# ELECTRIC AND FUEL CELL FORKLIFTS IN MEXICO:
# A COMPARATIVE LIFE-CYCLE ASSESSMENT

by
Tania Miranda

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## Abstract

A recent overhaul of Mexico's energy sector launched by a Constitutional reform in 2013 started the decarbonization of the economy by tapping into Mexico's vast renewable resources and through the deployment of new energy technologies. This, in addition to health concerns due to high pollution levels in large urban populations, encouraged the government to kick-start an effort to roll out alternative-fuel vehicles.

One of the alternative-fuel vehicles currently explored in the United States and other countries, like Japan and the EU, are fuel cell vehicles powered by hydrogen, yet this technology requires complex supply chains with large up-front costs. Thus, governments are exploring early market applications that can help jump start the hydrogen market through demonstration projects, like city-owned buses, and through government incentives for hydrogen-powered material handling equipment.

This study takes a first stab at delving whether the Mexican government should consider incentivizing the deployment of fuel cell technologies, in their effort to accelerate the de-carbonization of the transportation system and more generally to tackle climate change, through hydrogen-powered forklifts—as these are a proven early market application that is widely used in the United States. Yet this can only be argued for if the new technology presents a solid environmental benefit vis-à-vis the incumbent one – in this case battery-powered forklifts.

The methodology used in the study was a life-cycle assessment, that estimates the emissions and energy used throughout the hydrogen supply chain, and compares them to the electricity one, using a model developed by the Argonne National Laboratory and Mexico-specific data. The results show a clear advantage of using hydrogen over batteries when produced via electrolysis powered by wind electricity; a large disadvantage when using electrolysis powered by the average Mexican electric mix; and mixed results when using hydrogen produced through the reforming of natural gas. However, there is also a case for fuel cells in material handling equipment due to potential reductions in cost of ownership that argue in favor of the hydrogen scenario.

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## 3. Introduction

One of the most interesting solutions explored today for reducing pollution in large urbanized regions and dealing with climate change is the electrification of the transportation system through battery-electric vehicles, as well as the use of alternative fuels for vehicles – including biofuels, natural gas, and hydrogen. This is because fossil fuels, which currently power most vehicles around the world, consume large amounts of energy, contribute to pollution through the emission of particulate matter, and significantly contributes to global warming through the emission of greenhouse gasses (GHG).

Unfortunately, the deployment of newer technologies faces several obstacles, like lack of supply chains, due to their state of maturity. Aside from, first of all, high -and sometimes prohibiting- costs, drivers are many times reluctant to buying these vehicles as it proves burdensome to find component replacements and even refueling stations. However, as long as there is a small number of vehicles on the road and market penetration remains low, companies both upstream and downstream of the value chain will doubt before investing in developing the supply chains. For instance, when talking about fuel-cell vehicles (FCV's), it has been shown[1] that the auto manufacturers prove reluctant to producing more units unless hydrogen manufacturers can in parallel guarantee the needed supply of the fuel. Yet hydrogen producers are also unwilling to provide supply of hydrogen unless there is a guaranteed demand for their product, thus

[1] https://www.c2es.org/technology/factsheet/HydrogenFuelCellVehicles

creating a chicken-and-egg problem. And while there is a low number of units on the road, refueling stations – which require high capital and operational costs – remain under-utilized and results unprofitable to invest in them.

To break this market penetration challenge, aside from offering policy- and economic-based incentives to buy the product, companies start by introducing early market applications of the technology that rely on less complex supply chains and by clustering refueling stations around large demand centers that guarantee a certain utilization rate – sometimes through government-funded demonstration projects. In the case of hydrogen-based vehicles, a proven early market application is the use of fuel cell-powered forklifts and material handling equipment (MHE): “Hydrogen fuel cells are being used today to satisfy a commercial need in early market applications such as material handling and backup power, and these uses are furthering the development of fuel cells and related hydrogen fueling infrastructure and helping expand the market for these promising technologies” (Renquist, 2012).

Fuel cell forklifts present several advantages over battery-powered ones, like reduced charging time, less space needed for battery replacement and changing areas, as well as better and longer performance, and the ability to utilize them in a wider range of temperature. Furthermore, large distribution centers with a considerable amount of forklifts make an economic case for this technology, as they are a constant and large enough demand center for hydrogen – lowering costs due to economics of scale. In an effort to help the technology mature, the Department of Energy has deployed more than 500 fuel cell-powered MHE units in commercial facilities and 100 more in distribution centers throughout the United States, and the National Renewable Energy Laboratory (NREL) performed a cost of ownership evaluation of these and found that costs can be lowered by substituting battery-powered forklifts with comparable fuel cell technology – even without federal tax incentives (Ramsden, 2013).

Mexico, through domestic policies and legally binding international commitments to climate change abatement, and delving with deep-rooted pollution problems in most of its highly-populated cities, recently kickstarted an effort to introduce alternative fuel vehicles—mostly hybrid electric and natural gas, yet fuel cells have not been explored thus far. As explained before, these technologies are likely to require government intervention to certain extent to help them mature. One possibility would be through public-private partnerships, in which city and local government subsidized companies with large distribution centers to deploy fuel cell-powered forklifts and support the establishment of the necessary fuel supply chains. Currently, all indoor-use forklifts are battery-powered, as by regulation internal combustion engine (ICE) forklifts are not allowed due to emissions at point of use. This means that the government needs an environmental reason (well beyond any economic one) to subsidize the deployment of fuel cell-powered forklifts.

The United States fuel cell forklift deployment has been analyzed in detail by the Department of Energy, and its studies show that for some hydrogen production pathways, changing the battery fleet for a fuel cell one in fact reduces energy demanded and pollution emissions. A study performed by the Argonne National Laboratory in 2009 analyzed the full fuel-cycle emissions and primary energy use by fuel cell, battery, and ICE powered forklifts, and concluded that:

> "The greenhouse gas impact of fuel-cell forklifts using hydrogen from steam reforming of natural gas are considerably lower than those using electricity from the average U.S. grid. If fuel-cell generation technologies approach or exceed the target efficiency of 40%, they offer significant reductions in energy use and GHG emissions compared to alternative combustion technologies" (Elgowainy, 2009).

This study will explore whether changing the battery forklift fleet in Mexico to a fuel cell one would lead to those same reductions – something that would be of great interest to the policy community in Mexico because of the climate change and public health implications, thus building the case for providing incentives for the deployment of such technology, as well as to the private sector, since it would create new markets and business opportunities.

## 4. State of the Art

According to the DOE, "the global market for fuel cells grew by almost 400% between 2008 and 2013, with more than 170 MW of fuel cell capacity added in 2013 alone" (IEA, 2015). Most of them are used for back-up and remote power systems, as well as for stationary applications, and more recently, for vehicles. To date, Hyundai and Toyota Motor Company have produced FCV's for a couple of years, and other original equipment manufacturers inter alia BMW, GM, Honda, Mercedes, and Ford are expected to introduce their own FVC to the market soon – some of them through demonstration project. The FCV market is likewise growing for city buses and heavy-duty vehicles (Clean Cities, 2015). Nonetheless, regardless of this laudable market penetration of the past few years, high initial investment costs and lack of supply chains are still important barriers for the technology to fully mature.

The DOE funds a number of research and demonstration projects through its Fuel Cell Technologies Office, as these systems have the potential of reducing pollution and GHG emissions, as well as the U.S. transportation sector dependency on foreign oil, and of diversifying domestic energy sources. The projects usually focus on increasing efficiency and life durability, as well as testing vehicle driving range and minimizing decentralized hydrogen production costs – which are currently high.

<u>Fuel Cells in MHE</u>

The most relevant early-market applications for fuel cells today are for power production for end-use applications (specially for auxiliary and backup power), as fuel cells can transform chemical energy directly to electricity, and for specialty vehicles, and a few of these applications are already commercially viable – material handling equipment (including narrow aisle lift trucks, pallet jacks, stock pickers and counterbalanced forklifts) being one of them.

Forklift trucks are available in many variations and load capacities – ranging from 450 kg to over a ton – and are classified from Classes I to VII, mainly depending on load capacity and size. They can be powered by batteries (usually lead-acid), or by ICEs fueled by gasoline, propane, or diesel. Battery-powered forklifts (Class I, II, and III) are typically used for indoor applications that do not require large lift capacities and are sometimes selected for worker safety, including confined spaces, cold storage, and food retail – as they do not create emissions of any type at point of use.

There are several advantages of using fuel cells instead of batteries for forklift trucks. Fuel cells can be refueled in about two to three minutes (instead of taking 8 hours, like lead-acid batteries), and require 75% less space than battery recharging infrastructures, that typically include space for battery replacements, charging equipment, and charging-designated areas (Mahadevan, 2007). This makes fuel cell-powered forklifts particularly advantageous in warehouse applications where the systems are needed for several shifts a day – since it means battery systems would need to be charged, replaced, and cooled down more than once. Furthermore, fuel cells can operate under a much wider temperature range than batteries, making them useful for refrigerated distribution centers.

## Comparison of Cost of Ownership

As part of a demo project funded by the National Renewable Energy Laboratory, they performed a comparison of the annualized costs of an electric forklift unit vs a hydrogen one, by analyzing costs related to operation (including capital expenditures), infrastructure needed, maintenance, space, and labor.

Overall, NREL cost of ownership analysis found that "when deployed in larger-scale, multishift warehouse applications, fuel cell MHE can provide cost savings compared to traditional, battery-powered MHE" (Ramsden, 2013). This means that, albeit results are dependent on factor like hours of operation per shift, number of shifts per day, operating days per year, fleet size (the larger the fleet, the more the per-lift truck cost of hydrogen infrastructure is minimized), and onsite fuel-cell systems (to lower the per-lift truck cost of hydrogen fueling infrastructure), fuel-cell forklifts can provide lower total costs of ownership for large companies – as shown in Fig 1 below.

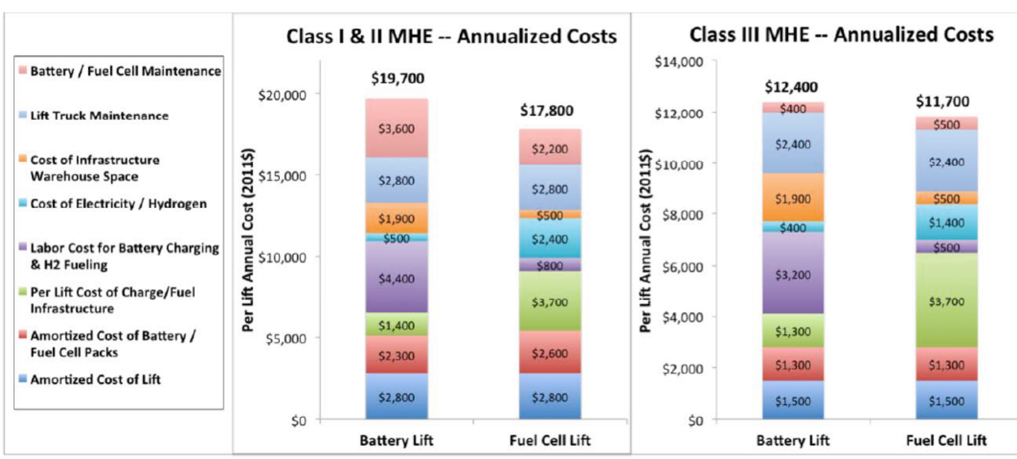


***Fig.1.*** *Itemized break-down of cost of ownership of fuel-cell vs battery electric forklifts for Classes I, II, and III. (Ramsden, 2013)*

Likewise, Ballard—global leader in innovative clean energy solutions—performed a similar analysis for the net present value of undergoing a change in an electric forklift fleet for a fuel-cell powered one, and concluded that when dealing with forklifts that work multiple shifts in places like warehouses and distribution centers, adopting a fuel-cell technology fleet can minimize total cost of ownership (Ballard, 2010).

Wal-Mart Canada deployed 95 fuel cell-powered forklifts, classes I, II, and III, for a perishable food distribution center in Balzac, Alberta, Canada. Hydrogen for this fleet is generated through electrolysis, using predominantly hydroelectric power from Quebec. The company estimated that the project “will reduce operating costs by $1.1 million over seven years, compared to using battery-powered forklifts” and that “even when factoring in transportation of the fuel to Alberta, the lift truck fleet avoids 530 tons of CO2 emissions per year” (Ballard, 2012). This technology was also more recently deployed in two other Wal-Mart distribution centers in Cornwall, Ohio, and Bartlesville, Oklahoma.

A few years after this government program started, there has been an industry investment of more than 5,000 fuel cell lift trucks without DOE funding:

> “Central Grocers in Illinois is operating solely on fuel cell-powered MHE with over 200 fuel cell lift trucks in one of its distribution centers. Sysco Foods is operating fleets totaling over 750 lift trucks for its operations in Texas, Pennsylvania, Massachusetts, New York, and Virginia. Fuel cell lift trucks are

also operated in numerous automotive-related manufacturing facilities, including plants operated by Mercedes-Benz, Toyota, BMW, Nissan, and Michelin" (Renquist, 2012).

Fuel Cells Basics

A fuel cell converts a fuel (input) into electricity (output), without converting the energy of the fuel into mechanical energy first, as an ICE would. Different fuel cells can use different energy carriers to create electrical energy, hydrogen being one of the most common ones.  By spatially separating the fuel combustion reaction into two different electrochemical half reactions with an electrolyte (material that allows the free flow of ions but not electrons), the electrons transferred from the fuel are forced through an external circuit. A load is then introduced along the path of the electrons, creating an electric current and providing power to the load. The electrons then continue their path and the reaction is completed. By skipping the mechanical energy step of the ICE, this technology has a more efficient use of the fuel's energy, achieving efficiencies in a range between 52-56%.

Fuel cell's half reactions:

1. $H2 \rightarrow 2H^+ + 2e^-$ (anode)
2. $\frac{1}{2}\ O2 + 2H^+ + 2e^- \rightarrow H2O$ (cathode)

The different types of fuel cells are usually categorized by the electrolyte they use to separate the electrons. This study will focus on Polymer Electrolyte Membrane Fuel Cells (PEMFCs) because their characteristics make them good candidates for portable power and transport applications:

- Good for operating at low temperatures.
- They have a fast start and best on/off cycle.
- High power density.

Furthermore, fuel cells can be powered by many different fuels, like hydrogen, natural gas, and some liquid fuels, like methanol or diesel. The most widely used fuel, however, is pure hydrogen (H2), in which case water vapor is the only exhaust gas of the cell, releasing no carbon dioxide or pollutants—minimizing the technology's environmental impact. However, even though H2 is the gas that is found in the highest percentage in our atmosphere, it is not found in its pure form, and thus it is necessary to "produce" it.

## Hydrogen Production Methods

Hydrogen can be produced through different methods, with different feedstocks, and transported and distributed in multiple manners as well, and the energy intensity and carbon footprint of the process will depend on those factors. To date, the three most widespread production methods for producing hydrogen are coal gasification, steam methane reforming, and electrolysis.

1) Coal Gasification

- Viable only if there exists a large coal reserve nearby.
- "Dirtiest" production method since it emits the highest amount of $CO_2$ and air pollutants.
- Produces high levels of unburned solid waste byproducts.
- As Mexico's coal reserves are limited (reason why only 10% of the country's electricity production comes from coal), this pathway was not analyzed in this study.

2) Steam Reforming of Natural Gas (Steam Methane Reforming – SMR)

- The most common H2 production method (close to 50% of H2 world demand is produced this way).[2]
- Produces less GHG emissions than H2 produced from coal, as methane contains a lower percentage of GHG in its composition.
- Higher efficiency process than coal gasification (70% to 80% efficient).
- Lower levels of solid waste products.
- If produced on a mass-scale, the main driver of the cost of this process is the price of natural gas.

First, methane is reacted with steam in an endothermic reaction (in which the system absorbs energy from outside of it), in the presence of a catalyst, to produce H2, CO, and $CO_2$. The CO is further reacted with steam to produce more H2 and $CO_2$, and the latter is removed to obtain pure hydrogen. This model of SMR has an efficiency of about 72% and the most common feedstock for this process is natural gas. Natural gas exploration,

[2] https://www.hindawi.com/archive/2013/690627/

production, and pipeline transmission consume 10% of the higher heating value (HHV) of the feedstock; natural gas reforming into hydrogen (through steam methane reduction) consumes 30% of the HHV of the feedstock, and hydrogen compression consumes about 10% of the HHV of the fuel. The corresponding specific (i.e. per kg of NG) emissions are reported in Table 1.

***Table 1.*** *SMR Emission Factors*

| Emission Type | kg of emission/kg of NG |
|---|---|
| $CO_2$ | 2.6 |
| $CH_4$ | 0.000048 |
| PM | Negligible |
| $SO_2$ | Negligible |
| $NO_x$ and $NO_2$ | 0.00046 |
| CO | 0.0000033 |
| VOC | 0.00000066 |

3) Electrolysis

By passing an electric current through $H_2O$ molecules, the current breaks these apart, separating the hydrogen.

- GHG emission intensity will depend directly (and only) on the carbon intensity of the electricity used for the water separation process. If power comes from a renewable source, like wind, the process is basically emission-free.
- Cost is mainly determined by the cost of electricity (IEA, 2015).
- Process is 70% efficient (Elgowainy et al. 2013).

Hydrogen Transportation

Hydrogen can be stored and transported in either a gaseous or a liquid state, and each method has its own set of advantages and disadvantages:

A) Gas Form

- Needs to be compressed at high pressures prior to delivery in order to achieve higher energy density.
- Consumes around 10% of the fuel's energy value.
- Cannot be transported through existing pipelines, as they would degrade in the presence of hydrogen. Either produced on site or shipped through tube trailers.

B) Liquid Form

- Must be cooled and slightly compressed prior to delivery.
- Consumes around 30% of the fuel's energy value.
- Usually transported by truck.
- Ceteris paribus, if the same electricity source is used for either compression or liquefaction, gaseous H2 produces less GHG emissions, air pollutants, and solid waste.

While the economics of scale will favor high-volume, pipeline transportation – like in the case of natural gas, pipelines that can transport hydrogen are not yet an economic reality, and thus this study will model the fuel's transportation through tube trailers.

Forklifts

Data on characteristics, operation, and use of forklifts was obtained – both first-hand and from existing literature – by the Argonne Labs for a commissioned study, which purpose was to "determine the savings of energy and petroleum, as well as reductions in greenhouse gas emissions, that could be accomplished by using hydrogen to power forklifts" (Gaines, 2008). This study found that forklifts can be used from a couple of hours a day up to 24 hours for seven days a week. Generally speaking, battery-powered forklifts are class I and II; motorized hand class III; and internal combustion engine classes IV, V and VI, and load capacity rises with class.

Specifically for electric MHE, the battery is important as it not only provides power for the forklift and can recover regenerative energy from braking, but also serves as a counterweight for stability – reason why so far lead-acid batteries lead the market, and why, if replaced by a fuel cell stack, the latter should be able to fulfill that purpose as well. These classes have usually a load capacity ranging from 1,360 to 2,700 kg and are mostly used for indoor activities – like storage warehouses and food retail – where worker safety mandates the use of forklifts with no emissions at the point of use. They are also used for applications where ICE-powered forklifts are not practical due to size. Because of their common applications, electric forklifts are typically used for multi-shifts operations at distribution centers and warehouses. This is a problem, however, as lead-acid batteries provide enough power for, at most, an 8-hour shift, require eight hours to cool down, and eight hours to recharge. This implies the need for three different batteries for running an electric forklift for a day-long shift, plus a designated space for replacements, and a battery charging room, as lead runoff requires special treatment.

Fuel cell forklifts have hybrid systems in which the fuel cell is the main power source, plus a battery or super capacitor that handles peak energy demand using stored energy (recovered from breaking or supplied by the fuel cell). This technology is particularly suited to replace lead-acid batteries in MHE because of a few key characteristics. Firstly, it can operate for more than 12 hours and takes only 2-3 minutes to refuel, and it does not need to cool down after use. This reduces costs not only in inputs, as you do not need as many fuel cell stacks, and space to store them, but also in labor costs. Secondly, fuel cells provide power with constant voltage throughout the shift, contrary to batteries, which suffer voltage degradation as the battery discharges (see Fig. 2). Lastly, batteries also have degraded performance in cold temperatures, and PEMFCs do not – extremely useful for applications such as industrial freezers and food distribution centers.

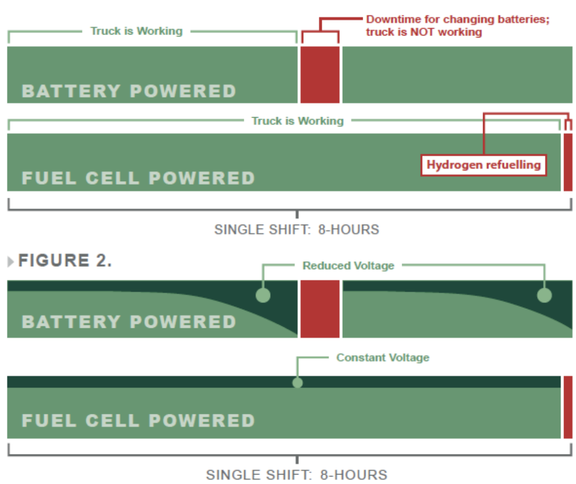


***Fig. 2.*** *Battery vs Fuel Cell Working Time and Voltage Performance (Source: Ballard, 2010)*

## 5. Methodology

To fully gauge the environmental impact of each type of technology to run the forklifts, either battery or PEMFC, this study performed a Life Cycle Assessment (LCA), a methodology for performing a systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle: “LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life-cycle. By including (these) impacts, LCA provides a comprehensive view of the environmental aspects of the product and a more accurate picture of the true environmental trade-offs in product and process selection" (EPA 1). This paper will evaluate and compare total energy demand and emissions from the full fuel-cycle and vehicle efficiency of the battery- and fuel cell-powered MHE fleet in Mexico, to assess whether this change would present emission (GHG and pollution) advantages for the country.

Although neither hydrogen FCV nor battery electric ones have tailpipe emissions or use fossil fuels for running, the upstream fuel cycles are frequently overlooked, although they can easily result in large amounts of emissions and resource use, depending on how the primary energy is converted and how the fuel is transported (as explained before). Furthermore, the light molecular weight of hydrogen requires significant compression and/or cooling to increase its volumetric density for transportation, distribution, and refueling. This step requires electricity use, which also generates emissions from power plants.

Life-Cycle Assessment

The LCA is a technique for:

> "[…] assessing the environmental aspects and potential impacts associated with a product by: compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts associated with those inputs and outputs; and interpreting the results of the inventory analysis and impact assessment phases" (Baumann, 2004).

This LCA study was conducted in compliance with the ISO 14040 series (ISO, 2006), including four phases: goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and interpretation of results and conclusions.

1. Goal and Scope Definition

    - Determine whether changing Mexico's MHE battery fleet to a fuel cell fleet would result in reductions of energy use and emissions. The purpose of such study is to put forth a policy recommendation to Mexico's Energy Ministry, if the hypothesis is affirmative, to subsidize a demo project that could stimulate the deployment of fuel cells in Mexico through an early-market application.

- The study will perform the analysis on a well-to-wheel (WTW) basis, and the functional unit[3] (FU) will be a kWh provided at the fork.

2. Inventory Analysis of Energy Demanded and Emissions

   - Flow model.
   - Data collection of raw materials and energy carriers, products, and waste (from GREET model, introduced below).
   - Calculation of resource use and pollutant emissions of the system (from GREET model).

This study used the GREET[4] model (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), developed by the Argonne National Laboratory of the DoE, to calculate the resulting fuel-cycle energy use and emissions. This model contains all the corresponding data for over 100 fuel production pathways and 70 vehicle/fuel systems, and calculates, separately, the following: consumption of total energy (in both non-renewable and renewable sources), fossil fuels (petroleum, fossil natural gas, and coal together), petroleum, coal and natural gas; emissions of $CO_2$equivalent GHG – primarily $CO_2$, methane ($CH_4$), and nitrous oxide ($N_2O$), and; emissions of six criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen

[3] Functional Unit: measure of the function of the studied system. It provides a reference to which the inputs and outputs can be related, enabling the comparison of two different systems which can provide the same or very similar functions.

[4] GREET relies on the efficiency of each step in obtaining and refining the fuel in order to calculate the total energy consumption of each fuel's production. $CO_2$ emissions associated with this process are calculated depending on the methods used. GREET follows a built-in table with emission factors for each step. In addition, GREET relies on the lower heating values of fuels in its calculations.

oxide ($NO_x$), airborne particulate matter with sizes smaller than 10 micrometers ($PM_{10}$), smaller than 2.5 micrometers ($PM_{2.5}$), and sulfur oxides ($SO_x$).

To simulate the model as realistic as possible, this analysis used Mexico-specific data (such as emission factors, electricity mix, natural gas composition, and transmission and distribution loss factors) wherever possible; otherwise, the model used default data provided by GREET (such as efficiency of electrolysers, water used in power production, etc).

The fuel-cycle total energy use for the H2 forklifts calculated by GREET included the following: energy use associated with recovery and transportation of the feedstock to the H2 production site; conversion of the feedstock to H2; H2 compression and transportation; and H2 use by the forklift given the PEM fuel cell efficiency and the hydrogen's lower heating value (LHV). The fuel cycle total energy for electric forklift includes energy use associated with the recovery, processing, and transportation of primary fuels to the power plant; electricity generation; charger and battery energy losses; and energy use by the forklift given the lead-acid battery's efficiency. Lastly, it is important to note how GREET distinguishes between the main two stages of the entire life-cycle, as shown in Fig. 3.

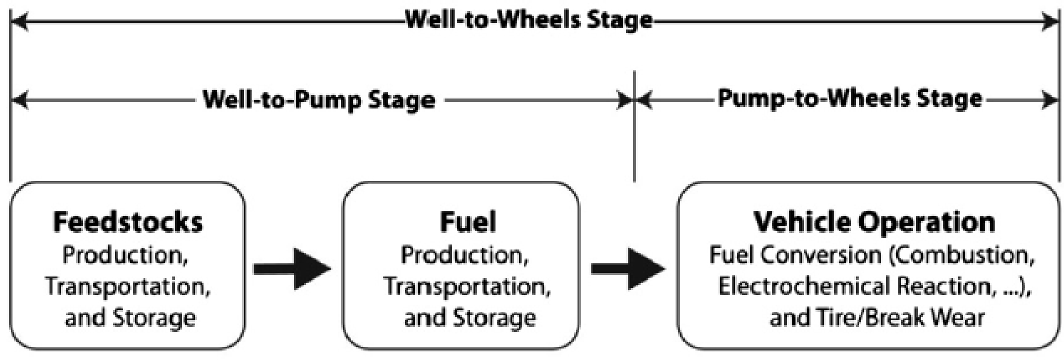


***Fig. 3.*** *GREET's stages of fuel-cycle*

3. Impact Assessment of the Environmental Loads

The life cycle impact assessment (LCIA) method used for this step of the LCA was TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and other environmental Impacts), developed by the U.S. EPA[5]. TRACI was developed for sustainability metrics, LCA, industrial ecology, and process design impact assessment with the goal of developing increasingly sustainable products and processes, and it includes the following impact categories: ozone depletion, global warming, acidification, eutrophication, photochemical smog formation, human health particulate effects, human health cancer, human health noncancer, ecotoxicity, and fossil fuel depletion effects.[6] This tool uses the amount of the chemical emissions or resources use and the estimated potency of the stressor. The latter are based on international models for each impact category. To calculate the score for each impact category, the study multiplied

[5] https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

[6] To read more on these categories, and the TRACI model in general, refer to the model's manual: https://nepis.epa.gov/Adobe/PDF/P100HN53.pdf

the mass of each substance (in kg), given by the GREET results, times the characterization factor for that substance in each impact category given by TRACI. The general equation for the characterization factors is (EPA, 2012):

$$\boxed{\mathbf{I^{i} = Sum_{(x,m)}\ [CFi_{(x,m)} * M_{(x,m)}]}}$$

Where $I^{i}$ = potential impacts of all chemicals (x) from a specific impact category.

$CF^{i}_{(x,m)}$ = characterization factor of chemical (x) emitted to media (m) for impact category (i), provided by the U.S. EPA.

$M_{(x,m)}$ = mass of chemical (x) emitted to media (m), which come from the results provided by GREET.

4. Interpretation and Analysis of Results

Normalization:

"Relates the magnitude of the calculated impact scores to a common reference, putting the impact scores in relation to the impact of society's production/consumption activities, thereby gaining a better understanding of the contribution of the product system under study to each impact score in relation to those of the reference system" (Ryberg, 2013). The reference system should be a reference point given by space and time and should be, to the extent possible, appropriate to the system under study; in this case the hydrogen supply chain in Mexico. It is worth noting, however, that normalization, besides being based on a convention (normalizing means dividing by a quantity that, by convention, is considered as meaningful to obtain interpretable results), is an optional step in LCA and it is affected by uncertainty at several levels (Benini and Sala, 2016). This study used the normalization factors (NFs) for all impact categories included in TRACI 2.1 calculated using inventories from the U.S. (2008), as reported in Ryberg, 2013[7]. More precisely, the NFs are calculated by dividing the total sum of the characterized flows of emissions or resources by the number of inhabitants within the designated geographical area and within a certain time frame (the United States population in the year 2008 in this case), following the equation below (Ryberg, 2013):

$$\boxed{\mathbf{NF^{i} = [Sum\ (CF_{i,s}) * E_{s}]/Pop}}$$

Where $NF^i$ = normalization factor (impact capita$^{-1}$ year$^{-1}$) for impact category i,

$CF_{(i,s)}$ = characterization factor (impact kg$^{-1}$ emitted of a given substance s) for impact category i,

$E_s$ = emissions of substances for a given geographical reference area (kg year$^{-1}$), and

P = human population of the reference area (capita).

The NFs were then used to normalize the TRACI results according to the following equation:

$$\boxed{\mathbf{N^{i} = IS^{i}/NF^{i}}}$$

[7] Refer to Figure A1 in Appendix for the entire list of NFs used in this study per Ryberg, 2013.

Where $N^i$ = normalized impact score for each impact category i,

$IS^i$ = impact score of a product or service in impact category i, and

$NF^i$ = normalization factor of impact category i.

After normalization, the impacts in each impact category are expressed in the same unit, namely equivalent persons (i.e. the equivalent number of U.S. inhabitants that would produce the same impact). Once the results for each impact category, for each pathway, were normalized, they were added up to get a single result indicator per pathway so that they could be compared and ranked by their environmental impact. The normalized results are shown in Table 2 and Fig. 4 below.

***Table 2.*** *Normalized Emissions (in person equivalent) per Pathway*

| | **Acidification** | **Human Health Particulate** | **Eutrophication** | **Smog (Photoch. Ozone Formation)** | **Global Warming** | **Fossil Fuel Depletion** | **Total** |
|---|---|---|---|---|---|---|---|
| **Grid-to-Battery** | 2.05E-04 | 3.08E-05 | 7.97E-05 | 9.49E-06 | 3.42E-05 | 8.05E-06 | **3.67E-04** |
| **Grid-to-H2** | 4.47E-04 | 6.77E-05 | 1.67E-04 | 2.15E-05 | 7.51E-05 | 1.29E-05 | **7.92E-04** |
| **SMR-to-H2** | 9.59E-05 | 5.62E-05 | 1.01E-04 | 1.25E-05 | 3.51E-05 | 1.45E-05 | **3.15E-04** |
| **Wind-to-H2** | 4.29E-05 | 6.37E-06 | 3.14E-05 | 2.86E-06 | 7.39E-06 | 1.45E-06 | **9.24E-05** |

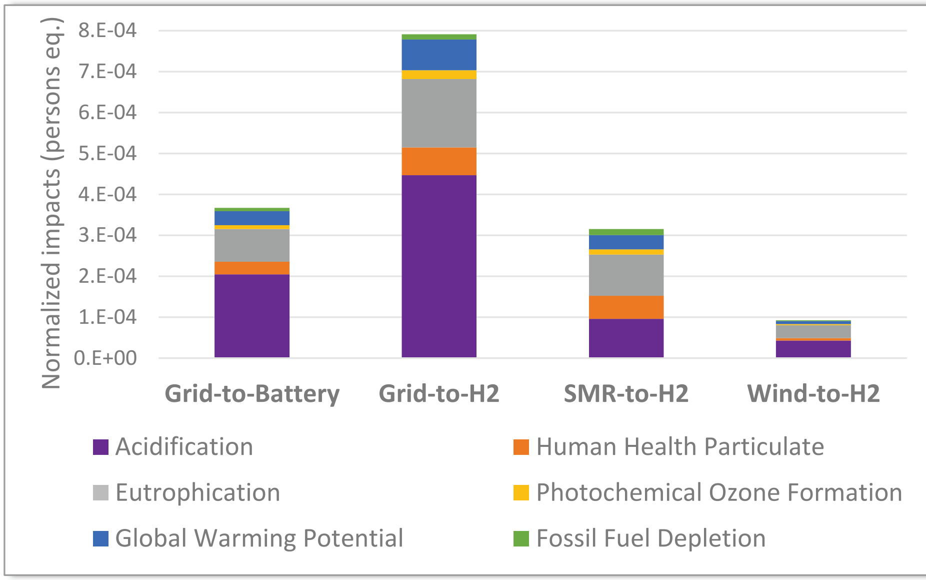


***Fig. 4.*** *Stacked Column Representation of the Normalized Emissions per Pathway*

5. Recommendations and Conclusions

### *5.1 Data Description*

For the analysis, this study compared the following fuel pathway scenarios: steam reforming of natural gas to hydrogen (SMR-to-H2); electricity from the average Mexico grid to hydrogen (Grid-to-H2); electricity from wind power to hydrogen (Wind-to-H2); and electricity from the average Mexico grid to battery (Grid-to-Battery). The decision of leaving out of the study ICE-powered forklifts comes from the fact that they cannot be used indoors because of emissions at point of use, so they do not directly compete with either battery or fuel cell technologies. Furthermore, all forklift class sizes that have been used for fuel cell technology thus far are those that were originally powered by lead-acid batteries.

Aside from otherwise specified, the study used the default values provided in GREET[8] (for simplification purposes or due to lack of more specific data on Mexico's energy supply chains).

Mexico's Data and Assumptions:

- Average transmission and distribution (T&D) loss factor = 10% (CFE, 2016).
- Mexico's average electric matrix of actual production in 2015, shown in Table 3 (SENER, 2016):

***Table 3.*** *Mexico's Average Electric Mix 2015*

| Technology | Share of Total |
|---|---|
| **Natural Gas Combined Cycle** | 50 |
| **Thermoelectric (steam turbine)** | 12.7 |
| **Coal** | 10 |
| **Hydro** | 10 |
| **Single Cycle Gas Turbine** | 3.8 |
| **Nuclear** | 3.7 |
| **Wind** | 2.8 |
| **Geothermal, Solar, and Distributed Gen** | 2.1 |
| **Bioenergy and Bio-waste** | 1.7 |

- 2015 Natural Gas Technology Shares:
    - NGCC (Natural Gas Combined Cycle) = 75%
    - Steam Turbine = 19%

[8] To read more on the GREET model refer to the program's manual: https://greet.es.anl.gov/greet/documentation.html

- Simple Cycle = 6%

- 2015 Sources of Natural Gas: Mexico imports approximately 20% of its natural gas yearly demand from the United States, and produces the other 80% domestically. Furthermore, GREET.net uses, for the U.S. average electric mix, a specific averaged natural gas production from both conventional and shale gas. For Mexico's source of natural gas, this paper assumed that same U.S. average for the 20% of imported fuel, and the 80% of domestic production as coming from conventional natural gas, as shale production is still in its infancy in Mexico.
- H2 Compression: GREET.net assumes compression pressure at 413.7 bars, which is reasonable for forklift trucks.
- Technology Efficiency (Tab. 4).

***Table 4.*** *Efficiency of Power System by Technology*

| **PEM Fuel Cells** | **Lead-Acid Batteries** |
|---|---|
| LHV of H2 = 33.3 Kwh/kg | Battery Efficiency = 76% |
| Power Train Efficiency = 45% | Charger Efficiency = 84% |
| Projected Efficiency = 56% | Projected Powertrain Efficiency = 64% |

- According to research performed by the Elgowainy paper (2009) referenced earlier, this study assumed that 1 kg of hydrogen on the fuel-cell forklift is equivalent to 15 kWh at the wheels of the battery- electric forklift. Given the projected powertrain efficiency of the battery, this means that 1 kg of hydrogen on the fuel-cell unit would require 24 kWh from the wall to power an equivalent battery-powered forklift.[9]

- The analysis assumed the functional unit as per 1 kWh provided at the wheels:
    - For the battery-powered forklift, if 24 kWh are needed from the wall to get 15 kWh at the wheels, then 1.6 kWh are needed from the grid to get 1 kWh at the wheels.
    - For the fuel cell forklift, if hydrogen has a LHV of 33.3 kWh per kg, then 2.2 kWh of hydrogen are needed in order to get 1 kWh at the wheels.
    - This means that this paper will compare the impact of producing 1.6 kWh of electricity from the average grid in Mexico vs the impact of producing 2.2 kWh of hydrogen (which both produce the same 1 kWh at the fork).
    - Likewise, as the GREET model provides results in a kJ per MJ basis, the conversion factors to convert them to kJ per kWh are the following:
        - Battery-powered forklift: 1 MJ = 0.278 kWh → 1/0.278 *1.6kWh = 5.76
        - Fuel-cell powered forklift: 1 MJ = 0.278 kWh → 1/0.278 *2.2kWh = 7.9

### *5.2 Flow Models for Hydrogen Production Pathways*

The system boundaries of the studied pathways are shown in figures 5 to 7.

[9] The study also assumed that the amount of hydrogen that substituted for a kWh of electricity was the same regardless of the class size of the forklift (Elgowainy, 2009).

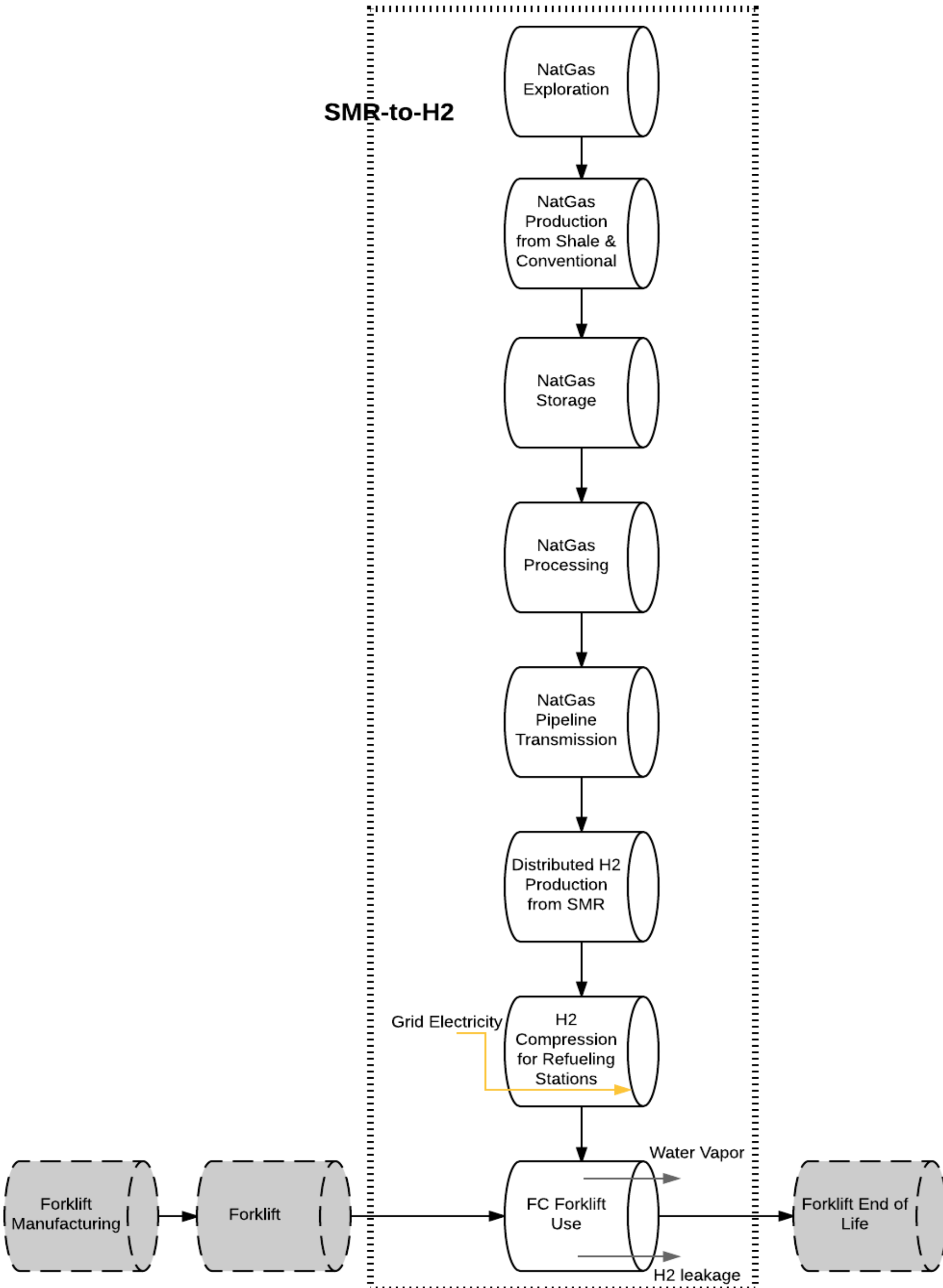


***Fig. 5.*** *Flow Model for Steam Methane Reforming to Hydrogen Pathway*

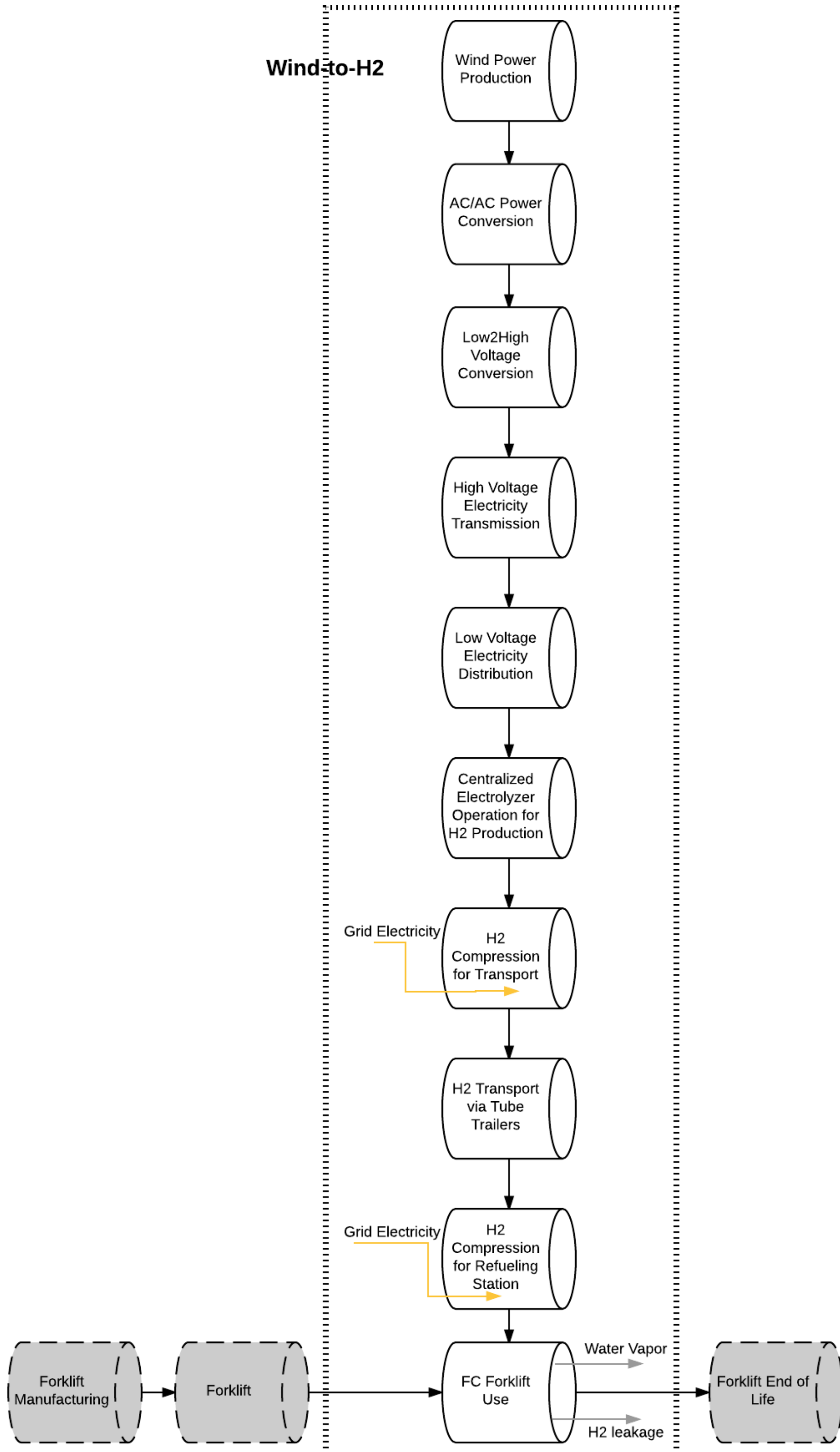


***Fig. 6.*** *Flow Model for Wind Power to Hydrogen Pathway*

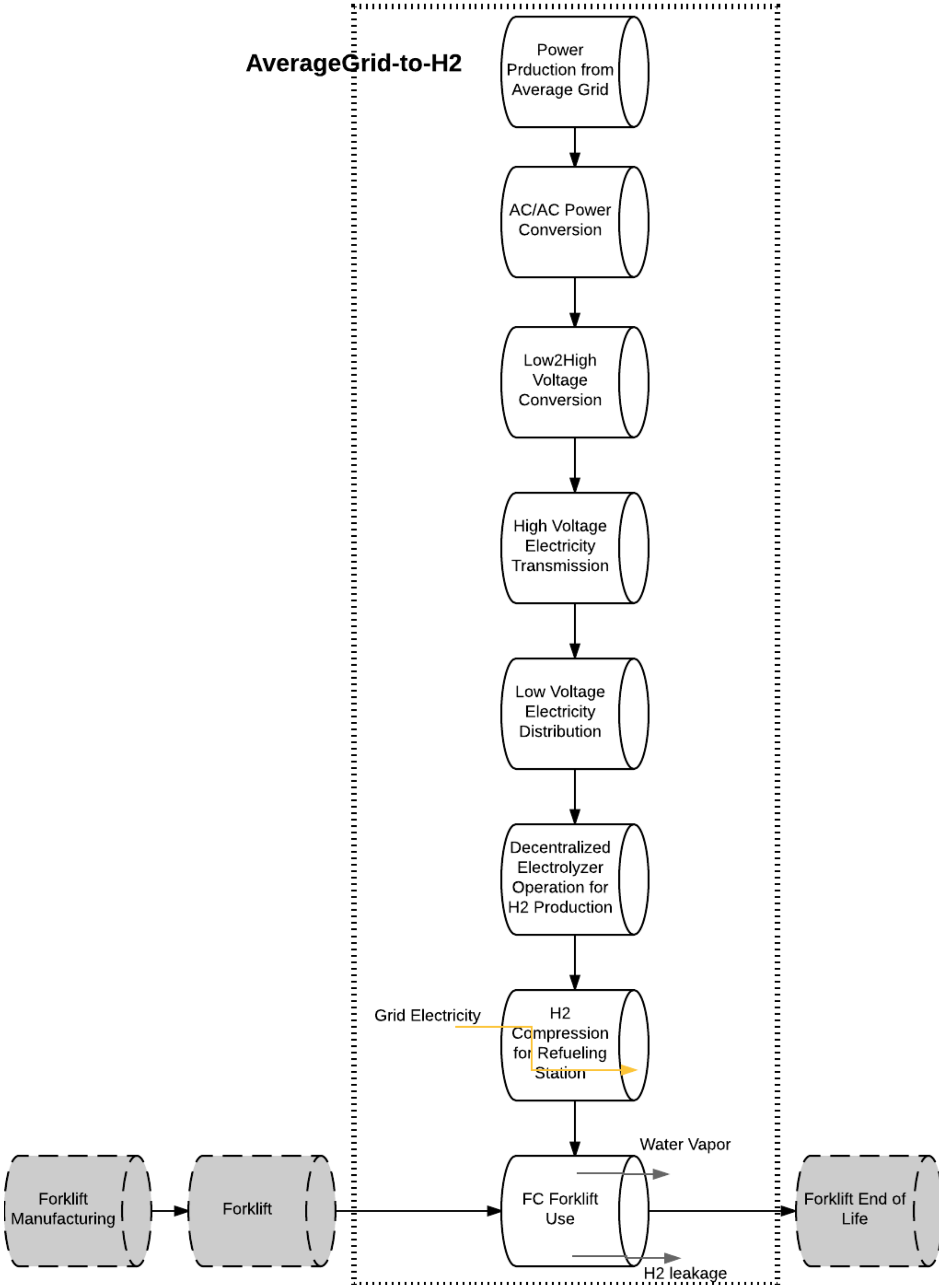


***Fig. 7.*** *Flow Model for Average Grid Electricity to Hydrogen Pathway*

The following assumptions have been made for the studied fuel pathways:

- Electricity for hydrogen compression and for the battery-powered forklifts comes from the average electricity mix.
- Hydrogen compression uses about 10% of the lower heating value of hydrogen.
- The pathway for the electric forklift is the same as the Grid-to-H2 scenario, but jumps straight from low-voltage electricity distribution to forklift use.
- The only emissions at point of use are water vapor and hydrogen leakage.
- In all hydrogen pathways, the most energy-intensive step is hydrogen production.
- The vehicle cycle (from manufacturing of the components to dismantling and recycling), was not considered, as the study assumes that the same forklift would be used regardless of the power system—which seems to be the case in general.
- According to a study by the National Argonne Laboratory (Elgowainy 2016) on a Cradle-to-Grave LCA of light-duty vehicle-fuel pathways, the contribution of the vehicle cycle is of about 10-22% of the total GHG emissions and energy use (of the cradle to grave fuel plus vehicle cycles). Furthermore, the study found that from the vehicle's cycle impacts, the power system impact contribution is of about 1-8%. This implies that the impacts from the components and manufacturing of the fuel cell stack and the lead-acid battery are an order of magnitude smaller than the fuel life-cycle impacts. It is important to underline, however, that even though this analysis did not take them into consideration, it could prove relevant to do so in further research.

- Everything outside of the dotted box falls out of the system boundaries.[10]

## 6. Results

Results include the entire fuel-cycle impacts – from initial recovery of primary energy, conversion to the fuel used by the forklift, and the efficiency of the forklift's technology. In general, the Grid-to-H2 pathway has the largest environmental impact in most categories, Wind-to-H2 the least, and both Grid-to-Battery and SMR-to-H2 pathways show comparable results.

Figure 8 shows total energy consumption and total fossil fuel consumption per kWh supplied to the wheels. Wind-to-H2 uses the least amount of fossil fuels by and large, as well as the least amount of energy overall—yet the latter is only slightly lower than the SMR pathway. The reason for this is that, on the one hand, centralized H2 production on the Wind-to-H2 pathway means hydrogen must be transported by truck to the point of use (only pathway that includes such a step, and can be seen (data in the Appendix) that it is the pathway with highest use of petroleum), and on the other hand it also means that hydrogen needs to be compressed twice (first for transportation via tube trailer and again for storage in refueling stations for forklift supply). The Grid-to-H2 pathway uses the highest amount of energy and fossil fuel, since it uses the average electric mix of the country for initial power production, for production of hydrogen through electrolysis, and once more for $H_2$ compression. On the other hand, the SMR-to-H2 and the Grid-to-

[10] The system boundary determines which unit processes are and are not included in the LCA.

Battery pathways are similar in both categories, the former using slightly higher amounts for both categories.

It is important to note that, when talking about steam methane reduction for hydrogen production—today the most commercially viable option—it uses more energy than the battery pathway when looking at it on a kJ per kWh at the wheels basis (well-to-wheels analysis). However, this changes when looked at on a kJ per MJ of fuel provided basis (well-to-pump analysis), as shown by Figure 9. This implies that distributed hydrogen production through natural gas reforming is potentially more efficient to power MHE than an electric-based technology, yet the actual PEM fuel cell is less efficient than the battery itself. Were PEMFC to become more efficient, something entirely possible as this technology is currently much less mature than lead-acid batteries, it could potentially lead to a more efficient pathway on a WTW basis overall.

Figure 10 compares the Global Warming Potential (GWP) of each pathway and shows that SMR-to-H2 and Grid-to-Battery contribute almost equally to global warming; Grid-to-H2 contributes more than double than the former two, and; Wind-to-H2 impact's on global warming is minimal. Figure 11 compares the Fossil Fuel Depletion Potential,[11] and, as expected, the SMR-to-H2 pathway presents the highest potential given the nature of the process, followed by Grid-to-H2 and Grid-to-Battery, and Wind-to-H2 is an order of magnitude smaller. Likewise, emissions of particulate matter (of diameter of

[11] Includes natural gas, crude oil, and coal.

2.5 µm or less) are noticeably higher for the SMR pathway than for the battery one, as shown by figure 12.

Results for the rest of the impact categories are shown by figures 13 through 16, and the life-cycle inventory of energy use and emissions for each scenario are found in detail in the Appendix.

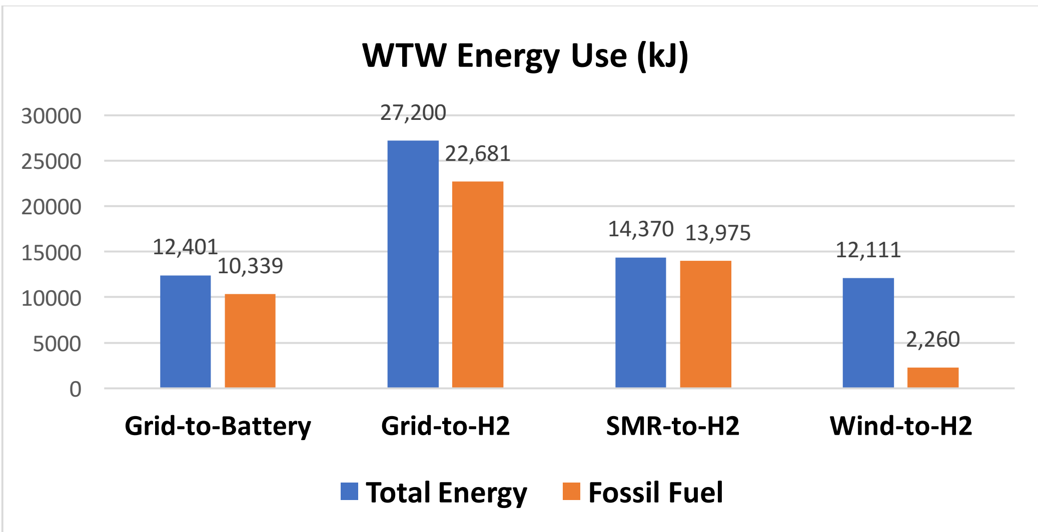


***Figure 8.*** *Total Energy Consumption and Total Fossil Fuel Consumption, by Fuel Pathway, in kJ per kWh Supplied at the Wheel (Well-to-Wheels)*

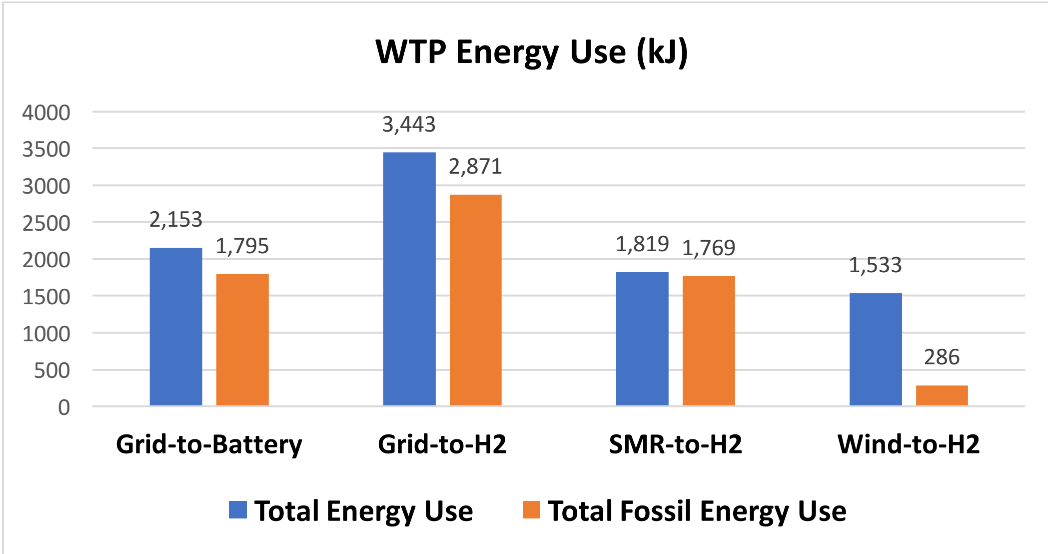


***Figure 9.*** *Total Energy Consumption and Total Fossil Fuel Consumption, by Fuel Pathway, in kJ per MJ of Fuel Provided (Well-to-Pump)*

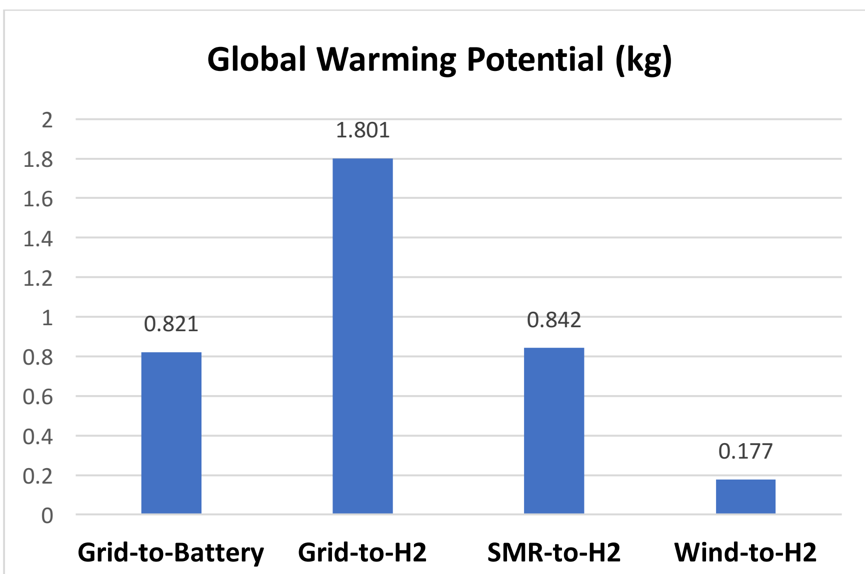


***Figure 10.*** *Global Warming Potential of Each Pathway in kg of $CO_2$ equivalent*

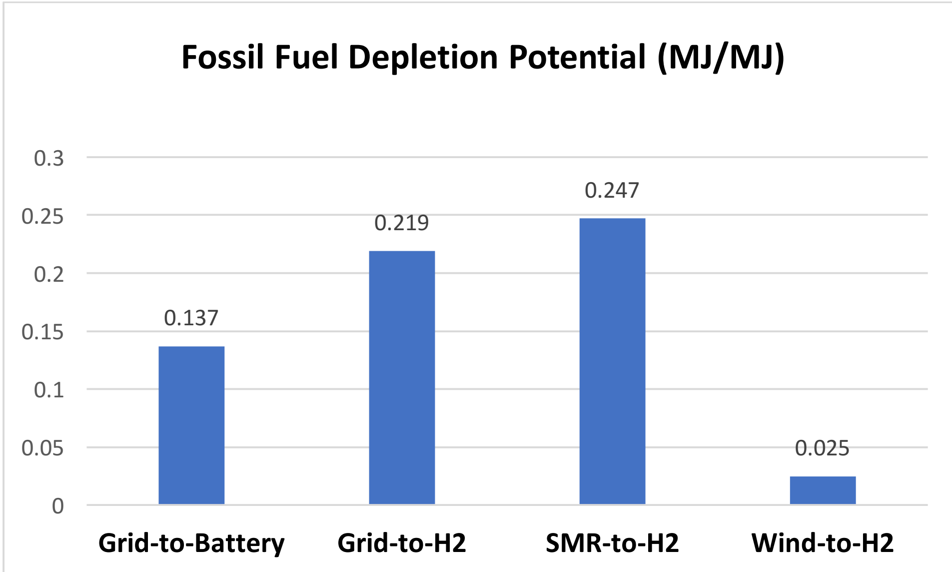


***Figure 11.*** *Fossil Fuel Depletion Potential of Each Pathway in MJ of Fossil Fuel per MJ of Fuel Provided*

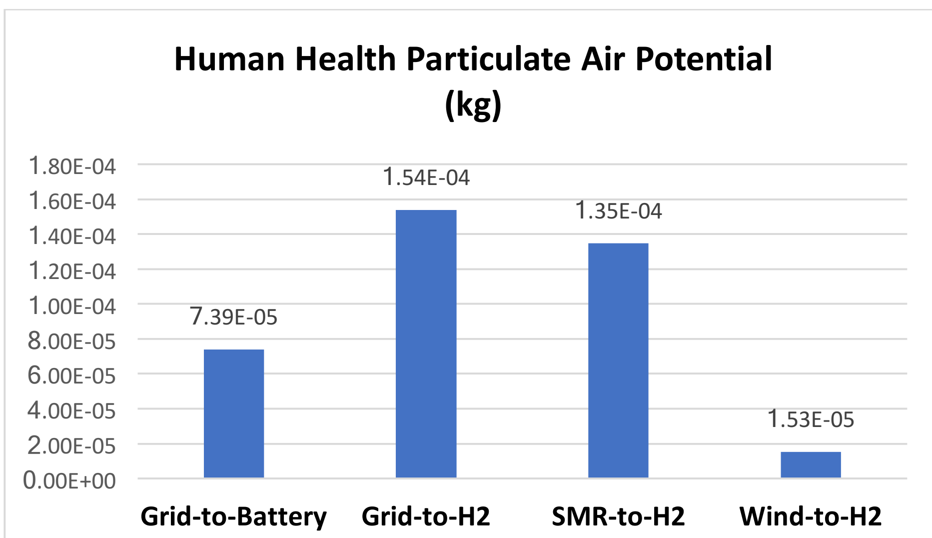


***Figure 12.*** *Human Health Particulate Air Potential of Each Pathway in kg of Particulate Matter$_{2.5}$ equivalent*

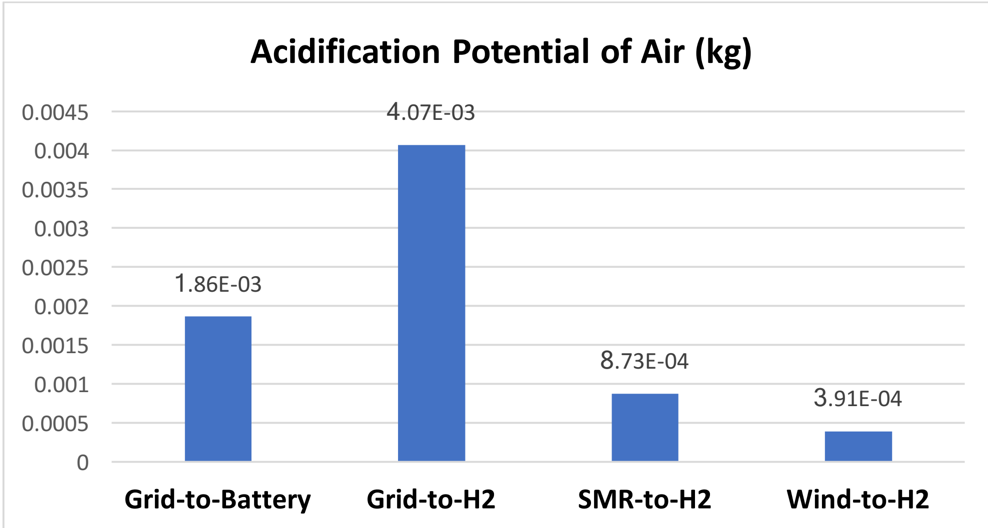


***Figure 13.*** *Acidification Potential of Air of Each Pathway in kg of SO2 equivalent*

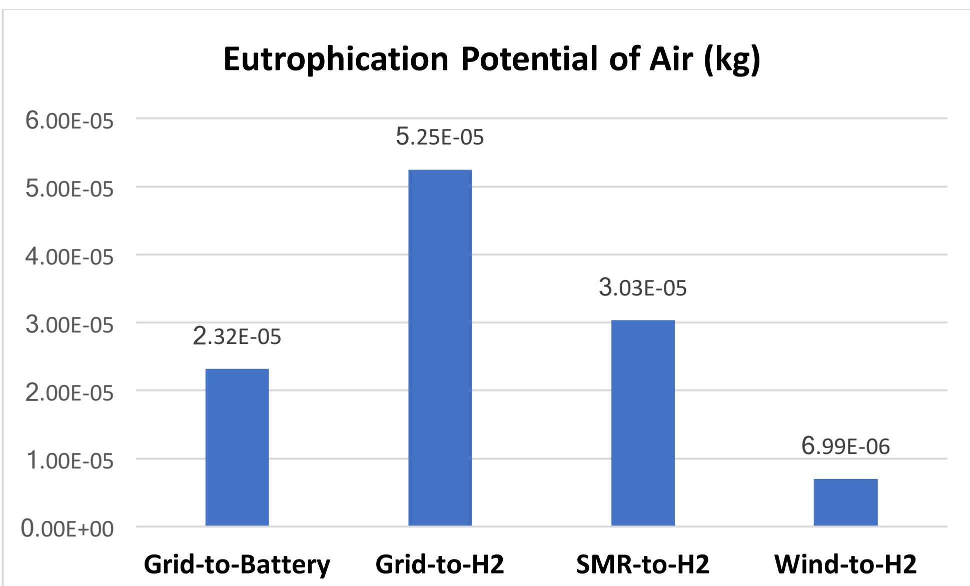


***Figure 14.*** *Eutrophication Potential of Air of Each Pathway in kg of N equivalent*

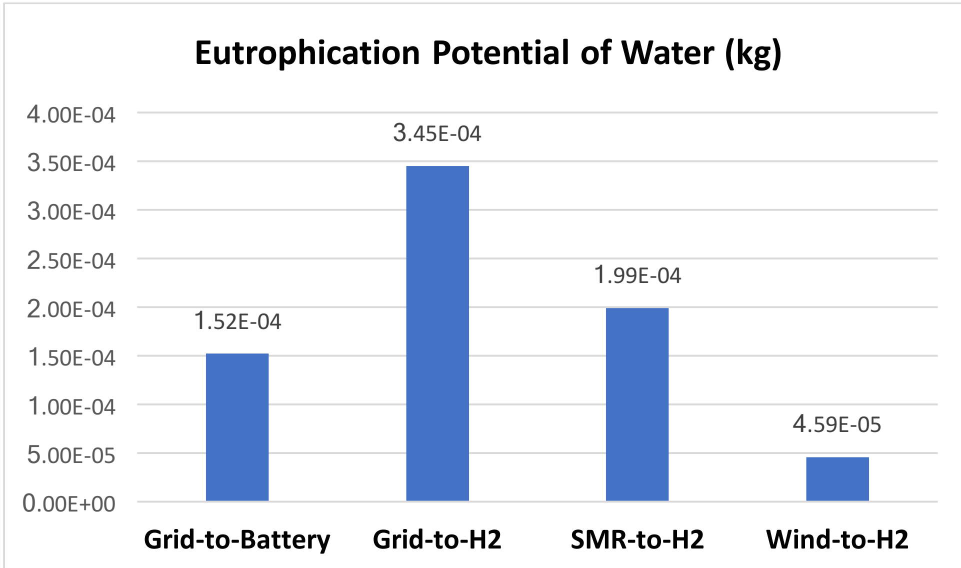


***Figure 15.*** *Eutrophication Potential of Water of Each Pathway in kg of N equivalent*

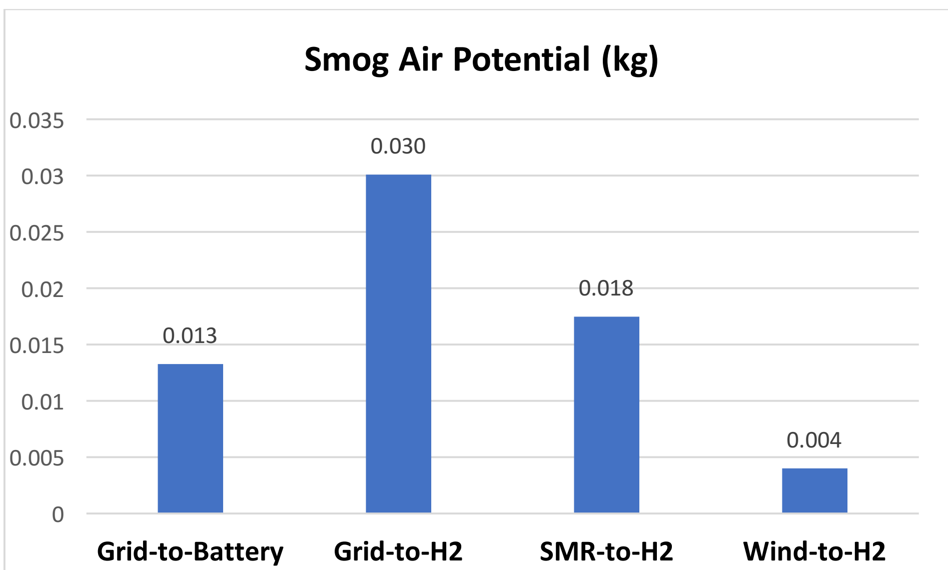


***Figure 16.*** *Smog Air Potential of Each Pathway in kg of O3 equivalent*

## 7. Analysis, Conclusions, and Recommendations

All impact categories show large reductions when using wind power for hydrogen production through electrolysis. Furthermore, centralized hydrogen production allows for economies-of-scale benefits that could in the long run bring large cost reductions. However, in Mexico, wind farms are usually located far away from large urban centers where the refueling stations are likely to be located. This could pose logistical challenges, in addition to currently high up-front costs of setting up this supply chain. On the other hand, producing hydrogen from the average electric mix would not bring any gains in changing the forklift fleet from batteries to fuel cells.

Given that de-centralized hydrogen production is already feasible through reforming of natural gas, this could be a potential substitute for battery-powered forklifts, particularly in a moment in time when Mexico is investing strongly in developing natural gas infrastructure for power production, capitalizing from historic-low natural gas prices. As the results show, this pathway could bring reductions in energy demand and pollution emissions if the PEMFC efficiency were to increase through technology improvements. Furthermore, it is important to consider that changing the fleet from battery to fuel cells could, in addition, bring reductions in costs for companies from factors such as lower refueling time, battery replacements, and space – as mentioned in detail earlier in the study. However, it is also important to note that Mexico is committed to increasing penetration of renewables to its grid as part of the energy sector’s overhaul. Engrained in its domestic legislation, as well as through the Paris

Agreements, Mexico has set the ambitious goal of producing 35% of its electricity through clean technologies by 2024. This could give an edge to the Grid-to-Battery pathway as the average electricity mix is decarbonized and renewables replace fossil fuels for power generation.

Lastly, it is worth emphasizing that this study was conducted as a preliminary assessment in the hypothesis of a fully elastic market, meaning that the dimension of the functional unit under scrutiny is not large enough to suffer the effects of market constraints or to be affected by the production capacity of the background system. In this sense, the study is still of an attributional LCA (ALCA) type and not of a consequential LCA (CLCA) type. The evaluation of market effects is beyond the scope of this study, yet performing the CLCA to seize the effects of an entire fleet change, for instance, in a general equilibrium model, is a potential avenue for further research that could prove relevant to the hypothesis of this paper (Frischknecht and Stucki, 2010 and Marvuglia et al., 2013). Along the same lines, assessing the environmental impacts of the lead-acid battery and PEMFC stacks on a cradle-to-grave analysis to include these in the LCA would also contribute with relevant insight to this study that could, potentially, give an indisputable edge to either the Grid-to-Battery or the SMR-to-H2 pathways (the two most scenarios contended in most categories).

## 8. Appendix

Life-Cycle Inventory (GREET.net)

| **Battery Forklift – Grid-to-Battery** | | | |
|---|---|---|---|
| **Concept** | **WTP** | **Operation Only** | **WTW** |
| Total Energy | 1153 kJ/MJ | 1000.00 kJ/MJ | 2153 kJ/MJ |
| Fossil Fuel | 1795 kJ/MJ | 0 J/MJ | 1795 kJ/MJ |
| Coal Fuel | 1025 kJ/MJ | 0 J/MJ | 1025 kJ/MJ |
| Natural Gas Fuel | 750.31 kJ/MJ | 0 J/MJ | 750.31 kJ/MJ |
| Petroleum Fuel | 19.69 kJ/MJ | 0 J/MJ | 19.69 kJ/MJ |
| Water_Reservoir Evaporation | 316.90 cm^3/MJ | | 316.90 cm^3/MJ |
| Water_Cooling | 315.98 cm^3/MJ | | 315.98 cm^3/MJ |
| Water_Mining | 24.82 cm^3/MJ | | 24.82 cm^3/MJ |
| Water_Process | 10.80 cm^3/MJ | | 10.80 cm^3/MJ |
| VOC | 15.33 mg/MJ | 0 g/MJ | 15.33 mg/MJ |
| CO | 43.17 mg/MJ | 0 g/MJ | 43.17 mg/MJ |
| NOx | 90.75 mg/MJ | 0 g/MJ | 90.75 mg/MJ |
| PM10 | 18.80 mg/MJ | 0 g/MJ | 18.80 mg/MJ |
| PM2.5 | 7.88 mg/MJ | 0 g/MJ | 7.88 mg/MJ |
| SOx | 0.26 g/MJ | 0 g/MJ | 0.26 g/MJ |
| CH4 | 0.31 g/MJ | 0 g/MJ | 0.31 g/MJ |
| CO2 | 141.82 g/MJ | 0 g/MJ | 141.82 g/MJ |
| N2O | 2.19 mg/MJ | 0 g/MJ | 2.19 mg/MJ |

| | | | |
|---|---|---|---|
| SO2 | 26.95 ng/MJ | | 26.95 ng/MJ |
| BC | 0.58 mg/MJ | 0 g/MJ | 0.58 mg/MJ |
| POC | 1.35 mg/MJ | 0 g/MJ | 1.35 mg/MJ |
| CO2_Biogenic | -0.35 g/MJ | 0 g/MJ | -0.35 g/MJ |
| GHG-100 | 151.35 g/MJ | 0 g/MJ | 151.35 g/MJ |
| VOC Urban | 1.09 mg/MJ | 0 g/MJ | 1.09 mg/MJ |
| CO Urban | 9.10 mg/MJ | 0 g/MJ | 9.10 mg/MJ |
| NOx Urban | 22.40 mg/MJ | 0 g/MJ | 22.40 mg/MJ |
| PM10 Urban | 3.60 mg/MJ | 0 g/MJ | 3.60 mg/MJ |
| PM2.5 Urban | 2.27 mg/MJ | 0 g/MJ | 2.27 mg/MJ |
| SOx Urban | 92.01 mg/MJ | 0 g/MJ | 92.01 mg/MJ |
| CH4 Urban | 2.83 mg/MJ | 0 g/MJ | 2.83 mg/MJ |
| CO2 Urban | 49.41 g/MJ | 0 g/MJ | 49.41 g/MJ |
| N2O Urban | 0.69 mg/MJ | 0 g/MJ | 0.69 mg/MJ |
| SO2 Urban | 0 g/MJ | | 0 g/MJ |
| BC Urban | 0.14 mg/MJ | 0 g/MJ | 0.14 mg/MJ |
| POC Urban | 0.35 mg/MJ | 0 g/MJ | 0.35 mg/MJ |
| CO2_Biogenic Urban | -0.08 g/MJ | 0 g/MJ | -0.08 g/MJ |
| BC_TBW | | 0.47 mg/MJ | 0.47 mg/MJ |
| POC_TBW | | 0.59 mg/MJ | 0.59 mg/MJ |
| PM10_TBW | | 12.99 mg/MJ | 12.99 mg/MJ |
| PM2.5_TBW | | 3.32 mg/MJ | 3.32 mg/MJ |

| | | | |
|---|---|---|---|
| VOC_evap | | 0 g/MJ | 0 g/MJ |
| BC_TBW Urban | | 0.33 mg/MJ | 0.33 mg/MJ |
| POC_TBW Urban | | 0.41 mg/MJ | 0.41 mg/MJ |
| PM10_TBW Urban | | 8.96 mg/MJ | 8.96 mg/MJ |
| PM2.5_TBW Urban | | 2.29 mg/MJ | 2.29 mg/MJ |
| VOC_evap Urban | | 0 g/MJ | 0 g/MJ |

## FC Forklift – AverageGrid-to-H2

| Concept | WTP | Operation Only | WTW |
|---|---|---|---|
| Total Energy | 2443 kJ/MJ | 1000.00 kJ/MJ | 3443 kJ/MJ |
| Fossil Fuel | 2871 kJ/MJ | 0 J/MJ | 2871 kJ/MJ |
| Coal Fuel | 1640 kJ/MJ | 0 J/MJ | 1640 kJ/MJ |
| Natural Gas Fuel | 1200 kJ/MJ | 0 J/MJ | 1200 kJ/MJ |
| Petroleum Fuel | 31.48 kJ/MJ | 0 J/MJ | 31.48 kJ/MJ |
| Water_Reservoir Evaporation | 506.78 cm^3/MJ | | 506.78 cm^3/MJ |
| Water_Cooling | 505.31 cm^3/MJ | | 505.31 cm^3/MJ |
| Water_Mining | 39.69 cm^3/MJ | | 39.69 cm^3/MJ |
| Water_Process | 269.14 cm^3/MJ | | 269.14 cm^3/MJ |
| VOC | 24.51 mg/MJ | 0 g/MJ | 24.51 mg/MJ |
| CO | 69.04 mg/MJ | 0 g/MJ | 69.04 mg/MJ |
| NOx | 0.15 g/MJ | 0 g/MJ | 0.15 g/MJ |
| PM10 | 30.06 mg/MJ | 0 g/MJ | 30.06 mg/MJ |
| PM2.5 | 12.61 mg/MJ | 0 g/MJ | 12.61 mg/MJ |
| SOx | 0.41 g/MJ | 0 g/MJ | 0.41 g/MJ |
| CH4 | 0.49 g/MJ | 0 g/MJ | 0.49 g/MJ |
| CO2 | 226.79 g/MJ | 0 g/MJ | 226.79 g/MJ |
| N2O | 3.51 mg/MJ | 0 g/MJ | 3.51 mg/MJ |
| SO2 | 43.10 ng/MJ | | 43.10 ng/MJ |
| BC | 0.93 mg/MJ | 0 g/MJ | 0.93 mg/MJ |

| | | | |
|---|---|---|---|
| POC | 2.16 mg/MJ | 0 g/MJ | 2.16 mg/MJ |
| CO2_Biogenic | -0.57 g/MJ | 0 g/MJ | -0.57 g/MJ |
| GHG-100 | 242.04 g/MJ | 0 g/MJ | 242.04 g/MJ |
| VOC Urban | 1.74 mg/MJ | 0 g/MJ | 1.74 mg/MJ |
| CO Urban | 14.55 mg/MJ | 0 g/MJ | 14.55 mg/MJ |
| NOx Urban | 35.82 mg/MJ | 0 g/MJ | 35.82 mg/MJ |
| PM10 Urban | 5.76 mg/MJ | 0 g/MJ | 5.76 mg/MJ |
| PM2.5 Urban | 3.63 mg/MJ | 0 g/MJ | 3.63 mg/MJ |
| SOx Urban | 0.15 g/MJ | 0 g/MJ | 0.15 g/MJ |
| CH4 Urban | 4.53 mg/MJ | 0 g/MJ | 4.53 mg/MJ |
| CO2 Urban | 79.01 g/MJ | 0 g/MJ | 79.01 g/MJ |
| N2O Urban | 1.10 mg/MJ | 0 g/MJ | 1.10 mg/MJ |
| SO2 Urban | 0 g/MJ | | 0 g/MJ |
| BC Urban | 0.22 mg/MJ | 0 g/MJ | 0.22 mg/MJ |
| POC Urban | 0.56 mg/MJ | 0 g/MJ | 0.56 mg/MJ |
| CO2_Biogenic Urban | -0.13 g/MJ | 0 g/MJ | -0.13 g/MJ |
| BC_TBW | | 0.30 mg/MJ | 0.30 mg/MJ |
| POC_TBW | | 0.38 mg/MJ | 0.38 mg/MJ |
| PM10_TBW | | 8.22 mg/MJ | 8.22 mg/MJ |
| PM2.5_TBW | | 2.10 mg/MJ | 2.10 mg/MJ |
| VOC_evap | | 0 g/MJ | 0 g/MJ |
| BC_TBW Urban | | 0.21 mg/MJ | 0.21 mg/MJ |

| | | | |
|---|---|---|---|
| POC_TBW Urban | | 0.26 mg/MJ | 0.26 mg/MJ |
| PM10_TBW Urban | | 5.67 mg/MJ | 5.67 mg/MJ |
| PM2.5_TBW Urban | | 1.45 mg/MJ | 1.45 mg/MJ |
| VOC_evap Urban | | 0 g/MJ | 0 g/MJ |

## FC Forklift – SMR-to-H2

| Concept | WTP | Operation Only | WTW |
|---|---|---|---|
| Total Energy | 818.75 kJ/MJ | 1000.00 kJ/MJ | 1819 kJ/MJ |
| Fossil Fuel | 1769 kJ/MJ | 0 J/MJ | 1769 kJ/MJ |
| Coal Fuel | 141.48 kJ/MJ | 0 J/MJ | 141.48 kJ/MJ |
| Natural Gas Fuel | 1620 kJ/MJ | 0 J/MJ | 1620 kJ/MJ |
| Petroleum Fuel | 8345.16 J/MJ | 0 J/MJ | 8345.16 J/MJ |
| Water_Reservoir Evaporation | 43.72 cm^3/MJ | | 43.72 cm^3/MJ |
| Water_Cooling | 43.60 cm^3/MJ | | 43.60 cm^3/MJ |
| Water_Mining | 9.50 cm^3/MJ | | 9.50 cm^3/MJ |
| Water_Process | 89.20 cm^3/MJ | | 89.20 cm^3/MJ |
| VOC | 18.10 mg/MJ | 0 g/MJ | 18.10 mg/MJ |
| CO | 61.88 mg/MJ | 0 g/MJ | 61.88 mg/MJ |
| NOx | 86.59 mg/MJ | 0 g/MJ | 86.59 mg/MJ |
| PM10 | 14.63 mg/MJ | 0 g/MJ | 14.63 mg/MJ |
| PM2.5 | 13.08 mg/MJ | 0 g/MJ | 13.08 mg/MJ |
| SOx | 49.88 mg/MJ | 0 g/MJ | 49.88 mg/MJ |
| CH4 | 0.45 g/MJ | 0 g/MJ | 0.45 g/MJ |
| CO2 | 105.75 g/MJ | 0 g/MJ | 105.75 g/MJ |
| N2O | 2.37 mg/MJ | 0 g/MJ | 2.37 mg/MJ |
| SO2 | 3.72 ng/MJ | | 3.72 ng/MJ |
| BC | 0.34 mg/MJ | 0 g/MJ | 0.34 mg/MJ |

| | | | |
|---|---|---|---|
| POC | 0.54 mg/MJ | 0 g/MJ | 0.54 mg/MJ |
| CO2_Biogenic | -0.05 g/MJ | 0 g/MJ | -0.05 g/MJ |
| GHG-100 | 119.96 g/MJ | 0 g/MJ | 119.96 g/MJ |
| VOC Urban | 2.41 mg/MJ | 0 g/MJ | 2.41 mg/MJ |
| CO Urban | 13.31 mg/MJ | 0 g/MJ | 13.31 mg/MJ |
| NOx Urban | 20.87 mg/MJ | 0 g/MJ | 20.87 mg/MJ |
| PM10 Urban | 8.50 mg/MJ | 0 g/MJ | 8.50 mg/MJ |
| PM2.5 Urban | 8.32 mg/MJ | 0 g/MJ | 8.32 mg/MJ |
| SOx Urban | 12.90 mg/MJ | 0 g/MJ | 12.90 mg/MJ |
| CH4 Urban | 6.22 mg/MJ | 0 g/MJ | 6.22 mg/MJ |
| CO2 Urban | 61.45 g/MJ | 0 g/MJ | 61.45 g/MJ |
| N2O Urban | 0.40 mg/MJ | 0 g/MJ | 0.40 mg/MJ |
| SO2 Urban | 0 g/MJ | | 0 g/MJ |
| BC Urban | 63.81 ug/MJ | 0 g/MJ | 63.81 ug/MJ |
| POC Urban | 0.16 mg/MJ | 0 g/MJ | 0.16 mg/MJ |
| CO2_Biogenic Urban | -0.01 g/MJ | 0 g/MJ | -0.01 g/MJ |
| BC_TBW | | 0.30 mg/MJ | 0.30 mg/MJ |
| POC_TBW | | 0.38 mg/MJ | 0.38 mg/MJ |
| PM10_TBW | | 8.22 mg/MJ | 8.22 mg/MJ |
| PM2.5_TBW | | 2.10 mg/MJ | 2.10 mg/MJ |
| VOC_evap | | 0 g/MJ | 0 g/MJ |
| BC_TBW Urban | | 0.21 mg/MJ | 0.21 mg/MJ |

| | | | |
|---|---|---|---|
| POC_TBW Urban | | 0.26 mg/MJ | 0.26 mg/MJ |
| PM10_TBW Urban | | 5.67 mg/MJ | 5.67 mg/MJ |
| PM2.5_TBW Urban | | 1.45 mg/MJ | 1.45 mg/MJ |
| VOC_evap Urban | | 0 g/MJ | 0 g/MJ |

**FC Forklift – Wind-to-H2**

| Concept | WTP | Operation Only | WTW |
|---|---|---|---|
| Total Energy | 532.77 kJ/MJ | 1000.00 kJ/MJ | 1533 kJ/MJ |
| Fossil Fuel | 286.12 kJ/MJ | 0 J/MJ | 286.12 kJ/MJ |
| Coal Fuel | 139.27 kJ/MJ | 0 J/MJ | 139.27 kJ/MJ |
| Natural Gas Fuel | 106.37 kJ/MJ | 0 J/MJ | 106.37 kJ/MJ |
| Petroleum Fuel | 40.48 kJ/MJ | 0 J/MJ | 40.48 kJ/MJ |
| Water_Reservoir Evaporation | 43.04 cm^3/MJ | | 43.04 cm^3/MJ |
| Water_Cooling | 42.99 cm^3/MJ | | 42.99 cm^3/MJ |
| Water_Mining | 5.56 cm^3/MJ | | 5.56 cm^3/MJ |
| Water_Process | 182.51 cm^3/MJ | | 182.51 cm^3/MJ |
| VOC | 2.91 mg/MJ | 0 g/MJ | 2.91 mg/MJ |
| CO | 8.63 mg/MJ | 0 g/MJ | 8.63 mg/MJ |
| NOx | 19.97 mg/MJ | 0 g/MJ | 19.97 mg/MJ |
| PM10 | 2.67 mg/MJ | 0 g/MJ | 2.67 mg/MJ |
| PM2.5 | 1.18 mg/MJ | 0 g/MJ | 1.18 mg/MJ |
| SOx | 35.49 mg/MJ | 0 g/MJ | 35.49 mg/MJ |
| CH4 | 48.06 mg/MJ | 0 g/MJ | 48.06 mg/MJ |
| CO2 | 22.33 g/MJ | 0 g/MJ | 22.33 g/MJ |
| N2O | 0.31 mg/MJ | 0 g/MJ | 0.31 mg/MJ |
| SO2 | 3.66 ng/MJ | | 3.66 ng/MJ |
| BC | 95.77 ug/MJ | 0 g/MJ | 95.77 ug/MJ |

| | | | |
|---|---|---|---|
| POC | 0.23 mg/MJ | 0 g/MJ | 0.23 mg/MJ |
| CO2_Biogenic | -0.05 g/MJ | 0 g/MJ | -0.05 g/MJ |
| GHG-100 | 23.82 g/MJ | 0 g/MJ | 23.82 g/MJ |
| VOC Urban | 0.63 mg/MJ | 0 g/MJ | 0.63 mg/MJ |
| CO Urban | 2.88 mg/MJ | 0 g/MJ | 2.88 mg/MJ |
| NOx Urban | 7.54 mg/MJ | 0 g/MJ | 7.54 mg/MJ |
| PM10 Urban | 0.54 mg/MJ | 0 g/MJ | 0.54 mg/MJ |
| PM2.5 Urban | 0.35 mg/MJ | 0 g/MJ | 0.35 mg/MJ |
| SOx Urban | 12.75 mg/MJ | 0 g/MJ | 12.75 mg/MJ |
| CH4 Urban | 0.96 mg/MJ | 0 g/MJ | 0.96 mg/MJ |
| CO2 Urban | 8.65 g/MJ | 0 g/MJ | 8.65 g/MJ |
| N2O Urban | 97.10 ug/MJ | 0 g/MJ | 97.10 ug/MJ |
| SO2 Urban | 0 g/MJ | | 0 g/MJ |
| BC Urban | 24.89 ug/MJ | 0 g/MJ | 24.89 ug/MJ |
| POC Urban | 71.19 ug/MJ | 0 g/MJ | 71.19 ug/MJ |
| CO2_Biogenic Urban | -0.01 g/MJ | 0 g/MJ | -0.01 g/MJ |
| BC_TBW | | 0.30 mg/MJ | 0.30 mg/MJ |
| POC_TBW | | 0.38 mg/MJ | 0.38 mg/MJ |
| PM10_TBW | | 8.22 mg/MJ | 8.22 mg/MJ |
| PM2.5_TBW | | 2.10 mg/MJ | 2.10 mg/MJ |
| VOC_evap | | 0 g/MJ | 0 g/MJ |
| BC_TBW Urban | | 0.21 mg/MJ | 0.21 mg/MJ |

| | | | |
|---|---|---|---|
| POC_TBW Urban | | 0.26 mg/MJ | 0.26 mg/MJ |
| PM10_TBW Urban | | 5.67 mg/MJ | 5.67 mg/MJ |
| PM2.5_TBW Urban | | 1.45 mg/MJ | 1.45 mg/MJ |
| VOC_evap Urban | | 0 g/MJ | 0 g/MJ |

| Impact Category | Normalization Factor (impact per person per year) |
|---|---|
| Global Warming (kg $CO_2$ eq) | 24000 |
| Acidification (kg $SO_2$ eq) | 9.1 |
| Human Health Particulate Air (PM2.5 eq) | 2.4 |
| Eutrophication (kg N eq) | 2.2 |
| Smog (Photochemical Ozone Formation) (kg $O_3$ eq) | 1400 |
| Fossil Fuel Depletion (MJ surplus) | 17000 |

***Figure A1.*** *Normalization Factors for TRACI's Impact Categories (Ryberg, 2013)*

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## 10. Curriculum Vitae

Tania Miranda studied a Bachelor of Arts in Economics with a Minor in International Policy and Management at the University of Southern California, where she graduated Magna Cum Laude. She worked for a year as Deputy Trade and Investment Commissioner at ProMexico (Los Angeles), where she assisted American companies exporting and investing in Mexico through government relations, market analysis, and due diligence. Later on, she worked as an analyst at the Embassy of Mexico in Washington D.C., at the Consular Section, where she was in charge of accounting reports. A year after, she began her Masters of Science in Energy Policy at the Johns Hopkins University as a full-time student. During her last semester, she also interned at Manatt Jones Global Strategies—consulting firm that specializes in providing American businesses with advice and stakeholder engagement support to drive market entry and business expansion efforts in Latin America. She moved back to Mexico City after completion of her Masters to work for the Foreign Ministry as the Director of Economic Affairs and Financial Education.