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Research Recommendations for Industrial Decarbonization

Additional submitted attachment is included below.

Industrial Decarbonization EPIC 4 Research Suggestions

Energy and Efficiency Institute
University of California-Davis

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California's goals of reducing greenhouse gas emissions by 40% below 1990 levels by 2030 and to net-zero GHG emissions by 2045 are consistent with the international goal of net-zero carbon emissions by 2050 (IEA, *Net Zero Energy by 2050*, 2021). No business-as-usual scenario achieves these goals; instead, the rate of decarbonization must accelerate by over 2x (CEC, Integrated Energy Resources Report, 2018). Achieving these goals requires a bifurcated approach the emphasizes accelerated adoption of existing technologies in the short run and development of new CO_2 abatement technologies in the long run. Moreover, cross-cutting research along major industrial energy vectors is likely to have the greatest overall impact.

Research Suggestion 1: Decarbonizing Industrial Steam Production with Process-Integrated High-Temperature Heat Pumps

About 28% of manufacturing energy use utilizes fossil fuels with combustion temperatures >1,800 C to produce steam at temperatures <120 C with overall steam-system efficiencies of about 75%. The second law efficiency of this process is about 18% - meaning that 82% of the high-quality available work in fuel is wasted when it is used to produce low-temperature steam. Moreover, during combustion, natural gas and air reform themselves as a potent combination of waste gasses including 3x more CO_2 by weight than the fuel. Thus, the low efficiency and high CO_2 emission rates of fuel-based steam production make it a prime target for decarbonization by high-efficiency electrification.

Electrically-powered heat pumps use vapor-compression cycles to transfer energy from low temperature sources to high temperature sinks at efficiencies that exceed 100%. Currently, 20 models of high-temperature heat pumps from 13 manufacturers can deliver energy above 90 C when integrated with sources of industrial waste heat (Cordin Arpagau, Frederic Bless, Michael Uhlmann, Jürg Schiffmann, Stefan Bertsch, "High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials", Energy 152 (2018) 985-1010). Moreover, advanced low-temperature energy storage technologies can compensate for instances when the source and sink are not in phase. The combination of process-integrated industrial heat pumps, energy storage, and clean electrical power combine to produce an attractive alternative to fossil-fuel steam generation.

The potential for high-temperature heat pumps in industry has been studied by the International Energy Agency (IEA). IEA Annex 48 lists over 300 applications around the globe, but none in California (International Energy Agency, Annex 48, Industrial Heat Pumps, HPT-AN48-1, 2020). Unlocking this potential in California requires a focused applied research effort. The goal of the proposed research is to quantify the benefits, costs, barriers and opportunities of replacing fossil-fuel based industrial steam production in California with high-temperature process-integrated heat pump steam production. Potential research steps may be:

1. Develop catalog of market-ready high-temperature heat pump capabilities and costs.
2. Develop a catalog of market-ready low-temperature energy-storage capabilities and costs.
3. Develop a simple industry-relevant screening tool for identifying relevant heating and cooling energy flows, and organizing them in terms of the need for energy storage and high-temperature heat pump potential.
4. Identify ten California industrial facilities and work with them to apply the high-temperature heat-pump screening tool.
5. For each of the ten California industrial facilities, quantify CO_2 emission reductions, energy cost savings, and first costs associated with installing and operating process-integrated high-temperature heat pumps (with energy storage when needed).
6. For each of the ten California industrial facilities, interview decision makers to identify barriers and opportunities for implementation.
7. Expand the results to identify the industrial sectors most likely to adopt the technology and estimate sector-wide CO_2 emission reduction potential.

<u>Research Suggestion 2: Decarbonizing Electricity Through Enhanced Demand Shaping</u>
About 23% of manufacturing energy use is supplied by electricity. CO_2 emissions from electricity generation are falling as more power is produced from solar and wind farms. California's average of 0.44 lb-CO_2 per kWh (EIA, California Electricity Profile 2019) is already about 5x less CO_2 intensive than electricity generated by coal power plants. However, renewable solar and wind power do not always coincide with electrical system demand. As solar power decreases in the early evening, system-wide electrical demand increases. The balance of electricity is then supplied by expensive and CO_2-intensive fossil-fuel power plants. CO_2 emissions and electricity pricing follow nearly identical trends. In fact, the R^2 between CO_2 emissions and electricity pricing is above 0.90 on most days.

The strong correlation between electricity CO_2 emissions and prices creates an opportunity to reduce CO_2 emissions while lowering industrial electricity costs by shaping electrical demand to reduce electricity costs. To realize this opportunity, utilities must offer a real-time pricing rate in which the unit cost of electricity varies every hour and industry must have the capability and controls to shape electrical demand. For most industries the keys to enhanced demand shaping are capacitance and process-control capability. In this context, capacitance is defined as storage capability that enables electrical demand shaping. Examples of industrial capacitance abound. Water treatment facilities are built to handle peak flows, but seldom operate at those conditions; thus, on-site water storage can enable demand shaping. In the food processing industry, the inherent thermal storage ability of refrigerated spaces can enable demand shaping. In manufacturing and assembly industries, work-in-progress inventory can be manipulated to enable demand shaping. Moreover, direct energy storage also enables demand shaping. The key is to understand and quantify how to use industrial capacitance to enhance demand shaping for cost and CO_2 emission reductions. Finally, industries need data-driven process controls that can respond to price signals while enabling operator override and modification. In most cases, the required controls are simplified versions of model predictive control (MPC) at the supervisory level with enhanced human interface.

Unlocking the potential of decarbonizing electricity through enhanced demand shaping in California requires a focused applied-research effort. The goal of the proposed research is to quantify the benefits, costs, barriers and opportunities of enhanced industrial demand shaping. Possible research steps include:

1. Characterize the hourly correlation between SCE's real time electricity rate and electrical CO_2 emissions to determine the range of CO_2 emission and cost reductions from industrial demand shaping.
2. Investigate changes in demand profiles after SCE industrial customers switched to SCE's real-time rate to determine baseline demand shaping for cost reduction.
3. Develop a simple industry-relevant screening tool for identifying industrial capacitance and predicting electrical demand shaping potential based on that capacitance.
4. Identify ten California industrial facilities and work with them to apply the 'capacitance utilization for demand shaping' screening tool.
5. For each of the ten California industrial facilities, develop, modify or identify simplified model predictive control strategies to enhance demand shaping based on real-time pricing.
6. For each of the ten California industrial facilities, quantify CO_2 emission reductions, energy cost savings, and first costs associated with enhanced demand shaping.
7. For each of the ten California industrial facilities, interview decision makers to identify barriers and opportunities for implementation.
8. Expand the results to identify the industrial sectors most likely to adopt enhanced demand shaping and estimate sector-wide CO_2 emission reduction potential.

<u>Research Suggestion 3: Green hydrogen production</u>

Green hydrogen production using water electrolysis has a fairly high capital expenditure requirement making it expensive to run these processes intermittently to take advantage of very low-cost renewable energy. Electrolysis processes have chemical kinetic and mass transfer limitations that reduce efficiency as the rate of hydrogen production is increased. For these two reasons it is more likely that electrolysis hydrogen production plants would be operated continuously but that the hydrogen production rate would be varied depending on the price of electrical power. This tradeoff between electrolysis hydrogen production rate and efficiency needs to be studied to understand how it influences the capital expenditure required to build green hydrogen plants and its impact on the cost of green hydrogen with different future grid energy mixes and price trend shapes. This assessment should include existing ambient temperature and high temperature electrolysis processes with and without waste heat integration as well as newly developed green hydrogen production processes.

Green hydrogen production using water electrolysis also generates pure oxygen which can be a valuable co-product. Studies of the markets for this co-product oxygen are needed to inform where electrolysis sites should be located. Oxygen markets include high value medical oxygen, oxygen enriched air combustion to reduce NOx emissions while increasing equipment power and efficiency, pure oxygen combustion to reduce cost of carbon capture, and emerging oxygen uses like Sierra Energy FastOx garbage to methane conversion.

Green hydrogen production using high temperature water electrolysis can take advantage of waste heat form industrial processes to improve hydrogen production efficiency. Studies of the available waste heat sources and how they match the requirements of the high temperature electrolysis will inform decisions on what electrolysis processes to invest in, where to site these facilities, and how to design them.