Design of an Autothermal Reforming Blue Hydrogen Production Plant

Analysis of the Failure to Develop California's Proposed "Hydrogen Highway Network"

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By
Brenna Bartholomew

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Technical Project Team Members:
Collin Barbosa, Jack Carroll, Jonathan Paul, Alex Ton

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISORS

Benjamin Laugelli, Department of Engineering and Society

Eric Anderson, Department of Chemical Engineering

Introduction

As global average temperatures continue to warm and the disastrous effects of climate change — from raging wildfires to dangerous heat waves — are starting to be felt around the globe, strategies to reduce carbon dioxide emissions are growing increasingly urgent. The transportation and electricity production sectors especially require extensive emissions reductions, as vehicles are largely dependent on petroleum for liquid fuel, and power generation relies most heavily on fossil fuels like natural gas and coal (U.S. Environmental Protection Agency, 2022). To reduce these emissions, several paths are being explored, including renewable electricity from hydrogen fuel cells. Current hydrogen production, however, limits the net-zero emissions potential of hydrogen fuel cells, as hydrogen is most often reformed from natural gas, which produces carbon dioxide and requires extensive energy inputs (Nikolaidis & Poullikkas, 2016). To address the technical challenges associated with current hydrogen production techniques, I propose a design for a blue hydrogen plant using autothermal reforming, which requires less energy input than typical steam methane reforming and captures the carbon dioxide produced by the process.

While technical improvements to the design of hydrogen plants may increase the availability of hydrogen, there are many additional social and political factors that influence the viability of hydrogen fuel cell technologies. For example, the proposed "California Hydrogen Highway Network" struggled to develop not only due to lagging hydrogen storage technologies in the early part of the century, but also because of political influence from environmental and fossil fuel organizations (Slater, 2004; California Climate & Energy Report, 2011). Failing to fully understand the social factors that contribute to technological systems may hinder the successful implementation of new technologies on the path to achieving global climate goals.

Thus, to effectively reduce emissions using hydrogen fuel cells, both the technical and social aspects of this issue must be addressed. Below, I outline a technical process for producing blue hydrogen via autothermal reforming that reduces the energy intensity and carbon footprint of hydrogen production. Additionally, I will analyze the variety of social, technical, political, and economic actors that contributed to the failed development of the California Hydrogen Highway Network to determine how human and non-human factors can influence the trajectory of emerging technological systems.

Technical Project Proposal

Hydrogen has seen growing potential in recent years as an energy source for electricity production in homes and vehicles, as the development of other renewable sources and biofuels remains slow in many regions. Hydrogen is not abundantly available in nature however and instead has to be produced from other energy sources (Nikolaidis & Poullikkas, 2016). Traditional hydrogen production, often called "gray hydrogen," consists of reforming fossil fuels like coal and natural gas to create hydrogen gas and other emissions, including carbon dioxide (CO_2), a significant greenhouse gas. Steam methane reforming (SMR) is the most common strategy deployed in this production (Yu et al., 2021). In SMR, a high temperature reformer converts hydrocarbons and steam into syngas which is reacted to produce hydrogen and CO_2, but the CO_2 is not captured and stored. (Nikolaidis & Poullikkas, 2016). While this process has been widely used in industry, its large energy requirements and considerable CO_2 emissions make it unattractive for continued widespread use in producing hydrogen for a cleaner energy future.

The process we propose will instead produce "blue hydrogen". This can be made in the same ways as gray hydrogen; however, the CO_2 produced during the reformation of methane is captured and stored, lowering the overall carbon emissions of the hydrogen plant. While this process is not net-zero, it is a major step towards emissionless energy production. However, carbon capture requires energy, lowering the plant's efficiency and increasing costs of production. One way in which we are mitigating these effects is by using autothermal steam methane reforming (ATR). This method involves reacting pure oxygen and steam with methane to produce carbon monoxide and hydrogen in an exothermic reaction (Lamb et al., 2020). Therefore, the heat generated through this reaction can be used to sustain the process with far less energy input than a typical SMR reactor, decreasing costs and the overall carbon footprint.

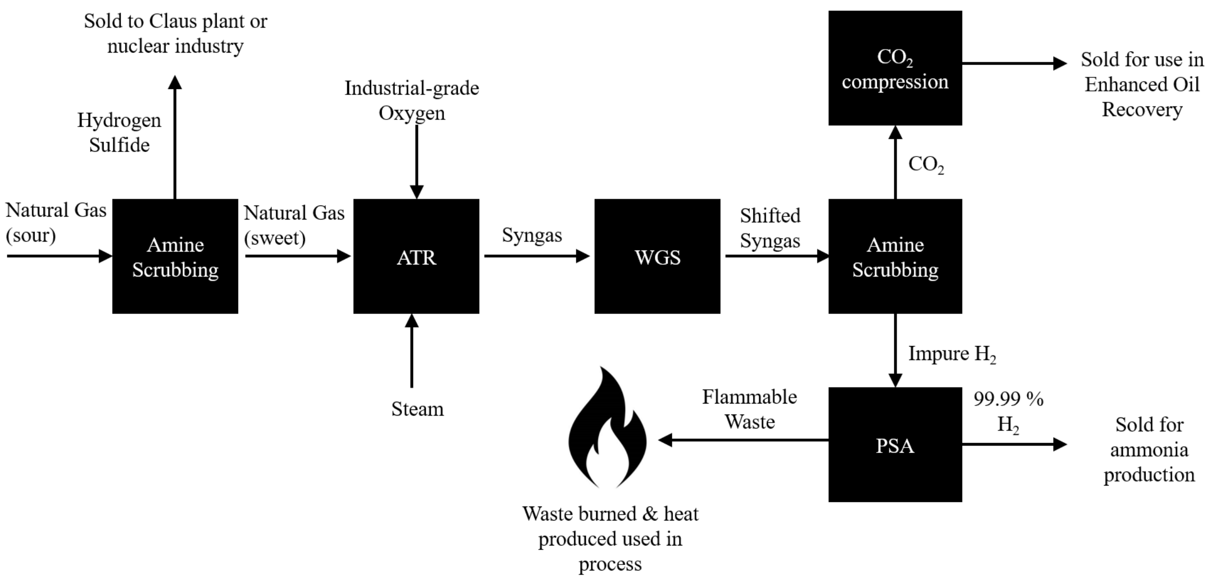

Figure 1. Block flow diagram for proposed blue hydrogen plant

A process flow diagram for our proposed blue hydrogen production process is given in Figure 1. To perform autothermal reforming at the optimal reaction conditions, pure oxygen must be fed to the ATR unit to increase the efficiency and yield. For this project, industrial grade oxygen will be supplied from an on-site air separation unit operated by a third party, reducing capital costs and operational costs (U.S. Bureau of Labor Statistics, n.d.). After the materials flow through the ATR, a water-gas shift reactor will be used to convert the carbon monoxide produced into additional hydrogen gas and CO_2. Amine scrubbing will be used to remove sulfides from the feed and to separate CO_2 and H_2 in the product streams (Carver Pump, 2021). The CO_2 produced from the reactor will be refined to be sold for enhanced oil recovery (EOR). Although EOR is not the most environmentally conscious route for use of captured CO_2, it is currently the most profitable. 88% of total CO_2 use across the world in 2017 was "gaseous," meaning that it was directly used for fossil fuel recovery (Roberts, 2019). Keeping the captured CO_2 as a gas instead of liquefying or solidifying it is also more cost effective, as it eliminates the need for additional condensers and pumps.

We plan to use Aspen Plus to simulate the complex chemical behavior and unit operations within our designed plant. Additionally, we plan to incorporate Microsoft Excel and Powerpoint for presenting and processing data. Design data will come from papers that have already performed basic economic analysis and conceptualized the entire process down to the unit operations (Oni et al., 2022). Economic analysis is crucial to determining the project's feasibility, and influences several design choices. (Ali Khan et al., 2021). This project will be completed as a team of five students over the course of two semesters in the classes CHE 4474 and CHE 4476. Gantt charts will be used to organize our workflow and establish deadlines, and work will be divided equally amongst teammates.

STS Project Proposal

On April 20th, 2004, Governor Arnold Schwarzenegger of California signed Executive Order S-7-04, calling for the rapid commercialization of hydrogen fuel cell technologies with the intent to transform California's interstate system into a vast network of hydrogen fueling stations, dubbed the "California Hydrogen Highway Network" (Exec. Order No. S-7-04, 2004). The executive order directed the state legislature to develop a California Hydrogen Economy Blueprint Plan which outlined the development of 50-100 hydrogen fueling stations along California's highways by 2010, ensuring that every Californian would have access to clean hydrogen fuel for their vehicles (Exec. Order No. S-7-04, 2004; Pavley, 2005). An initial investment of $10.5 million was proposed for fuel station development, as well as tens of thousands of dollars in cash incentives for hydrogen fuel cell vehicle owners, in order to jumpstart the program (Pavley, 2005).

Yet by 2012, two years after the proposed deadline, only six fuel stations were operational and open to the public, and today the number has barely reached 60, which is still significantly lower than the 100 stations expected twelve years ago (California Fuel Cell Partnership, 2012**;** California Energy Commission, 2022). While California continues to invest in hydrogen infrastructure, hydrogen vehicle sales never experienced the exponential growth that was once expected and a full "hydrogen highway" extending the length of California has yet to be realized (California Fuel Cell Partnership, 2012**;** California Energy Commission, 2022). The failure of this proposed system is often attributed to the technical shortcomings of hydrogen fuel cell technology, including low efficiency and difficulties with hydrogen storage, as well as the considerable economic hurdles for both hydrogen powered vehicles and fueling stations (Halper 2021; Morris, 2021). However, these outlooks fail to consider social and conceptual factors that contributed to the system's lack of success, including opposition from both environmental groups and oil and gas companies and competition with other zero-emission vehicles (Slater, 2004; California Climate & Energy Report, 2011).

During the project's development stages, groups like the Sierra Club highlighted how greenhouse gasses released during hydrogen production prevent hydrogen fuel cell vehicles from being truly “emissions free,” and argued that hydrogen powered vehicles detract from strategies that could reduce emissions faster, such as the widespread deployment of hybrid vehicles (Slater, 2004). Additionally, fossil fuel companies have fluctuated between supporting and opposing the development of fueling stations, using their lobbying influence to sway legislators and regulatory commissions like the California Air Resources Board (California Climate & Energy Report, 2011). If we continue to focus solely on the technical challenges facing new hydrogen infrastructure projects, we will fail to fully understand how non-technical actors influence the timeline and trajectory of these projects, and similar proposals, whether for hydrogen fuel cells or other green vehicle technology, may face failures in the future unrelated to their technical feasibility.

Drawing on Actor-Network Theory, I argue that hydrogen storage difficulties, in conjunction with the inhibitive costs of hydrogen fuel cell vehicles and fueling stations, environmentalist skepticism, oil industry opposition, and competition with battery electric vehicles, led to the failure and continuing struggles in developing California’s “Hydrogen Highway Network.” Actor-Network Theory seeks to understand how different actors, both technical and non-technical, interact to accomplish a specific goal and are recruited by a network builder to form a technological network. (Cressman, 2009) The process by which various actors interconnect to form and maintain these networks is known as translation. (Cressman, 2009) Utilizing this concept, I will analyze how the California Hydrogen Highway Network initially began to form and the process by which it eventually stalled and struggled to develop further in order to understand both the human and non-human actors involved in hydrogen infrastructure projects. To support my argument, I will analyze data and reports from the California state legislature and California's environmental regulatory agencies, as well as press releases from various environmental groups, oil companies, and vehicle manufacturing companies.

Conclusion

The technical project proposed in this paper will contain the complete design of a full scale blue hydrogen production plant that captures carbon dioxide emissions while using less energy than conventional steam methane reforming plants. The STS project will use Actor-Network Theory to determine why the largest proposed hydrogen infrastructure project in the country failed to achieve success by analyzing the technical and non-technical actors at play in the project's development. Combined, the results of both the technical and social projects will address the challenges facing a transition to hydrogen technologies, including hydrogen production and its applications in fuel cells. Highlighting not only the technical improvements critical for hydrogen production, but also the social, political, and economic components required for the implementation of hydrogen fuel cells may shed light on key considerations for deploying net-zero emissions technologies.

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