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Clean Energy Systems

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Executive Summary

A healthier future with affordable and accessible clean energy

The generation, transmission, distribution and consumption of energy are very closely interlinked to advancement in human prosperity. Renewable energy is the fastest growing energy sector, but contributes only to about 12% of energy consumption today, projected to grow to about 20% in 2040. Even under the most optimistic scenario, fossil-derived sources will provide more than 75% of our total energy consumption in 2040. Energy generation from fossil fuels is inevitably accompanied by emissions that are detrimental to the environment and/or to human health. While it is idealistic (and somewhat comforting) to project an energy outlook based entirely on renewables and to demand a moratorium on all emissions, such an outlook/demand would be rather misguided and ill attuned to techno-economic reality. Considering the above background and ground realities, the relative maturities and potential of the various technologies, and the strengths and capabilities extant at WashU and SEAS, we propose a strategic clean energy systems (CES) research portfolio comprising:

Solar Energy and Energy Storage (SEES) initiative: The SEES initiative will aim to mitigate global energy inequality through sustainable energy harvesting and storage strategies that transcend scientific, scale-up, cost, and reliability barriers. The SEES Center will focus on translational research in energy harvesting and storage across a wide range of technological readiness levels, ranging from fundamental understanding to systems deployment.

Cleaner Energy from Fossil Fuels (CLEFF) initiative: The CLEFF initiative seeks to develop new solutions to mitigate carbon dioxide emissions from power plants, improve public understanding of the role of fossil fuels as energy sources, and train talented researchers who can address future challenges associated with fossil fuels.

Bioenergy and Biofuels (B2) initiative: The synergistic B2 initiative should pursue an understanding the structure of energy-dense lignocellulosic biomass for deconstruction, developing microbial-based biosynthetic processes for efficient conversion of deconstructed biopolymers into biofuels, and enabling conversion technologies that increase the yield, value, and diversity of bioenergy and biofuels from lignocellulosic biomass.

The proposed initiatives build on current strengths within SEAS and WashU. These include multimillion-dollar funded research projects and infrastructure in renewable energy storage and in clean fossil technologies, and a strong core of current faculty members in each domain. SEAS is primed leverage the excellent relationship with local industries such as Ameren and a global network, within the framework of the MAGEEP partnership. Each initiative has a clear value proposition, a unique selling point, and distinctive features. A common distinguishing feature that will set SEAS apart is the emphasis on translational technology and technology deployment. Collectively, the impact of the proposed initiatives will transcend the techno-economic domain and provide significant societal impact on a global scale.

Preamble

The generation, transmission, distribution and consumption of energy are very closely interlinked to advancement in human prosperity. To provide some context with respect to the scale of the energy enterprise, global energy consumption (across all sectors) today is on the order of 600 quadrillion BTU (quads; *for reference, 1 quad is equivalent to the energy contained in 8 billion gallons of gasoline*). Global energy consumption is projected to increase to about 820 quads by 2040 (about a 40% increase in 25 years). However, it is important to recognize that this increase is highly asymmetric. While consumption during this period will increase by about 18% in OECD (Organization for Economic Cooperation and Development) countries, the corresponding increase in non-OECD countries is about 70% (85% in non-OECD Asian countries — largely driven by India and China).

Renewable energy sources (including hydroelectricity) contribute to about 12% of energy consumption today (about 70 quads), growing to about 20% (160 quads) is 2040. The reality is that even under the most optimistic scenario, we will have fossil-derived sources (coal, liquid fuels, and natural gas) provide more than 75% of total energy consumption in 2040. That said, renewables will be the largest growing sector over the next 25 years, with an annual growth of about 2.6% (compared to 2.3% for nuclear, 1.9% for natural gas and 0.6% for coal). Among renewable generation sources, solar, wind and bioenergy represent the principal growth sectors, with hydroelectric power being constrained by geography (most readily accessible sites have already been accessed).

The other equally important part of the energy equation relates to the impact of fossil-derived energy generation on the environment and on human health. Energy generation from fossil fuels are inevitably accompanied by emissions that are detrimental to one or the other. CO2 (and other greenhouse gas) emissions typically dominate the narrative, but other contaminants (SOx, NOx, mercury etc.) have a more pronounced and immediate effect on human health. While a ca. 35% overall increase in CO2 emissions is projected between now and 2040, the increase is again highly asymmetric: 9% in OECD countries and about 50% in non-OECD countries (dominated by India and China). Given the current disparity in GDP-per-capita between OECD and non-OECD economies and the correlation between energy consumption and GDP-per-capita, it is unlikely that non-OECD countries will divest from fossil fuels, regardless of the positions they take in non-binding climate agreements.

Thus, while it is idealistic (and somewhat comforting) to project an energy outlook based entirely on renewables and to demand a moratorium on all emissions, such an outlook/demand would be rather misguided and ill-attuned to techno-economic reality. As an example, replacing all the coalderived electricity in China with solar-PV-derived electricity would require a capital investment of $2 trillion, while addressing only about 15-20% of overall energy consumption/emissions.

Defining the CES strategic research portfolio

Considering the above background and ground realities, the relative maturities and potential of the various technologies, and the strengths and capabilities extant at WashU and SEAS, we propose a strategic CES research portfolio composed of:

1. The Solar Energy and Energy Storage (SEES) initiative
2. The Cleaner Energy from Fossil Fuels (CLEFF) initiative
3. The Bioenergy and Biofuels (B2) initiative

This portfolio will allow for global impact and visibility. It includes the dominant source of future energy production, namely fossil-derived energy, from the important perspective of mitigating the environmental/human health impact by minimizing, capturing and sequestering harmful emissions. It includes the fastest-growing renewables sector, namely solar energy as well as energy storage technologies that will accelerate the deployment of both wind and solar energy at the grid-scale. Finally, it includes bioenergy and biofuels, which represent an important CO2-neutral liquid-fuel component of any transition away from fossil-derived transportation fuels.

Strategic advantages to pursuing proposed CES-related research at WashU SEAS:

As an engineering school aspiring to a global reputation for excellence, it is imperative for WashU SEAS to exhibit leadership across multiple domains that are universally considered to be grand challenges. Energy has for long been identified as an integral component of several grand challenges, for example, the NAE grant challenges in engineering. WashU SEAS is uniquely positioned to advance the state of the art in the SEES, CLEFF and bioenergy/biofuel domains.

Current strengths and ongoing activities: In the SEES initiative, ongoing activities include multiple multimillion efforts ($2M from ARPA-E for energy storage, $ 3M from DOE-EERE for energy conversion and $4M from SERIIUS for solar energy) and a pending $30M proposal for an Indo-US center on smart grids and energy storage. A team of about 15 faculty members across WashU are engaged alongside the core researchers in SEES-related activities. Accessible infrastructure includes a state-of-the-art spectroscopy facility that was acquired under an EFRC and can be used in solar PV research. In the CLEFF initiative, WashU SEAS is home to a unique multi-million-dollar pilot-plant facility that can be used to study the mitigation of emissions harmful to the environment and to human health. WashU is also home to a world-class aerosol center (CASE) and there is a natural collaboration pathway that can be leveraged (many emissions analysis and emission mitigation strategies have roots in aerosol science). Research in this domain has attracted significant industry and federal support (to the tune of about $12M) and engages a team of about 20 faculty members across WashU.

In the bioenergy and biofuels initiative, arguably the youngest of the three initiatives, SEAS and WashU is home to an elite group of five proactive young faculty members with complementary expertise that covers biomass engineering and catalysis, synthetic biology, metabolic engineering, bioprocess engineering, and systems biology. This group is highly recognized and has secured about 10 prestigious Early Career awards among them. Through these faculty members, SEAS has invested significant startup resources into infrastructure in this domain. Ongoing research activities include both the conversion of lingo-cellulosic biomass into tractable intermediates and the complementary problem of converting the intermediate efficiently into useful fuels and chemicals.

Local advantages: St. Louis has been identified as the ideal test-bed for solar PV panels given the prevalent climatic conditions. Moreover, the local utility, Ameren, is highly supportive of and engaged with efforts to promote renewable energy generation/storage and integration with the grid and has committed to participate on joint center-type proposals (it is rare to find utilities that embrace change to the extent that Ameren has indicated they will). The Midwest remains a major producer and consumer of both coal and natural gas, with local coal companies providing significant amounts of support to research activities within SEAS. The Midwest is also a major producer of crops (and remnant biomass such as corn stover) that can be converted to biofuels. Access to the Tyson center and to the Donald Danforth Plant Science Center are added local advantages in the bioenergy/biofuels domain.

Global reach: The MAGEEP partnership is unique to WashU and SEAS and can be very effectively leveraged in all three proposed research domains. Both SEES and CLEFF initiatives already enjoy significant international collaboration (e.g. proposed global PV test bed). With time, the bioenergy initiative will also grow to encompass fruitful collaborations across this partnership.

Achieving excellence in proposed CES research at WashU SEAS:

Proposed research thrust — Solar energy and energy storage: The goal is to launch the SEES Center to support the work currently underway and promote further growth in this area of research, education and deployment. The overarching **vision** of the SEES Center is *to mitigate global energy inequality through sustainable energy harvesting and storage strategies that transcend scientific, scale-up, cost, and reliability barriers. The mission of the SEES Center is to perform translational research and promote educational activities in energy harvesting and energy storage across a wide range of technological readiness levels (TRLs), ranging from fundamental understanding to systems deployment.* To fulfill this mission, the SEES Center will engage the SEAS and WashU community and relevant external stakeholders (including MAGEEP partners) in a wide portfolio of renewable and sustainable energy technologies, with emphasis on integration and deployment of energy generation, storage, transmission and distribution. The Center will interface with a global network of partners in industry, government and academia to advance its mission. SEES will focus on the following topics, which span the entire TRL range:

1. Fundamental solar PV and energy storage research (SERIIUS, ARPA-E, DOE)
2. Fundamental studies of light harvesting technologies (PARC and solar fuels work)
3. Grid penetration of intermittent renewables through judicious integration with storage
4. Distributed energy platforms for regions lacking grid-penetration
5. Vehicle-to-infrastructure (V2I) and vehicle-to-grid (V2G) platforms
6. Energy arbitrage utilizing large-scale storage solutions
7. Establishing an evolving renewable energy smart-micro-grid test-bed on campus
8. Establishing a global PV test facility (in conjunction with MAGEEP)

The impact of SEES activities will extend past the techno-economic domain. By enabling and deploying technologies (such as distributed energy platforms in areas lacking grid penetration) that impact the most resource challenged segment of the world's population, significant societal impact will be achieved globally, consistent with WashU and SEAS mission.

Proposed research thrust — Cleaner energy from fossil fuels: CLEFF is designed to address challenges that remain to ensure that fossil-derived energy is extracted and used in a way that does not adversely affect climate or human health. The methods employed will include (1) developing new solutions to mitigate carbon dioxide emissions from power plants, (2) improving public understanding of the role of fossil fuels as sources of energy and (3) training talented engineers and researchers who can address future challenges associated with fossil fuels. CLEFF will grow from the strong base that has been established at WashU by the Consortium for Clean Coal Utilization (CCCU), and will significantly broaden this base to address not only cleaner coal utilization, but the cleaner use of fossil fuels in general. CLEFF will be a center of research for carbon capture technologies and for the

utilization or safe storage of carbon dioxide (CCUS). Renewable fuels and biomass will also be considered where, when combined with CCUS, they can result in negative emissions. Specific focus topics include:

1. Advanced oxy- and pressurized-combustion, and chemical looping for carbon capture.
2. Development of solvents and nanomaterials for post combustion capture of CO2.
3. Safe and effective geologic sequestration of CO2.
4. Conversion of CO2 to products via biological, electrochemical, or solar-catalytic means.
5. Reduction of power plant CO2 footprint by co-firing with biomass.
6. Control technologies for other hazardous pollutants (SOx, NOx, metals, fine particles).

By enabling the environmentally-friendly and non-hazardous extraction and use of fossil-derived energy sources for primary electricity generation, this initiative will have a global impact in terms of air quality and human health.

Proposed research thrust — Bioenergy and biofuels: Energy-dense biopolymers lock solar energy through photosynthesis and store atmospheric CO2 in reduced forms, which can be potentially converted to a diverse array of useful fuels through the power of synthetic biology. Although having great potential, to realize such conversion in an economical and scalable way is an immense challenge that requires integration of expertise in multiple disciplines including structural biology, catalysis, synthetic biology, metabolic engineering, process engineering, and systems biology. The key research objectives are to:

1. Understand the structure of energy-dense lignocellulosic biomass for deconstruction,
2. Develop microbial-based biosynthetic processes for highly efficient conversion of deconstructed biopolymers into renewable biofuels, and,
3. Investigate the underlying science and engineering to enable conversion technologies that increase the yield, value, and diversity of bioenergy and biofuels from lignocellulosic biomass.

By enabling the efficient conversion of lignocellulosic biomass (currently wasted) into dense, CO2-neutral liquid fuels, this initiative will have significant impact by providing an environmentally friendly energy solution for the transportation sector.

Unique selling points (USP) and distinctive opportunities: The SEES center is committed to transcend the initial fundamental research stage common to most University-based centers and extend its purview and expertise to translation and deployment of technology, with an overarching emphasis on mitigating global energy inequality. A second distinctive opportunity in this initiative lies in identifying the primary entry markets for solar energy/ energy storage technologies. While most competitors are focused on the very challenging grid-storage sector (in the US), we will concomitantly explore the much more market-entry-friendly distributed energy sector globally. We will also engage with utilities on the topic of using large-scale energy storage options for energy arbitrage and the elimination of spinning reserves. The center is poised to play a transformative role in advancing renewable energy deployment through cutting-edge research and education initiatives. By virtue of the outstanding infrastructure in place at WashU and its extensive collaboration and alumni network, SEES is very well placed to identify and engage the appropriate stakeholders to participate in advancing its mission.

The CLEFF initiative recognizes that fossil-derived sources will continue to play a key role in the energy sector for the conceivable future and consequently emphasizes technologies that mitigate degradation of human health and the environment. The CCCU has established WashU as a major university center for the advancement of advanced coal research and technology and has positioned WashU amongst a small number of universities that publically acknowledge the importance of maintaining fossil fuels in the energy mix. SEAS and the CLEFF are uniquely positioned to make global contributions in this important area of research, especially in the current political context.

The bioenergy and biofuels initiative is unique in promoting diversification of bio-production beyond biofuels into the co-generation of chemicals and materials with defined structures and functions. This will lead to a sustainable future based on technologies that can obtain lignocellulosic biomass-derived energy, fuels, chemicals, and materials through efficient, low-cost, scalable processes.

Strategic investments needed to achieve leadership through excellence:

To enable and sustain proposed research efforts under each initiative, we project the following strategic investments:

SEES:

1. A shared SEES laboratory space (about 2500 sq. ft.) will be required. Brauer 2029/2030 and/or Brauer 6 and/or Whitaker 345 are candidate spaces for this purpose. The emphasis in this shared facility will be on fabrication and testing of device components and devices.
2. A SEES-centric cluster-hire initiative with a target of six to eight faculty members across SEAS (EECE, MMAE, ESE) spread over three years (2017-2019), with emphasis on theoretical and experimental aspects of energy harvesting, energy storage and smart-grid integration.
3. To ensure the smooth and sustainable operation of the center, we aim to initiate a three to five year fundraising campaign to set up a SEES endowment, with a target corpus of $15M. We will accomplish this in close collaboration with SEAS Dean's and WashU Chancellor's offices.

CLEFF:

1. A dedicated space for CLEFF facilities, in light of east campus expansion and eventual vacation of Urbauer Hall.
2. Faculty hires in CLEFF research thrust areas identified above
3. Support for organizing a clean fossil fuel session at the 2019 McDonnell Academy Symposium and a DOE-sponsored workshop on clean fossil fuels.
4. Establishment of an endowment for CLEFF to allow for scholarships, seed grants and equipment funds. Target: $15M.

Bioenergy and biofuels:

1. Cluster-hire initiative (four to six faculty over 3three years across SEAS) with emphasis on (a) biocatalyst discovery, (b) multi-scale modeling of catalytic and biological systems, (c) high-throughput enzyme/ catalyst design and screening, and (d) bio-systems engineering, and applied data visualization, data mining, machine learning, and material informatics.

2. Mechanism for internally funded collaborations between SEAS and The Division of Biology and Biomedical Sciences and/or Donald Danforth Plant Science Center.

3. Continued investment in large equipment focused on lignocellulosic biomass and microbialbased biosynthesis characterization.

Execution, accountability and metrics:

For each initiative, upon approval, an inter-departmental steering committee will be established under an initiative/center director (Vijay Ramani for SEES, Richard Axelbaum for CLEFF, and Fuzhong Zhang for Bioenergy/ biofuels). The director, in conjunction with the steering committee, will assume responsibility to put together a roadmap that clearly identifies targets and metrics for success. As an example, the current roadmap (with accompanying metrics/numbers and timeline) for launching the SEES center is as follows:

1. Create the framework for SEES and formally launch the Center (May 2017);

2. Recruit five industry partners and three to five advisory board members (initiate in May 2017);

3. Secure lab space in Engineering for shared SEES facility (ca. 2500 sq.ft; May 2017);

4. Hire two new faculty members in EECE (hire in April 2017; arrive Fall 2017);

5. Infrastructure investment for equipment ($575,000 + full time technician; initiate in June 2017);

6. Global PV test facility with storage with MAGEEP partners ($200,000, initiate by June 2017);

7. SEES Center cluster hire (six faculty members across SEAS and A&S; AY 17-18; 18-19) and

8. Create SEES endowment fund (Target $15,000,000 over three to five years, multiple donors; launch quiet phase in May 2017)

Similar roadmaps with quantifiable metrics to define success will be prepared for the other initiatives once the extent of investment is ascertained. Among the first tasks in each roadmap will be establishing an external advisory board. The director and steering committee will be accountable to the board, and the board chairman will provide periodic progress reports to the SEAS Dean.