Energy and Climate Research: Reflections from the Princeton Energy and Climate Scholars

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Abstract

This paper is a collection of essays from the Princeton Energy and Climate Scholars (PECS) at the end of the group's first year. Individual pieces convey the author's research goals in the broad context of climate and energy issues as well as reflections on the interdisciplinary nature of the problem in general, the author's work, and/or the PECS group. The introduction presents some common themes addressed by many of the articles and highlights the goals of PECS. The conclusion summarizes the early successes of PECS and indicates future challenges and directions for next year's scholars.

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1 Introduction

1.1 Climate change: a truly interdisciplinary challenge

The energy and climate problem is interdisciplinary in its nature in two distinct ways: vertically, in the separate organizational scales that are affected, and horizontally, in the range of expertise that must be tapped. Although the issues are global in scope, organizations from clusters of nations to single businesses and local institutions face unique circumstances that require individualized science, technology, and policy. Solutions may be rolled out from the global arena but sub levels will have to retain the autonomy to satisfy specific needs. Meanwhile, at each level, understanding the problem and implementing solutions requires cooperation from diverse fields that may not already interact.

Mitigating climate change will require new energy solutions to replace current, non-renewable and carbon-intensive energy sources. Renewable energy, including solar, wind, hydro, and geothermal is likely to play an important role. Developing each of these requires input from many science disciplines in order to harness the potential energy, utilize the energy, and store the energy as fuel. Similarly, improvements to current technology, such as adding carbon capture and storage to fossil fuel plants or improving efficiencies, also calls for collaborative efforts across several fields.

Science and policy will need to cooperate in order to bring these energy solutions to maturity and establish them on both a local and global scale. Governments play a key role in funding scientific research. The US wind industry, for example, is largely supported by science conducted at the National Renewable Energy Laboratory. When NREL's funding was cut during the Bush administration, progress into more efficient and reliable turbines was slowed, which affected technological progress. Policy makers and analysts, guided by sound economic assessments, will also need to design effective policies in order to support the timely deployment of these new technologies, through subsidies, carbon pricing or other approaches. This circular dependence of energy policy on energy-science research necessitates an open dialogue between researchers in all fields, communicating the progress, challenges, and goals of each of their subdivisions.

The policy making process is also underpinned by advances in the scientific understanding of future climate change. The expertise of climate scientists specializing in disciplines from radiative transfer to cloud micro-physics is needed to reduce uncertainty in both modeling and observational efforts. This will help define the best approaches to follow, combining emission reduction and adaptation efforts. Scientists must therefore effectively communicate their findings to economists, engineers, anthropologists, historians, geographers, and politicians for analysis of risk and adaptation requirements specific to small regions.

1.2 New approaches to a new challenge

Due to these characteristics, addressing climate change requires not only highly skilled individuals in a large variety of different fields, but also an elevated level of cross-disciplinary understanding and cooperation. Most commonly, however, expertise is gained at the expense of cross-disciplinary understanding. In academia, doctoral studies typically imply several years of research on a small aspect of a given problem, set within the boundaries of a given discipline. As progress is made, the scope of collaborative exchanges typically shrinks to a circle of experts working on similar issues. While a proven and effective way to generate new expertise, the process is not conducive to cross-disciplinary understanding.

There are of course exceptions. When synergisms are identified between different fields, they are brought together through workshops, or collaborative works. But this tends to be a clumsy process, limited to rare occasions and usually restricted to two areas of investigation. The challenge of climate change therefore requires new approaches on how to create expertise and an enhanced cross-disciplinary understanding.

The Princeton Energy and Climate Scholars (PECS) group is a step in this direction. It was created with the specific objective of fostering cross-disciplinary exchanges among doctoral students working on different aspects of the climate change and sustainable energy problem. It offers the opportunity for students from different departments to learn from each other's research and think about how various topics fit in the greater energy and climate puzzle. By drawing students away from familiar academic grounds on a regular basis, PECS raises questions and offers new perspectives.

One student described the process as follows: A student's research is a leaf on a tree the tree of energy and climate knowledge perhaps. PECS invites you to leave your leaf and make your way to the trunk. It is when you to turn around to make your way back that you realize how many branches there are. The branch to which your leaf is attached is only one among others.

This kind of interaction on the graduate level will set the stage for how PECS members will approach problems more holistically in their future careers in industry, government, academia or elsewhere.

2 Reflections from Princeton Energy and Climate Scholars

This paper offers a collection of short articles by PECS students. In each case, the student introduces his or her research to the reader, describes how it fits in the broader scheme of energy and climate knowledge and offers his or her own thoughts on these interdisciplinary challenges.

2.1 Mechanism for the H_2/O_2 reaction in high pressure flames

Michael Burke, Mechanical and Aerospace Engineering

In my Ph.D. research, I am studying the process by which H_2 reacts with O_2 to form H_2O and release energy in high pressure flames. The H_2/O_2 system is a fundamental topic in combustion science that has historically received significant attention due to both its rich kinetic behavior and its importance to a variety of applications in energy conversion. Understanding oxidation of H_2 is an essential start point to understanding the oxidation of all hydrocarbon or oxygenated fuels, from natural gas to gasoline to biofuels. Recently, there has also been considerable interest in H_2 (either pure or mixed with CO, CO_2, and H_2O) as a fuel itself - as synthetic gas from coal or biomass gasification or as H_2 gas from electrochemical or photochemical processes from water.

For example, Integrated Gasification Combined Cycle (IGCC) processes involve gasifying a solid hydrocarbon feedstock like coal or biomass to produce synthetic gas that is typically combusted in gas turbine engines. Such processes offer promise for efficient, low-emission power generation with increased potential for carbon capture and storage compared to conventional coal technologies. Lean, premixed combustion of synthetic gas allows for reduction of the peak flame temperature to lower NO_x emissions. However, premixed combustion has not been utilized in commercial syngas applications due to a number of technical challenges associated with the approach, including blowout, flashback, auto-ignition, and combustion dynamics. In this particular application as well as most combustion devices, combustion takes place with dilution to reduce the flame temperature to lower NO_x emissions and higher pressures to increase efficiency. Identification of the important kinetic pathways and accurate kinetic-transport models at these conditions are essential for the design of efficient, reliable engines and controlling emissions.

While the global reaction for H_2 oxidation is written as $2H_2 + O_2 = 2H_2O$, Semenov and Hinshelwood demonstrated in the 1930s that the actual mechanism is considerably more complicated. In reality, there are several short-lived species, such as H, O, OH, HO_2, and H_2O_2, that are formed and consumed in the process and even more reactions that occur among these species, such as $H_2 + O_2 = H + HO_2$. Most of the controlling species and reactions were discovered decades ago and most recent work has focused on obtaining more accurate quantification of the properties of those species and the rates for those reactions. It is generally accepted that the mechanism consists of 20 reactions involving 8 species. My work thus far has indicated that there might be unconsidered, high-pressure reaction pathways that strongly influence overall system behavior. The ultimate goal of my Ph.D. research is to identify these new kinetic pathways and construct an H_2/O_2 mechanism validated for high pressure flames for use in the design of efficient, reliable gas turbines for synthetic gas combustion.

In my time here at Princeton, I have also been involved in a project focused on the spontaneous ignition of hydrogen and natural gas during high pressure tank ruptures.

My lab group has shown experimentally and numerically that hydrogen or natural gas tank leaks can ignite without an external ignition source. We are working to identify the circumstances that cause the spontaneous ignition so that this hazard can be avoided.

In a Mechanical Engineering department at a university like Princeton that stresses fundamental science, my research lies in the realm of technology-relevant science - policy decisions and promising technologies motivate the problems that I study. Being aware of what problems need to be addressed allows me to focus my attention on the most relevant topics so that my contributions can have the largest impact and I can anticipate future pertinent research directions. For example, more stringent regulations on NO_x emissions, incentives for CO_2 mitigation, and favorable economics could stimulate oxyfuel IGCC processes, where H_2 is burned in pure O_2 instead of air. In order to reduce the high flame temperatures associated with burning H_2 in pure O_2 to a level that engine materials can tolerate, dilution with H_2O is being considered as a potential strategy. One of my next research papers will address the effect of H_2O dilution on H_2/O_2 flames.

At the same time, the work of applied scientists like me can also help to inform policymakers and engineers of perhaps lesser known advantages or drawbacks of potential technologies. The findings from our H_2 spontaneous ignition study could guide safety standards for H_2 storage or even motivate regulations to keep H_2-fueled cars off the road.

Many fields especially in engineering are interdisciplinary by nature, but the alternative energy field, which is relatively young and is currently receiving extraordinary attention, moves very quickly. In such a fast-paced interdisciplinary field, more direct and more rapid lines of communication are required to keep all parties informed of the most recent progress. For instance, new carbon footprint analyses for potential biofuels are presented every couple weeks. A study that shows that a biomass-to-liquids fuel produced in a Fischer-Tropsch process has half the carbon emissions as a bio-ethanol produced by fermentation would indicate to me that my research efforts would be better spent finding ways to increase the octane rating of a Fischer-Tropsch fuel than finding ways to reduce formaldehyde emissions in ethanol combustion. The frequent meetings, contacts, and open dialogue of an energy-and-climate-focused group like PECS, which is comprised of specialists from varied diverse disciplines, creates these much-needed lines of communication such that its members can stay up to date on the latest progress on topics such as carbon footprint analyses of biofuels and H_2 safety issues.

2.2 Nitrogen production and algal growth

Sarah Fawcett, Geosciences

Primary production by marine phytoplankton (microscopic plants) is important to both the global carbon and nitrogen cycles. Presently, about one third (approximately 2 Gt C y^{-1}) of anthropogenic CO_2 emissions end up in the surface ocean. Phytoplankton use this CO_2 along with inorganic nitrogen (e.g. nitrate, ammonium) during photosynthesis and growth according to:

$106\ CO_2 + 16\ NO_3^- + HPO_4^{2-} + 78\ H_2O + 18\ H^+ \rightarrow C_{106}H_{175}O_{42}N_{16}P + 150\ O_2$
or $106\ CO_2 + 16\ NH_4^+ + HPO_4^{2-} + 48\ H_2O + 14\ OH^- \rightarrow C_{106}H_{175}O_{42}N_{16}P + 118\ O_2$
where $C_{106}H_{175}O_{42}N_{16}P$ *represents organic matter (biomass).*

Eventually the phytoplankton either sink out of the surface ocean or are exported into the ocean interior as byproducts of grazing by larger organisms. This mechanism, termed the biological pump, results in the drawdown of CO_2 from the atmosphere, and the subsequent sequestration of carbon in the ocean interior. Thus the biological pump helps to buffer the effects of increasing atmospheric CO_2, and significant effort has been spent quantifying its efficiency. However, the biological, physical and chemical mechanisms constituting the biological pump are difficult to measure since their interactions are complex and occur from the surface to deep in the water column. Nonetheless, understanding the biological pump is essential for understanding the current and future role of the oceans in CO_2 uptake and sequestration.

As an essential nutrient, biologically available nitrogen has the potential to limit productivity in the surface ocean and determine the composition of phytoplankton communities, thus affecting the removal of carbon from the atmosphere. N cycling is extremely dynamic in the surface ocean; fluxes tend to be high, while concentrations remain very low. There exists an oceanographic paradigm explaining how primary production supported by nitrogen from outside the well-lit surface ocean is equivalent to the amount of production (carbon) that is exported from this surface layer and sequestered at depth. Primary production supported in this manner is thus directly responsible for the removal of CO_2 from the atmosphere. This ‘new’ nitrogen comes from sources such as nitrate supplied to the surface from the deep ocean by physical mixing, atmospheric deposition (rain), or biologically mediated nitrogen fixation (i.e. inert N_2 gas is converted to inorganic forms accessible to phytoplankton). The alternative to ‘new’ nitrogen is sources of N recycled in situ due to remineralization of organic matter by bacteria, or leakage from grazed cells. This N is usually in the form of ammonium or dissolved organic nitrogen (e.g. amino acids), and the primary production it supports does not result in export to the deep ocean. Thus the efficiency of the biological pump depends on the fraction of photosynthesized carbon that escapes recycling and is exported from the surface ocean. Determining the amount of primary production supported by various forms of N provides a means to quantify this export and determine how much atmospheric CO_2 the ocean will sequester.

The objective of my research is to identify the N source to individual phytoplankton groups in the ocean, in part to quantify their contribution to carbon export and sequestration. We are currently developing a method that allows for the high-resolution measurement of various proxies in the surface ocean that tell us about the nitrogen source phytoplankton use for photosynthesis. Conclusions regarding the strength and efficiency of CO_2 drawdown by the ocean via the biological pump can be inferred from such measurements. The method allows us to separate individual cells into populations that share various characteristics of interest (i.e. we can separate different species or trophic levels) and then discern their favoured nitrogen source. Since climate change may cause changes in marine ecosystem structure, information regarding species-specific contributions to carbon export is important. We are also interested in seasonal patterns in phytoplankton use of nitrogen, and aim to quantify instantaneous rates of N transformation between different components of the ecosystem. This has the potential to tell us if the rate and amount of CO_2 sequestration by the oceans changes seasonally, or in response to some other forcing such as temperature or stratification. Ultimately, we hope to construct a model of N cycling in the surface ocean that will allow for prediction of ecosystem response (in terms of structure, N cycling and carbon uptake) to increased atmospheric N and CO_2 supply due to anthropogenic inputs.

The distribution and concentration of N in the surface ocean affects the fertility of the sea on a global scale. It is important to understand the current oceanic N cycle in high resolution in order to predict the potential impact of human activities. Warming and decreased pH (from increased CO_2) is expected to change productivity and community composition, compounding the effects of anthropogenic N. Climate change may further affect the biological pump as increasing temperature result in the stratification of the surface ocean, decreasing the supply of nutrients (i.e. nitrogen) from below, reducing primary production and thus CO_2 drawdown and sequestration.

Ocean fertilization is a potential CO_2 mitigation strategy that proposes adding iron or other nutrients to the ocean to cause large phytoplankton blooms that will draw down atmospheric carbon. The principle behind this idea is directly related to workings of the biological pump, yet it seems many proponents of ocean fertilization do not understand this mechanism. It is generally accepted among the oceanographic community that a better fundamental understanding of the biological pump is required before ocean fertilization can be considered a legitimate climate mitigation option. Research such as mine will help us refine our perception of how the ocean works, and thus inform whether it is appropriate to implement geo-engineering strategies like ocean fertilization. It has been particularly useful for me to discuss the potential applications of my research with the PECS. My work does not directly address questions of climate change or energy, yet integrating my knowledge with the expertise of political scientists, economists and engineers not only allows me to probe broader applications for my research, but represents the type of collaboration that may ultimately result in wiser, scientifically-sound policy decisions.

2.3 Energy storage with a focus on ultracapacitors

Elena Krieger, Mechanical and Aerospace Engineering

Energy storage plays a critical and increasingly profound role in the world's energy systems. Energy storage is most visibly apparent in portable electronics, but can come into play any time that energy generation is either temporally or physically displaced from demand. Electricity generation and load are often only partially aligned, and in many cases excess off-peak electricity is wasted while peak demand may require that electric plants hover in stand-by mode to be turned on only when demand spikes. Storage can enable off-peak electricity to be utilized during peak periods, meaning that generators can run closer to capacity and therefore more efficiently. Furthermore, storage can smooth intermittent generation from renewable energy sources like solar and wind, allowing for much greater grid penetration. Currently, this unpredictable intermittency caps wind generation at approximately 20%. Rural, off-grid electrification requires storage for solar and micro-wind systems to deliver energy to isolated homes and villages. The replacement of carbon-intensive gasoline-driven cars with battery electric vehicles is made possible only with energy storage. The list of applications is nearly infinite. However, each storage technology is limited in application by factors such as cost, cycle life, portability, and energy and power density, in addition to poor systems analysis of energy storage systems which would allow for greater penetration of the technology into the market.

Depending on the size and location of the demand, energy can be stored in a wide array of systems. The portfolio is mostly composed of mechanical-based energy storage, thermal energy storage, and electrochemical energy storage. The most common grid-based storage system is pumped hydro, where off-peak electricity is pumped up a hill and runs back down during periods of high demand. Compressed air energy storage (CAES), which is not a pure storage technology, stores pressurized air underground in aquifers or above ground in pipes and releases it to help run a natural gas turbine. Both of these systems are highly geography-dependent. Flywheels store energy in a rapidly rotating shaft and are good for short, high-power applications. Thermal energy storage can take many forms, including solar thermal heating of molten salts that can later be used to run a steam turbine. Another important class of energy storage technologies are electrochemical systems. These can be very large or small and portable, and typically include common batteries, flow batteries, fuel cells, and ultracapacitors. Batteries are composed of two electrodes connected by an electrolyte and store energy in a chemical reduction-oxidation reaction. Flow batteries function rather like a battery but with liquid active material, and fuel cells resemble flow battery with gas reactants instead of liquids. Finally, ultracapacitors superficially look like a battery with two electrodes and an electrolyte, but instead of relying on a chemical reaction, they primarily store energy in the electrochemical double layer which forms between the electrolyte and the charged plates.

My research at Princeton centers on this last form of energy storage. Because ultracapacitors store their energy in the separation of charges instead of in a chemical reaction, they can charge and discharge more rapidly than batteries. This means that their power capacity (energy in a given amount of time) is much higher than batteries, although this feature also results in a lower energy density than batteries. This charge separation is also much more reversible than a chemical reaction, so ultracapacitors can be charged and discharged many more times than batteries and therefore have a much longer lifespan. The two technologies couple well. A battery can store the majority of the energy while rapid charging and discharging can be managed by an ultracapacitor, saving the battery life and allowing for greater power output than a stand-alone battery. The range of ultracapacitor applications would grow if their energy density could be increased. The total amount of energy stored depends, in part, on the surface area of the electrodes and on how much voltage the electrolyte can withstand before breaking down. My research focuses on creating very high surface area carbon electrodes, novel electrolytes based on ionic liquids that can withstand higher voltages than traditional electrolytes, and examining the nanoscale material interactions that govern ultracapacitor capabilities. This last component entails examining the interaction between the feature size of the electrodes and the ion size in the electrolytes, and determining the optimal combination in order to maximize capacitance. Improvements in these areas will hopefully lead to greater energy and power density in the ultracapacitors.

Further increases in ultracapacitor energy density will be valuable in a number of carbon-mitigating applications. Hybrid electric vehicles and battery electric vehicles can utilize ultracapacitors for regenerative breaking and rapid acceleration, greatly increasing battery life. Increased energy density also reduces the amount of equipment that has to be hauled around in the car. Ultracapacitors can also play a role in power quality applications in the grid, and in smoothing the output of wind and solar energy generation in off-grid locations, obviating the need for a diesel generator and maximizing the efficiency of the system. However, the full potential for ultracapacitors can only be realized by examining a range of possible applications and directing research to fill those needs, whether they be cost, energy, power, safety, lifespan, or some other aspect. Ultracapacitors and other energy storage systems can have an important role to play in smoothing renewable energy generation, enabling the usage of battery electric vehicles, rural electrification, a distributed Smart Grid, and so on, but identifying these needs and utilizing storage systems effectively requires stepping out of the lab and examining the interplay between energy storage and other fields. Carbon pricing, alternative energy generation schemes, and development infrastructure, among other areas, all affect both the utility of ultracapacitors and other storage technologies and highlight which features are most useful and which need to be developed further. An analysis of pricing and efficiency on a grid level, for example, would allow for the identification of whether storage should be optimized for power, energy, cost, cycle life, and so on. A further study of transportation can also inform whether power or energy density are the top goals for ultracapacitor research, and cap and trade or other carbon mitigation efforts may pay a role in determining the cost-effectiveness of the technology compared to other approaches. I ultimately hope to step out of the lab for a period to take a systems approach to energy storage and evaluate energy storage applications in order to inform future research directions.

2.4 Technological change and the role of emerging economies

Nicolas Lefevre, Woodrow Wilson School

Perhaps the two biggest challenges in addressing climate change are the development of new climate friendly technologies and the participation of large emerging economies in reducing emissions. If these are not successfully addressed our climate problem risks remaining unsolved. These challenges are most often considered independently. However, one possible solution would be for developing countries to take an active part in climate friendly technological change; effectively addressing both challenges at once. This possibility is at the heart of my PhD research proposal.

Adopting a theoretical approach based on economic modeling is tempting. However, integrating distinctions among countries based on levels of development is not straightforward given the high level of aggregation of models of technological change. I therefore propose instead to assess the potential role of emerging economies in climate friendly technological change through case studies. In particular I wish to focus on two promising technological avenues in two large emerging economies: biofuels in Brazil and carbon capture and storage in China. These case studies are relevant because of the significance of the growing greenhouse gas emission trajectories in both countries but also because both countries are already engaged, though to different degrees, in the development of each technology.

I hope to define a general framework that will allow me to assess the potential role of a country in the development of a given technology. This framework will take a range of possible technological development trajectories based on best available information. It will then identify the basic needs for the successful accomplishment of each trajectory identified, including resources, capital, labor, infrastructures, industrial capabilities and institutions. Finally it will assess the extent to which a country may be able to fulfill these needs compared to more technologically advanced economies. The framework will then be applied to the case studies mentioned above, based on a combination of technology assessments, literature reviews and interviews.

In addition to the technological and industrial implications, I hope to draw some broader conclusions from my findings. In particular, I think the industrial perspective I adopt may shed some new light on the ongoing debate about incentives for developing countries' participation in an international agreement on climate change. Indeed most proposals focus on the funding of emission reductions in developing countries. Yet if it can be shown that some developing countries can gain from climate friendly technological change efforts through industrial development, this would effectively broaden the set of incentives for participation. This may have important implications for the nature of future international cooperation efforts.

Contrary to most doctoral studies, this research agenda draws from a variety of disciplines. It notably requires an understanding of technological change processes and the role of government. It draws on detailed technological assessments in the field of biofuels and carbon capture and storage. It also requires an understanding of economic development processes at the country level, the role of industrial policy and of how this has shaped development in China and Brazil. Finally, this research also draws on the climate policy literature to understand how this technological change assessment may influence mitigation efforts in the countries of interest and at the international level.

Such research can only be undertaken in the scope of an interdisciplinary program such as the Science, Technology and Environmental Policy Program of Princeton's Woodrow Wilson School, of which I am part. It does not benefit from the structure of an established field such as economics, physics or engineering. Instead of building on a strand of research it takes from various fields to create a new edifice. At the same time this multidisciplinary approach seems particularly well suited to the issue of climate change, which, as detailed in the introduction to this paper, is inherently multidisciplinary. It allows researchers to fill the gap between various fields and raise questions which may not be addressed in more traditional academic disciplines. The growing number of interdisciplinary programs in US and foreign universities focusing on climate change and sustainable development is a tribute to the need for dedicated multidisciplinary expertise.

2.5 Hurricane-related risk assessment and decision making

Ning Lin, Civil and Environmental Engineering

The Eastern United States is vulnerable to the potentially devastating impacts of hurricanes. Associated with extreme winds, heavy rainfall, and storm surge, landfalling hurricanes often cause enormous structural damage and economic losses to coastal regions. For example, although only a category 2 hurricane, Isabel (2003) produced more than 3.6 billion dollars in damage and resulted in 51 fatalities. Due to the fast development of coastal regions, hurricane damage and losses have been rapidly increasing in recent decades. Climate change may exacerbate global hurricane and typhoon damage and many otherwise modest storms may become truly destructive.

Hurricane damage risk assessment provides the basis for policy making. Studies on the impact of climate change on long-term hurricane risk may have important applications in decision-making processes that are related to both climate adaptation and climate mitigation, two responses that are identified by the United Nations Framework Convention on Climate (UNFCC) as essential to reduce the expected impacts of climate change on human society and environment. Assessing hurricane damage risk in the future climate, however, requires a comprehensive understanding of the scientific, engineering, and political aspects of the problem. Although science funding and engineering practice provide the basis to access the hurricane damage risk, public policy research plays an important role in enabling state of the art information to ultimately reduce the risk to society. However, scientific results are often not well interpreted to facilitate policy decisions. This is, in general, due to the lack of communication between scientific researchers and policy makers, and in particular, because of the large uncertainties associated with global warming and its impact on the already complex hurricane problem.

My research objective is to construct an informative hurricane risk analysis framework, within which key components of the hurricane damage process are consistently modeled, including a hurricane event module, which predicts hurricane landfall probability; a hazard environment module, which describes the multiple hazards associated with landfalling hurricanes, including extreme winds, heavy rainfall, and storm surge; and a structural vulnerability module, which estimates the hurricane wind damage to residential neighborhoods. The effects of climate variation and climate change are mainly considered in the hurricane event module, by investigating the non-stationarity of the time series of hurricane frequency and intensity. The hazard environment module involves the application of advanced weather and hydrodynamic forecasting tools, such as the GFDL hurricane model and the Advanced Circulation model (ADCIRC). The structural vulnerability module accounts for the essential damage mechanism to residential developments during a storm's passage, involving the interaction between wind pressure and windborne debris that leads to structural failures.

As a STEP/PEI fellow, my goal is to couple risk assessment with policy analysis to facilitate decision making related to insurance and its regulation, urban planning and development, and climate change adaptation and mitigation. Analyses show that a category-2 hurricane, making landfall around Atlantic City, NJ, would cause a storm surge of more than 10 feet in the Manhattan area. Future sea-level rise, along with a possible increase in storm intensity in a warming environment, would lead to a marked reduction in extreme-flood return periods. Combining risk assessment and policy analysis, I am trying to derive the probabilistic distribution of coastal-flood heights in New York City, in current as well as projected future climate environment, and investigate the effectiveness of the National Flood Insurance Program (NFIP) in providing risk-reduction incentives.

The Princeton Energy and Climate Scholars (PECS) group consists of faculty and graduate students working on various aspects of the climate change and sustainable energy problem while having the common interest of pursuing cross-disciplinary research and collaboration. As a PECS scholar, I am benefited from the opportunities to explain my research ideas to scholars from broader but related fields, and to reflect their comments and questions from different perspectives. My research on hurricane risk analysis, centering on civil and environmental engineering modeling, is thus enriched with views from scientists, policy makers, and engineers of other fields. I have also had a great experience learning about other aspects of the climate and energy problem that are out of my current research scope but fit in my general research interests. Global challenging problems, particularly, the ones that are related to climate and energy, can only be solved with collaborations from various disciplines, parties, and countries all over the world. PECS is unique in that it established an environment for young scholars to start to collaborate on climate and energy research from the early stage of their research careers.

2.6 Confronting uncertainty in sea-level and climate

Christopher Little, Geosciences

The threat of sea-level rise due to the melting of continental ice sheets is highly relevant to climate change mitigation and adaptation efforts, yet several key physical processes limit our ability to adequately characterize this risk. One of these processes is the ocean-driven melting of floating ice shelves ("basal melting"); over the past decade, research has indicated that observed increases in ice sheet discharge have been initiated by this oceanic trigger. My Ph.D. research extends our knowledge of the ocean dynamics that control the location and rate of basal melting, as well as its sensitivity to changing oceanic conditions. I utilize numerical ocean models (similar to weather models) to isolate the mechanisms – sub-shelf thermodynamic and dynamic controls, tides, and winds – by which heat drives basal melting. Like other areas of climate science, I attempt to validate these models with observations, and have collected oceanic data on two separate cruises to the Antarctic continental shelf. The understanding of basal melting derived from my research will illuminate its role in the regulation of ice sheet stability, oceanic freshwater balance, and global climate.

Basal melting at the ice-ocean interface is a process that may influence the manifestation of climate change on society (through its control on the rate of sea level rise), but it is currently poorly understood. It is not represented in the primary tools used to inform climate policy. In fact, no Ocean-Atmosphere General Circulation Model (GCM) currently incorporates an ice sheet that represents deglaciation processes realistically. More sophisticated treatments of ice sheets are in development, but will take time, and will require an improved understanding of key dynamic processes.

Because ice sheets are not the only source of structural error in climate models, my exposure to this issue has forced me to confront broader issues relating to risk and uncertainty through the climate community in particular, how uncertainty is carried across the science-policy interface. Climate policy (and thus energy policy) is likely to be implemented within a "risk management" framework, where risk is calculated as the product of a potential impact and its likelihood (the probability of occurrence, derived from scientific assessments). This risk will likely be weighed against costs associated with reducing GHG emissions. However, the likelihood of specific climate impacts is often highly uncertain. Our knowledge of the climate system's response to anthropogenic forcing is limited by simplifications to governing equations, ignorance of climate system components, and small-scale, chaotic, processes, as well as uncertainty in the forcing itself. As policy makers become comfortable using the output of climate models, excluded processes (i.e. ice dynamics) may provide false consensus and an incomplete scope of potential impacts. There is an ongoing need for the reassessment of uncertainty in climate projections, the development of tools to adequately characterize climate risks, and for communicating uncertainty across disciplines.

As scientists, we learn to probe, document, and critically assess assumptions in our models of nature. Yet as science-based decisions are translated to policy, critical assumptions limiting the scope of scientific models may get lost in translation. Where risk assessments may not be wholly quantitative or comprehensive, there will always be a role for expert opinion and communication. As climate projections become accepted as a basis for policy, scientists should be aware of the process by which projections and models are used. It is my hope that scientists who simplify highly complex systems are cognizant of their eventual use, and that these scientists involve themselves in the assessment and policy-making process.

Though my graduate studies focus on one process of particular interest (i.e. one small leaf), the concepts of deep uncertainty, risk assessment, and communication lie deep in the roots of the climate tree. These issues pervade climate science and extend across disciplinary lines. By engaging Ph.D. students with common interests across the disciplines, PECS has provided for me, and will provide for future fellows, a chance to practice communicating risk and uncertainty to future policy makers.

2.7 Predicting leakage in geologic storage of carbon dioxide

Edward Matteo, Chemical Engineering

My research looks at the very near term deployment of carbon, capture, and storage (CCS) applied to the use of depleted oil wells as storage sites for CO_2. While these formations represent a small fraction of the total potential for geologic storage of CO_2 (as compared to saline aquifers), they represent an important opportunity to test and demonstrate the reliability of CCS as a whole. Oil fields are also an attractive option as these formations are not subject to the regulatory obstacles that apply to saline aquifers.

Leakage of CO_2 from storage formations is a major source of concern and needs to be well understood before widespread implementation of CCS can occur. Clearly, the viability of CCS as a carbon mitigation strategy is compromised if stored CO_2 returns to the atmosphere through leakage. There is also an improbable, but serious risk to human health and safety if a plume of CO_2 were to escape to the surface or migrate underground to adjacent formations.

In depleted oil wells, the greatest likelihood of leakage is through the cement used to complete the well-bore. When CO_2 is injected into the formation, it reacts with water to form carbonic acid. This acid can degrade well-cement, possibly creating cracks and fissures that would allow CO_2 to escape from the formation. My research focuses on designing experiments to evaluate the mechanical and transport properties of corroded cement, as well as to understand the chemistry of the corrosion process. This information is critical in determining the extent to which corrosion of the well-bore increases the likelihood of leakage.

Given uncertainties regarding the sources of energy for the future, the extent to which

CCS is implemented could have a potentially major impact on future scenarios for carbon emissions. CCS has a unique capacity in that it offers reduced emissions with existing technology. It can also help to create a smooth transition to carbon-free or low carbon energy use, until the technologies for renewable energy are honed for widespread implementation. When coupled with biomass-derived fuels (a possible future fuel source), CCS is a carbon negative mitigation option. CCS may thus have a future beyond fossil fuels.

There is, however, a distinct possibility that the leakage issue, if not thoroughly proven safe, could create a barrier to implementation through a negative public perception of the technology. There is also a perception, among some proponents of renewable energy, that CCS impedes the development and implementation of renewable energy. This being the case, it is important that the role for CCS in the portfolio of future energy options is well defined. If this is done properly, current mitigation can optimize the balance between implementation of existing technologies and development of game-changing technologies in such a way that opportunities to cut CO_2 emissions sooner rather than later' are not missed.

A perfect example of the importance of resolving both the leakage issue and defining a role for CCS can be seen in the dispute over legislative bill AB 705 in California. This bill aimed to establish statewide regulations for CCS. And despite support from major environmental groups such as NRDC, AB 705 was successfully blocked by a grassroots movement with a preference for renewable energy as a stand-alone solution to climate change. The technical uncertainties of leakage were central to the dispute over the proposed legislation, even though the science showed that a finite but highly improbable risk existed. Another key aspect of this group's opposition to CCS was the fact that, in principle, CCS would enable a continued reliance on coal and possibly displace funding for research into renewable energy technology. While it is true that there are risks to the environmental associated with continued or increased use of coal, this risk must be considered alongside climate change risks associated with not making effective emissions cuts or making them too slowly.

Defining the role of CCS in coordination with various carbon mitigation technologies is a great example of an interdisciplinary problem that sits squarely at the interface of climate change and energy. This complex issue requires expertise in several areas, including policy mechanisms to spur and moderate technology diffusion, the ability to discern the technical feasibility and potential of various technologies, and practical understanding of the energy market. There is also a critical need to incorporate risk analysis into the process of choosing technologies for carbon mitigation. CCS also poses several unique legal issues, as regulations for implementation, monitoring, and liability are non-existent in many countries. Policy can be a critical tool in ensuring a well-defined role for CCS in carbon mitigation and a renewable energy future. For example, policy could be crafted to provide the following: a) incentives and regulations to establish CCS as a transitional technology (at least when associated with coal use), b) disincentives to protracted extension of coal-use, and c) certainty that research and development funding is in place to implement a renewable energy future. In order for experts from all of these fields to construct a useful dialogue towards making progress on effective carbon mitigation, they must, to some degree, be conversant across several disciplines.

PECS has been a great opportunity to gain skill in engaging in an interdisciplinary dialogue. As the diversity of disciplines in the group grows, so to will the breadth of the PECS experience. PECS Meetings have given fellows the opportunity to have a dialogue with leading experts in a diversity of fields including climate modeling, post-Kyoto climate agreements, oil in the middle east, and the development of new catalytic materials for the production of biofuels. From my own lunchtime presentation, I gained a great deal of understanding about the best ways to present my research, as well new avenues to explore in the policy oriented aspects of my research.

2.8 Microbial biofuels as an alternative fuel source

Kelsey McNeely, Chemistry

Solar energy represents a largely untapped resource of energy for the Earth: the sun provides more incident energy to the earth's surface in one hour than humans use as fuel and electricity in one year. Photovoltaic cells are currently the most widely used means to capture the sun's energy; however, these provide electricity while about 2/3 of the energy used by man is in the form of fuel. A biofuel can be generally defined as solar energy directly or indirectly stored via a biological process in terrestrial or aquatic plants or microorganisms. A clear advantage of biofuels is that, with the exception of supplemented nutrients and water, photosynthesis harnesses solar energy for "free." Terrestrial plants are currently being used for biomass, ethanol, cellulose and syngas formation. Recently, fuels from terrestrial plants have come under scrutiny due to the land and water use that they require. Farmland is valuable for growing edible crops, and utilizing a fraction of it for corn ethanol, for example, drives up the prices of food crops. Switchgrass and other plants that can be grown on non-arable land are currently being genetically improved so that biofuel availability will not necessarily add significant pressure to food availability and cost. Another alternative is to use microbial sources of biofuels that require no land at all and instead can be cultivated in lakes, bays, or man-made pools on non-arable lands.

Microbial-based biofuels could either utilize biomass from an outside source (e.g. addition of celluose which the microbes could digest to form usable alcohols) or, in the case of photosynthetic microbes, they could directly synthesize their own biomass from sunlight and atmospheric CO_2 and then convert this biomass into lipids for biodiesel, hydrogen, or alcohols. Photosynthetic microbes offer another advantage over land plants in their greater photosynthetic efficiency during the conversion of sunlight into biomass. Aquatic microbial photosynthetic organisms are thus an important alternative to terrestrial plants for fuel production.

Theoretically, microbes could be engineered to produce any biofuel. Because most microbes reproduce by cloning themselves, there are no complicated genetics to master in order to improve the next generation and genetic manipulation is straightforward with immediate results. New genes encoding enzymes which synthesize biofuels can be inserted just as easily as unnecessary genes - for example those that code for metabolic pathways which waste substrate - can be removed. Since photosynthetic microbes already exist in extreme environments, such as hot spring and alkaline lakes, there exists a diverse range of energy storage molecules. Diatoms, for example, accumulate lipids, which can be utilized for biodiesel. Cyanobacteria and algae store energy as sugar and starch, which can be used as biomass in a number of processes or further processed by the microbes themselves. Certain strains of these microbes posses the capability to synthesize alcohols and hydrogen gas, among other potentially relevant small molecules, under certain conditions.

My research is focused on altering a marine strain of cyanobacteria, Synechococcus 7002, in order to improve the rate at which it makes hydrogen. This cyanobacterium synthesizes sugar during the day, with sunlight driving the splitting of water and capture of CO_2 from the atmosphere. As a byproduct of photosynthesis, the cyanobacteria make oxygen. At night, when photosynthesis is no longer producing energy for the cells, they catabolize their stored sugars and use the oxygen remaining to carry out respiration. When the oxygen is consumed, this metabolism switches again to fermentation. During fermentation, the cells must release their waste because there is no oxygen remaining to process it further into useful metabolites. It is during this time that the cells make lactate, acetate, and hydrogen gas. In order to increase the amount of hydrogen gas, the extra product, lactate, can be removed through genetic manipulation. In such a mutant, where we deleted lactate production, we have observed 5-times more hydrogen accumulated than the original strain. In principle, this method can be applied to strains of cyanobacteria that make ethanol instead of hydrogen or to diatoms, which make lipids needed for biodiesel, to increase their yields.

Investigating the formation of fuel by biological processes is beneficial not only in finding ways to improve upon the biological system, but also in discovering the ways in which nature has already perfected these processes through evolution. For example, the hydrogenase enzyme that catalyzes the formation of H_2 gas from protons and electrons (in some bacteria and higher organisms) uses two commonly available metals, nickel and iron, at the protein's catalytic site. In fuel cell research, many metals, including nickel and iron, have been studied for their ability to catalyze this reaction, with platinum, a rare and expensive metal, being the most efficient catalyst in these studies. However, when comparing a platinum catalyst to the biologically active hydrogenase enzyme, the enzyme is actually more efficient, providing more current density than a platinum catalysts, with the added benefit of the lower cost of nickel and iron as compared to platinum. One downside of the biological catalyst is the short life of enzymes; for this reason among others, harnessing the power of the enzyme for extended periods outside of a cell is not yet feasible. The enzyme could, however, act as inspiration for an inorganic analog utilizing readily available nickel and iron in place of expensive platinum. In this way, biologists and synthetic chemists can communicate in order to express how Nature does chemistry in order to inspire better ways of doing synthetic chemistry.

There are, of course, many other collaborations and communications within the field of alternative energy. For example, while basic science is still being investigated, engineers are developing usable technologies to implement the science. An open communication between chemists/biologists and engineers makes the process of developing new technologies more efficient. Similarly, there also must be a more open dialogue between natural scientists and social scientists in order to make the implementation of these technologies more efficient as well. I hope that PECS will prove to be, and already has to some extent, a forum for forming these collaborations.

2.9 Reducing uncertainty in climate models

Lauren Padilla, Mechanical and Aerospace Engineering

My research grew out of a desire to use my engineering background to address issues in climate change. During my first term at Princeton, I met with potential advisors in Mechanical and Aerospace Engineering and the Program in Atmospheric and Oceanic science. It was very exciting to find that there were many, in addition to my eventual advisors, who were interested in developing an interdisciplinary project.

Our research focuses on reducing the uncertainty in predictions of future climate change by applying methods from optimization and control theory to simple climate models. We are specifically interested in how uncertainty in climate feedbacks affects the overall uncertainty of two metrics representing climate change: the equilibrium climate sensitivity and the transient climate response. Our eventual goal is to provide narrower estimates of the probability density function of these responses and to assess the validity of the characteristic ‘fat tail’ in the distribution, that arises from the skewed relationship between feedback strength and equilibrium climate sensitivity.

Since interactions among feedback processes, which enhance or dampen the climate’s basic radiative response to natural and anthropogenic forcing, are not easily investigated in coupled climate models, we develop simple energy balance models, parameterizing individual feedbacks, to study the propagation of uncertainty from feedback to climate response. Then we use observations of the actual climate from the past century to place boundaries on our simple model parameters and thus reduce the uncertainty of the response.

As I think about my specific research project in the bigger energy and climate context, I trace my work back to uncertainty in climate change and explore how many topics branch from there. An important branch, the scientific understanding of uncertainty, which includes my work, involves improved model development, physical understanding, and observational networks. These three areas rely on the collaborative work of climate scientists, statisticians, engineers and physicists. However, even with major advances in this area, there will always be some degree of uncertainty in climate science that other disciplines will have to address.

In the policy arena, leaders at all vertical scales from global agencies down to single businesses, will have to decide how much to insure against a small probability of extreme change. The economics of uncertainty will play a major role in how conservatively governments and industries adapt regulations and infrastructure to prevent and cope with the threat of a vastly different climate.

The planning of engineering adaptations to climate change must include assessment of the risk that the adaptation may be insufficient, perhaps leading to more cautious designs. Uncertainty determines how seriously we should consider geo-engineering schemes, which are hotly debated ideas in ethics. The government and the public have a moral responsibility to preserve the planet for future generations. Directly manipulating the climate, which has its own uncertainty, may be overstepping our jurisdiction, however, knowingly neglecting to act on potential disaster scenarios may be unethical as well.

In my experience, interdisciplinary collaboration seems to be increasing in academia as well as industry and government. In just the two years I have been at Princeton, we have had seminar series on Ethics and Climate Change, and Oil, Energy and the Middle East, the development of PECS, joint workshops with climate scientists and engineers, and new courses co-taught by instructors from different departments.

While I worked at the Environmental Protection Agency (EPA) in Ann Arbor, I was part of a research team in collaboration with Ford Motor Company working to develop more efficient engine technology. At the same time, the EPA began responding to the Supreme Court decision compelling the agency to regulate greenhouse gases under the Clean Air Act. My supervisors on the engine research team became active participants in the policy debate.

These kinds of examples cause me to be optimistic that established links will grow stronger and new collaborations will develop. As these connections improve, however, we will have to be careful about redundancy. It would be detrimental to our progress to have each discipline try to tackle every part of the problem. A mechanical engineering department with its own climate-modeling lab, for example, would be a poor use of resources. We will have to carefully define interfaces between disciplines so as not to lose our specialization.

2.10 SO_2 mitigation in China

Yuan Xu, Woodrow Wilson School

Energy and environmental policies could be the title of my major. In my PhD research, I developed expertise mainly in China's environmental protection at coal power plants. The SO_2 emissions goal in the 11th Five-Year Plan (2006-2010) directed my PhD thesis with a specific focus on China's deployment of over 300 GWe SO_2 scrubbers at coal power plants in the first three years of the plan. It could be the best empirical case from which China can learn to attain future CO_2 goals. The deployment and later successful operation were not expected considering both China's previous unwillingness to protect the environment and the central government's lack of capability to implement its environmental will. My PhD thesis tries to understand the logic and the methods behind China's realized emissions reduction.

An empirical study was carried out to better distinguish China's environmental performance, particularly from the perspectives of regime type (democracy vs. autocracy), the strength of rule of law, and income level. China's data on SO_2 scrubbers and SO_2 emissions were carefully examined. Although correcting China's mistakes in its official statistics could adjust upward SO_2 emissions from the coal power sector by generally over 30%, China's coal electricity was still tied to a rapidly decreasing amount of SO_2 emissions, which confirmed the phenomenon for research.

To perform the investigation, a five-step analytical framework was established from studies on goal in the discipline of social psychology. This methodology was chosen because of the central status of goals in China's efforts to control SO_2 emissions. Three of the five steps of the investigation are derived from goal studies on individuals: goal setting, goal acceptance and goal attainment. To accommodate the difference between a governmental and an individual goal, two additional steps on policy tools were formulated: policy enactment and policy enforcement. China's efforts were examined following the line of these five steps. In addition, China's market of SO_2 scrubbers was analyzed to shed light on why China was able to accelerate the technology deployment so fast. To test the legitimacy of the analysis, a field campaign was designed to collect information through both questionnaires and interviews.

Energy is a solution to many problems and a foundation of modern society. However, just like almost every positive factor in this world, it has some negative impacts. Electricity generated in coal power plants the focus of my research is a particular representative. The issue is whether we can take its advantages but minimize disadvantages. The coal electricity market on its own is not successful in protecting the environment, thus governmental intervention is necessary. My PhD research focuses on SO_2, a crucial pollutant from the electricity generation process. From the perspectives of scope and costs, SO_2 could be the most comparable air pollutant with CO_2 among those the world has seriously dealt with. China is a giant in the worlds of both energy and the environment. My research could help China learn from its past and demonstrate to other countries a successful case that does not fit into conventional wisdoms of green economies.

Policy research is problem-oriented, and problems in the real world often ignore the division of disciplines. Energy and environmental problems naturally require interdisciplinary cooperation for recognition and solutions. For example, findings in natural sciences establish the relationship between anthropogenic emissions of greenhouse gases and global warming. Other scientific studies demonstrate the dire consequence of global warming to complete the arguments for mitigating greenhouse gases.

Natural sciences can answer the question why, but another crucial question how will rely on engineering for technological options and policies for their actual implementation. Our PECS scholars commit time and passion mainly in answering these two questions. The PECS arena facilitates communication across disciplines and helps locate each scholar's research in the whole picture. Furthermore, research alone cannot make the mitigation come true. NGOs, industries, politicians and many other components of the society are all stakeholders to mobilize the individuals, institutions and governments. No PECS scholar is primarily involved with these on-the-ground efforts, but the exposure in our field trip to Washington (under planning) could at least compensate this aspect a little and probably motivate future interest.

3 Conclusion

3.1 Balancing multidisciplinary and unidisciplinary expertise

While a few PECS students are engaged in programs that specifically aim to generate multidisciplinary expertise, the bulk of the PECS cohort works within departments more accustomed to unidisciplinary research. Still, several such students work on topics which bridge more than one discipline and this is likely to be a growing characteristic of climate research.

Developing multidisciplinary expertise requires both time and resources taken away from developing deeper expertise within a given discipline. Enhanced multidisciplinary awareness, however, aids in both learning from the approaches of others and communicating findings to non-experts. Given how quickly climate knowledge is accumulating, this awareness also helps scholars to adjust their research directions accordingly and to know when their findings should best be communicated to the broader community and eventually decision makers. How then should the balance between multidisciplinary and unidisciplinary expertise be struck? There is no simple answer to this question, yet what seems certain is that the climate change and energy problem requires both types of expertise.

In its first year, PECS has provided a discussion forum for students using various strategies to achieve an effective balance. Although no ideal strategy was found, the process was helpful in illuminating roadblocks and key questions. For example, it is unclear what level of understanding of each discipline is sufficient in a cross disciplinary project. Does the student need to be on the cutting edge of each field they span or is an understanding that allows addressing the research topic sufficient? Another challenge is that academic supervisors may not be familiar with multidisciplinary research. This may be further exacerbated when bringing supervisors from different departments together. How then can existing expertise best be used to guide new multidisciplinary research?

We hope future PECS members continue to address these questions and others. The following section details some initial thoughts with respect to fostering interdisciplinary approaches for both PECS scholars and Princeton University as a whole.

3.2 Collaborative programs and Princeton

With the sense of urgency that climate change elicits, especially among scientists and policy makers, a new generation of collaborations have emerged that aim to address climate and energy problems. In the academic setting, the emphasis on collaboration has brought together researchers from different departments. For example, at the Massachusetts Institute of Technology (MIT) the Center for Global Change Science was developed to address climate change issues with a primary focus on engineering sciences. In a separate MIT initiative, the Center for Energy and Environmental Policy Research was established for social scientists. These two centers now collaborate under a joint program which has shown recent success with interdisciplinary publications and lectures. The MIT program may prove a good starting point for other universities and research institutes interested in facilitating interdisciplinary study.

Princeton University has shown recent initiative in developing collaborative research efforts. The Science Technology and Environmental Policy (STEP) program works to teach graduate students about policy relevant to science and energy. More recently, the establishment of the Andlinger Center for Energy and the Environment will encourage greater collaboration within the engineering departments in order to work towards the common goal of energy security and environmental responsibility. The development of this center is an important first step in both strengthening and creating collaborations among similar engineering research groups. However, the Andlinger Center could even more effectively address its goals if it facilitated dialogue among engineering, natural, and social sciences.

The first PECS group has successfully achieved such a dialogue. The scholars have learned a great deal from candid, round-table, dinner presentations with faculty experts in diverse yet related fields. Additionally, we have benefited from lively and slightly less formal student led discussions of each scholars' research, which have given the group a sense of partnership in the pursuit of common goals, and have opened channels for communication, including the development of a group blog. Although this group is currently not focused on forming technical collaborations, it lays the groundwork for the communication that would necessarily precede any such relationship. As graduate students, there is little opportunity to branch out beyond the narrow focus of one's research. Students' interactions are often limited to their department or field. PECS has planted the seeds which will grow into multidisciplinary collaborations as its members go on to become the professors, researchers, and policy makers who will be responsible for climate and energy security in the near future.

3.3 The future of PECS

To further improve the scholarly communication of the group, PECS would like to see interactions among its members become more seamless by holding casual evening meetings, perhaps monthly, or as informal follow up to dinner discussion. We also look forward to becoming more active in the Princeton community and beyond. The group is planning an outing possibly to Washington, D.C. and has discussed hosting a symposium on campus.

As a highly motivated group, PECS is also making efforts to transition to greater student involvement in its leadership. We envision inviting speakers from a broader range of disciplines, hopefully including the politics, physics and psychology departments, and perhaps even inviting a climate dissenter for some debate. We are interested in discussing competing ideas within climate and energy topics at some PECS events. We would like to reformat our monthly dinners to make them more dynamic by asking that speakers provide some materials for discussion before the meeting. This would allow scholars to come to the table more prepared for energetic exchange.

Along the lines of expanding diversity, next year we look forward to new scholars that hail from economics, atmospheric and oceanic science, engineering, and politics. We hope that these new members will bring continued enthusiasm to the lunch meetings. As detailed in section 2, the current scholars have received lessons in diverse topics ranging from modeling hurricanes, to China's approach to atmospheric pollutants. The new scholars will further diversify these lunch lectures and expand our collective knowledge of the challenges we face as researchers at the forefront of the climate and energy problem.