Widening the Lens on Innovation for Clean Manufacturing

Technical Appendices

Introduction

The project seeks to bring underappreciated opportunities for clean manufacturing innovation to greater prominence with the goal of shaping the climate and manufacturing policy agenda. The project team hosted four virtual workshops focused on themes that cut across many of the traditional industrial sectors involved in advanced manufacturing initiatives. Rather than organize the project around traditional sectors (steel, cement, chemicals, food processing, etc.), the goal was to focus on the important underlying technology and process developments relevant to several industries and engage these industries together with thematic experts in a small number of thematically-focused groups. The four main themes about which the workshops where centered included High-Temperature Processes, Low-Temperature Processes, Bio-manufacturing Solutions, and Alternative Materials Solutions. The project team assembled a group of 31 speakers and 76 additional participants across the four workshops.

Workshop 1: High-Temperature Industrial Processes

Presentations and Papers: http://www.bu.edu/ise/research/widening-the-lens-on-innovation-for-clean-manufacturing/high-temperature-manufacturing/

Workshop Summary

The High-Temperature workshop explores promising technologies for decarbonizing chemicals, steel, cement, and other high temperature manufacturing processes. There are large greenhouse gas emissions in this area both associated with the combustion of fossil fuels to achieve the necessary temperatures, and with some of the chemical processes

The workshop examined both direct electrification of industrial processes as well as the use of hydrogen. Both have the potential to drastically reduce emissions from the industrial sector assuming that they use green electricity. However, both electrification technologies and hydrogen have the major issue of higher cost as a roadblock to becoming competitive with fossil fuels such as natural gas. The workshop explored many opportunities for significant cost reduction. Advanced electrolysis technologies look particularly promising for reducing hydrogen costs.

Electrifying many of the major manufacturing processes would lead to less energy consumption for these processes, and subsequently would lead to less net carbon dioxide emissions in the future as the electric grid becomes cleaner. This would be true both when substituting all-electric boilers, or when implementing new electrification technologies such as heat pumps.

However, the energy cost associated with all-electric processes would be much higher than that of natural gas used in a standard boiler or furnace. All-electric technologies can only become cost competitive if the price of electricity is decreased significantly.

The area of hydrogen production has plenty of room for innovation to allow for use at a mass-scale. Hydrogen has realistic application potential for use in energy storage, as transportation fuel, and in industrial processes. Hydrogen does have value for its use as a fuel option, but its main value stems from its chemical properties. Although hydrogen is currently used for some industrial applications such as refining, the price is currently too high to be competitive with natural gas for many other applications. An innovative R&D approach to advancing electrolysis technologies can help reduce the production cost. Producing hydrogen through electrolysis has the much needed environmental advantage over other traditional methods of hydrogen production (such as methane steam reforming) as it does not have any direct carbon dioxide emissions. If renewable electricity used as the energy source for the electrolysis, then hydrogen can be produced without greenhouse gas emissions.

The production of chemicals is one of the largest sources of emissions in the industrial sector. Chemicals such as ammonia, ethylene, methanol, propylene, and many others all contribute large amounts of greenhouse gas emissions during their production. These processes typically require high temperature heat, which is often higher than 400°C. Ammonia is one chemical of particular interest as its production typically involves the methane steam reforming process, but its chemical composition (NH_3) does not inherently require a carbon feedstock like many other common chemicals do. There is potential for an inorganic chemical like ammonia to be produced with atmospheric nitrogen and water as the only required feedstocks, and diatomic oxygen would be the only byproduct. However, deep decarbonization of the chemicals sector requires innovative solutions for a variety of chemicals, not just ammonia. Similar strategies of producing chemicals without major emissions need to be explored for chemicals such as ethylene, methanol, propylene, etc.

Steel production is another high temperature manufacturing area where fossil fuels are the dominant source of heat for novel production. Although about two-thirds of US steel production is scrap-based, the other one-third uses a coal-based coke in the process of converting mined iron ore into pure iron. The use of coal in this process, both as the heat source and in the chemical reaction, is the source of large quantities of industrial emissions. A technology such as hydrogen direct reduction steelmaking can be explored as an alternative option to displace the carbon emissions involved in the iron ore to pure iron step. Hydrogen direct reduction involves a reaction of hydrogen gas with the iron ore to produce iron and emit water as a byproduct. This reaction removes carbon dioxide from the equation completely. This technology is mainly limited by a lack of R&D and by the currently high price of hydrogen. Other technologies such as direct electrolysis and plasma smelting are under development as well but are in early stages of development and are less likely to make a major impact by 2050. However, these technologies should continue to be explored and researched as longer-term possibilities.

The cement industry produces emissions both from the combustion of fuel and from the chemical process of calcinating limestone. The cement-making process requires high temperatures of around 1450C to produce the required chemical reactions. Reducing emissions in this sector certainly will require the use of alternative fuels such as hydrogen to provide the necessary high temperature heat. However, the process emissions also need to be addressed with solutions other than just fuel switching for full decarbonization. The use of supplementary cementitious materials (SCMs) have a large potential to reduce emissions. Cement alternatives such as alkali-activated materials could also be explored as well. However, many alternative cement options require less abundant elements in their structure, which causes them to be more difficult to produce at such a large scale. Therefore, there will be no silver bullet solution to solve the cement emissions. It is important for the cement industry to focus on direct options such as fuel switching and alternative cement substitution, as well as indirect options such as materials demand reduction and carbon capture and sequestration.

Presentation 1: Ali Hasanbeigi, CEO, Global Efficiency Intelligence

Slides: http://www.bu.edu/ise/files/2021/01/1.-Hasanbeigi-Industrial-Electrification-1.26.2021-Ali.pdf

Recording: https://www.youtube.com/watch?v=msvawsdPZDU&t=4s

The production of heat is the most dominant energy consumer for US manufacturing. Two-thirds of the energy consumption is used in thermal-related processes, mainly consist of either process heating, combined heat and power (CHP), cogeneration, or conventional boiler use. To remove the direct fossil fuel emissions from manufacturing, these processes require an alternative source of energy, such as electricity. However, with the exception of electric arc furnaces for scrap-based steel production, the higher temperature thermal processes are difficult to electrify. Processes such as cement production are not likely to be electrified in the near future, due to the lack of available, cost effective electric technologies able to produce drastically high temperatures.

However, low and medium temperature industrial heat has more of a near-term opportunity to be electrified. About two-thirds of process heat across all industries operates below 300C. Industrial sectors such as food processing, pulp and paper manufacturing, chemicals, glass, and even some metals have been studied for their electrification potential. Some electric technologies are already available for these processes and are just waiting to be adopted. Electrification can be implemented both by electrically powering an existing boiler, or by introducing a completely different technology such as a radio-frequency heater.

The Global Efficiency Intelligence and David Gardner & Associates report titled “Electrifying U.S. Industry” explores the energy consumption, carbon dioxide emissions, and cost of the electrified processes when compared to the traditional processes. The study finds that less energy consumption is required for the completely electrified processes. The associated carbon dioxide emissions are found to increase in the near term, but drastically decrease as the electric grid becomes cleaner. Major industries such as steel, ammonia, paper, and plastic would have major emissions reductions if produced with clean electricity. However, the energy cost of all-electric processes would be much higher than that of a traditional natural gas boiler. It would be necessary for grid electricity prices to decrease in order for the all-electric processes to be cost competitive.

Link to the “Electrifying U.S. Industry” report: https://www.globalefficiencyintel.com/electrifying-us-industry

Presentation 2: Mark Ruth, Senior Engineer, National Renewable Energy laboratory

Slides: https://www.nrel.gov/docs/fy21osti/79011.pdf

Recording: https://www.youtube.com/watch?v=zrMnfP0zCw0

Hydrogen implementation has the potential to reduce US carbon emissions across all sectors by 20%. Hydrogen is used in industry today for sectors such as refining and ammonia production, but the US annual consumption has the potential to increase by 2-4x its current amount. Major available applications for hydrogen include grid energy storage, transportation fuel (including fuel cells), and industrial processes including chemical and biofuel production, refining, and metals manufacturing. Some other minor applications include high temperature industrial heat production, rail and marine and rocket transportation, among others.

Hydrogen's chemical properties give it a higher value in the industrial sector than its heat production potential does. For example, biofuel production has a higher carbon efficiency when a direct source of hydrogen is utilized. Also, hydrogen can be utilized chemically in the direct reduction of iron ore, as an alternative to traditional coke-based steel production.

The estimated threshold price for hydrogen to become a valuable option varies depending on its application. The price for use in metals production is estimated at $1.70 per kg, and at $1.40 to supplement natural gas as the only supply of all heat in the entire process. However, the threshold price for major use in refining is much higher due to the aforementioned chemical property value. The hydrogen price is driven by low temperature electrolysis and allows for electricity to be the dominant energy source for hydrogen production, as opposed to a process such as steam methane reforming.

Additional RD&D is necessary to allow hydrogen to advance into new areas. Fuel cells, onboard storage, and fueling station availability are key factors for the light and heavy duty vehicle markets. Emissions control (such as an increase in nitrous oxides due to a higher hydrogen flame temperature) is an important challenge for combustion to provide electricity and/or heat. Managing atmospheric humidity in combustion gases that is greater than those gases produced by combusting fossil sources (natural gas or coal) is important for drying processes. Additionally, the hydrogen infrastructure needs to be built out to meet the needs of additional markets. These challenges must be considered as RD&D priorities for hydrogen to be used in major electrochemical processes such as metals production, fuels, and hydrocarbon-based products.

Presentation 3: Mark Johnson, Director, Clemson University Center for Advanced Manufacturing

Slides: http://www.bu.edu/ise/files/2021/01/ITIF-BU-Workshop-Jan-27-2021-Mark-Johnson.pdf

Recording: https://www.youtube.com/watch?v=dHZIUd2mPDY

There are many important tradeoffs between under-utilized energy sources such as renewable electricity or hydrogen and energy sources used to manufacture products today such as natural gas or syngas. There is no silver bullet technology to solve all the necessary industrial-related emissions reductions, so a portfolio solution will be necessary for deep decarbonization.

Importantly, we need to explore the crossovers between the new technologies and the current infrastructure to avoid major increases in capital expenses.

The two largest industrial energy consumers are the chemicals sector and the petroleum refining sector. Not surprisingly, these are also the two largest sources of emissions in the industrial sector. The demand for high temperature heat is very large across some of the highest emitting sectors. For example, the reactions for iron to steel require temperatures around 1600-1800°C, cement production requires about 1400-1450°C, methane steam reforming requires about 900-1000°C, and ethylene cracking requires about 800-850°C.

There are three major cost parity points to consider for advantaging a new technology over an existing technology, which are: a.) cross-over parity, b.) transformation parity, and c.) tear-down cost. The cross-over parity occurs when a demand for the product would increase if the new technology were added to the existing technology. The transformation parity point occurs when the existing demand would be best satisfied by the new technology and can then replace the current technology. And finally, the tear-down cost occurs when the land being used for the old technology would have more value if replaced by the new technology instead of keeping the old infrastructure standing idle.

The necessary price points for renewable electricity to replace hydrogen can be estimated in comparison to the current natural gas price. Using a low estimate for natural gas price of \$3.50-\$4 per MBTU, the breaking point for renewable electricity is estimated at \$10-\$15 per MWh, including storage. For hydrogen, the target industry price would be about \$1 per kg. The target should be to achieve these two prices points by 2030 or 2035 for mass implementation, but this would be difficult to achieve.

Presentation 4: Everett Anderson, Vice President of Advanced Product Development, Nel Hydrogen

Slides: http://www.bu.edu/ise/files/2021/01/E-Anderson_Nel-LT-ELY-Overview_BU-ISE_ITIF-Wkshp_20210127.pdf

Recording: https://www.youtube.com/watch?v=0rXCZ3owDgI

There are fast growing applications for hydrogen in the transportation sector and the “power to X” (renewable electricity to hydrogen production) area. The production of hydrogen from electrolysis is important as net-zero-carbon goals are implemented. However, reductions in the cost of electrolysis are necessary to achieve a major increase in hydrogen demand. The hydrogen cost reduction is related to the current density and energy efficiency of the electrolysis. Higher current densities lead to a decrease in capital expenses, and higher efficiencies lead to a decrease in operation expenses. However, current density and energy efficiency are tradeoffs that inversely affect each other, and thus more R&D is required to find a working solution.

The two major types of electrolyzers worked on by Nel Hydrogen including proton exchange membrane (PEM) systems and alkaline systems. The PEM systems use a solid electrolyte and can allow for higher gas purity and a better start/ stop behavior. PEM systems have been traditionally used for smaller-scale applications (10kW-0.2 MW range) but are transitioning to use in large scale applications as well (10-25 MW range). This technology has a high efficiency when compared to alkaline systems but has lower current densities, which leads to higher capital expenses. However, the PEM systems have more of a potential opportunity to lower their capital expenses than alkaline systems do.

In contrast, alkaline systems use a liquid electrolyte and have a long history of use in larger-scale industrial applications (2.5 MW on the small side, 100's of MW with larger combined systems). The strategy for improving alkaline systems is to achieve incremental technology advancements, such as cell stack design improvements to increase the current densities.

Scaling the electrolysis process to larger-size, higher volume applications is one route to decrease the overall capital cost. Additionally, reducing the cost of power conversion with lower cost power electronics is an option, as well as optimizing the stack size versus the power rectifier. And finally, automation is another necessary advancement. It is believed that a price of $400/kW can be achieved in 5-6 years if these improvements are made.

Presentation 5: Karthish Manthiram, Associate Professor, Massachusetts Institute of Technology

Slides: http://www.bu.edu/ise/files/2021/01/5.-Manthiram-Electrication-and-Decarbonization-of-Chemical-Manufacturing.pdf

Recording: https://www.youtube.com/watch?v=1oFEBh8MS3U

Chemicals are used in almost all sectors of the economy in some capacity. However, there are large industrial carbon emissions associated with the production of chemicals. Dr. Manthiram's lab is focused on decarbonizing chemicals production with renewable energy as the primary energy source. Additionally, a major goal is to complete all of the necessary chemical processes at ambient conditions of 25°C and 1 bar.

Ammonia production can be studied as a major example of decarbonization potential. Current production with steam methane reforming involves reacting methane and water at a high temperature (greater than 700°C) to produce hydrogen, with stoichiometric emissions of carbon dioxide. Then, the hydrogen is used in the Haber-Bosch process as it reacts with atmospheric nitrogen at temperature between 400-500°C and pressure between 150-250 bar to produce ammonia. Producing these large temperatures and pressures is difficult for smaller, modular production facilities.

Alternatively producing ammonia at atmospheric conditions with no carbon dioxide emissions involves splitting water by way of electrolysis to produce hydrogen, and then combining the hydrogen with atmospheric nitrogen to produce the ammonia. An electrochemical process to combine the hydrogen and nitrogen can be explored as an alternative to the traditional thermochemical process; such a process involves using voltage in the place of pressure and temperature to drive the chemical reaction. The key challenge with this process is energy efficiency and the cost associated with this energy consumption. A major contributor to cost is that associated with the electrolysis of water as compared to steam methane reforming. One additional challenge outside of cost is developing an efficient catalyst for the conversion of nitrogen to ammonia.

Ammonia is the largest greenhouse gas emitting chemical, but many other chemicals such as ethylene, methanol, propylene, etc. also require solutions for deep decarbonization of the chemical industry. An important goal for the chemicals sector would be to produce this diverse set of chemicals at atmospheric temperature and pressure by using only renewable electricity as the energy source and atmospheric carbon dioxide, nitrogen, and water as the only feedstocks.

Presentation 6: Marlene Arens, Research Scientist, Fraunhofer Institute for Systems and Innovation Research

Slides: http://www.bu.edu/ise/files/2021/01/6.-Arens_20210127_BostenUniversity_v1.pdf

Recording: https://www.youtube.com/watch?v=FA6OEHPplH0

Current steel production involves large emissions of carbon dioxide, both in the production of the necessary heat and in the chemical reactions to produce iron. Currently two-thirds of US steel production is scrap-based and uses electricity as the energy source, but the remaining one-third is much more difficult to decarbonize. The newly-mined iron ore undergoes a reaction with either coal or natural gas at high temperatures to produce pure iron and emit carbon dioxide as a byproduct. This process can have net-zero emissions if carbon capture is used, but this would increase the cost of production. Additionally, there could be a future ban or carbon tax associated with the use of coal, so alternative options are being explored.

A promising alternative to coal-based iron production is through hydrogen direct reduction. This process takes the iron ore and reacts it with hydrogen to produce pure iron and emit water as a byproduct. As of now, it appears that this technology is the best commercially available option with zero carbon emissions. However, the major drawback is the higher price of hydrogen when compared to that of coal or natural gas.

Another alternative technology option is direct electrolysis, which involves directly reducing iron ore with electricity to produce pure iron and emit oxygen. This technology is in the early stages of development (such as the Siderwin project) and thus is less likely to have a major impact of emissions reduction by the year 2050. A third zero-emissions alternative technology is plasma smelting, which involves a one-step process to produce steel directly from iron ore. Although this is a more energy efficient option, the technology is also in a very early stage and is also unlikely to have a major impact on emissions reductions by the year 2050.

The major setback in the way of decarbonizing steel production is the large cost associated with transitioning to a new technology such as hydrogen direct reduction. In addition to the operational costs associated with using hydrogen, there are also large capital costs needed to replace many traditional plant components, include the blast furnace, coke oven, sinter plant, and steelmaking section. One idea to make this transition feasible would be to transition to primarily natural gas-based steelmaking now as a bridge fuel between coal and hydrogen. A natural gas infrastructure for steelmaking is much more similar to a hydrogen infrastructure, and many of the major capital costs could be covered in this bridge step while the price of hydrogen is still too high to be a feasible option. Then, once the price of hydrogen is lowered to be more competitive, the full change can be implemented.

Presentation 7: Maria Juenger, Professor, University of Texas at Austin

Slides: http://www.bu.edu/ise/files/2021/01/7.-Juenger-Cement.pdf

Recording: https://www.youtube.com/watch?v=rAWycYy8p0g

Concrete is the most used material in the world, and the amount of cement produced is greater than the amount of food consumed annually. Producing cement results in large greenhouse gas emissions, both from the combustion of fuel to provide the necessary heat and from the chemical process to produce the cement. The thermal fuel emissions account for about 40% of total emissions, which involve taking a kiln fuel and combusting it to achieve a temperature of about 1450°C. The chemical process accounts for the majority of the carbon dioxide total emissions, involving the decomposition of limestone (calcium carbonate) to lime (calcium oxide), which subsequently reacts with silicon dioxide to produce tricalcium silicate (the major component of cement). The remaining "other" emissions are a smaller portion associated with the transportation and processing of the cement.

There are five major levers for emissions reduction in cement production, which are: 1.) Energy efficiency, 2.) Alternative fuels, 3.) Alternative cements/clinker substitution, 4.) Carbon capture and sequestration, and 5.) Efficient use of materials.

Clinker substitution has a large potential to drastically reduce emissions, and the partial substitution options (called supplementary cementitious materials (SCMs)) have a more rapid implementation potential than other strategies. Some ambitious goals can be explored to produce cement alternatives such as alkali-activated materials, calcium sulfoaluminate belite cement, and magnesium-based cements. However, it is more difficult to mass produce alternative cements using elements like magnesium that are not as available and abundant as silicon and oxygen are.

Alternative kiln fuels such as hydrogen are also very important but have more of a long-term outlook potential. Carbon capture and sequestration is another viable option to reduce emissions, but this also has more potential in the long-term than in the short-term because of the high cost of implementation. Finally, energy efficiency and efficient use of materials are also available near-term options but would not have as large of an impact on reducing emissions. It is important to work on both the short-term and long term goals simultaneously in order to achieve deep decarbonization.

Workshop 2: Low-Temperature Industrial Processes

Presentations and Papers: http://www.bu.edu/ise/research/widening-the-lens-on-innovation-for-clean-manufacturing/low-temperature-manufacturing/

Workshop Summary

The Low-Temperature workshop focused on technologies that can produce heat at or below 150 ^{o}C with a net-zero carbon source of energy. In addition, the workshop explored options to alter existing manufacturing processes to reduce the quantity or temperature of heat required, or to even remove the demand for heat altogether. The latter includes methods of mechanical drying such as ultrasonics that can remove water from material in applications where traditional thermal-based drying is traditionally used.

Heat pumps are explored extensively as an option to provide process heat. They could potentially be used for low temperature manufacturing sectors such as food processing, pulp and paper manufacturing, and some chemicals production. Heat pumps are also a focus of research efforts to electrify building space and water heating, resulting in some common R&D priorities for these two applications. Important advancements can be made for heat pumps to produce reliable heat at higher temperatures than existing applications, including larger heat exchangers, new refrigerants, and their compressors. There are also innovative architectures that can increase heat pump system efficiency, such as waste heat recovery and cascading systems.

Furthermore, some emerging alternative (i.e., non-vapor compression) heat pump cycles operate without a vapor-compression cycle. Options such as magnetocaloric and electrocaloric heat pumps can potentially provide the low-temperature heat necessary for many industrial processes. However, their current complexity, cost, and performance pose major challenges to developing viable alternatives to vapor compression cycles in both buildings and industrial applications. Nonetheless, these heat pumps could possibly benefit from advanced research and become a viable option.

Many traditional industrial drying processes in the food processing sector are dominated by natural gas-fueled thermal drying. There has not been much push to electrify these processes, as the cost of gas-fired heat is significantly lower than that from electricity. However, all-electric drying can potentially provide controlled drying, which can reduce energy consumption and often prevent damage to the product. Thermal drying has the major disadvantage of needing to provide the latent heat of evaporation to remove water from material. Alternative methods such as mechanical drying avoid evaporation entirely by simply vibrating the material to release the water. From there, the water can be moved away and condensed for reuse. This process consumes much less energy per unit mass of water, especially when drying a thicker material.

Hybrid drying systems that can switch between convective heat, infrared radiation, direct contact conduction heat, mechanical vibrations, etc. are useful to maximize both energy efficiency and drying quality. Using artificial intelligence can optimize system energy performance, quality, and speed. This also creates a research priority to develop advanced sensors that can accurately measure moisture content in the materials.

Removing water from air is another area where large gains in energy efficiency are possible. Traditional condensation-based dehumidification is relatively inefficient and has the potential to be improved dramatically with the use of membranes. Certain membranes have the ability to remove moisture content from airflow with a vacuum. The membrane-based systems can decrease the energy input needed to remove equivalent amounts of water from air when compared to traditional dehumidification. Main development goals for these membranes are to reduce the cost of production and to use lower-cost materials that still have high-performance capabilities.

Presentation 1: Antonio Bouza, Technology Manager, DOE Advanced Manufacturing Office

Slides: http://www.bu.edu/ise/files/2021/02/Tony-Bouza-Heat-Pumps.pdf

Recording: https://www.youtube.com/watch?v=4Nyx8FrMTbM

Heat pumps are an important energy efficiency technology but will require some preplanning, engineering work, and innovation to be implemented into large-scale industrial processes. Industrial heat pumps are still expensive to produce and will require cost reduction to become competitive with traditional fossil fuel-based boilers and furnaces.

Better equipment will be required in the future for heat pumps to produce the required industrial temperatures in the range of 150-250 °C. More efficient compressors and heat exchangers will be needed, as well as alternative refrigerants options that can operate at these high temperature values. Non-traditional cycles and working fluids options such as supercritical carbon dioxide or hydrogen should be considered. Low technology readiness level (TRL) alternatives such as non-vapor compression heat pumps are also important to consider for heating or cooling applications.

Presentation 2: Kurt Roth, Head of Energy Systems, Fraunhofer Center for Manufacturing Innovation

Slides: http://www.bu.edu/ise/files/2021/02/Fraunhofer-LowTempIndustrialHeat-HP-Intro.pdf

Recording: https://www.youtube.com/watch?v=ofQqAGxxsQU

Heat pumps have the potential to produce heat for “low-temperature” (<150C) industrial processes, but there has been limited innovation in the US in this area due to the low price of domestic natural gas. Other countries that lack low-cost natural gas, notably Japan, have had a larger push to develop heat pump solutions for low-temperature industrial processes. Researchers and companies can leverage existing heat pump research in the buildings sector to advance industrial heat-pump technology, particularly around novel system architectures such as cascading systems, refrigerant economizers, and multi-stage systems. However, industrial heat pumps need to operate at higher temperatures than in buildings applications, and with higher temperature lift as well, and subsequently have different equipment requirements. They require the use of different refrigerants with properties more suitable for higher temperatures and will require development of compressors designed to operate under those conditions. In addition, alternate heat-pump cycles hold promise. Finally, applied research should explore re-engineering industrial processes around heat pumps (including pinch analyses) to optimize system performance and cost. This includes reducing process temperatures as much as possible (to reduce heat pump lift) and maximizing the use of waste heat (heat upgrading).

Presentation 3: Lena Schnabel, Group Leader, Fraunhofer Institute for Solar Energy Systems

Slides: http://www.bu.edu/ise/files/2021/04/Lena-Schnabel-Heat-Pumps.pdf

Recording: https://www.youtube.com/watch?v=pdolqMVy_CM

The European Union has the goal to become carbon-neutral by 2050 through a combined strategy of hydrogen usage, electrification, and energy efficiency. Industrial heat pumps would help to promote two of these three strategies, electrification and energy efficiency. We will need a higher production of heat pumps in the near future to help mitigate climate change.

Heat pumps have potential for implementation in major industries such as food, tobacco, paper, and chemicals production. Much of the thermal energy required in these industrial sectors operates at temperatures under 150C. However, more experimentation will be required in the coming years to convince companies that heat pump technologies will work for their specific production.

It is important to keep both simple and natural solutions in mind. For example, choosing natural refrigerants with low global warming potential (GWP) is necessary to promote sustainability by avoiding the high GHG emissions of hydrofluorocarbon (HFC) refrigerants. Propane is one example of a natural refrigerant that has been experimented with recently. It will also be important to focus heat pump design on safe operation before focusing on energy efficiency. Bringing simple systems without the use of complex materials to the market will be important to allow heat pumps to be a factor in reducing the effects of climate change in the next 30 years.

Presentation 4: Kashif Nawaz, Senior Research Scientist, Oak Ridge National Laboratory

Slides: http://www.bu.edu/ise/files/2021/04/Kashif-Nawaz-Heat-Pumps.pdf

Recording: https://www.youtube.com/watch?v=MWqL4OWZHtk

Heat pumps have the future potential to provide low temperature industrial heat both with a higher energy efficiency and a lower carbon footprint than current technologies. However, the cost effectiveness of the systems is a major barrier to large-scale adoption. There are many important concepts that still need to be studied to fully optimize heat pumps and allow them to be a competitive option for providing them low temperature industrial heat. The design, the materials, and the manufacturing process all need to be optimized to allow for a cost-effective end product. Each component of the entire system should be analyzed and improved, all the way from the waste heat source to the end application.

For example, heat exchangers are a key component to improve to make the heat pump more efficient. Using ceramic-based materials can make heat exchangers more efficient compared to using metal-based materials, mainly due to their capabilities with additive manufacturing to be used in complex designs. Also, alternative refrigerant options in designs should include supercritical carbon dioxide, ammonia, hydrofluoroolefins (HFOs), and water. The global warming potential (GWP) is a metric that should be considered but should not be the only metric used to evaluate a refrigerant. Additionally, waste heat recovery is key to decarbonizing industrial heat.

Presentation 5: Matthew Gurwin, CEO, Heat X

Slides: http://www.bu.edu/ise/files/2021/02/Matthew-Gurwin-Heat-X.pdf

Recording: https://www.youtube.com/watch?v=NPTmmv9H_Xg

Heat X is a company established in 2018 that focuses on magnetocaloric and magnetic induction technology to provide heating with no direct fossil fuel emissions. Magnetocaloric heat pumps are a non-vapor compression cycle technology, and consequently do not require any refrigerant. The magnetocaloric effect is a reversible and nearly instantaneous process that uses magnetic fields generated from an electric source of energy to heat or cool a material. The Heat X technology can currently produce an air to air temperature of 49 ^{o}C, a surface temperature of 510 ^{o}C, and a water temperature of 121 ^{o}C from a starting ambient temperature. These temperatures can likely be increased in the near future with more research and development.

Any heat pump needs to be affordable, energy efficient, sustainable, and safe to be considered as a viable alternative option to traditional water heaters/boilers, cooktops, and furnaces. Major challenges in the way of magnetocaloric heat pumps have included expensive and toxic materials, inefficient designs, and ability to scale for residential, commercial, and industrial applications. Heat X states to have a magnetocaloric technology that not only solves these challenges but also includes the necessary benefits of energy efficiency and affordability, as well as scalability, modularity, and clean air. These heat pumps can also be used as a complement to other existing technologies (including electric resistive heating). Heat X technology has been tested by Underwriters Laboratories (UL) for 2.5 kW and 5kW air heaters, and 1.5 kW cooktops. Heat X states that the Technology Readiness Level (TRL) is now at the point of commercialization.

Presentation 6: Paul Scheihing, Principal, 50001 Strategies

Slides: http://www.bu.edu/ise/files/2021/02/Paul-Scheihing-Heat-Pumps.pdf

Recording: https://www.youtube.com/watch?v=l011QTZ9l9w

Heat pumps are a great opportunity to increase the energy efficiency of process heat production in various industrial processes. A prior US DOE study found eight key industries that were identified for industrial heat pump potential, which are: corn milling, TMP pulp, unbleached kraft linerboard, beet sugar refining, bleached kraft pulp, bleached kraft pulp and paper, high fructose corn syrup, and synthetic rubber. The current use of industrial heat pumps (IHPs) are limited to applications under 160 ^{o}C but can be increased in the future with advanced IHP technology to over 200 ^{o}C. There are limited IHP equipment suppliers in the US, while Japan and the European Union are currently the leaders in this area.

It is currently difficult for IHPs to compete from a cost perspective with traditional process heating systems that use natural gas, such as a steam boiler, as the cost of heat from a natural gas driven boiler is lower than that from electricity-driven IHP, unless the IHP application has a low “lift temperature” (e.g., <10 ^{o}C). As such, looking only at electric-driven IHPs, the number of economic applications will be limited. Therefore, the number of economic opportunities will increase when considering heat-activated IHP technologies. These technologies are able to decrease the total amount of electricity required over a wider range of IHP lift temperature. Heat-activated heat pumps such as absorption (type 1) or heat transformer (type 2) should be researched. Expanding the IHP temperature range to 250 ^{o}C while simultaneously being able to economically lift heat up to 100 ^{o}C will greatly increase the number of IHP opportunities.

Likewise, integration of the IHP into the process is critical. One important process integration IHP aspect is to apply the IHP around the process “pinch point”; that is, pumping heat from a heat source below the “pinch point” to a heat sink above the “pinch point”.

Some important R&D performance targets can be set for IHPs to make them more competitive with traditional boilers and furnaces. For example, the total installed capital cost of the waste-driven, heat activated IHPs will need to be less than $1,000/kW$_{th}$. Likewise, the heat delivery targets should be for temperatures above 200 ^{o}C, and ideally up to 250 ^{o}C. The IHP lift temperature target should be up to 100 ^{o}C. If these targets are met, then it will be possible to achieve a five year payback period or less for many industrial processes at current US natural gas prices, which should motivate industrial companies that are aggressively striving for carbon neutrality to consider applying IHPs.

Presentation 7: Henry Kelly, Senior Fellow, Boston University Institute for Sustainable Energy

Industrial drying can involve removing water from air or from materials such as food, paper, clothing, and chemicals. Current leading drying technologies that rely on evaporating or condensing water (a phase change) are inherently inefficient. Next-generation technologies using membranes, mechanical drying, microwave, infrared, and electrostatic technologies can achieve large gains in efficiency and should be explored as alternatives.

Presentation 8: Jamal Yagoobi, Director, Center for Advanced Research in Drying

Slides: http://www.bu.edu/ise/files/2021/04/Jamal-Yagoobi-Industrial-Drying.pdf

Recording: https://www.youtube.com/watch?v=0s0FW1bM9mc

Industrial drying is an important field within US manufacturing, as it accounts for about 10% of all process energy consumption. Drying is very useful to produce a variety of products, including food, paper, chemicals, textiles, and biopharmaceuticals. There is a large potential for creating energy efficiency gains in this area, as well as reducing the carbon footprint and improving product quality at faster drying speeds.

The areas of artificial intelligence and machine learning are very important to increase energy efficiency in drying processes. The use of advanced sensors is critical to understanding the exact moisture content and quality of the product during the drying process. Advanced drying technologies are being worked on to adjust their operation based on the characteristics of the product that is being dried. This approach can employ multiple different methods of conventional drying and new technologies currently being developed, such as ultrasonic drying.

Presentation 9: Ayyoub Momen, CEO, Ultrasonic Technology Solutions

Slides: http://www.bu.edu/ise/files/2021/04/Ayyoub-Momen-Ultrasonic-Drying.pdf

Recording: https://www.youtube.com/watch?v=C49g486cqt4&feature=emb_imp_woyt

Mechanical drying is a valuable option that should be considered as an alternative to traditional thermal drying. Ultrasonic dryers are one mechanical technology that uses a piezoelectric material vibrating at an ultrasonic frequency (greater than 20 kHz) to shake and remove water from a material. This technology uses only electric power as its energy source and does not require any heat. The target manufacturing industry for ultrasonic drying is in textiles, with the pulp and paper industry as a long-term goal. Drying material is not an intrinsically expensive concept, as evidenced by people drying their clothes naturally on clothing lines. However, strict industrial requirements such as process speed, product quality, extent of drying, and lack of wrinkles make cost effectiveness a large challenge to overcome.

Thermal-based drying methods are disadvantaged from an energy perspective as they need to input energy to overcome the latent heat of evaporation to remove water from materials. Some high-speed pulp and paper drying processes require temperatures up to 227C to dry the material rapidly. Mechanical drying technologies such as ultrasonics do not need to include this heat and have the important benefits of energy efficiency and faster drying speeds, especially for thicker material.

One downside to mechanical drying is the need for a customized dryer based on the material from which the water is being removed. A thermal-based solution simply heats up the material in a large oven, so they can be used for a variety of different products. Even if they are unable to completely replace a thermal drying technology, ultrasonic dryers could retrofit existing solutions and act as pre-dryers, as to lower the total amount of thermal energy required to complete the drying task.

Presentation 10: David Claridge, Director of the Energy Systems Laboratory, Texas A&M University

Slides: http://www.bu.edu/ise/files/2021/02/David-Claridge-Membrane-Dehumidification.pdf

Recording: https://www.youtube.com/watch?v=Ln88VZC_e6A

Alternative options can be explored to reduce energy consumption for removing water from air. Dehumidification systems are used for many heating and cooling applications, including manufacturing processes. The energy efficiency to remove the water can be increased greatly with the use of a membrane to “filter” the water vapor from a flow of air.

A zeolite membrane is one option that can remove moisture content from a flow of air/water vapor mixture without changing its temperature. The membrane removes a desired amount of water vapor from air flowing past the membrane by controlling the water vapor pressure on the “other” side of the membrane to a value below the desired water vapor pressure in the air. From there, the water is condensed to liquid water and can be pumped away. This technology is important because it can remove water with less energy input than desiccants or standard air conditioners that condense water from air.

Some important developments are still required to increase the performance of these membrane solutions. Higher efficiency compressors, pumps, and condensers can increase the energy efficiency of these systems even more. Also, unwanted air leakage can decrease the efficiency of the system. Producing membranes with an air permeance of $10^{-11} - 10^{-12}\mathrm{kmol/kPa \cdot m^2 \cdot s}$ is a key development goal. Lastly, producing these membranes with a lower cost is necessary to allow for their use at a large scale. Specifically, finding a substrate with a lower cost than the currently used porous nickel is an important development need.

Workshop 3: Bio-Manufacturing Solutions

Presentations and Papers: http://www.bu.edu/ise/research/widening-the-lens-on-innovation-for-clean-manufacturing/bio-manufacturing/

Workshop Summary

The Bio-Manufacturing Solutions workshop dives into some technologies that could help reduce emissions in two of the most challenging areas, which are agriculture and chemicals production.

Agricultural emissions generally originate from livestock used for the production of meat, dairy, and egg products. Animals such as cows and pigs are extremely inefficient producers of protein. They consume lots of food to support their own bodily functions and emit lots of greenhouse gases in the process. Therefore, the development of alternatively sourced protein options is essential to meet a net-zero emissions goal by 2050. Alternative options such as plant-based protein, fermentation, and cultivated meat are able to produce equal quantities of protein with significantly less greenhouse gas emissions. These products have seen large growth across the globe over the past decade.

The major obstacle for these types of alternative protein products is the cost of production. With appropriate levels of research throughout the entire value chain, this cost could be reduced to be competitive with traditional protein sources. Importantly, the growth of alternative proteins is not limited by consumer demand, but rather by constraints in the available manufacturing capacity. Another obstacle for alternative protein is the regulation and labelling challenges required to get to the market. There is a lack of universal agreement on regulation especially in the area of cultivated meat, and federal departments such as the FDA will need to adapt to make sure these products can get to the market safely.

The production of chemicals is another leading source of greenhouse gas emissions. Some of the most emission-intensive chemicals include ammonia, ethylene, methanol, and propylene, all of which are essential across many different sectors of the economy. These compounds are traditionally produced with fossil fuel feedstocks, as they are a relatively inexpensive source of carbon and hydrogen atoms. However, displacing the use of fossil fuels in this sector requires alternative bio-based solutions that do not produce net positive carbon emissions. A goal for a net-zero chemicals technology is to produce the necessary compounds while only using natural compounds such as water, atmospheric nitrogen, oxygen, and carbon dioxide as feedstocks. For example, a chemical such as ammonia (NH3) is traditionally produced with the Haber-Bosch process, combining atmospheric nitrogen with diatomic hydrogen. There are no direct carbon emissions from this process, but the hydrogen is commonly produced from methane-steam reforming, a process that takes methane (CH4) and reacts with steam (H2O) to produce the hydrogen and emit carbon dioxide. The ammonia production can potentially be done completely with no direct emissions if a technology such as H2O electrolysis is utilized to produce the necessary hydrogen.

There is a relatively limited amount of carbon on the planet, and it is essentially to utilize its chemical properties optimally in the food, fuels, and chemicals that need it the most. Bio-based solutions have the potential to produce each of these three categories of products with low to zero emissions. We need to utilize the available knowledge of biology to produce bioproducts as a sustainable alternative to traditional chemistry. The major barrier to implementing these solutions is the large financial cost associated with them. Advanced R&D and scale-up are important priorities to allow bio-manufacturing to be cost competitive with traditional production of food and chemicals.

Presentation 1: Daniel Nocera, Professor, Harvard University

The available net-zero emissions chemicals production technologies are expensive and are typically unable to compete with the existing dominance of the oil and gas industry. With no carbon pricing, it is difficult for bio-based technologies for fuels production to be cost competitive. Technologies where carbon mitigation comes for free are necessary for clean chemicals production with a reasonable cost.

One example to be explored is the bionic leaf, which uses a natural source of solar energy to produce fuels with water and atmospheric carbon dioxide as feedstocks. This technology utilizes water splitting to produce hydrogen, and then uses the hydrogen to drive carbon dioxide fixation in a bio-organism to produce complex chemicals including C5+ols and C8+ hydrocarbons. The bionic leaf operates with about 11% efficiency from the solar energy source. The process uses the enzyme hydrogenase as a catalyst to split diatomic hydrogen into two protons and two electrons. The price of the hydrogen produced from the bionic leaf comes out to about $5 per kilogram. Although this price is higher than that of competing water electrolysis technologies, the bionic leaf has the added benefit of sequestering carbon dioxide from the atmosphere.

Alternatively, the hydrogen can be combined with atmospheric nitrogen to create an inorganic compound such as ammonia. This would help with large amounts of carbon mitigation as the traditional Haber-Bosch process to produce ammonia is a large source of industrial emissions. The bionic leaf would be able to produce the ammonia without the same carbon dioxide emissions. In this case, carbon pricing is not needed and comes for free with production of the biofertilizer. Such a strategy allows carbon mitigation to be achieved without carbon pricing.

Presentation 2: Liz Specht, Director of Science and Technology, The Good Food Institute

Slides: http://www.bu.edu/ise/files/2021/03/2021.02.10-Specht_BU-ITIF-FI-Workshop_sharable.pdf

Recording: https://www.youtube.com/watch?v=YFrZkBxaV2I

Current agricultural practices have a large carbon footprint, specifically from products such as meat, dairy, and eggs. This is largely because animals are inefficient producers of protein and emit large quantities of greenhouse gases to perform their bodily operations. However, plants are able to produce protein as well and leave a much smaller carbon footprint when doing so when compared to animals. Alternative plant-based protein options have had great traction in recent years and are likely to continue to see growth in the international market.

When considering alternative food options, it is important to find solutions that are able to reduce the existing carbon emissions without having people necessarily change their diets. This can be done by producing alternative meat, dairy, and egg products that taste and feel the same as traditional food, but do not come directly from animals. Fermentation is one option that uses microbial species to produce protein that has the proper flavor, texture, and structure expected by consumers. Cultivated meat is another option that has taken off within the past 5 years. This process involves cultivating protein directly from animal cells without needing the full organism.

Each of these alternative protein options are not limited by consumer demand, but rather by the lack of useful R&D and the limited manufacturing capacity available.

Presentation 3: Brian Sylvester, Special Counsel, Covington & Burling

Recording: https://www.youtube.com/watch?v=jmfxmrIBBMw

Cellular agriculture companies around the world are developing dairy ingredients, eggs, gelatin and even meat and seafood without the animal. This revolutionary technology has garnered significant investments from leading food stakeholders on a global basis and presents fascinating regulatory questions.

In particular, because products such as cell-cultured meats have not been commercially produced in the past, they aren't expressly contemplated by existing US food law. Regulators (i.e., FDA and USDA) together with industry are actively considering how to tailor existing rules on the books to products of this novel technology. Most important, these novel products must be able to demonstrate safety before they become commercially available.

Under a Memorandum of Understanding published in 2019, the FDA and USDA share responsibility when it comes to regulating production of amenable cell-cultured meat products. The FDA exercises oversight up until the "point of harvest" and concerns itself with the substances being used in the food manufacturing as well as the manufacturing process itself. USDA takes over responsibility after this "point of harvest" for tasks such as inspection and labeling.

Another key issue -- labeling of alternative protein food products -- is a source of much debate that is yet to be fully settled. There is a lack of universal agreement about what types of labeling should be required for many of these new products (such as cell cultured meat, as well as plant-based dairy analogues). More specifically, there are questions as to whether these products can lawfully bear terms such as "meat" or "milk". Both cell cultured meat products and plant-based products will require more discussion between federal regulators and industry representatives to agree on proper labeling.

Presentation 4: Timothy Gardner, CEO, Riffyn

Slides: http://www.bu.edu/ise/files/2021/02/Tim-Gardner-Riffyn.pdf

Recording: https://www.youtube.com/watch?v=ywN2kYPQchI&feature=emb_imp_woyt

The complexity of new bio-products is increasing, and the time required to develop these products is decreasing. However, the overhead R&D costs for these projects are becoming much more expensive, causing less products to be able to make it to the market due to the higher capital investment that is required. Due to this, only products that have end-uses in multi-billion dollar markets are able to succeed. There needs to be solutions available for new bioproducts to be developed more efficiently and with less cost. This involves analyzing each step in the manufacturing process carefully to find where the problems may be.

Manufacturing-related problems in biological production are often actually R&D problems. Insufficiently or inaccurately characterized cells or bioprocesses in R&D often lead to failed technology transfer to manufacturing scale. This is extraordinarily costly in time, labor, and other resources. Achieving better characterization of bioprocesses requires capturing, integrating and analyzing large amounts of experimental data. And it means applying the tools of modern statistics and machine learning. Such data needs to be of high quality, so precise and accurate conclusions can be drawn; it must be multivariate to generate predictive models of larger-scale performance; and it must be quickly accessible by machine learning and AI tools. When these tools are brought together effectively, companies have succeeded in doubling (or more) the speed to market for new products and cutting development costs by factors of 2-5X.

Properly developing data can certainly help to lower the cost of production for new bioproducts. The complexity of these products has increased drastically over time, and it is critical to continue discovering new insights without needing multi-billion dollar investments. Taking risks will be necessary to advance the bioproducts industry.

Presentation 5: Karim Cassimjee, CEO, EnginZyme

Slides: http://www.bu.edu/ise/files/2021/02/Karim-Cassimjee-EnginZyme.pdf

Recording: https://www.youtube.com/watch?v=z6UO6rJZyd8

The chemicals industry produces large amounts of greenhouse gas emissions, and these emissions are likely to continue to increase as the growth of the chemicals industry continues. Reducing these emissions will be challenging and will require alternative and innovative solutions. It is important to try to bring biological and natural concepts into factories, as nature is already able to produce an advanced and diverse set of chemicals.

The future of chemicals production needs to be both sustainable and efficient, as consumers are unlikely to pay extra for “green” products and will not be willing to sacrifice the product quality either. Traditional chemistry is very efficient but has proven to not be sustainable. On the other side, fermentation-based production is sustainable but not very efficient. Therefore, a third option can be explored. Cell-free synthetic biology is an alternative option with the potential to produce chemicals both efficiently and sustainably.

EnginZyme’s cell-free synthetic biology removes the complex organisms that are a part of a fermentation process and uses only the necessary enzymes bound to a hybrid solid material designed to retain the enzyme’s activity. This technology enables use in the already established equipment and use in flow chemistry, thus reaching the necessary efficiencies of traditional chemistry but with the greener production processes enabled by nature. According to EnginZyme, scaled production has been proven. The future goal of this technology would be to increase the efficiency of bioproduction and scale to commodity chemicals, while using existing infrastructure. If this is accomplished, then cell-free bioproduction could replace most of the classic chemicals production.

Presentation 6: Aindrila Mukhopadhyay, Senior Scientist, Lawrence Berkeley National Laboratory

Slides: http://www.bu.edu/ise/files/2021/02/Aindrila-Mukhopadhyay-Biofuels-and-Bioproducts.pdf

Recording: https://www.youtube.com/watch?v=IxWtHCp0qfs&feature=emb_imp_woyt

Chemicals and transportation fuels are currently two of the largest sources of greenhouse gas emissions. To reduce these emissions, biological solutions are necessary as an alternative supplier of fuels and products in the future. Major institutions such as the DOE Bioenergy Research Centers have the mission to develop the science necessary for producing various biofuels and bioproducts at a comparable cost to modern day chemistry-based production. There are no silver bullet solutions, but the goal is to use many different feedstock options and produce all necessary products with net-zero greenhouse gas emissions. There is still much research to be done in this area, and collaboration will be required between different agencies and research centers.

Ideal biochemical and biofuel production involves using the most abundant, accessible, and sustainable feedstock and finding the organism to produce the chemical or fuel from this feedstock. The feedstocks can be various types of biomass such as agricultural waste or municipal solid waste, and they all need appropriate and customized solutions. In addition to waste streams, non-food crops can be grown as feedstocks as well.

A major obstacle for many biological solutions is the time and investment required to scale-up from the laboratory to the large scale production. To help solve these problems, the Department of Energy has a consortium of national laboratories known as the Agile BioFoundry that enables biorefineries to reduce the amount of capital required for scale-up. Additionally, the DOE Bioenergy Technologies Office has a laboratory called the Advanced Biofuels and Bioproducts Process Development Unit (ABPDU) that works to solve scale-up related challenges.

Workshop 4: Alternative Materials Solutions

Presentations and Papers: http://www.bu.edu/ise/research/widening-the-lens-on-innovation-for-clean-manufacturing/alternative-materials-manufacturing/

Workshop Summary

The Alternative Materials Solutions workshop discusses innovative materials options that could help reduce the traditional emissions associated with production of materials such as steel, cement, and plastic. The workshop also focuses on solutions to reduce the demand for these materials, as well as pathways to a circular materials economy.

Three main areas can be looked at to reduce emissions from materials manufacturing, which occur in the material production, the material use efficiency, and the circularity model. The material production view looks at the amount of greenhouse gas emissions per the volume of material produced. The material efficiency view looks at the amount of material used for the end product that is needed. And finally, the circular model looks at getting the most use out of a product for the service of which it is created.

A critical research priority for materials development is finding materials that have better structural performance (such as strength-to-weight ratio) than traditional materials while also contributing to net-zero carbon sustainability goals. Development alternative cement chemistries with less process emissions is certainly important but will require lots of research and investment to find cost-effective solutions. The US federal government can contribute by incentivizing manufacturers to develop more sustainable cements, while also incentivizing structural engineers to use sustainable concretes in their designs.

The use of biomaterials is another area with room for large potential growth in the near future. Biomaterials work within the net-zero confines and have potential to produce a variety of products with less energy input than traditional production. Biomanufacturing can allow for a decrease in physical labor requirements as well as energy consumption. Additionally, important natural materials such as mass timber are gaining more traction as a structural building material. Sustainability goals can be achieved with the help of net-zero carbon materials, as well as even materials that store carbon. However, the major drawback for these options are typically the cost of development and production that acts as a roadblock to scale-up. The federal government can help with the necessary research to decrease these development costs, as well as create incentives for engineers to use net-zero or carbon storing materials in their designs.

Another important goal for reducing materials production emissions is to create value streams from traditionally wasted materials. Using waste materials such as plastic as feedstocks can reduce emissions associated with traditional petrochemical plastics production. It is important to adapt existing infrastructure to allow for the circular use of these waste products. This does not necessarily require tearing down the existing infrastructure, but rather creating recycling solutions that can work in tandem with the presently available infrastructure.

Presentation 1: Meghan Lewis, Senior Researcher, Carbon Leadership Forum

Slides: http://www.bu.edu/ise/files/2021/02/Meghan-Lewis-Embodied-Carbon.pdf

Recording: https://www.youtube.com/watch?v=yK_4yFySILQ&feature=emb_imp_woyt

The Carbon Leadership Forum has a mission to eliminate embodied carbon in buildings and infrastructure. Embodied carbon can be evaluated as the greenhouse gases emissions created throughout the entire lifetime of a material, including raw material extraction, production, installation, use, demolition and material disposal, etc. The impact of these emissions are significant and should be considered as a major decarbonization priority. Despite this, embodied carbon is primarily excluded from the current global policy discussions.

Some low carbon materials are available in the market today, such as alternative cements, recycled products, and a number of carbon-storing materials, such as mass timber, bamboo, and others. There are also emerging materials options that are still being research for future use, such as synthetic limestone aggregates and algae-based products.

There are three major strategies to reduce embodied carbon in buildings, with the first being to optimize the project. This involves strategies such as reusing buildings and materials and designing the overall project to reduce the required floor area. The second strategy is to optimize the system, which involves optimizing the design to increase material or structural efficiency and choosing the appropriate structural and envelope system materials to maximize carbon reductions. Finally, the third strategy is to optimize procurement, which involves using available data to choose the lowest carbon product among functionally equivalent products.

It is important to for embodied carbon policies to be developed, both to incentivize architects and structural engineers to design buildings with less embodied carbon and to incentivize manufacturers to produce materials with less carbon input. This policy action can occur at the local, state and federal level simultaneously. Examples of policy pathways for supporting the three optimization strategies include zoning and land use regulations and incentives, reuse and waste policies, building codes, green build incentives and certifications, and procurement policies (such as “Buy Clean”).

Presentation 2: Robert Moser, Senior Technical Manager, US Army Engineer Research and Development Center and Eric Kreiger, Research Engineer, US Army Engineer Research and Development Center

Slides: http://www.bu.edu/ise/files/2021/03/Robert-Moser-Full-Project-Lifecycle-Sustainability.pdf

Recording: https://www.youtube.com/watch?v=vJ7ZV_1QiXI

The US Army Corps of Engineers has initiatives to develop and utilize new materials that provide specific advantages for its two different missions, military and civil works. Sustainability is a sole driver for the Corps; innovation opportunities are mainly driven by requirements of performance enhancement and materials optimization.

Most construction products rely on commodity materials, which often creates a challenge to introduce new and innovative materials into the market which require new criteria and specifications for acceptance. Thus, economic and policy drivers are needed in this area to promote more sustainable construction materials use.

There are many materials-related developments being worked on, including nature-based materials, advanced material designs, manufacturing and construction process improvements, and 3D printing. Natural materials such as cross-laminated timber have potential for use in infrastructure that is typically dominated by concrete and steel. There is expected to be large growth in the use of these materials in the near future. The use of 3D printed concrete structures is also expected to see growth in military applications. These structures can be made into any shape with locally available materials and can reduce the amount of required labor. This additive process can lower the amount of material used while also improving the structural properties. The use of alternative cements in 3D printing structures is being studied, as well as different materials altogether such as geopolymers and metals.

Deep decarbonization of materials such as cement will require lots of work and innovation. Reducing the process emissions from cement production entails reducing the calcination of limestone necessary to produce the cement. Some of the alternative cement chemistries that are being worked on include PLC, CSA, CAC, MPS, LC3, belite, and carbonating cements. These cements could help to achieve sustainability goals as well as performance enhancements.

Presentation 3: Per Klevnas, Partner, Materials Economics

Greenhouse gas emissions from plastics production are significant and difficult to avoid at a large scale. A major problem is that emissions are released at multiple points: in feedstock production, in the creation of base chemicals, in production of polymers, and when plastics are burned as part of waste management. Eliminating all emissions thus is a major challenge, and measures that address just one emissions source do not guarantee that low emissions can be achieved for the system as a whole.

A broad menu of emissions reductions options is available. First, there is significant scope to get more utility out of the material and products, through materials efficiency and new business models. Second, recycling offers the promise to cut all sources of emissions from new plastic production. However, for high levels of circularity it is necessary to look both to mechanical and various options for chemical recycling, and to ensure high mass balance (and thus low CO_2 emissions from the recycling process), something that can require very large energy inputs. Third, plastics can be produced from non-fossil feedstock, including biomass and atmospheric CO_2. Finally, carbon capture and sequestration is possible at various points in the value chain, from refineries to crackers and waste incineration.

Different scenarios for emissions reduction can be formulated by emphasizing certain options from the “menu” above others. Scenarios for a net-zero plastics economy in the European Union reveal several lessons. First, there is no “silver bullet”, but a mix of all mitigation strategies is needed in all scenarios. Second, high levels of materials circularity is all but indispensable to achieve low CO_2 emissions, and especially to avoid large emissions from waste incineration. Third, all low-CO_2 production routes require major investments, both because of intrinsically high capital intensity and because there is a need for rapid changes to production assets. Fourth, a large change to new energy sources, feedstocks and process routes will be required, including a much larger role for biomass as a source of carbon, for novel platform chemicals such as methanol, and for low-CO_2 electricity and hydrogen. Finally, all scenarios lead to a substantial increase in production costs. While costs are modest for consumers, it can pose a major problem for companies competing in international commodity markets. The increase in costs also suggests that some degree of substitution of plastics with other materials will be a feature of plausible pathways to net-zero plastics system.

In summary, a net-zero plastics system is possible but will require a major transformation. To succeed by mid-century, investment decisions must start to shift already in the early 2020s.

Presentation 4: Patrick Rose, Science Director for Synthetic Biology, Office of Naval Research Global

Slides: http://www.bu.edu/ise/files/2021/02/Patrick-Rose-Bioindustrial-Manufacturing.pdf

Recording: https://www.youtube.com/watch?v=nyRZzJxyXEs

Biomaterials have the potential to be a major contributor in the overall materials market. Biology has traditionally not been considered properly when thinking about new materials designs. A total reevaluation of the ways biology can be used to produce precursor materials, fine chemicals, components for additive manufacturing, etc. should be completed. The intent would be to understand how biomanufacturing can help design materials that can be produced within the net-zero carbon confines. Engineering biology can be harnessed to make materials stronger, more effective in their uses, and more efficiently used.

Biomanufacturing of chemicals, precursors, or components for composites can contribute to a more circular economy of products. For example, waste streams of materials such as wood, plastics, and agricultural residue can be used as feedstock for biomanufacturing instead of being landfilled. Microbes such as yeast, bacteria, or algae view any of these organic materials as a food source and will break them down into usable molecular structures for reuse. This concept is important because traditional petrochemical distillation of crude oil to make fine chemicals and other components depends directly on the cost of oil; however, biomanufacturing relies on a variety of different cheap waste products that are consumed as feedstock. Different regions of the United States have different types of waste streams (e.g., agricultural waste), and biomanufacturing can orient itself on these local feedstocks and be regionally distributed.

Engineering of biology also enables the creation of novel materials that previously may have been considered to be too expensive or too difficult to produce. Additionally, biomanufacturing will have a smaller footprint for production, both from the perspective of labor and energy consumption. This method of production can be close to a net-zero carbon input to the new products depending on the feedstock. It is important to note that not all biomaterials necessarily have the potential to replace existing materials production, but can rather complement and combine with existing materials to make them more effective.

Presentation 5: Jill Martin, Global Sustainability Fellow, Dow

Plastic has a lot of value in our modern society and has transformed the way we operate in all aspects of life. However, only about 9% of produced plastic is recycled at the end of its life. In order to achieve a circular economy, initiatives aimed at collection of materials (stop the waste) and incorporation of the materials back into new products (closing the loop) are central to the success. Examples of programs include those aimed at designing materials to be recycled through simplification of structures and more mono-material solutions, and incorporation of post-consumer recycled products through the use of recycling technologies.

Designing for recyclability involves developing materials for applications that can be readily recycled in existing processes. This is done by minimizing material types and reducing the number of non-polymeric components, such as additives and fillers. The technologies to effectively recycle and re-use materials in other applications cover a broad spectrum. Mechanical recycling, or re-processing without breaking down to the molecular building blocks, is most commonly used for mono-material articles in rigid packaging including PET and HDPE. Alternatively, flexible films vary in their composition from mono-materials structures containing polyethylene, to those containing PET, NYLON (polyamides), and ethylene-vinyl alcohol (EVOH). The former is recycled at a rate of 5% in the US but the infrastructure for the latter is limited to take-back programs at a small scale. To properly recycle these packages, they can either be redesigned to become mono-material, or another advanced recycling process can be used. Technologies such as gasification and pyrolysis can take the plastic waste back to feedstock which enables its use in the production of new polymers. However, these technologies are higher in energy and capital than the mechanical recycling processes. Opportunities do exist to improve on them and deliver high quality materials when the plastic waste is converted back to a feedstock.

There is an important distinction between materials that are bio-based and materials that are biodegradable. Bio-based materials are produced with biological feedstock inputs but will not necessarily biodegrade on their own at the end of their life. On the other hand, biodegradable materials are designed to biodegrade naturally, but are not necessarily produced with biological feedstocks. Bioplastics such as polylactic acid (PLA) are both bio-based and biodegradable, and thus are able to be produced without fossil fuels and do not require advanced recycling options and the end of their usable lifetime. Decisions about the use of any one material need to take into consideration the suitability of the product for its intended use, the carbon footprint to produce and recover, and the ability to scale production at a at a level meaningful enough to solve the challenges of plastic waste.

Presentation 6: Greg Olson, Professor, Massachusetts Institute of Technology

Slides: http://www.bu.edu/ise/files/2021/02/Greg-Olson-Computational-Materials.pdf

Recording: https://www.youtube.com/watch?v=FxXBeS1ilKs

A majority of sustainability issues stem from various aspects of materials technology for which the slow and costly traditional “trial-and-error” approach to materials and process development has posed a major barrier to needed change. The new technology of computational materials design and accelerated qualification (now known as Integrated Computational Materials Engineering or ICME) provides the opportunity for a system of affordable change to respond to these challenges.

A historic milestone in the development of this technology was the first flight in 2010 of aircraft landing gear constructed from QuesTek’s Ferrium S53 stainless steel, representing the first fully computationally designed and qualified material to reach flight. The demonstration of this technology was followed by the presidential Materials Genome Initiative (2011), an inter-agency initiative with the goal of further reducing both the cost and development time for new materials. The technology has since been rapidly adopted by leading companies such as Apple (2012), SpaceX, and Tesla (2015) who have exploited the benefits of predictability and reliability of designed materials to reduce the full materials development cycle time to 2 years or less. This timeline better enables full integration into the concurrent engineering of materials and products for the first time.

Much of the current focus of the Materials Genome Initiative concerns applications of existing fundamental data in computational materials design. One recommendation going forward would be to take a step back and put more focus into the genome level research defining new methods for affordable high-throughput measurement of the fundamental data enabling knowledge-based design.

Numerous novel materials responding to sustainability challenges have already been designed by QuesTek. Design of the Ferrium S53 stainless landing gear steel was in fact supported by the multi-agency Strategic Environmental R&D Program (SERDP) to enable elimination of toxic Cadmium plating in landing gear systems. Other SERDP projects have delivered replacement alloys for Be-Copper and Leaded Bronze. Toward enhanced alloy recyclability, a scrap-based low-cost Titanium alloy has been designed for casting applications. Numerous high-strength steel and aluminum alloy projects have addressed lightweighting for transportation systems, including high performance gear steels for lighter gearboxes. In support of renewable energy, QuesTek's new Ferrium N63 nitridable stainless bearing steel offers much needed reliability enhancement for wind turbine systems. Alloys for energy-efficient propulsion have ranged from 3D printable high-temperature aluminum for automotive pistons, to burn-resistant nickel superalloys for space travel. Recognizing that the far greatest energy losses and associated excess emissions are associated with primary power generation, a high performance Rhenium-bearing single-crystal Nickel-based superalloy has been designed with the necessary process scalability to bring aeroturbine blade performance to Industrial Gas Turbine (IGT) systems for major efficiency gains. The ARPA-E "ULTIMATE" program is now supporting the design of printable refractory metal alloy systems that will enable 1300°C turbine blades to enable even greater IGT performance.