m not sure that there is a great need for additional R&D. It is better addressed by improving incentives, building codes etc. On the other hand, CCS is not being properly addressed because of its high initial costs and inadequate incentives, so there is an urgent need for large R&D investment to accelerate development and demonstration. This might explain the apparent disagreement on funds allocation to energy efficiency. It's actually hard even for experts to keep these issues separate in their (our) minds. It might be helpful in a future iteration to separate out assessment of the importance of technology progress in each area from the importance of additional R&D funds to achieve potential progress.

Another key issue is the allocation of R&D funds to near-term development of technologies with demonstrated potential where the need is to improve performance and move them down the cost curve vs. longer range research into ideas that may have huge potential but high probability of failure. I would argue the importance of allocating more R&D to the latter. Long-range research typically receives inadequate funds because private sector and governments find it hard to invest in high-risk, high-potential, long-range projects. Examples include GM or artificial organisms to produce biofuels from sunlight; intervention in marine ecosystems to accelerate ocean sequestration of carbon; and many others. In a future iteration, it would be helpful to address this dimension explicitly in requested allocations.

Jane Long, Environmental Defense Fund

Four key steps will result in decarbonization of energy: Efficiency, de-carbonization of electricity, electrification, and de-carbonization of fuel. Application of efficiency technology, while largely available, may actually spur the use of more energy. Electricity decarbonization is the linch-pin, but we need to have all options on the table including nuclear power, CCS and renewables to expect results by mid-century. Ensuring demand matches supply at all times presents the major technical challenge for a reinvented electricity system. Decarbonization of fuel is the biggest technical gap, but sufficient quantities of a truly decarbonized fuel would be a silver bullet for energy. More or less all the available ideas are very expensive, will not scale up enough, require very complicated industrial relationships, don't actually reduce emissions on a life-cycle basis or have major undesirable impacts.

Teryn Norris, independent (now at PIRA Energy Group)

The foundation of a low-carbon future is the electrical power sector. Not only is power the largest source of carbon dioxide emissions, but reaping the benefits of downstream shifts—such as switching from gasoline-powered to electric vehicles—requires a clean electricity supply upstream. According to IEA's latest analysis, the share of fossil-fueled power plants in the world's electricity supply must plummet from 70 percent to just 7 percent by 2050—a full order of magnitude decrease—in order to keep global warming under two degrees Celsius, unless the carbon emissions from those plants are captured and stored.

The central problem is that the low-carbon technologies making progress on the margins of the fossil-fueled world today may not suffice tomorrow when clean energy must dominate instead. For example, the costs of wind and solar are nearing those of natural gas and coal. But this is largely possible because flexible fossil-fuel generators can smooth out highly variable power output from wind and solar. More of these intermittent sources will oversupply the electric grid at certain times, making renewable power less valuable and requiring extreme swings in the dwindling output of fossil generators. New hydroelectric projects have run into stiff environmental opposition, and nuclear's share of global electricity has declined for two decades because of cost overruns and public fears about its safety. As a result, trying to create a zero-carbon power grid with only existing technologies would be expensive, complicated, and unpopular.

Similarly, cleaning up the transportation sector will require major technological advances. Today, alternative fuels are barely competitive when oil prices are high. But in coming decades, if climate policies succeed in reducing the demand for oil, its price will fall, making it even harder for alternative fuels to compete. So the recent dive in oil prices—which has already put biofuel companies out of business and lured consumers away from electric vehicles—may foreshadow trouble for decarbonizing the transportation sector. All of this means that a clean, affordable, and reliable global energy system will require a diverse portfolio of low-carbon technologies superior to existing options.

Appendix C: Discussion follow-up questions

During the discussion, participants were asked two follow-up questions about relative priorities for R&D, regarding electrification of transportation and efficiency of energy use. For experts who gave a detailed response, their comments are printed below.

Should electrification of transportation be a top priority?

Jay Apt, Carnegie Mellon University

Not until the electric power system is significantly cleaner than it is today.

Morgan Bazilian, World Bank

This is a big question that needs to be refined to assure useful answers. Still, if one conceives of the electrification of transport to include aspects of: smart grids, new communication systems, demand management, and support for grid integration of RE, then yes, it is a key area to pursue. Alternatively, if one is focused on batteries, material science, or charging infrastructure, that too makes sense for further R&D.

Laura Diaz Anadon, Harvard University and University College London

I agree that it is an option to be further explored and coupled with cleaner electricity generation. With this in mind, I include this as a top priority because: (a) I have in mind an investment of at least 20 billion USD per year; (b) it is a sector that may be harder to decarbonize; (c) small changes in cost can result in big savings; and (d) I believe there are still possible game changers in battery technologies. Having said that, infrastructure challenges in some places may still be difficult to overcome.

Paul Ekins, University College London

Agree. There are unlikely to be sufficient biofuels to decarbonise ground-based transport, and electrification, along perhaps with hydrogen fuel cell vehicles in the more distant future, currently seems like the best low-carbon option

Steven Hamburg, Environmental Defense Fund

Agree - can address light duty vehicle needs most directly and with the least new infrastructure. Combined with self driving vehicles there is real potential to use existing infrastructure effectively and efficiently in the developed world - more so than a large investment in mass transit.

Max Henrion, Lumina Decision Systems

Yes, especially R&D aimed at new technologies for lower cost batteries.

Paulina Jaramillo, Carnegie Mellon University

Electrification of the transportation sector offers a great opportunity for reducing greenhouse gas emissions and other criteria air pollutants, as long as efforts to electrify the transportation sector are linked to progress in a cleaner electricity system. Linking the two systems offers opportunities, but also creates new challenges in the design and operations of more interconnected/interdependent systems. Research in this area should thus include system-level implications beyond those related to emissions.

Kejun Jiang, Energy Research Institute (China)

Yes, it is crucial for future near 0 emission transport

Dan Kammen, University of California, Berkeley

A high priority, but mode-shifting out of individual vehicles is an even higher priority for new R&D and vehicle electrification has already started.

Valerie Karplus, Massachusetts Institute of Technology

Yes (off-grid) and No (on-grid). On-grid electrification of transportation will not significantly reduce CO2 emissions in the near term because it depends on the CO2 footprint of the grid, and in the long term other options in transportation (including efficiency and conservation, as well as off-grid hybrid technologies), will offer significant CO2 emissions reductions. R&D funds and effort would be more cost effectively allocated to the electricity and industrial sectors. Battery research for off-grid PHEVs should be a priority.

Lee Lane, Hudson Institute

No. Other more appealing options exist, notably development of algal fuels. This option, which could take place incrementally, could preserve much of the existing fleet, and might limit the need for dirigiste public policies. But given the uncertainties surrounding all options, some investment in R&D in electrification probably has merit.

Arun Majumdar, Stanford University

I agree as long as the electricity comes from clean sources. But we cannot electrify planes and trucks. Hence R&D to create carbon-neutral liquid hydrocarbon fuels cost effectively using carbon-free energy should be a top priority.

William Moomaw, Tufts University

Yes. The electrification of transportation that is “fueled” by hydro and geothermal power, and renewable solar and wind. The onboard storage will help make wind and solar technologies more viable by providing for storage for the grid. EVs also reduces emissions in the transportation industry more rapidly than any other option.

Per Peterson, University of California, Berkeley

I agree. Electrification of ground transportation has the best potential to reduce carbon and pollution emissions.

Nancy Pfund, DBL Partners

Yes, it should be a top priority considering that over a third of our emissions come from the transportation sector. EV vehicles could also help the development of the smart grid by acting as distributed energy resources.

Ed Rubin, Carnegie Mellon University

Net zero or low-carbon transportation should be the top priority -- electrification is one of the options.

Dale Simbeck, SFA Pacific

Yes, but not in the way most people think. All electric vehicle EV are expensive and limited in range/ performance until a radical technology breakthrough in battery technology which may never come. More importantly, EVs can have very low overall efficiency (well-to-wheels) and high emissions (well to wheel) depending on the source of electricity. Nevertheless hybrid electric vehicles (HEV) like the Toyota Prius doubles the vehicle efficiency compared to the same performance/cost vehicle with just an internal combustion (IC) engine, like a Toyota Corolla. Electrification via regenerative breaking (small electric storage) with engine stopping and electric assistance from a dead stop is the key. Thus electrification to better HEV is a key short to medium term priority with plug-in HEV and EV a long term priority once we have peak and off-peak grid power (on a marginal load dispatch economic bases) that is low carbon and much better battery technology (both cost & performance). Hope this make sense as electrons used to charge EVs do not come from heaven like the advocates suggest. The electrons generally come from low efficiency NG fired simple cycle combustion turbines if peak power and coal power plants if off peak power.

Youba Sokona, South Centre

This cannot be a general question. It is a country or context specific. Depending on the situation it could be a top priority or not. In any case transport approaches or strategies should be revisited in light of climate and SDGs imperatives. Before thinking on electrification of the transport it may be important to assess it the system is the most efficient one in term of helping mobility problems. The electrification should not happen in current mostly inefficient transport systems.

Neil Wilmshurst, Electric Power Research Institute

Yes. Decarbonization of energy will require reduced use of oil.

John Woolard, Google

It is almost impossible to solve for 450ppm without a significant focus on transportation. However, pre-supposing that the solution is electrification (compared to zero-carbon-fuel based) cuts off a path with great potential. We should study how to de-carbonize the transportation sector most efficiently.

Should energy efficiency R&D be lower priority than R&D in other sectors?

Laura Diaz Anadon, Harvard University and University College London

It depends on what type of energy efficiency R&D. Certainly incremental improvements to the energy-efficiency of current technologies should not be a top priority, since private sector actors already have incentives to work on this. But more fundamental research to develop more radical technologies harnessing new phenomena, materials, etc., still deserves some attention.

Jay Apt, Carnegie Mellon University

The first page asked about “energy system efficiency”, not energy efficiency. I really don’t know what you mean. End-use energy efficiency is quite different from energy extraction, production and transmission.

Morgan Bazilian, World Bank

This strikes me as presenting an unnecessary choice. Many aspects of EE are integral to the deployment of other technologies, including RE. I think that the varied aspects of the technologies, systems and business models that together compromise the new definition of energy efficiency are fundamental for the clean energy agenda. So, no, they should not be de-prioritized.

Paul Ekins, University College London

The private sector has incentives to implement energy efficiency R&D for its processes. Energy efficiency in transport is best driven by regulation. The priority for energy efficiency in buildings it to implement existing technologies more widely. So I think energy efficiency R&D is a lower priority.

Steven Hamburg, Environmental Defense Fund

No - the ability to make existing global infrastructure efficient is key to reducing GHG emissions quickly. While new infrastructure is required turnover of existing investments will take a minimum of 50 y, we do not have that amount of time.

Max Henrion, Lumina Decision Systems

Somewhat lower. But there is room for important R&D to reduce cost of retrofitting buildings and industry to improve efficiency.

Paulina Jaramillo, Carnegie Mellon University

I agree with one of the comments that R&D in efficiency at the equipment level may not be a priority. I also agree, however, that R&D on how to design more efficient systems (energy, infrastructure, urban systems) is still needed, particularly in developing countries where we have the opportunity to try new ideas that avoid past mistakes.

Kejun Jiang, Energy Research Institute (China)

yes, end use sector will use more electricity, low carbon electricity is the key

Valerie Karplus, Massachusetts Institute of Technology

No, energy efficiency R&D, and studies of the impact of policy on promoting uptake of energy efficiency solutions, are essential. These solutions are lower cost and have at least as much emissions reduction potential as clean energy production technologies.

Lee Lane, Hudson Institute

Yes, much lower. Market incentives for fuel savings are already substantial and the gap between the actual incentives and the socially optimal levels is less than in other areas.

Arun Majumdar, Stanford University

Technology alone cannot address energy efficiency in sectors such as buildings. It needs strong policies as well. Otherwise there is too much fragmentation in this sector to get any benefits of R&D.

William Moomaw, Tufts University

Energy efficiency should be at top of the list. It needs to focus on improved building performance through renovation of existing structures and new construction. In addition to new techniques, finding ways to raise building code standards, train building inspectors and train architects, engineers and builders is essential.

Per Peterson, University of California, Berkeley

Yes. Efficiency will increase regardless, and is much less important than increasing clean energy supply give very large numbers of people in the developing world that lack access to even minimal amounts of energy compared to us in the developed world.

Nancy Pfund, DBL Partners

No. Energy efficiency and demand response (in conjunction with distributed generation, energy storage, and more efficient appliances/machines) are important components of the transformation of our grid and electrical system.

Ed Rubin
Carnegie Mellon University

I put energy efficiency R&D as 2nd highest priority, just behind transportation (which I see as the toughest sector to decarbonize relative to status quo). Clearly, efficiency is critical everywhere with lots of avenues to pursue.

Dale Simbeck, SFA Pacific

Energy efficiency R&D has no sex appeal, no big ribbon cutting and no heroes for major funding. Nevertheless energy efficiency reduced energy use and emissions while at the same time reducing costs. There are few if any other CO2 emission options that can “honestly” make that claim. Nevertheless most R&D funding goes for the great clean, green and “too cheap to meter” claimed advanced energy technology of the future “forever.”

Youba Sokona, South Centre

Here again this is context specific question. It will depend and differ if you are in the context of a LDCs or industrialized or emerging economy country.

John Woolard, Google

Efficiency will primarily be driven by higher prices and clear policy, so R&D on efficiency could involve a lower spend than other sectors.

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