THE UNPRECEDENTED SPEED [AND COST] OF SEA LEVEL RISE

A recently published article in the Proceedings of the National Academy of Sciences (PNAS) by Kopp et al. found that the rate of sea level rise in the 20th century was greater than in any other over the last 3,000 years. This unprecedented rate translated to a mean increase in global sea level rise of 13.8cm (5.5in) between 1900 and 2000 (illustrated in the figure below). The study goes on to compare models with and without anthropogenic climate change, and found that in the absence of global warming, sea levels would have risen by less than half of what was observed.

Determining global rates of sea level rise is harder than one might think. Regional sea levels can vary immensely depending on local conditions such as prevailing winds, ocean currents, vegetation, and ice cover. Likewise, the gravitational pull of certain geological features – like the polar ice sheets, or above- and below-sea level mountain ranges – attracts water towards them resulting in regions with permanently higher sea levels. Kopp et al. accounted for these factors as well as global surface temperatures, historical records from 24 locations around the world (reconstructed from carefully vetted datasets of indicators from marshes, coral atolls, and archaeological sites dating back three millennia), and 66 tidal gauge records (the earliest dating
back to 1700) – all then analyzed in their custom-developed statistical model to generate data about global sea level rise.

As if the process of determining global sea level rise isn’t complicated enough, climate change is projected to alter the patterns and intensity of many of the regional conditions that affect regional sea level rise. Prevailing wind patterns, ocean currents, and the gravitational pull of dwindling polar ice caps are all forecasted to be affected in the coming centuries if society continues to rely upon burning carbon-intensive fossil fuels for energy production.

The implications of this rapid sea level rise are countless. Saltwater intrusion on freshwater aquifers, extreme tidal and storm conditions, flooding, erosion, and degradation of valuable wetlands and their many ecosystem services. Many modelers including Kopp et al. (2016) forecast a rise in sea level of over 1m (3ft) by 2100, enough to wipe out 78% of the world’s wetlands (Spencer et al. 2016). Wetlands, which are naturally adaptive, are compromised in their ability to move with changing sea level due to upland development and building of dams that disrupt normal sediment deposition in coastal areas.

Quantifying the costs of damages expected from projected sea level rise is difficult, but the latest estimates indicate that for every doubling in projected rise of sea level, there is a quadrupling in cost of associated damages (Boettle et al. 2015). This effect may very well be compounded by the fact that models show storms (like Superstorm Sandy) intensifying in strength, size, heavy rainfall, and destructive potential when forming over warmer oceans (Lau et al. 2016). Improved climate and cost modeling will be increasingly important tools for present and future planners, who will face sudden and significant sea level rise in the coming decades, even if carbon emissions were to cease immediately.


REGIONAL IMPACTS OF CLIMATE CHANGE ARE INCONGRUOUS WITH RESPONSIBILITY

In an ambitious new article, Hansen and Sato (2016) not only examine the regional variation of climate change impacts, but also identify responsibilities and viable climate policies to address the causes of global warming in an equitable way.
The paper starts off by comparing the last 66 years of climate data (seasonal mean temperatures) to a base period of 1951-1980, confirming findings of significant global warming and increasing extreme climate events. They note that, due to the more variable nature of winter climate conditions, warming was more easily detected during summers in both the Northern and Southern Hemispheres (see figure below). They also detail the incredible variability of warming observed across different regions around the world and the obvious difference in land area between the hemispheres the figure illustrates.

While the United States exhibited summer warming in the last decade on the order of 1 standard deviation higher than base period temperatures, this trend is accentuated in Europe, China, and India where warming was 1.5 standard deviations higher. These trends are further accentuated in the lower latitudes. The Sahara, the Sahel, and Southeast Asia all had summer warming over 2 standard deviations higher, and the Mediterranean, Middle East, and African Rainforest had warming closer to 2.5 standard deviations higher than the base period temperatures. All of these observed trends, however, pale in comparison to the impact of 6 standard deviations in temperature rise that would be associated with a 2°C increase in those regions.

The implications of these warming trends are global and serious – from new human health threats, to diminished economic productivity, to potential increases in human conflicts and associated migration patterns. Human health will face magnified challenges with the increase in the numbers of droughts, storms, floods, and heat waves. The ranges of vector-borne diseases are also expected to broaden as mosquitos and ticks are able to survive in broader ranges.

Outdoor livelihoods and even basic residence may be compromised in regions with amplified warming. For instance, certain areas in the Middle East are expected to exceed the habitable range of humans – with wet bulb temperatures projected to exceed the level at which the
human body can cool itself. Productivity in the southern U.S., southern China, Indonesia, India, and Nigeria are likewise expected to be significantly compromised.

And past research indicates that increases in temperature increase the likelihood of both interpersonal and inter-group conflict. Conflict coupled with extended drought, as in the case of Syria in recent years, can result in migration. The same can be said for populations who in the future will be displaced by sea level rise (which threatens many of the planet’s major cities).

Hansen and Sato (2016) then go on to point out that many of the regions projected to be most impacted by climate change, such as Southeast Asia, the Sahara, and the Sahel are not those that generated greenhouse gases. Some regions are projected to see severe warming, like the Mediterranean and the Middle East, which do have per capita emissions far above average (even greater than the U.S.). But ultimately, the majority of the responsibility for climate change rests on the United States, Europe, and Eurasia (see figure to the right).

In order to stabilize the climate, Hansen and Sato (2016) argue for the implementation of a price on carbon accounting for the ‘external’ costs to society posed by fossil fuels. This tactic would rely upon international cooperation, with economically strong countries implementing the carbon fee along with border duties to ensure that the carbon footprint of goods made in non-participating countries would also be accounted for. With the true costs of fossil fuels incorporated into their prices, the rise of carbon-free energy technologies would be greatly accelerated. This approach, they argue, would ultimately stabilize the climate with the fewest economic hardships.


ADVANCES IN SOLAR ENERGY

Nate Lewis from the California Institute of Technology is at the forefront of technological advances in solar energy technology. He has provided a review of these state-of-the-art advances in a recent issue of Science (2016). The story of how photovoltaic solar energy panels (PVs) have had an amazing ride down the manufacturing learning curve is disruptive to the conventional wisdom that solar electric is too expensive. Panel prices have plummeted over the last 20 years – achieving approximately a 20% reduction in price for each doubling in global panel production. Over the same period of time, however, the balance of system costs (BOS)
remain stubbornly resistant to the same economies of scale. Savings in installation labor, power condition equipment, permitting, and inspections, while improving, are not dropping in cost at the same rate as the cells themselves. The BOS cost issue is partially compensated for by having panels with higher efficiency thereby reducing the installed area for the same peak power.

The above figure of a utility-scale PV system from the Lewis (2016) paper shows how some components of the system scale with the required array area – such as installation labor (middle column), while some do not – such as those tied to the power produced (in right column).

Less obvious is what is happening on the solar energy research front beyond just solar electric conversion. In this review paper, Lewis explores three distinct advanced technologies: solar thermal, solar fuels technologies, and solar electricity. Here we discuss the latter two.

Regardless of the conversion technology, solar has two fundamental hurdles compared to electricity sources with very high power density, such as nuclear or a fossil fuel power plants: 1) the solar average power density available at the surface of the Earth of about 250 W/m², and 2) the intermittence of supply due to clouds and the day-night cycle.

**Solar Electricity**

On the solar electricity front, Lewis discusses commercially available PVs, advanced cells that are currently in a demonstration mode, and cells types that are still in the laboratory research stage of development. Materials used in these technologies range from mono-silicon and multi-silicon cell types with conversion efficiencies of about 18-23%, to thin film and more exotic types utilizing dye-sensitized materials, organics, perovskites, and quantum dot approaches. Techniques are being explored to exceed the single band-gap theoretical limit of 32% conversion efficiencies in direct sunlight without concentration to cells reaching over 40% efficiencies in concentrated sunlight.
Cell types can take years of development in the lab to move up in conversion efficiency, but also must solve manufacturing hurdles to move from the lab to the market. In the field, consideration must also be given to degradation in performance over time and other practical issues such as panel weight. Overall achievements have been impressive in a relatively short period of time and are continuing. Lewis provides present day installed cost of about $1.80 per peak watt and a levelized cost of electricity (LCOS) at $0.10-$0.15/kWh for utility-scale systems with the range in cost depending on sunlight potential and other factors.

Solar Fuels
Solar fuel technologies offer an exciting complement to direct solar for electric conversion. By using sunlight to generate fuels, solar can be attached to the difficult problem of decarbonizing energy sources for the transportation sector serving modes other than light-duty vehicles. The impact could be significant, given that ships, heavy duty trucks, and aircraft make up about 40% of global transportation fuel requirements (Lewis 2016).

The paper outlines four types of systems. Here we will discuss the approach used in artificial photosynthetic systems that attempt to mimic biological photosynthesis but with non-biological architectures. In a sense these systems use an approach that integrates PV technology with an electrolyzer to produce H₂ and O₂ in a type of photoelectrochemical (PEC) cell that uses sunlight to split water. The H₂ produced can be stored, combusted, used in a fuel cell, or combined with carbon dioxide or carbon molecules derived from biomass to, for example, produce carbon-based fuels.

In order to play a major role commercially, this emerging technology will need to outcompete existing technologies such as conventional electrolysis of water driven by conventional PVs at $7-$20/kg of H₂ produced, or the fossil fuel approach of producing H₂ from natural gas steam reforming (~$2/kg). This figure from Lewis (2016) shows an idealized schematic of a PEC configuration where water on the cathode side (left in figure) is reduced to a fuel in the form of H₂, or alternatively CO₂ and H₂O are reduced to a carbon-based fuel. At the anode (right side) O₂ is liberated from water. The central membrane preventing unwanted chemical combinations between sides supports H₂ collection.

Overall Lewis finds great progress in solar technologies in pursuit of “…higher efficiencies, lower costs, improved scalability, and new functionality…”.

In the next Quarterly Summary we will explore storage technologies that further enable the penetration of renewable energy discussed in this paper and from other sources.