Energy alternatives to reduce the University of Illinois at Urbana-Champaign campus CO_2 emissions

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INTRODUCTION

Energy is one of the major contributors to economic growth. In the future, economies and populations will continue to expand, and their energy demand will accompany such a change. Meeting these future needs requires the addition of energy sources into the grid. In 2019, electricity generation was one of the economic sectors that released the most greenhouse gases (GHGs) in the US [1]. Decarbonizing electricity generation will allow us to meet the increases in demand and address the environmental concerns simultaneously.

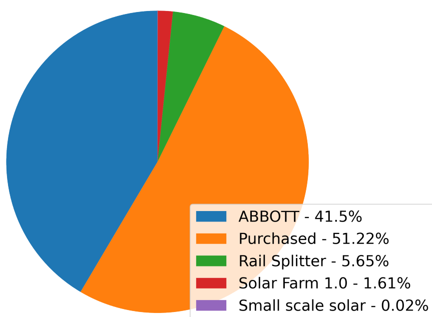

Fig. 1: Distribution of electricity generation of UIUC campus in fiscal year 2019 [2].

This work studies several energy alternatives for decarbonizing the University of Illinois at Urbana-Champaign (UIUC) campus grid. The alternatives presented here can be extrapolated to any other grid. We focus on the UIUC campus grid because it is a well-characterized grid integrating a diverse mix of energy sources, as shown in Figure 1. The Abbott Power Plant is a co-generation facility that supplies the campus with electricity and steam. The plant has multiple gas turbines and boilers that run on natural gas, fuel oil, or coal. The production of high-pressure steam spins a turbine to drive a generator and produce electricity. The low-pressure exhaust steam fulfills the space heating, water heating, and space cooling requirements from campus. Abbott's maximum capacity is 85 MW for electricity and 800 klbs/h for steam [3]. To provide cost-effective utilities, the university purchases electricity with the assistance of a market advisor [4]. The Rail Splitter Wind Farm has 67 wind turbines of 1.5 MW each, providing the farm a maximum power output of 100.5 MW. Through a power purchase agreement, the university buys 8.6% of the wind farm's total generation [5, 4]. The Solar Farm 1.0 comprises 18,867 modules, which cover a land area of 20.8 acres and produce a power output of 4.68 MW [6]. The small-scale solar generation comprises all the solar generation distributed around campus, considered negligible in this work.

The main objective of this work is to analyze multiple electricity generation alternatives for decreasing CO_2 emissions on the UIUC campus. For this reason, this paper evaluates two scenarios increasing the wind and solar generation capacity. The second scenario also considers the addition of a nuclear reactor into the mix. Due to the non-dispatchable nature of wind and solar generation, both scenarios incorporate electricity storage mechanisms.

ELECTRICITY STORAGE MECHANISMS

This work considers two storage mechanisms, Li-ion batteries, and hydrogen produced via electrolysis of water. This section briefly describes each of them and their integration into the grid.

The first prototype of a Li-ion battery was developed in 1985, becoming recently popular in the last two decades. Li-ion batteries are rechargeable and are commonly used in laptops, cellphones, electric vehicles, Uninterruptible Power Supplies (UPS), and for communication and medical applications. A high energy density and low self-discharge characterize this type of battery. Additionally, its charge-discharge efficiency of 80-90% makes it a good candidate for electricity storage [7]. This work considers the charge-discharge efficiency of Li-ion batteries to be 85%.

The electrolysis of water is a well-known process whose commercial use began in 1890. This process produces approximately 4% of the worldwide hydrogen. Three electrolysis technologies exist. Alkaline-based is the most common, the most developed, the lowest in capital cost, and the least efficient. Proton exchange membrane (PEM) electrolyzers are more efficient but more expensive than Alkaline electrolyzers. Solid Oxide Electrolysis Cells (SOEC) electrolyzers are the most electrically efficient but the least developed. The first two technologies work with liquid water, and the latter requires high-temperature steam. This work refers to the first two technologies as low-temperature electrolysis (LTE) and the latter as high-temperature electrolysis (HTE) [8].

Water electrolysis converts electric and thermal energy into chemical energy stored in hydrogen. The process enthalpy change ΔH determines the required energy for the electrolysis reaction to take place

$$\Delta H = \Delta G + T\Delta S \tag{1}$$

where ΔG is the specific electrical energy and $T\Delta S$, the specific thermal energy. In LTE, electricity generates the necessary thermal energy. Hence, ΔG determines the entire process's energy requirement. ΔG is equal to 60 kWh/kg-H_2 considering a 67% electrolyzer electrical efficiency. In HTE, a high-temperature heat source provides the necessary thermal energy. ΔG decreases with increasing temperatures, as shown in Figure 2. Decreasing the electricity requirement results in higher overall production efficiencies. This work considers the process to be at 3.5 MPa. Although ΔG increases with pressure, a high pressure saves energy, as compressing liquid water is cheaper than compressing the hydrogen. In his work, ΔG and $T\Delta S$ are 31.6 and 9.7 kWh/kg-H_2, respectively, for a reactor outlet temperature of 850 °C.

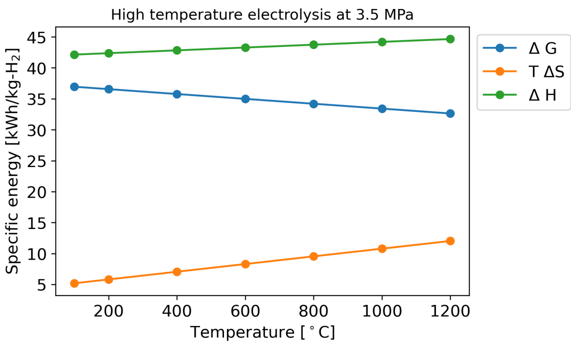

Fig. 2: Energy required by high-temperature electrolysis at 3.5 MPa. Image reproduced from [8].

After converting the excess energy into hydrogen, it is stored until the grid requires it. The conversion of hydrogen produces 40 kWh/kg-H_2 [9]. However, conventional fuel cells can use up to 60% of that energy [10].

METHODOLOGY

As mentioned earlier, the focus of this paper is to decrease the CO_2 emissions on the UIUC campus. This paper studies two energy alternatives, Scenario 1 and 2, and compares them to the default case, Scenario 0.

Scenario 0 considers the business as usual case. We calculate the CO_2 emissions using the electricity production hourly data. These data are available per request from UIUC Facilities and Services. To narrow down the scope, we focus on months of the two most demanding seasons of the year, January for the winter and June for the summer. Abbott and the purchased electricity are estimated to emit 0.39 MT CO_2/MWh and 0.75 MT CO_2/MWh, respectively [11, 2].

Scenario 1 studies the increase of the wind and solar generation capacity up to ten times fold. The increase in the wind and solar generation capacity requires the addition of electricity storage mechanisms into the mix. The development of a dispatch model is necessary to calculate the energy being stored, Abbott hourly production, and the purchased electricity. This model gives priority to the different sources in the following order: wind and solar, storage mechanism, Abbott, and purchases, as shown in Figure 3. The net demand (ND) is calculated by subtracting the wind and solar generation from the total demand. Abbott's electricity generation is preferred over purchases because of their lower CO_2 emissions.

Scenario 2 is similar to Scenario 1 but considers the addition of a nuclear reactor into the mix. This model gives priority to the different sources in the following order: wind and solar, nuclear reactor, storage mechanism, Abbott, and purchases. The ND is calculated by subtracting the wind, solar, and nuclear generation from the total demand. Given that UIUC campus demand is typically smaller than 80 MW,

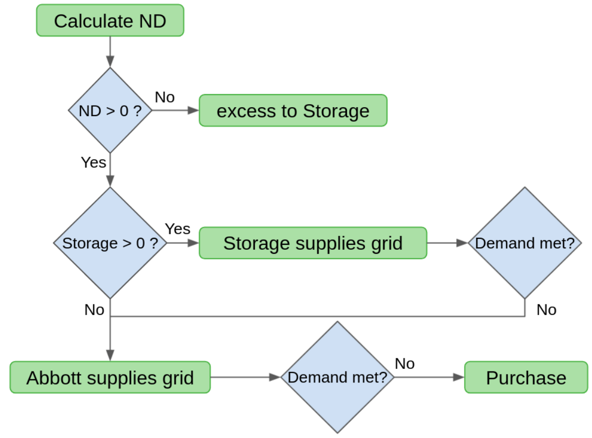

Fig. 3: Scenario 1 and 2 dispatch model that calculates the hourly generation of the different sources. *ND* is the net demand.

the following analyses consider reactors of small capacities, such as microreactors. This type of reactor shows several advantages such as requiring limited on-site preparation as their components are factory-fabricated and shipped out to the generation site. Moreover, these reactors use passive safety systems, minimizing electrical parts [12].

This scenario considers 2 reactor power levels, 10 and 20 MW_{th}, and 2 reactor outlet temperatures, 300 and 850 °C. Conventional Light Water Reactors (LWRs) – with outlet temperatures of 300 °C – have efficiencies around 33% while Gen-IV reactors, for example, Very High-Temperature Gas-Cooled Reactors (VHTRs) – with outlet temperatures of 850 °C – can achieve higher efficiencies around 48% [8].

Depending on the preferred electrolysis method, the microreactor can supply the hydrogen plant with both electricity and thermal power, as shown in Figure 4, where η is the thermal-to-electric conversion efficiency, and β and γ determine the distribution of the reactor thermal power P_{th} into P_E, P_{EH2}, and P_{TH2}. P_E is calculated by the dispatch model. The following formulas allow to calculate all the rest of the model variables

$$\beta = \frac{P_E}{\eta P_{th}},\ \gamma = \frac{\Delta G/\eta}{\Delta G/\eta + T\Delta S} \tag{2}$$

$$\dot{m_{H2}} = \frac{\gamma(1-\beta)\eta P_{th}}{\Delta G} \tag{3}$$

$$P_{EH2} = \dot{m_{H2}}\Delta G,\ P_{TH2} = \dot{m_{H2}} T\Delta S \tag{4}$$

where $\dot{m_{H2}}$ is the hydrogen production rate. This work considers an η of 0.32 for a reactor outlet of 300 °C and 0.49 for a reactor outlet of 850 °C.

Only the case considering a reactor with outlet temperature of 850 °C can achieve the high temperatures required by the HTE. This means that the HTE hydrogen production (H2-HTE) is only available to this case. It also means that the H2-HTE is limited by the reactor power, as solar or wind generation only produce electricity. If the net demand is lower or equal in magnitude than the total reactor electrical power,

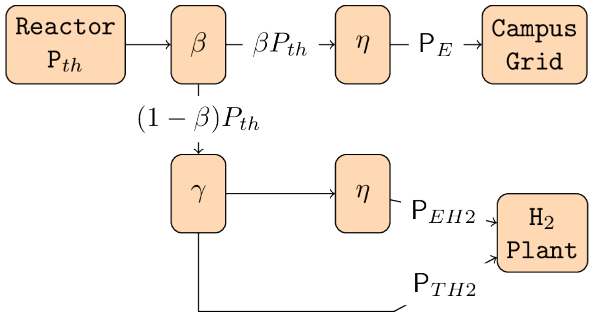

Fig. 4: Diagram of a nuclear reactor supplying the grid and a hydrogen plant.

H2-HTE is able to store all the excess energy. Otherwise, a secondary storage mechanism becomes necessary. This case study employs LTE hydrogen production (H2-LTE) as the secondary storage mechanism.

RESULTS

This section presents and discusses the results for the different scenarios. Table I displays the results for Scenario 0. The emissions in the winter are lower than in the summer due to lower total demand. This could be caused by a lower occupancy of campus during January or by the fact that the campus uses mostly steam for heating during the winter. Given that summer emissions are higher than in the winter, the following analyses focus only on the summer month.

10^3 MT CO_2	Abbott	Purchased	Total
Winter	6.6	8.5	15.1
Summer	4.8	16.7	21.5

TABLE I: Scenario 0 CO_2 emissions by source for the winter and summer months.

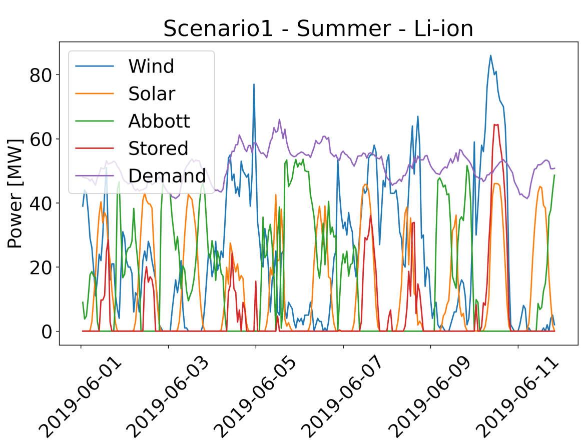

Fig. 5: Scenario 1 hourly generation distribution by source for a capacity increase factor of 10. Displayed data span from June 1st to June 11th.

Figure 5 displays an example of the hourly distribution calculated by the dispatch model for Scenario 1. Subtracting the wind and solar generation from the demand allows calculating the stored electricity, Abbott production, and the purchased electricity. This figure shows that Abbott has enough capacity to supply campus without the need for purchasing electricity. This study focuses on the reduction of the CO_2 emissions and not on the economics. Eliminating the electricity purchases already reduces the emissions by almost a half, as shown in Figure 6.

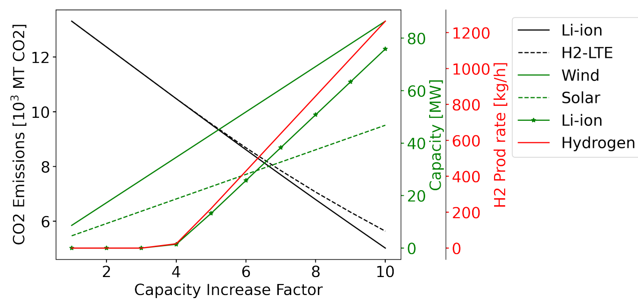

Fig. 6: Scenario 1 CO_2 emissions for different increases in the wind and solar generation capacities.

Figure 6 displays the CO_2 emissions as well as wind, solar, and storage capacities for the different capacity increase factors. Scenario 1 considers a linear increase in the wind and solar capacities. Hence, the CO_2 reduction is also linear as long as no energy storage is required. The campus wind and solar capacities can be increased up to 25.9 and 14 MW (increase factor of 3), respectively, without a need for installing a storage mechanism. Once the energy storage is needed, the higher the charge-discharge efficiency, the larger the emissions reduction is. This scenario achieves a higher CO_2 reduction employing Li-ion batteries.

Figure 7 shows the CO_2 emissions and the respective wind, solar, and storage capacities for the different capacity increase factors considering a reactor power of 10 MW_{th}. Once again, the Li-ion batteries cause the largest reduction in CO_2 emissions. On the other hand, increasing the solar and wind capacity by a factor of 10 requires Li-ion batteries with larger capacities than the wind generation or the solar generation, being close to 100 MW, which is even larger than the campus total demand.

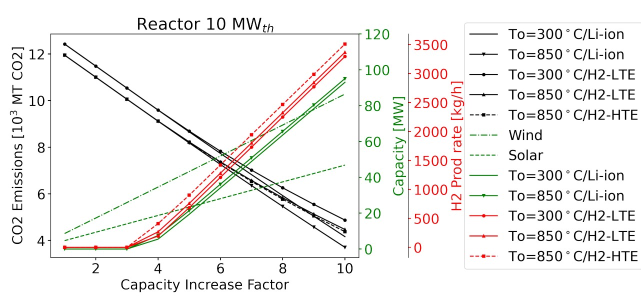

Fig. 7: Scenario 2 CO_2 emissions for different increases in the wind and solar generation capacities, with a 10 MW_{th} reactor. To is the reactor outlet temperature.

As mentioned earlier, a higher reactor outlet temperature translates into higher efficiencies, and for the same reactor thermal power, a higher electrical output can be achieved. H2-HTE does not show considerable advantages over H2-LTE, highlighting that a high outlet temperature is still desirable but only for attaining higher efficiencies. Additionally, incorporating a 10 MW_{th} microreactor reactor reduces the CO_2 emissions but does not eliminate them.

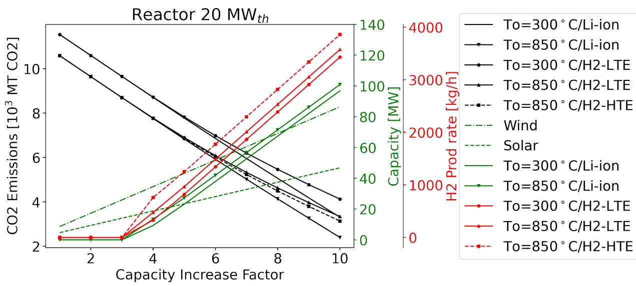

Fig. 8: Scenario 2 CO_2 emissions for different increases in the wind and solar generation capacities, with a 20 MW_{th} reactor. To is the reactor outlet temperature.

Figure 8 displays the results for the case considering a reactor of 20 MW_{th}. The Li-ion batteries show the best performance. A higher reactor power translates into a higher CO_2 reduction. Additionally, a higher reactor power allows for an increase in hydrogen production, and the H2-LTE and the H2-HTE curves show a wider separation.

CONCLUSIONS

The world faces energy challenges that compromise the efforts to stop climate change, being the electricity generation sector a major contributor to GHG emissions. These challenges underscore the need for cleaner sources. Nonetheless, the common belief that renewable energy is the solution to the problem highlights a caveat. A stand-alone increase in wind and solar generation capacities cannot eliminate all the carbon emissions. Such a strategy requires the addition of energy storage mechanisms into the grid.

This work studies several energy alternatives for decarbonizing the UIUC campus grid, including a variety of energy storage mechanisms. The UIUC campus grid is a good example of a diverse micro-grid, in which different energy sources need to work symbiotically to fulfill campus demand. This work focused on reducing the carbon emissions on campus, contemplating several approaches.

One of the main takeaways from Scenario 1 is that decreasing the electricity purchases has a strong impact on CO_2 emissions. However, this work considers that Abbott has a maximum capacity of 85 MW and that all that capacity is available if needed. As a co-generation plant, Abbott's steam production may limit the maximum available electric capacity, requiring the purchase of electricity. Additionally, the results showed that increasing the capacity of the renewable sources linearly decreases CO_2 emissions as long as no storage mechanism is needed.

Concerning Scenario 2, larger reactor capacities reduce further the CO_2 emissions. Additionally, a reactor with higher outlet temperatures increases the total electrical capacity and reduces even further the CO_2 emissions. Finally, Li-ion batteries are the most efficient storage mechanism for all the study cases.

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REFERENCES

1. US EPA, OAR, "Sources of Greenhouse Gas Emissions," (Dec. 2015), https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
2. INSTITUTE FOR SUSTAINABILITY, ENERGY, AND ENVIRONMENT, "Illinois Climate Action Plan (iCAP)," Full Report 2020, University of Illinois at Urbana-Champaign, Urbana, IL (2020).
3. FACILITIES AND SERVICES UNIVERSITY OF ILLINOIS URBANA CHAMPAIGN, "Abbott Power Plant Brochure," Tech. rep., University of Illinois Urbana Champaign.
4. FACILITIES AND SERVICES UNIVERSITY OF ILLINOIS URBANA CHAMPAIGN, "Energy Management Plan," Tech. rep., University of Illinois Urbana Champaign (Dec. 2015).
5. R. SPLITTER, "Illinois: Rail Splitter Wind Farm," Fact Sheet, Rail Splitter, Illinois (2016).
6. FACILITIES AND SERVICES UNIVERSITY OF ILLINOIS URBANA CHAMPAIGN, "PROJECT FACT SHEET: Solar Farm Project," Fact Sheet, University of Illinois Urbana Champaign (2017).
7. J. SUN, "Car Battery Efficiencies," (Oct. 2010).
8. R. FAIRHURST-AGOSTA, *Multi-Physics and Technical Analysis of High-Temperature Gas-Cooled Reactors for Hydrogen Production*, Master's thesis, University of Illinois at Urbana-Champaign, Urbana, IL (Dec. 2020).
9. A. URSUA, L. M. GANDIA, and P. SANCHIS, "Hydrogen Production From Water Electrolysis: Current Status and Future Trends," *Proceedings of the IEEE*, **100**, *2*, 410–426 (Feb. 2012).
10. ENERGY EFFICIENCY AND RENEWABLE ENERGY, "Fuel Cells [fact sheet]," Tech. rep., DOE (Nov. 2015).
11. INSTITUTE FOR SUSTAINABILITY, ENERGY, AND ENVIRONMENT, "Illinois Climate Action Plan (iCAP)," Full Report 2015, University of Illinois at Urbana-Champaign, Urbana, IL (2015).
12. US-DOE, "The Ultimate Fast Facts Guide to Nuclear Energy," Fact Sheet DOE/NE-0150, Department of Energy Office of Nuclear Energy, Washington D.C. (Jan. 2019), https://www.energy.gov/ne/downloads/ultimate-fast-facts-guide-nuclear-energy.