COMILLAS
UNIVERSIDAD PONTIFICIA
ICAI

# GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

# COMPARATIVE ASSESSMENT OF WELL-TO-WHEELS EFFICIENCY AND EMISSIONS OF *EV*S AND *FCV*S

Autor: Jorge Soldevilla Artajona

Director: George Gross

Madrid

Junio 2022

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

COMPARATIVE ASSESSMENT OF WELL-TO-WHEELS EFFICIENCY AND EMISSIONS OF *EV*S AND *FCV*S

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Fdo.: Jorge Soldevilla Artajona Fecha: 06/06/2022

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: George Gross Fecha: 06/06/2022

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Director: Gross, George.

Entidad Colaboradora: University of Illinois at Urbana-Champaign.

## RESUMEN EJECUTIVO DEL PROYECTO

El sector del transporte en *EE.UU.* representa el sector con más emisiones de gases de efecto de invernadero (*GEI*), produce un 31 *%* de las emisiones totales y genera más emisiones que los sectores de la electricidad, industria y edificios domésticos [1]. Estas emisiones proceden de la quema de combustibles fósiles, principalmente derivados del petróleo, como la gasolina o el diésel, para vehículos ligeros, camiones medianos y pesados [2]. En esta tesis, evaluamos la actuación de dos clases de vehículos cero emisiones en términos de eficiencia e impactos económicos y medioambientales. Para concretar nuestros resultados, realizamos nuestro análisis comparativo en función del vehículo eléctrico seleccionado -*Tesla Modelo* 3 *LR* y del vehículo de pila de combustible seleccionado -*Toyota Mirai XLE*.

**Palabras clave:** Vehículo eléctrico, vehículo de pila de combustible, emisiones de *GEI*

## 1. Introducción

El 60 *%* de las emisiones de *GEI* del sector del transporte en *EE.UU.* provienen de los vehículos ligeros [3]. En este sentido, es necesario implementar en gran escala una alternativa a los vehículos ligeros con motor de combustión interna altamente contaminantes.

El vehículo eléctrico tiene un motor eléctrico alimentado por una batería recargable localizada dentro del vehículo, y por ello, se necesita electricidad para cargar la batería. Al contrario que los coches alimentados por combustibles de diésel o gasolina que emiten emisiones de *GEI* por el tubo de escape debido a la combustión del combustible, los vehículos eléctricos no liberan estas emisiones. Sin embargo, hay emisiones de *GEI* producidas durante la generación de la electricidad necesaria para cargar la batería del vehículo eléctrico.

El vehículo de pila combustible es alimentado por $H_2$ y no libera emisiones por el tubo de escape. El vehículo de pila de combustible usa un sistema de propulsión donde la energía almacenada en forma de $H_2$ es convertida en electricidad por la pila de combustible. El problema del $H_2$ es que no se encuentra como molécula de $H_2$, sino formando compuestos con otros elementos de la tabla periódica. El $H_2$ puede ser producido por múltiples métodos, pero actualmente la producción está dominada por el reformado de metano con vapor y la gasificación del carbón. Ambos procesos de producción emiten gran cantidad de emisiones pero pueden ser descarbonizados si se combinan con la captura, utilización y almacenamiento del carbono. Por otra parte, las principales métodos de producción de $H_2$ con bajas emisiones de carbono son la gasificación de la biomasa y la electrolisis que utiliza energía solar, eólica o nuclear para la generación de electricidad. Según la convención de los medios de comunicación y la mayoría de los informes de la industria. Cabe destacar que se utiliza un código de colores de $H_2$ para indicar el nivel de emisiones asociado a cada método de producción de $H_2$.

Entre las mejoras del vehículo de pila de combustible respecto al vehículo eléctrico destacan una mejor autonomía y un menor tiempo de repostaje. Sin embargo, el coste de llenar el depósito de $H_2$ del vehículo de pila de combustible es mucho mayor.

## 2. Definición del proyecto

Esta tesis se centra en la actuación de dos específicas clases de vehículos cero emisiones, vehículos eléctricos y de pila de combustible, en términos de eficiencia e impactos económicos y medioambientales. *Well-to-wheels (w-t-w), "pozo a las ruedas"* es una estructura que fue originalmente introducida para evaluar la eficiencia de los vehículos con motor de combustión interna. El proceso del *w-t-w* implica una secuencia de subprocesos, cada uno de los cuales incurre en una pérdida de energía y, en consecuencia, repercute en la eficiencia global del proceso. Este proceso es aplicado con pequeñas modificaciones para evaluar la eficiencia de los vehículos eléctricos y de pila de combustible.

El proceso *w-t-w* del vehículo eléctrico puede descomponerse en dos componentes: subsistema *well-to-charger*, "*mina al cargador*" y subsistema *charger-to-wheels*, "*cargador a las ruedas*".

En este sentido, el subsistema *mina al cargador* comienza en la mina y su conversión energética para generar electricidad. Posteriormente, la electricidad se transmite a la red que suministra electricidad al cargador del vehículo eléctrico. Al final, el cargador del vehículo eléctrico alimenta la batería, la cual a su vez, alimenta el motor eléctrico que mueve las ruedas del vehículo eléctrico.

Del mismo modo, el proceso *w-t-w* del vehículo de pila de combustible puede descomponerse en dos componentes: subsistema *well-to-tank*, "*mina al depósito*" y subsistema *tank-to-wheels*, "*depósito a las ruedas*". En este sentido, describimos en detalle la cadena de procesos desde la producción de $H_2$ hasta el depósito de almacenamiento del $H_2$ dentro vehículo de pila de combustible. Una vez que se produce el $H_2$, se comprime o se licua para ser transportado en camiones a la estación de repostaje. Posteriormente, cuando el $H_2$ llega a la estación de repostaje, el $H_2$ se somete a una serie de subprocesos, que dependen de la fase del $H_2$, para alcanzar los 700 *bares* y los -40 *ºC* antes de ser dispensado en el depósito de $H_2$ dentro del vehículo. La pila de combustible situada en el interior del vehículo de pila de combustible convierte el $H_2$ en electricidad y alimenta el motor eléctrico que mueve las ruedas del vehículo.

## 3. Eficiencia de los procesos *w-t-w* del vehículo eléctrico y de pila de combustible

Para concretar los resultados, estudiamos la eficiencia del proceso *w-t-w* del vehículo eléctrico en función de un vehículo eléctrico seleccionado-*Tesla Modelo* 3 *LR* y la generación de electricidad mediante una planta de gas natural de ciclo combinado. Este informe considera dos pérdidas principales en el camino desde la fuente de generación de electricidad hasta las ruedas del vehículo. La primera pérdida está asociada a la pérdida de energía durante la distribución y transmisión de la electricidad. El segundo componente de pérdida incluye las pérdidas que son exclusivas de un vehículo eléctrico y que tienen lugar desde la toma de corriente en la pared hasta las ruedas del vehículo eléctrico. Llegamos a la conclusión de que la eficiencia del proceso *w-t-w* del vehículo eléctrico es del 38,5 *%* en lo que respecta a un vehículo eléctrico seleccionado-*Tesla modelo* 3 *LR* y a la generación de electricidad mediante un ciclo combinado de gas natural.

Análogamente, para concretar los resultados estudiamos la eficiencia del proceso *w-t-w* del vehículo de pila de combustible en función de un vehículo de pila de combustible seleccionado-

*Toyota Mirai XLE* alimentado por $H_2$ producido por electrólisis que utiliza energía nuclear para la generación de electricidad y la entrega y distribución de $H_2$ en fase líquida. Utilizamos un electrolizador de membrana de electrolito de polímero (*PEM)* para la producción de $H_2$. Una vez producido el $H_2$, se licua y se carga en camiones cisterna de líquido criogénico. Una vez que el $H_2$ llega a la estación de repostaje, se somete a una serie de subprocesos para alcanzar las características requeridas antes de ser dispensado en el depósito de almacenamiento de $H_2$ del vehículo. Llegamos a la conclusión de que la eficiencia del vehículo de pila de combustible es del 12,8 *%* en lo que respecta a un vehículo de pila de combustible seleccionado-*Toyota Mirai XLE*, alimentado con $H_2$ producido por electrólisis que utiliza energía nuclear para la generación de electricidad y la entrega y distribución de $H_2$ en fase líquida.

## 4. Análisis comparativo de los resultados económicos y medioambientales

Calculamos y comparamos los costes de combustible, es decir, la cantidad de energía en *kWh* que utilizan el *Tesla Modelo* 3 *LR* y el *Toyota Mirai XLE* para recorrer 100 *millas*. Llegamos a la conclusión de que el *Toyota Mirai XLE*, alimentado con $H_2$ producido por electrólisis y la entrega y distribución de $H_2$ en fase gaseosa, utiliza un 40 *%* más de electricidad que el *Tesla Modelo* 3 *LR* y un 60 *%* más de electricidad para la entrega y distribución de $H_2$ en fase líquida.

A continuación, presentamos las emisiones de *GEI* producidas por el recorrido de 100 *millas* del *Tesla Modelo* 3 *LR* y del *Toyota Mirai XLE*. En el caso del *Tesla Modelo* 3 *LR*, presentamos y comparamos los resultados medioambientales en cuatro estados estadounidenses seleccionados: *CA, FL, IL* y *NY*. A continuación, examinamos y comparamos los resultados medioambientales del *Toyota Mirai XLE* alimentado por los colores del $H_2$ y la entrega y distribución de $H_2$ en fase gaseosa y líquida.

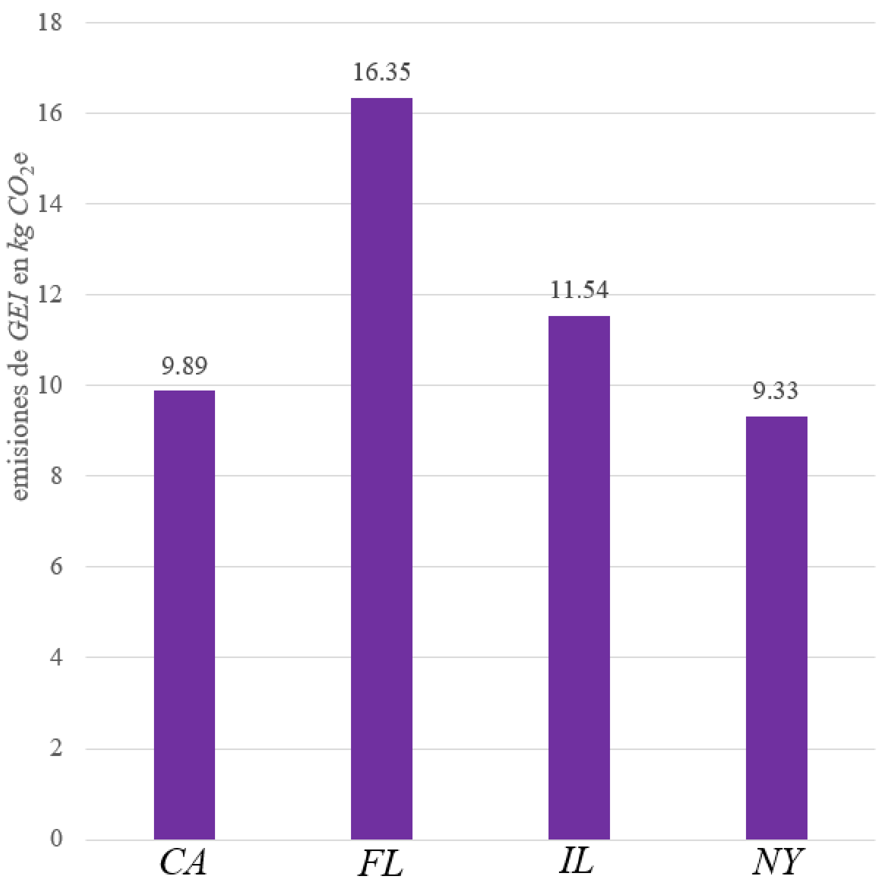

Figura 1: Emisiones de *GEI* producidas por el recorrido de 100 *millas* del *Tesla Modelo* 3 *LR* en determinados estados de *EE.UU*.

En la figura 1, observamos que, entre los estados seleccionados de *EE.UU.*, *NY* es el que menos emisiones de *GEI* produce, mientras que las mayores se dan en *FL*, en el supuesto de que el vehículo eléctrico se cargue con electricidad producida por el mix de la red eléctrica del estado. También observamos que las emisiones de *GEI* producidas por el viaje de 100 *millas* del *Tesla Modelo* 3 *LR* en *CA* son parecidas a las de *NY*, mientras que las emisiones de *GEI* en *IL* se sitúan entre las de *CA* y *FL*.

Observamos que en la tabla 1, existen diferencias significativas en las emisiones de *GEI* producidas por el viaje de 100 *millas* del *Toyota Mirai XLE* alimentado por los colores $H_2$. Observamos que el *Toyota Mirai XLE* alimentado por $H_2$ producido por la gasificación del carbón tiene las mayores emisiones de *GEI*, seguido por el reformado de metano con vapor.

Tabla 1. Emisiones de gases de efecto invernadero producidas por un viaje de 100 *millas* del *Toyota Mirai XLE* alimentado por métodos seleccionados de producción de $H_2$ y entrega y distribución de $H_2$ en fase gaseosa

| método de producción *del* $H_2$ | emisiones de *GEI* en *kg* $CO_2$e |
|---|---|
| reformado de metano con vapor | 12.82 |
| reformado de metano con vapor con captura utilización y almacenamiento del carbono | 5.28 |
| gasificación del carbono | 18.93 |
| gasificación del carbono con captura utilización y almacenamiento del carbono | 3.57 |
| electrólisis con energía solar para la generación de electricidad | 2.87 |
| electrólisis con energía eólica para la generación de electricidad | 1.7 |
| electrólisis con energía nuclear para la generación de electricidad | 1.59 |

Sin embargo, también observamos que cuando tanto el reformado de metano con vapor como la gasificación del carbón se combinan con la captura, utilización y almacenamiento del carbono, se produce una disminución significativa de las emisiones de *GEI*. Además, el *Toyota Mirai XLE* alimentado por electrólisis tiene muy pocas emisiones de *GEI*. Por lo tanto, entre los *Toyota Mirai XLE* alimentados por electrólisis, la energía solar para la generación de electricidad, tiene las mayores emisiones de *GEI*, mientras que la energía eólica y la nuclear para la generación de electricidad, tienen emisiones de *GEI* comparables.

En la tabla 2 observamos que las emisiones de *GEI* producidas por el viaje de 100 *millas* del *Toyota Mirai XLE* alimentado por $H_2$ en fase líquida durante entrega y distribución son mayores debido a un mayor uso de energía en la trayectoria del $H_2$ en fase líquida.

Tabla 2. Emisiones de gases de efecto invernadero producidas por un viaje de 100 *millas* del *Toyota Mirai XLE* alimentado por métodos seleccionados de producción de $H_2$ y entrega y distribución de $H_2$ en fase líquida

| método de producción del $H_2$ | emisiones de *GEI* en *kg* $CO_2$e |
|---|---|
| reformado de metano con vapor | 13.69 |
| reformado de metano con vapor con captura utilización y almacenamiento del carbono | 6.77 |
| gasificación del carbono | 20.42 |
| gasificación del carbono con captura utilización y almacenamiento del carbono | 5.06 |
| electrólisis con energía solar para la generación de electricidad | 4.36 |
| electrólisis con energía eólica para la generación de electricidad | 3.19 |
| electrólisis con energía nuclear para la generación de electricidad | 3.08 |

Observamos que el *Toyota Mirai XLE* alimentado por gasificación de carbón en la entrega y distribución de $H_2$ en fase líquida y gaseosa tiene más emisiones de *GEI* que el *Tesla Modelo* 3 *LR* en cada uno de los estados estadounidenses seleccionados. Sin embargo, el *Toyota Mirai XLE* alimentado por el reformado de metano con vapor y gasificación de carbón, y ambos combinados con la captura utilización y almacenamiento del carbono, tiene menos emisiones de *GEI* que el *Tesla Modelo* 3 *LR* en cada uno de los estados estadounidenses seleccionados.

Observamos que el *Toyota Mirai XLE* alimentado por $H_2$ producido por electrólisis tiene muchas menos emisiones de *GEI* que el *Tesla Modelo* 3 *LR* en cada uno de los estados estadounidenses seleccionados. De hecho, observamos que para la entrega y distribución de $H_2$ en fase gaseosa, el *Toyota Mirai XLE* alimentado con $H_2$ producido por electrólisis que utiliza energía nuclear para la generación de electricidad tiene 6 veces menos emisiones de *GEI* que el *Tesla Modelo* 3 *LR* alimentado por el mix de la red eléctrica de *CA* y *NY* y 7 y 10 veces menos emisiones de *GEI* que el *Tesla Modelo* 3 *LR* alimentado en *IL* y *FL* respectivamente. Del mismo modo, para la entrega y la distribución de $H_2$ en fase líquida, el *Toyota Mirai XLE* alimentado con $H_2$ producido por electrólisis que utiliza energía nuclear para la generación de electricidad tiene 3 veces menos emisiones de *GEI* que el *Tesla Modelo* 3 *LR* alimentado por el mix de la red eléctrica de CA y NY y 3,5 y 4 veces menos emisiones de *GEI* que el *Tesla Modelo* 3 *LR* alimentado por *IL* y *FL* respectivamente.

Además, comparamos las emisiones de *GEI* de ambos vehículos con el *Mitsubishi Mirage* 2021, el vehículo de gasolina con menor consumo de combustible. Evaluamos las emisiones de *GEI* del *Mitsubishi Mirage* 2021 y determinamos que el valor para un viaje de 100 *millas* del *Mitsubishi Mirage* 2021 es de 22,27 *kg* de $CO_2$e. En comparación con el *Mitsubishi Mirage*, el *Tesla Modelo* 3 *LR* tiene unas emisiones de *GEI* considerablemente menores en cada estado estadounidense seleccionado. Asimismo, observamos que el *Toyota Mirai XLE* alimentado con $H_2$, independientemente de su producción, entrega y distribución, tiene unas emisiones de *GEI* significativamente menores que el *Mitsubishi Mirage*. En particular, observamos que para la entrega y distribución de $H_2$ en fase gaseosa, el *Toyota Mirai XLE* alimentado con $H_2$ producido por electrólisis que utiliza energía nuclear para la generación de electricidad tiene 14 veces menos emisiones de *GEI* que el *Mitsubishi Mirage* 2021.

## 5. Conclusiones

El sector del transporte en *EE.UU.* se ha convertido en el mayor emisor de gases de efecto invernadero debido al uso de combustibles derivados del petróleo. En particular, los vehículos ligeros representan el 60 *%* de las emisiones de *GEI* en el sector del transporte en *EE.UU.* Este informe ha desarrollado las bases para afirmar efectivamente que los vehículos eléctricos y de pila de combustible reducen de forma significativa las emisiones de *GEI* emitidas por los vehículos ligeros con motor de combustión interna. En este sentido, la implantación a gran escala de los vehículos eléctricos y de pila de combustible será necesaria para descarbonizar el sector del transporte en *EE.UU.*

## 6. Referencias

[1] Rodhium Group, “Preliminary US Greenhouse Gas Emissions Estimates for 2021,” Enero 2022; disponible online en : https://rhg.com/research/preliminary-us-emissions-2021/; accedido en Marzo 1, 2022.

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# COMPARATIVE ASSESSMENT OF WELL-TO-WHEELS EFFICIENCY AND EMISSIONS OF *EV*S AND *FCV*S

**Author: Soldevilla Artajona, Jorge.**

Supervisor: Gross, George.

Collaboratory entity: University of Illinois at Urbana-Champaign.

## EXECUTIVE SUMMARY OF THE PROJECT

In the *US*, the transportation sector generates the largest share of Greenhouse gas (*GHG*) emissions more than electricity, industry, and buildings sectors since it accounts for 31 *%* of overall emissions [1]. These emissions come from burning fossil fuels, which are mainly petroleum-based such gasoline and diesel, for light-duty vehicles, medium- and heavy-duty trucks [2]. We examine the performance of two classes of zero-emissions vehicles (*ZEV*s) in terms of efficiency, environmental, and economic impacts. In this thesis, in order to make the results concrete we do our comparative analysis in terms of selected electric vehicle (*EV)-Tesla Model* 3 *LR* and fuel cell vehicle (*FCV*)-*Toyota Mirai XLE*.

**Keywords:** *EV*, *FCV*, *GHG* emissions

## 1. Introduction

We note that 60 *%* of the *GHG* emissions of the transportation sector in the *US* come from light-duty vehicles [3]. In this sense, it is urgent to implement on large-scale an alternative to high pollutants internal combustion engine vehicles *(ICEVs*).

*EV* has an electric motor that is powered by a rechargeable battery placed inside the vehicle, and therefore, an electricity input is required to charge the battery. Unlike cars that run on gasoline and diesel fuels and release tailpipe emissions that include *GHG* emissions by fuel combustion, *EV*s do not produce such emissions however, there are emissions released during the electricity generation to charge the *EV* battery.

*FCV* are powered by $H_2$ and do not release tailpipe emissions. *FCV* use a propulsion system where the energy stored as $H_2$ is converted to electricity by the fuel cell. The problem of $H_2$ is that it is not found as molecular $H_2$, but forming compounds with other elements of the periodic table. $H_2$ can be produced through multiple methods, but current production is dominated by just two, steam methane reforming (*SMR*) and coal gasification. Both of these production processes emit large amounts of emissions, but they can be decarbonized if combined with carbon capture utilization and storage (*CCUS).* On the other hand, the leading alternatives low-carbon $H_2$ production method are biomass gasification and electrolysis that uses solar, wind or nuclear energy for electricity generation. According to the convention in popular media and most industry reports, a color code for $H_2$ is used to indicate the level of emissions associated with each $H_2$ production method.

Among the improvements of *FCV* with respect to *EV*, higher autonomy and lower refueling time stand out but the cost to fuel the *FCV* storage tank is higher.

## 2. Definition of the project

This report focuses on the performance of two specific clases of *ZEV*s, *EV*s and *FCV*s, that are represented by *Tesla Model* 3 *LR* and *Toyota Mirai XLE*, in terms of efficiencies, economics and *GHG* emissions. The Well-to-Wheels (*w-t-w*) structure was originally introduced to evaluate *ICEV* efficiency; the process is applied, with small modifications, to assess *EV* and *FCV* efficiency. The *w-t-w* process involves a sequence of subprocesses, each of which incurs a loss of energy and consequently impacts the overall efficiency of the process.

The *EV w-t-w* process can be decomposed in two components: *well-to-charger* subsystem and *charger-to-wheels* subsystem. In this sense, the *well-to-charger* subsystem starts at the well and its energy conversion to generate electricity. Subsequently, the electricity is transmitted to the grid which supplies electricity to the *EV* charger. In the end, the *EV* charger supplies the *EV* battery wich powers the electric motor that move the wheels of the *EV*.

Similarly, the *FCV w-t-w* process can be decomposed in two components: *well-to-tank* subsystem and *tank-to-wheels* subsystem. In this sense, we describe in detail the chain of processes from the $H_2$ production to *FCV* onboard storage tank. Once $H_2$ is produced it is either compressed or liquified in order to be transported to the refueling station. Subsequently, when $H_2$ arrives to the refueling station, $H_2$ undergoes a series of subprocesses that depend on the $H_2$ delivery form in order to reach 700 *bar*s and -40 *ºC* before it is dispensed into the *FCV* onboard storage tank. The fuel cell placed inside the *FCV* converts $H_2$ into electricity and supplies the electric motor that move the wheels of the *FCV*.

## 3. Efficiency of *EV* and *FCV w-t-w* processes

In order to make the results concrete, we study the *EV w-t-w* efficiency in terms of a selected *EV-Tesla Model* 3 *LR* and electricity supply generation by a combined cycle natural gas (*CCNG*) plant. This report considers two major loss components in the path from the source of generation to the wheels of the *EV*. The first loss is associated with the energy loss during the distribution and transmission of the electricity. The second loss component includes the losses that are unique to an *EV* and take place from the outlet on the wall to the wheels of the *EV*. We conclude that the *EV w-t-w* efficiency is 38.5 *%* in terms of a selected *EV-Tesla model* 3 *LR* and electricity supply generation by a combined cycle natural gas (*CCNG*).

In analogy with the *EV*, in order to make the results concrete we study the *FCV w-t-w* efficiency in terms of a selected *FCV-Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for generation of electricity and liquid $H_2$ delivery and distribution. We use Polymer electrolyte membrane (*PEM*) electrolyser for the $H_2$ production. Once the $H_2$ is produced it is liquified and loaded onto cryogenic-liquid tank trucks. Once the $H_2$ arrives to the refueling station it undergoes to a series a subprocesses in order to reach the required characteristics before it is dispensed into the *FCV* onboard storage tank. We conclude that the *FCV w-t-w* efficiency is 12.8 *%* in terms of a selected *FCV-Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for generation of electricity and liquid $H_2$ delivery and distribution.

We stress that we do not generalize the ratio between the efficiencies of both *w-t-w* processes since we used a selected case for the *EV* and *FCV w-t-w* processes.

## 4. *EV* and *FCV* economic and environmental comparative results

We calculate and compare the fuel costs i.e. the amount of energy in *kWh* that *Tesla Model* 3 *LR* and *Toyota Mirai XLE* use to travel 100 *mi*. We conclude that *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis for gaseous delivery and distribution uses 40 *%* more electricity than *Tesla Model* 3 *LR* and 60 *%* more electricity for liquid $H_2$ delivery and distribution.

Subsequently, we present the *GHG* emissions produced by the 100 *mi*-travel by *Tesla Model* 3 *LR* and *Toyota Mirai XLE*. In the case of *Tesla Model* 3 *LR* we present and compare environmental results in four selected *US states*: *CA*, *FL*, *IL* and *NY*. Next we examine and compare the environemntal results from *Toyota Mirai XLE* fueled by $H_2$ colors and gaseous and liquid $H_2$ delivery and distribution.

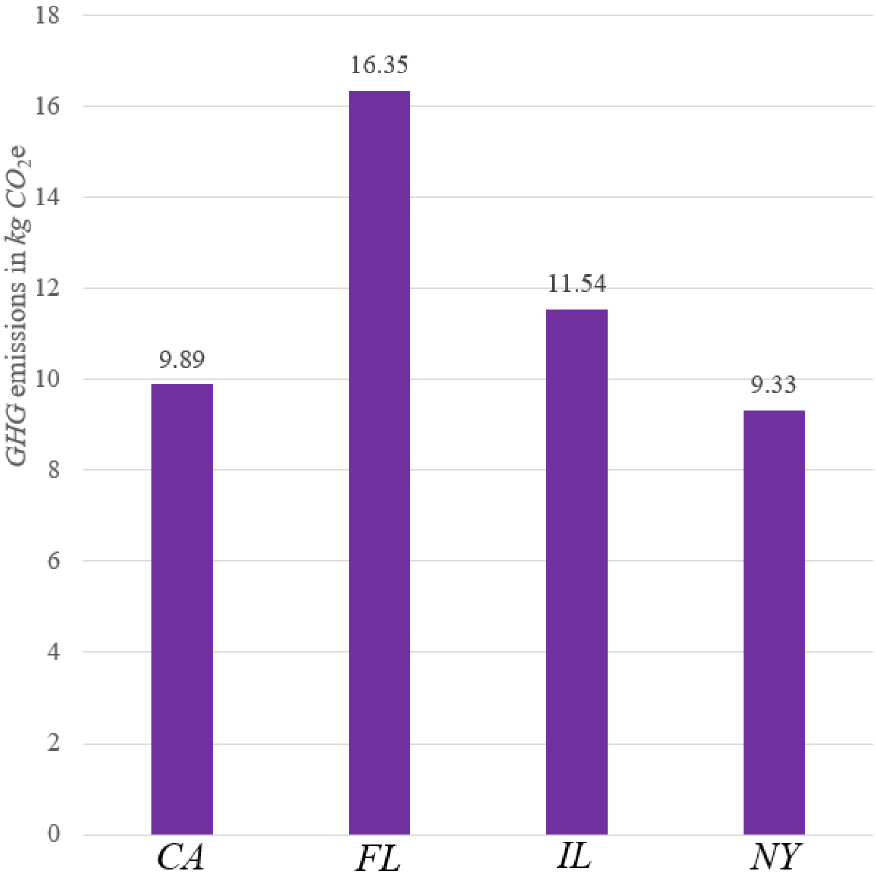

Figure 1: *GHG* emissions produced by 100-*mi* travel by *Tesla Model* 3 *LR* in selected *US states*

In figure 1, we note that among the selected *US states*, *NY* that the lowest *GHG* emissions while the largest are in *FL* under the assumption that the *EV* is charged with electricity produced by the state´s resource mix. We also observe that *GHG* emissions produced by 100-*mi* travel by *Tesla Model* 3 *LR* in *CA* are close to those in *NY* while The *GHG* emissions in *IL* are between those in *CA* and *FL*.

We note that in table 1, there exist significant differences in the *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by $H_2$ colors. We note that *Toyota Mirai XLE* powered by the coal gasification has the largest *GHG* emissions followed by *SMR*. However, we also observe that when both *SMR* and coal gasification and combined with *CCUS*, there is a significant decrease in *GHG* emissions. Also, *Toyota Mirai XLE* powered by electrolysis has very few *GHG* emissions. Therefore, among *Toyota Mirai XLE* powered by electrolysis, solar energy for electricity generation, has the largest *GHG* emissions while wind and nuclear energy for electricity generation, have comparable *GHG* emissions.

Table 1. *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by selected $H_2$ production methods and gaseous $H_2$ delivery and distribution

| $H_2$ production method | *GHG* emissions in *kg* $CO_2$e |
|---|---|
| *SMR* | 12.82 |
| *SMR* with *CCUS* | 5.28 |
| coal gasification | 18.93 |
| coal gasification with *CCUS* | 3.57 |
| electrolysis that uses solar energy for generation of electricity | 2.87 |
| electrolysis that uses wind energy for generation of electricity | 1.7 |
| electrolysis that uses nuclear energy for generation of electricity | 1.59 |

We observe in table 2 that *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by liquid $H_2$ delivery and distribution are larger due to a higher energy use the liquid $H_2$ pathway. We observe that *Toyota Mirai XLE* powered by coal gasification in both gaseous and liquid $H_2$ delivery and distribution has more *GHG* emissions than *Tesla Model* 3 *LR* in each of the selected *US state*.

Table 7. *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by selected $H_2$ production methods and liquid $H_2$ delivery and distribution

| $H_2$ production method | *GHG* emissions in *kg* $CO_2$e |
|---|---|
| *SMR* | 13.69 |
| *SMR* with *CCUS* | 6.77 |
| coal gasification | 20.42 |
| coal gasification with *CCUS* | 5.06 |
| electrolysis that uses solar energy for generation of electricity | 4.36 |
| electrolysis that uses wind energy for generation of electricity | 3.19 |
| electrolysis that uses nuclear energy for generation of electricity | 3.08 |

However, *Toyota Mirai XLE* fueled by *SMR* and coal gasification and both combined with *CCUS* has fewer *GHG* emissions than *Tesla Model* 3 *LR* in each of the selected *US* state. We note that *Toyota Mirai XLE* powered by $H_2$ produced by electrolysis has much fewer *GHG* emissions than *Tesla Model* 3 *LR* in each of the selected *US* state. Indeed, we note that for gaseous $H_2$ delivery and distribution, *Toyota Mirai XLE* powered by $H_2$ produced by electrolysis that uses nuclear energy for electricity generation has 6 times fewer *GHG* emissions than *Tesla Model* 3 *LR* powered by *CA* and *NY* electricity grid resource mix and 6 and 9 times fewer *GHG* emissions than *Tesla*

*Model* 3 *LR* powered by *IL* and *FL* respectively. Similarly, for liquid $H_2$ delivery and distribution *Toyota Mirai XLE* powered by $H_2$ produced by electrolysis that uses nuclear energy for electricity generation has 3 times fewer *GHG* emissions than *Tesla Model* 3 *LR* powered by *CA* and *NY* electricity grid resource mix and 3.5 and 4 times fewer *GHG* emissions than *Tesla Model* 3 *LR* powered by *IL* and *FL* respectively.

In addition, we compare the *GHG* emissions from both vehicles to the *Mitsubishi Mirage* 2021, the gasoline vehicle with highest fuel economy. We evaluate the *GHG* emissions of *Mitsubishi Mirage* 2021 and determine that value for 100-*mi* travel by *Mitsubishi Mirage* 2021 *is* 22.27 *kg* $CO_2$e. In comparison to *Mitsubishi Mirage*, *Tesla Model* 3 *LR* has considerably fewer *GHG* emissions in each selected *US* state. Also, we observe that *Toyota Mirai XLE* fueled by $H_2$ irrespective of its production, and delivery, and distribution has significant fewer *GHG* emissions that *Mitsubishi Mirage*. Particularly, we note that for gaseous $H_2$ delivery and distribution *Toyota Mirai XLE* powered by $H_2$ produced by electrolysis that uses nuclear energy for electricity generation has 14 times fewer *GHG* emissions than *Mitsubishi Mirage* 2021.

## 5. Conclusions

The transportation sector in the *US* has become the biggest *GHG* emitting sector due to the use of mostly petroleum-based fuel. In particular, the light-duty vehicles account for 60 *%* of the *GHG* emissions in the transportation sector in the *US*. This report developed the basis to effectively affirm that *EV*s and *FCV*s reduce significantly the *GHG* emissions emitted by *ICEV*s. In this sense, the implementation on large scale of *EV*s and *FCV*s will be necessary to decarbonize the transportation sector in the *US*.

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# COMPARATIVE ASSESMENT OF WELL-TO-WHEELS EFFICIENCY AND EMISSION OF *FCV*S AND *EV*S

By

Jorge Soldevilla

Senior Thesis in Electrical Engineering

University of Illinois at Urbana-Champaign

Advisor: George Gross

Author’s Signature:

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Advisors Signature:

# ABSTRACT

In the *US*, the transportation sector generates the largest share of Greenhouse gas (*GHG*) emissions since it accounts for 31 *%* of overall emissions. These emissions come from burning fossil fuels, which are mainly petroleum-based such gasoline and diesel, for light-duty vehicles, medium- and heavy-duty trucks.

The Well-to-Wheels (*w-t-w*) structure was originally introduced to evaluate *ICEV* efficiency; the process is applied, with small modifications, to assess *EV* and *FCV* efficiency. The *w-t-w* process involves a sequence of subprocesses, each of which incurs a loss of energy and consequently impacts the overall efficiency of the process.

The *EV w-t-w* process can be decomposed in two components: *well-to-charger* and *charger-to-wheels* processes. The *EV well-to-charger* process starts at the well and its energy conversion to generate electricity. Subsequently, the electricity is transmitted to the grid which supplies electricity to the *EV* charger. In the end, the *EV* charger supplies the *EV* battery which powers the electric motor that moves the wheels of the *EV*. In the *EV w-t-w* process, there are two major energy losses that have economic and environmental impacts. The first loss is associated with the energy loss during the distribution and transmission of the electricity. The second loss component includes the losses that are unique to an *EV* and take place from the outlet on the wall to the wheels of the *EV*.

Similarly, the *FCV w-t-w* process can be decomposed in two components: *well-to-tank* and *tank-to-wheels* processes. The $H_2$ pathway from its production to the vehicle´s tank comprises several subprocesses. Once $H_2$ is produced, it is either compressed or liquified in order to be transported to the refueling station where it undergoes to a sequence of subprocesses to reach 700 *bar*s and -40º*C*, before it is dispensed into the *FCV* onboard storage tank. Inside the *FCV*, the fuel cell converts $H_2$ in electricity and supplies the electric motor that moves the wheels of the *FCV*. In analogy with the *EV*, the *FCV w-t-w* process has energy losses that have environmental and economic impacts and affect the overall *FCV w-t-w* efficiency. In this thesis, in order to make the results concrete in terms of efficiency, economic, and environmental impacts, we do our comparative analysis in terms of selected *EV-Tesla Model* 3 *LR* and *FCV-Toyota Mirai XLE*.

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I would like to thank my advisor Professor George Gross for his dedication, patience, and availability to help me during this report.

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# CHAPTER 1

# INTRODUCTION

Air pollution is a worrying social issue caused by the emissions of certain substances that have harmful effects on the environment and health. Exposure to air pollutants increases the risk of developing different diseases. These diseases are divided into three broad categories: cardiovascular diseases, respiratory diseases and cancers. According to the World Health Organization (*WHO*), a total of 7 million people die each year due to exposure to air pollutants [1]. Specifically, 4.2 million deaths per year are caused as a result of exposure to ambient (outdoor) air pollution and 3.8 million deaths per year as a result of exposure to smoke from dirty cooking stoves and fuels in homes.

This pollution not only affects human beings, but also favors the deterioration of the environment, contributing to a further increase in the greenhouse effect. The increase of Greenhouse gas (*GHG)* emissions is the main cause of climate change. Therefore, since 1975 the average temperature of the earth has suffered an increase at a rate of roughly 0.15 to 0.2 *°C* per decade [2].

There exists a common thrust in the need to reduce the amount of *GHG* emissions emitted every year in order to effectively face the consequences of climate change. It is necessary to know the origin of *GHG* emissions sources and analyze alternatives to the emissions in these sectors. This report analyzes the economic and environmental performance of the zero-emissions vehicles (*ZEV*s) in order to reduce *GHG* emissions in the transportation sector in the *US*.

Therefore, in this chapter, we analyze the global evolution of the $CO_2$ emissions over the last 100 years. Subsequently, we illustrate the main *GHG* emissions sectors in the *US*. We claim that transportation is the biggest *GHG* emission sector in the *US*. In this sense, we describe the salient characteristics and key differences of the *ZEV*s. Finally, we describe the scope of the work which is the comparative analysis of two specific classes of *ZEV*s in terms of efficiencies and emissions.

## 1.1 Driving forces for the selected topic

In figure 1, we note that global carbon dioxide ($CO_2$) emissions have increased at a significant rate since 1950. Between 2016-2018, there was an increase of more than 1 billion tons of $CO_2$ emissions. However, in 2019 the total $CO_2$ emissions did not increase as it was claimed and the $CO_2$ emissions remained constantly even though the global economy grew around a 3 % [3]. The increase of the penetration of renewables in the electricity generation and the replacement of coal by natural gas have reduced the $CO_2$ emissions in the electricity sector. Global $CO_2$ emissions were reduced by nearly a 6 % in 2020, due to the Covid-19 pandemic that accounts to almost 2 $Gt\ CO_2$. This reduction has been the largest ever and five times greater than the 2009 decline due to the financial crisis.

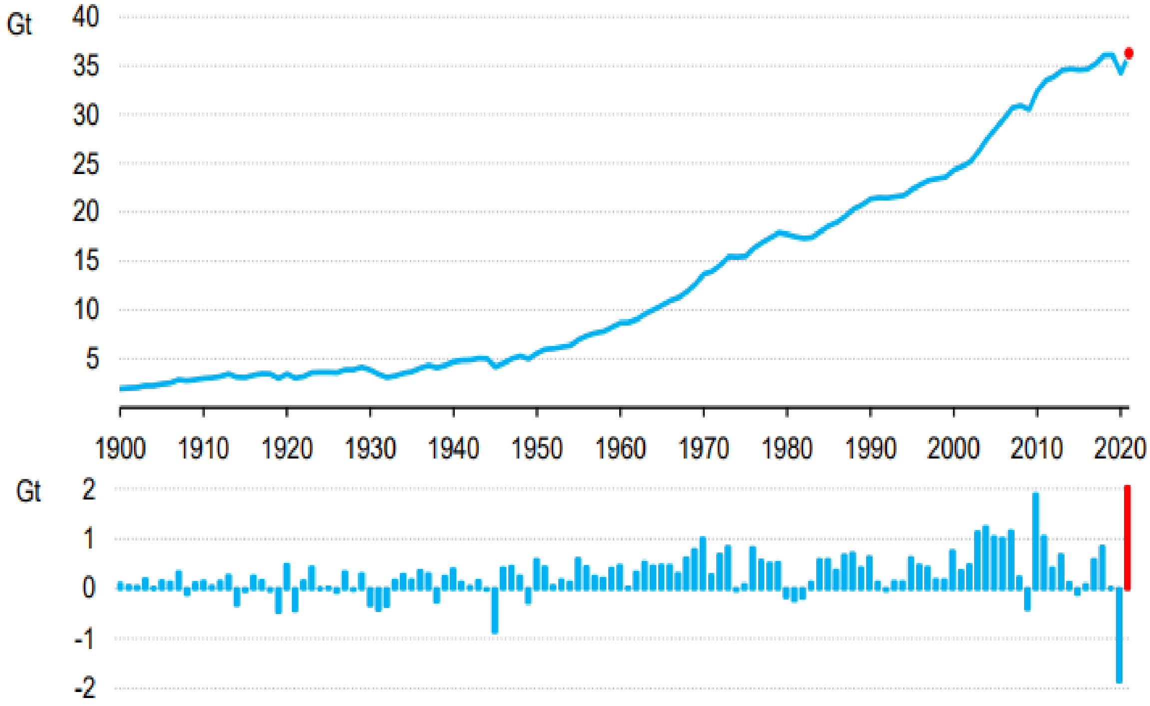


Figure 1. Global energy-related $CO_2$ emissions: 1900-2021 [4]

However, the world has experienced a very rapid economic recovery since then, driven by unprecedented fiscal and monetary stimulus and a rapid but uneven deployment of vaccines. The recovery in energy demand in 2021 was aggravated by adverse weather and energy market conditions, which led to more coal being burned despite the highest annual ever growth in renewable power generation. Therefore, $CO_2$ emissions increased by 6 $\%$ approaching the 2018-2019 highest peak in history.

The increase of $CO_2$ emissions in the last 100 years is absolutely worrying. The world is facing the great challenge of climate change. In 2015, the countries involved in the Paris agreement pledged to take action to keep global temperature rise this century below $2°C$, preferably $1.5°C$, above preindustrial levels [5]. There is a growing number of countries that have set their target to reach net-zero $CO_2$ emissions by 2050 with the goal of limiting average temperature rise to $1.5°C$. It requires a joint and wide-ranging action across all economies in order to achieve a full decarbonization.

However, the truth is that we have barely begun to reduce emissions. It has been estimated that 8.8 $\%$ less $CO_2$ emissions were emitted in the first six month of 2020 than in the same period of 2019, following the Covid-19 pandemic and subsequent shutdowns [6].

The energy transformation requires a greater shift in electricity generation from fossil fuels to non-pollutant sources such as nuclear or renewable sources like solar and wind. It is a fact that the replacement of coal plants to natural gas plants have contributed to a reduction in emissions [7]. Although natural gas plants emitted a considerable amount of $CO_2$ emissions, there exist technology in development, carbon capture utilization and storage (*CCUS*), that can capture $CO_2$ emissions before they are released into the atmosphere.

$CO_2$ is the most common *GHG* emitted by human activities, in terms of the quantity released and the total impact on global warming. As a result, the term $CO_2$ is sometimes used as a shorthand expression for all *GHG*s, however, this can cause confusion, and a more accurate form to refer to a number of *GHG*s collectively is to use the term carbon dioxide equivalent ($CO_2$e).

In this sense, the unit $CO_2$e represents the amount of a *GHG* whose atmospheric impact is standardized to that of 1 unit mass of $CO_2$, based on the *GHG*'s global warming potential (*GWP)*. E.g., 1 *kg* of $CH_4$ causes 25 times more warming over a 100-year period compared to 1 *kg* of $CO_2$, and so methane as a *GWP* of 25 [8].

## 1.2 Importance of *ZEV*s in the *US*

The use of transportation represents an essential activity for a large part of population, especially in developed countries. Currently, the use of transportation represents one of the sectors with biggest impact in the *US GHG* emissions since the major part of current vehicles are fossil fuel-based.

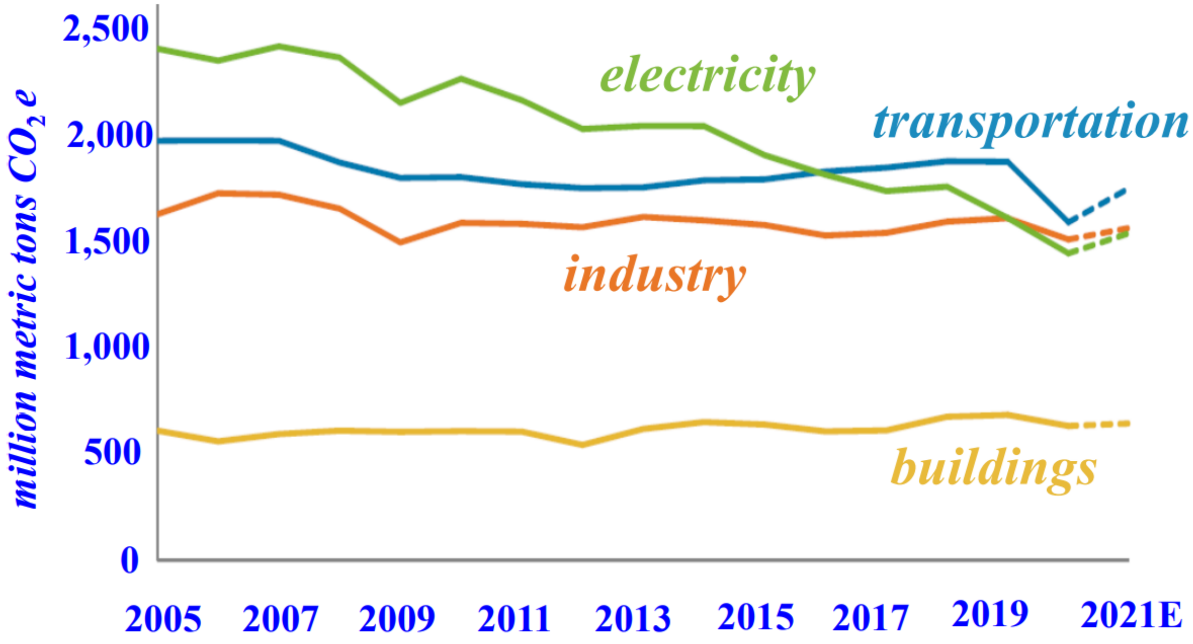


Figure 2. *US GHG* emissions by major emitting sector: 2005-2021 [9]

In figure 2, we note that in the *US*, the transportation sector generates the largest share of *GHG* emissions more than electricity, industry, and buildings sectors. In 2021, emits nearly 2,000 million metric tons $CO_2$e which accounts for 31 *%* of total *US* net emissions.

We observe that in 2020 the emissions in all major economy sectors were highly reduced due to the Covid-19 pandemic and the confinement of the majority of the population. However, in 2021, the world has experienced a very rapid economic recovery due to the availability of vaccines and there has been a considerably increase of the emissions. We can see that the largest increase in 2021 came from the transportation sector, as there has been a high demand for consumer goods and freight transport, and there has been a modest recovery in passenger travel. However, in 2021, transportation fuel demand did not reach 2019 levels. The gasoline demand which is an indicative of road transportation demand fall 13 % in 2020, but it increased at a steady rate in the first half of 2021 and it ended the year 10 % above 2020 levels [9]. The appearance of new Covid-19 variants such Delta or Omicron led to a breakout of new cases and the fuel demand in the second half of the year did not grow at previous rate.

*GHG* emissions from transportation come primarily from burning fossil fuels for light duty vehicles, trucks, ships, trains, and planes. More than 90 % of the fuel used for transportation is petroleum-based, which mainly includes gasoline and diesel fuel [10]. Therefore, an alternative to internal combustion vehicles should be implemented on large scale to reduce *GHG* emissions in transportation. We will consider the *GHG* emissions from the *US* transportation sector by source in 2019 because it is the last year with available data.

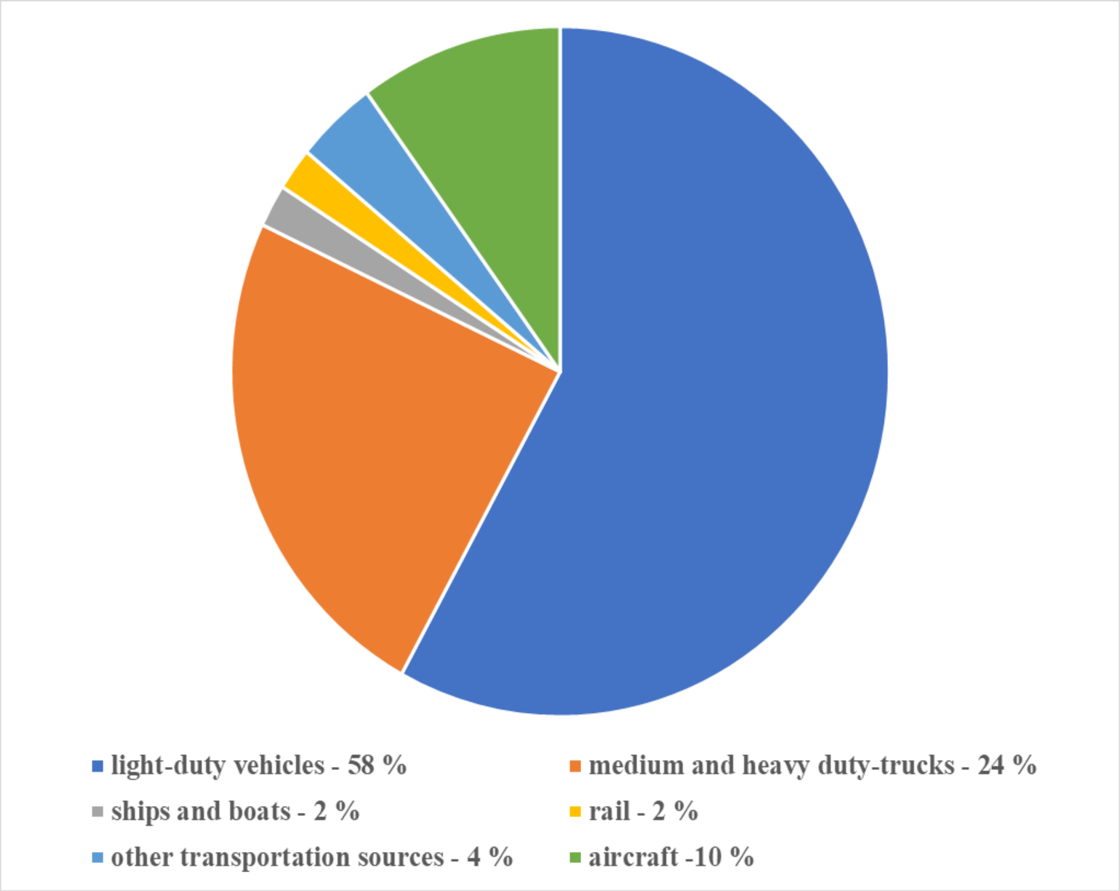


Figure 3. Share of *US* transportation sector *GHG* emissions by source in 2019 [11]

In figure 3, we observe that nearly 60 % of the *GHG* emissions of the transportation sector come from light-duty vehicles. In this sense, it is urgent to implement on large-scale an alternative to high pollutants internal combustion engine vehicles *(ICEVs*). This report will analyze the performance of fuel cell vehicles (*FCV*s) and electric vehicles (*EV*s) in terms of efficiencies and emissions.  We can claim that the high level of *GHG* emissions in the transportation sector of the *US* is a consequence of the fact that most of the vehicles are *ICEV*s, which are high pollutant vehicles. It is necessary to consider the implementation on large scale of other vehicles to reduce the emissions.

## 1.3 Review of the salient *ZEV*s

This report focuses on the economic and environmental performance of *ZEV*s. We use two specific classes of *ZEV*s which are *EV* and *FCV*. In this section, we describe the salient characteristics of both vehicles as well as the key differences between them.

*EV* has an electric motor that is powered by a rechargeable battery placed inside the vehicle, and therefore, an electricity input is required to charge the battery. Unlike cars that run on gasoline and diesel fuels and release tailpipe emissions that include *GHG* emissions by fuel combustion, *EV*s do not produce such emissions however, the electricity generation required for *EV* operation is accompanied by smokestack emissions at the polluting generation plants. Therefore, the emissions associated with the *EV* electricity consumption are called *EV* tailpipe emissions.

In addition to the *EV* tailpipe emissions, there are the emissions incurred in the manufacture of the *EV* and of the *EV* battery pack. We may reasonably assume that the energy requirements to manufacture an *EV* and those for other types of vehicles are rather comparable.  However, the manufacture of the *EV* battery pack requires sizeable amount of energy and entails the associated emissions to supply this energy.

Therefore, the emissions associated with the electricity generated to power the battery of the *EV* and the emissions associated with the manufacture of the *EV* battery determine the *GHG* emissions associated with *EV*. The volume of the *GHG* emissions reduced will be related to the larger deployment of non-pollutant energy sources. In the *US* there exist regions where the power generation is mostly fossil fuel-based, whereas there exist others where renewables sources play a major role in the power generation. As a result, the *GHG* emissions associated with *EV* can significantly vary depending on the *US state*.

Through October 2021, cumulative *EV* sales accounted for 448,434. Year to date, 2021 total *EV* sales are up by 87.8 % vs 2020 in the *US*. Through October 2021, the *US* had 48,775 *EV* charging stations and 125,078 charging outlets. Tesla models have accounted for over half (59.5%) of *EV* sales in October 2021 [12]. *CA* is the *US state* that leads the electrification of transportation since it accounts 930,811 *EV* and 34,185 that leads to a ratio of 27.14 *EV* for charger port [13].

The main disadvantages that *EV* present are their powering time and driving range. The powering time of *EV* depends on the voltage of the source. There are three different levels in terms of charging *EV*. Level one charging uses a common 120-volt household outlet and it adds between 3 and 5 *mi* of range per hour. Level two charging equipment can be installed at home, at the workplace, as well as in public locations. On average, level two charging can replenish between 12 and 80 *mi* of range per hour. Level 3 charging is the fastest type of charging available and can recharge an *EV* at a rate of 3 to 20 miles of range per minute. However, very few residential locations have the high-voltage supply that is required for level 3 charging [14]. However, we want to stress that the charger ports become leisure centers where the people could get together and spend time in restaurants, cinemas, or coffee shops.

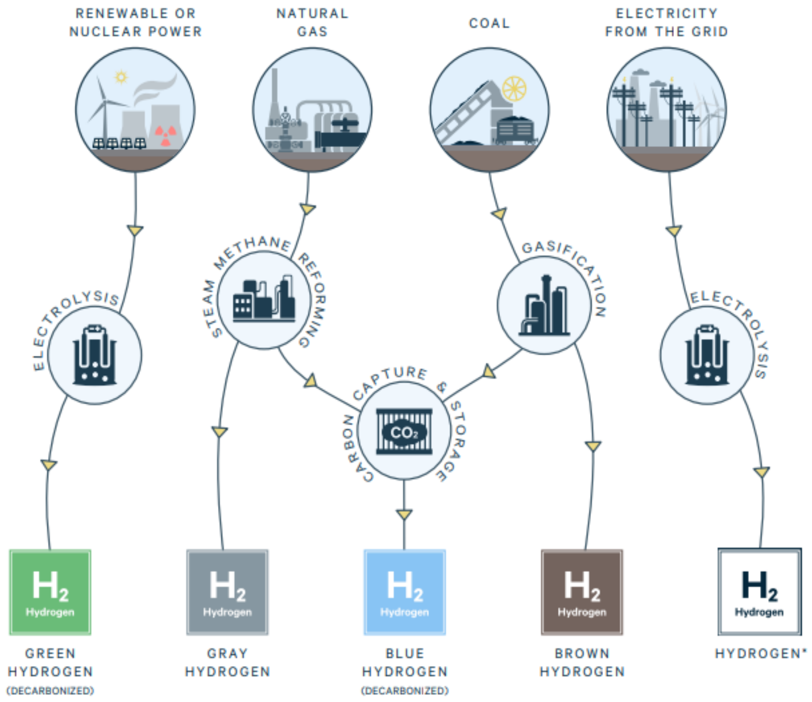
The other type of *ZEV* for which this report provides economic and environmental results is the *FCV*. This type of vehicle is powered as well with an electric motor, but there exist differences between *FCV* and *EV* in the supply source to the electric motor.

*FCV* are powered by $H_2$ and do not release tailpipe emissions. *FCV* use a propulsion system where the energy stored as $H_2$ is converted to electricity by the fuel cell. The fuel cell generates electricity through an electrochemical reaction, not combustion. Therefore, in a fuel cell, $H_2$ and oxygen are combined to generate electricity, heat and water. The electricity to the electric motor is mainly provided by the fuel cell, but the *FCV* has also a rechargeable battery. The *FCV* battery stores energy recovered from deceleration and assists the fuel cell electricity output when accelerating. The size of the *FCV* battery is not comparable with the *EV* battery. Therefore, we do not take into account the emissions associated with the manufacture of the *FCV* battery.

The problem of $H_2$ is that it is not found as molecular $H_2$, but forming compounds with other elements of the periodic table. Therefore, the $H_2$ production and delivery will determine the *GHG* emissions associated with *FCV*.

$H_2$ can be produced through multiple methods, but current production is dominated by just two, steam methane reforming (*SMR*) and coal gasification. Both of these production processes emit large amounts of emissions, but they can be decarbonized if combined with carbon capture utilization and storage (*CCUS)*. On the other hand, the leading alternatives low-carbon $H_2$ production method are biomass gasification and electrolysis that uses solar, wind or nuclear for electricity generation.

According to the convention in popular media and most industry reports, a color code is used to indicate the level of emissions associated with each $H_2$ production method. In figure 4, we illustrate $H_2$ colors due to the $H_2$ production methods.



Note: * Emissions depend on the mix of electricity sources on the grid

Figure 4: The possible colors of $H_2$ production [15]

As opposed to $H_2$ pollutant production methods, $H_2$ can be made from a wide range of low-carbon energy sources. Its potential generation includes production by electrolysis from renewable electricity, biomass and nuclear. In addition, low-carbon production from fossil fuels is also possible if *CCUS* is involved in the emissions during fossil fuel extraction and production of $H_2$.

*FCV* powered by low carbon $H_2$ production can contribute to a considerably reduction of *GHG* emissions in transportation. The main drawback of low-carbon $H_2$ production is its expensive cost in comparison with fossil fuel-based production. However, as renewable energy technology continues to mature, its electric power costs are expected to reduce over time. In fact, the costs of solar *PV* modules have been reduced by 99 % since 1980 and this reduction will continue in the future [16].

The lack development of large-scale batteries makes $H_2$ a key component in the decarbonization of the industry and electrification of transportation. There is a massive amount of energy that is wasted during off-peaks at multiple renewable power plants which could be implemented in the generation of $H_2$ by water electrolysis.

Among the improvements of *FCV* with respect to *EV*, higher autonomy stands out. In May 2021, *Toyota Mirai* drove over 622 *mi* on single fill [17] while the range of *Tesla Model* 3 is 358 *mi* according to *EPA* estimates [18]. In addition, *FCV* can be refueled as little as in five minutes, which provide customers a similar experience as *ICEV*s whereas the time to charge an *EV* can take several hours if the *EV* supercharger is not used.

In 2021, the *FCVs* sales have experimented a big growth in comparison with previous years and near to 3,500 *FCVs* were sold in the *US*. There were 602 *FCV*s sold in the *US* in March 2022. Cumulatively, 1,033 *FCV*s have been sold in 2022. In total, 13,315 *FCV*s have been sold since 2014 [19]. The growth in 2021 and 2022 is associated mostly with the success of *Toyota Mirai* and *Hyundai Nexo*. The key factors that impact the growth of the global market include surge in environmental concerns, increase in government initiatives for development of $H_2$ fuel cell infrastructure, high initial investment in infrastructure, and technological advancement and future potential. In mid-2021, there were 48 open retail $H_2$ stations in the *US*. Additionally, there were at least 60 stations in various stages of planning or construction [20].

## 1.4 Summary of the contributions and outlines of this report

The transportation sector in the *US* has become the biggest *GHG* emitting sector due the use of fuel that is primarly petroleum-based. In particular, the light-duty vehicles account for 60 *%* of the *GHG* emissions in the transportation sector in the *US*. *EV* and *FCV* are both driven by an electric motor but the supply source is different. In the case of the *EV*, the battery powers the motor while in the *FCV* the main supply source is the fuel cell powered by $H_2$.

This report focuses on the performance of two specific clases of *ZEV*s, *EV*s and *FCV*s, that are represented by *Tesla Model* 3 *LR* and *Toyota Mirai XLE*, in terms of efficiencies and *GHG* emissions. In the case of the *EV* we present environmental comparative results in four selected *US states*: *CA*, *FL*, *IL* and *NY*. *CA* is region that leads the electrification of transportation, since there are 930,811 *EV* on road. We present environmental results in *IL* due to the fact that this report is provided by a senior student of the University of Illinois at Urbana-Champaign. We also present environmental results in *NY* and *FL* due to their mixture of fuels that generates electricity known as the electricity resource generation mix. This report describes and computes the efficiency of the *EV w-t-w* (*well-to-wheels*) process in terms of a selected *EV-Tesla Model* 3 *LR* and electricity supply generation by a combined cycle natural gas (*CCNG*). Similarly, we evaluate the *FCV w-t-w* efficiency in terms of a selected *FCV-Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for generation of electricity and liquid $H_2$ delivery and distribution. We evaluate the energy uses and *GHG* emissions in selected $H_2$ production methods and gaseous and liquid $H_2$ delivery and distribution.

This report provides a comparative analysis of the fuel costs by the 100-*mi* travel by *Tesla Model* 3 *LR* and *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis and $H_2$ gaseous and liquid delivery and distribution. In this sense, we compute the amount of energy in *kWh* that need both vehicles to travel 100 *mi*. Finally, this report provides an environmental comparative analysis of the 100-*mi* travel by *Tesla Model* 3 *LR* and *Toyota Mirai XLE*. In the case of *Tesla Model* 3 *LR* we compute the *GHG* emissions in four *US states*: *CA*, *FL*, *IL* and *NY*. Next we examine, the *GHG* emissions produced by *Toyota Mirai XLE* powered by $H_2$ colors and $H_2$ gaseous and liquid delivery and distribution. In addition, we compare the *GHG* emissions from both vehicles to the *Mitsubishi Mirage* 2021, the gasoline vehicle with highest fuel economy.

# CHAPTER 2

# THE *EV* AND *FCV W-T-W PROCESSES*

The *w-t-w* structure was originally introduced to evaluate *ICEV* efficiency; the process is applied, with small modifications, to assess *EV* and *FCV* efficiency. The *w-t-w* process involves a sequence of subprocesses, each of which incurs a loss of energy and consequently impacts the overall efficiency of the process.

Firstly, in this chapter we explain in detail the chain of processes through each energy changes from the generation source to the wheels in the *EV w-t-w* process. The *EV w-t-w* process can be decomposed in two components: *well-to-charger* subsystem and *charger-to-wheels* subsystem. In this sense, we first explain the *well-to-charger* process which starts at the well and its energy conversion to generate electricity. Subsequently, the electricity is transmitted to the grid which supplies electricity to the *EV* charger. In the end, the *EV* charger supplies the *EV* battery which powers the electric motor that moves the wheels of the *EV*. In order to make the results concrete, we study the *EV w-t-w* efficiency in terms of a selected *EV-Tesla Model* 3 *LR* and electricity supply generation by (*CCNG*) plant.

Similarly, we explain the *FCV w-t-w* process which can be decomposed in two components: *well-to-tank* and *tank-to-wheels*. In this sense, we describe in detail the chain of processes from the $H_2$ production to *FCV* onboard storage tank. Once $H_2$ is produced it is either compressed or liquified in order to be transported to the refueling station. Subsequently, when $H_2$ arrives to the refueling station, $H_2$ undergoes a series of subprocesses that depend on the $H_2$ delivery form in order to reach the required characteristics before it is dispensed into the *FCV* onboard storage tank. The fuel cell placed inside the *FCV* converts $H_2$ into electricity and supplies the electric motor that moves the wheels of the *FCV*. In analogy with the *EV*, in order to make the results concrete we study the *FCV w-t-w* efficiency in terms of a selected *FCV-Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for generation of electricity and liquid $H_2$ delivery and distribution.

## 2.1 The *EV w-t-w* process

An *EV* is powered by a battery that is usually charged from a mixture of fuels that generates electricity known as the electricity resource generation mix. The fuel path of *EV* includes the electricity generation, transmission, and distribution to finally charge the *EV*.

We evaluate the case of electricity supply generation by a combined cycle natural gas plant which is a widely-used plant technology in the *US*. At the well, the energy for drilling and extraction incurs losses of 8.5 % of its energy content and the highly-efficient gas transport via pipelines incurs about 1.5 % loss of gas [21]. In this sense, the efficiency from the well to the *CCNG* plant is:

$$0.915 \times 0.985 = 0.9$$

A typical efficiency of a *CCNG* plant is 60 % , i.e. the conversion of the caloric contents of natural gas into electricity incurs a loss of 40 % [22]. This report considers two major loss components in the path from the source of generation to the wheels of the *EV*. The first loss is associated with the energy loss during the distribution and transmission of the electricity. The transmission and distribution efficiencies of *US sates* lie in the range of 95 % and are considerably uniform across the country [23]. The electricity output by the *CCNG* is injected into the transmission grid and, subsequently, the distribution grid to supply the electricity to the charger. The overall efficiency of the *CCNG* plant and the electricity delivery to the charger is:

$$0.6 \times 0.95 = 0.57$$

We add the efficiency from the well to the *CCNG* previously computed in order to assess the efficiency of the *well-to charger* process:

$$0.9 \times 0.57 = 0.514$$

In this sense, we observe that the efficiency of the *well-to-charger* process is 51.4 %.

The second loss component includes the losses that are unique to an *EV* and take place from the outlet on the wall to the wheels of the *EV*. We stress that these energy losses are caused by climate-related effects on the efficiency of the *EV*, losses in conversion *AC/DC,* and losses associated with charging equipment efficiency. The *EV* battery is charged and supplies electricity to the highly-efficient electric motor which uses the *DC* electricity from the battery, which an inverter transforms into *AC* to convert it into kinetic energy to produce the motion of the *EV*. Tesla estimates 75 % efficiency for the *charger-to-wheels* subsystem for their vehicles [21].

Therefore, the *EV w-t-w* efficiency is:

$$0.514 \times 0.75 = 0.385$$

We conclude that the *EV w-t-w* efficiency is 38.5 % in terms of a selected *EV-Tesla model* 3 *LR* and electricity supply generation by a combined cycle natural gas (*CCNG*).

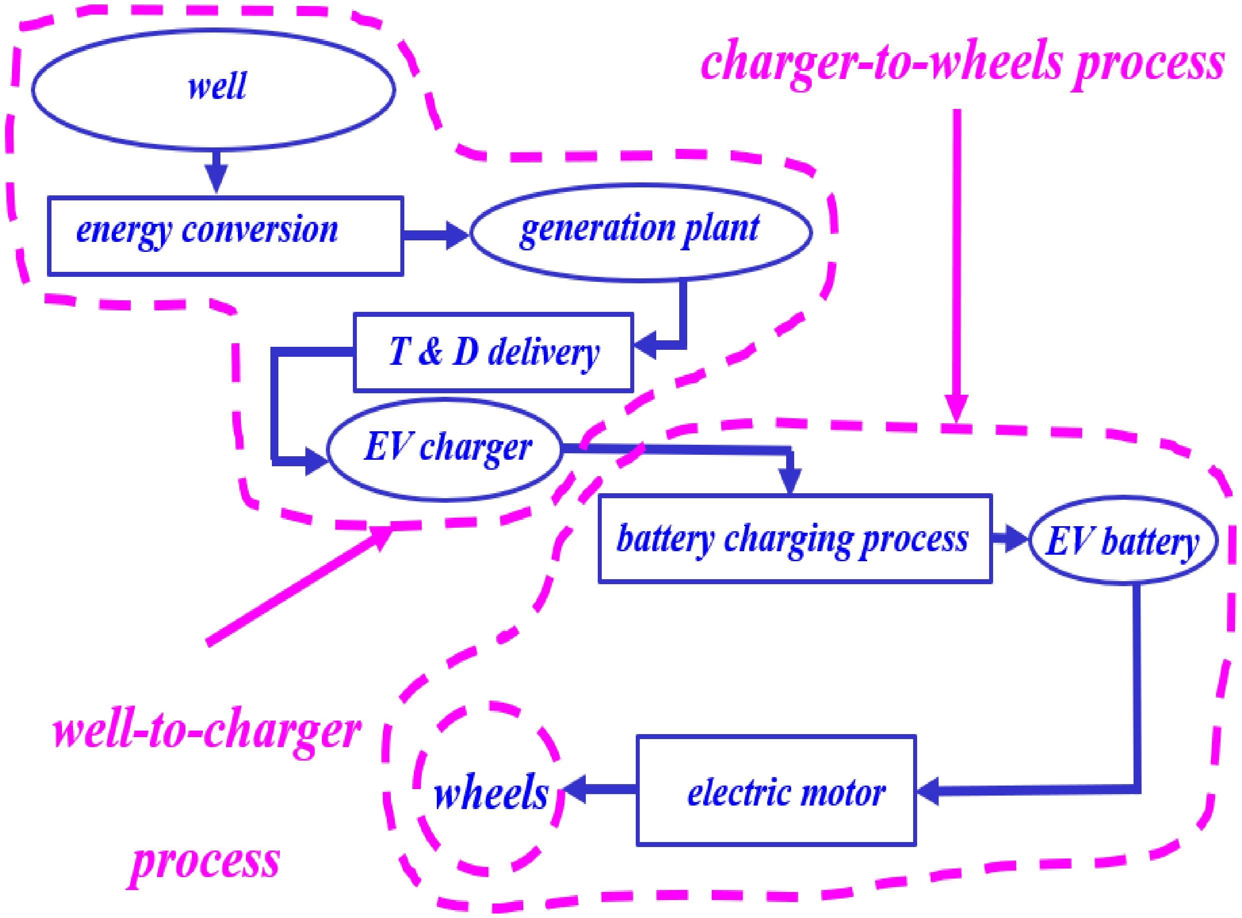


Figure 5: The *EV w-t-w* process

## 2.2 The *FCV w-t-w* process

*The FCV w-t-w* process is decomposed in two components: *well-to-tank* and *tank-to-wheels*. For simplicity, we assume that the $H_2$ production plant is placed at the distribution terminal. $H_2$ can be produced among a wide range production methods: steam methane reforming (*SMR*) with and without carbon capture utilization and storage (*CCUS*), gasification of coal with and without *CCUS,* and electrolysis that uses wind, solar or nuclear energy for generation of electricity. We assume that $H_2$ is produced at 20 *bar*s at the distribution terminal and it is either liquified or compressed so it can be loaded into compressed gaseous tube-trailers or cryogenic-liquid tankers for transportation to the refueling station.

Once the $H_2$ arrives to the refueling station, $H_2$ undergoes to a series of subprocesses depending on the $H_2$ delivery form in order to reach 700 *bar*s and -40 *ºC* before it is dispensed into the *FCV* onboard storage tank. We denominate $H_2$ delivery and distribution to all subprocesses involved from the $H_2$ compression or liquefaction at the distribution terminal to the $H_2$ injection into the *FCV* onboard storage tank.

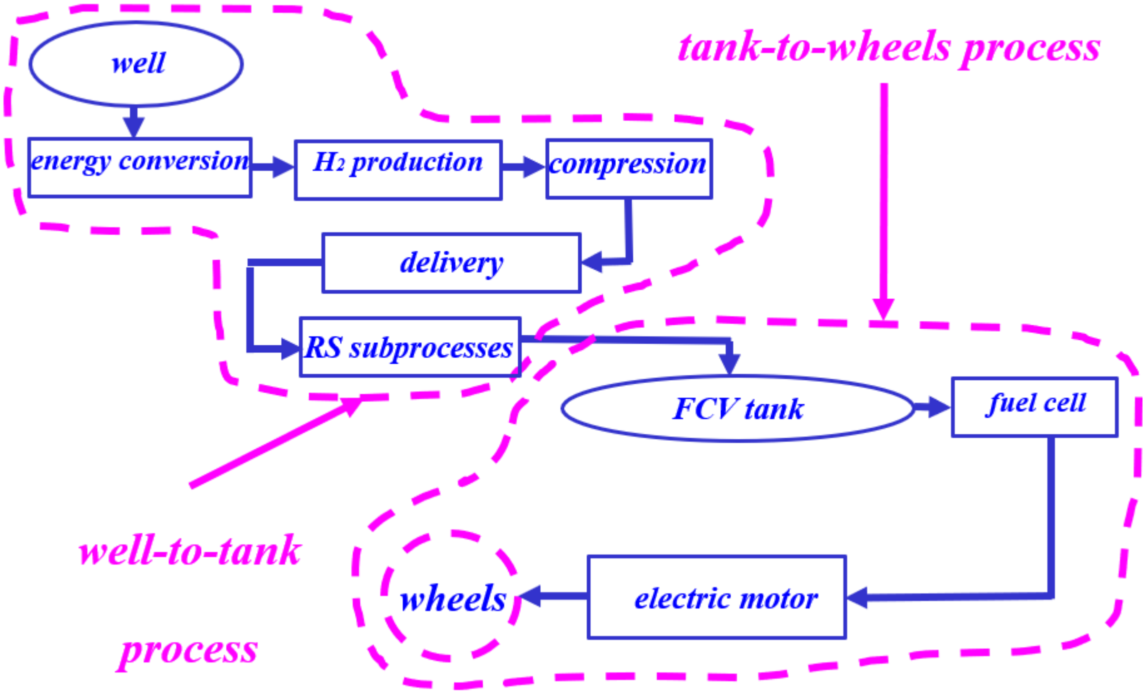


Figure 6: The *FCV w-t-w* process with gaseous $H_2$ delivery and distribution

In figure 6, we observe that for $H_2$ gaseous delivery, $H_2$ is compressed to a pressure of 200 *bar*s and loaded onto tube-trailers. The tube-trailer at the refueling station supplies $H_2$ to a gaseous compressor that compresses $H_2$ up to 700 *bar*s and $H_2$ is stored in a high-pressure buffer storage. When the $H_2$ needs to be dispensed into the *FCV* onboard storage tank it is precooled as cold as -40 °*C* to prevent overheating in the vehicle tank.

In figure 7, we note that for $H_2$ delivery, $H_2$ is liquified using liquid nitrogen to precool $H_2$ from ambient temperatures to 80 *K*, followed by a series of compression and expansion processes to reach cryogenic temperatures at 20 *K* needed for $H_2$ liquefaction. Then, liquid $H_2$ is loaded onto cryogenic tanker trucks. Liquid $H_2$ is stored at the refueling station´s cryogenic storage at a pressure between 2-8 *bar*s. Liquid $H_2$ is compressed up to 700 *bar*s by the high-pressure pump and before it is dispensed to the vehicle´s tank, the vaporizer heats $H_2$ up to -40 °*C*.

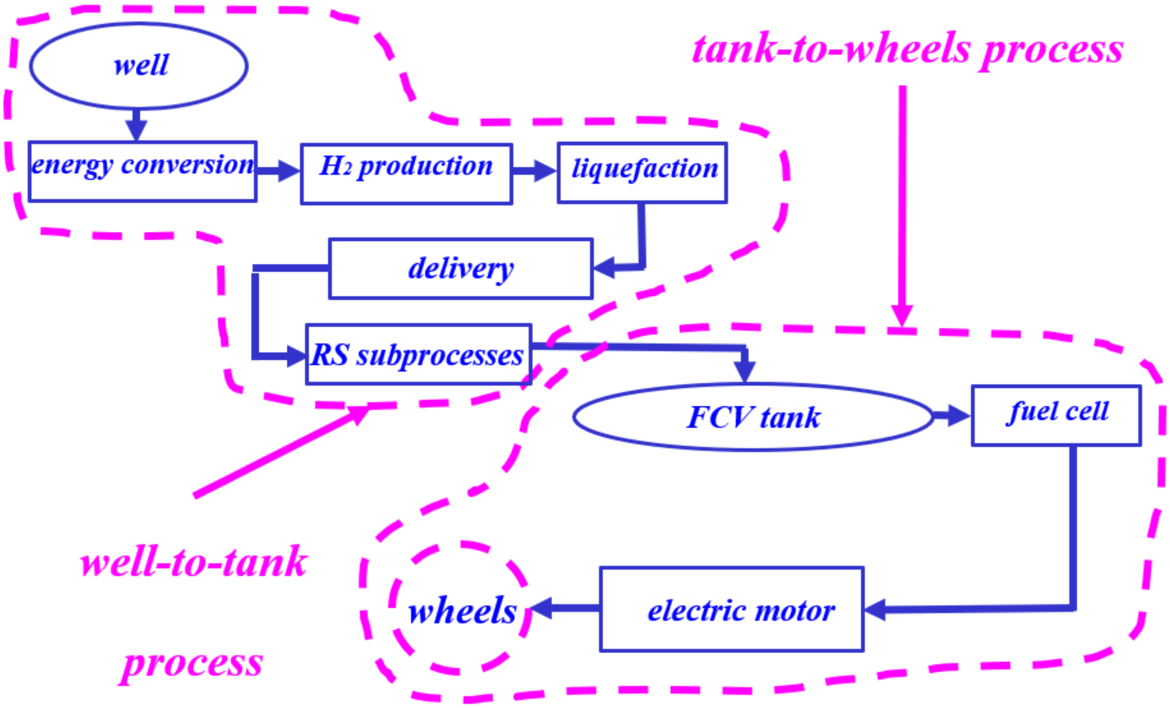


Figure 7: The *FCV* *w-t-w* process with liquid $H_2$ delivery and distribution

We evaluate the case of $H_2$ produced by electrolysis that uses nuclear energy for generation of electricity.The efficiency of a modern nuclear power plant is 39 *%* [24]. We use Polymer electrolyte membrane (*PEM*) electrolyser for the $H_2$ production that has an operating efficiency of 85 % [25]. Once the $H_2$ is produced it is liquified in order to be transported to the refueling station. The $H_2$ liquefaction is an energy intensive process and its efficiency is around 75 % [26]. The $H_2$ transportation to the refueling station by cryogenic-liquid has an efficiency of 99 % [26]. Once the $H_2$ arrives to the refueling station it undergoes to a series a subprocesses which have an efficiency of 80 %, in order to reach 700 *bar*s and -40 °*C* before it is dispensed into the *FCV* onboard storage tank [27].

In this sense, the efficiency of the *FCV well-to-tank* process is:

$$0.39 \times 0.85 \times 0.75 \times 0.99 \times 0.8 = 0.197$$

W note that the *well-to-tank* efficiency is 19.7 %. In analogy with *EV w-t-w* efficiency, we evaluate the *FCV w-t-w* efficiency in terms of a selected *FCV-Toyota Mirai XLE*. The overall *tank-to-wheel* efficiency of *Toyota Mirai XLE* is 64.7 % [27].

In this sense, we conclude that the analogue *FCV w-t-w* efficiency is:

$$0.197 \times 0.647 = 0.128$$

We conclude that the *FCV w-t-w* efficiency is 12.8 % in terms of a selected *FCV-Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for generation of electricity and liquid $H_2$ delivery and distribution.

## 2.3 Concluding remarks

The *EV* and *FCV w-t-w* processes involves a sequence of subprocesses, each of which incurs a loss of energy and consequently impacts the overall efficiency of the process. We conclude that the *EV w-t-w* efficiency is 38.5 % in terms of a selected *EV-Tesla model* 3 *LR* and electricity supply generation by a *CCNG* plant. We also conclude that the *FCV w-t-w* efficiency is 12.8 % in terms of a selected *FCV-Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for generation of electricity and liquid $H_2$ delivery and distribution. We stress that we do not generalize the ratio between the efficiencies of both *w-t-w* processes since we used a selected case for the *EV* and *FCV w-t-w* processes.

# CHAPTER 3

# FUEL ECONOMY AND ENVIRONMENTAL IMPACT ASSESSMENTS

In the previous chapter, we explain in detail the chain of processes through each energy changes from the generation source to the wheels in the *EV w-t-w* process. The *EV* and *FCV w-t-w* processes comprise a sequence of subprocesses, each of which incurs a loss of energy and consequently impacts the overall efficiency of the process. In this chapter, we evaluate the energy uses and *GHG* emissions associated with each subprocess involved in the *EV* and *FCV w-t-w* processes.

Analogously to the *EV w-t-w* efficiency study, we evaluate the energy uses and *GHG* emissions in terms of a selected *EV-Tesla Model* 3 *LR*. We assess the case of electricity supply from the electricity resource mix of the selected *US states*: *CA*, *FL*, *IL* and *NY*.

In analogy with the *FCV w-t-w* efficiency evaluation, we assess the energy uses and *GHG* emissions in terms of a selected *FCV-Toyota Mirai XLE*. We evaluate the $H_2$ produced by selected methods: *SMR* with and without *CCUS*, the gasification of coal with and without *CCUS*, and electrolysis that uses wind, solar or nuclear energy for generation of electricity. We also assess the gaseous and liquid $H_2$ delivery and distribution.

## 3.1 *EV* evaluation of the fuel economy and environmental impact

We evaluate the *GHG* emissions associated with the electricity grid resource mix of each selected *US state* in which we provide *EV* environmental results. We ignore the temporal variation of the electricity grid resource mix and assume the average value of the *GHG* emissions over the year. In this sense, we want to stress that for calculation purposes the average value of the *GHG* emissions over the year does not necessarily correspond to any physical location in the selected *US states*. However, we note that use of such average value of the *GHG* emissions for calculations seems reasonable since over the long run, the *EV* is likely to be charged at different times a day, and, therefore, the *GHG* emissions associated with the electricity used to charge the *EV* will tend to the average *GHG* emissions value associated with the production of each unit of electricity from the electricity resource grid mix.

Table 1. *GHG* emissions in *kg* $CO_2$e per *kWh* of generation in selected *US states* in 2020 [28].

| *US state* | *GHG* emissions in *kg* $CO_2e$ |
|---|---|
| *CA* | 0.205 |
| *FL* | 0.382 |
| *IL* | 0.252 |
| *NY* | 0.189 |

We stress that we use the *GHG* emissions associated with the electricity grid resource mix of each selected *US* state in 2020 since it is the last year with available data. We note that *NY* has the least *GHG* emissions associated with each unit of electricity.

We can reasonably assume that the energy requirements to manufacture an *EV* and those for other *FCV* are rather comparable. However, the manufacture of the *EV* battery requires a considerable amount of energy and entails the associated *GHG* emissions to provide this energy. *Tesla Model* 3 *LR* has a battery pack with a storage capability of 54 *kWh* and the *GHG* emissions associated with the manufacture of the battery pack are 2.7 *kg* $CO_2e$ / 100 *mi* [21]. The fuel economy of *Tesla Model* 3 *LR* is 25 *kWh*/100 *mi* [21].

## 3.2 *FCV* evaluation of the fuel economy and environmental impact

We assess the energy uses and *GHG* emissions associated with the selected $H_2$ production methods and $H_2$ gaseous and liquid delivery and distribution. In the case of the energy uses of $H_2$ production we evaluate for the fuel economy the energy associated with 1 *kg* $H_2$ production from electrolysis that uses solar, wind, or nuclear energy for generation of electricity. In this sense, electrolysis for $H_2$ production uses an overall energy requirement of 51.2 *kWh* assuming an efficiency of 85 *%* [25].

Table 2. *GHG* emissions in *kg* $CO_2e$ per *kg* $H_2$ of generation by selected $H_2$ production methods [25]

| $H_2$ production method | *GHG* emissions in *kg* $CO_2e$ |
|---|---|
| *SMR* | 12.82 |
| *SMR* with *CCUS* | 4.95 |
| coal gasification | 20.47 |
| coal gasification with *CCUS* | 3.01 |
| electrolysis that uses solar energy for generation of electricity | 2.21 |
| electrolysis that uses wind energy for generation of electricity | 0.88 |
| electrolysis that uses nuclear energy for generation of electricity | 0.76 |

In table 2, we evaluate the *GHG* emissions associated with the selected $H_2$ production methods in which we provide *FCV* environmental results. We note that $H_2$ produced from the coal gasification, brown $H_2$, has the largest *GHG* emissions followed by *SMR*. However, when the coal gasification and *SMR* and combined with *CCUS*, we note a notable decrease in the *GHG* emissions. We also observe that $H_2$ produced by electrolysis that uses solar, wind, or nuclear energy for generation of electricity has the fewest *GHG* emissions.

In the previous chapter, we explain in detail the *FCV well-to-tank process* which involves a series of subprocesses which incur in energy uses and consequently have environmental and economic impacts. In this sense, we asses the energy uses in 1 *kg* of $H_2$ gaseous and liquid delivery and distribution.

Table 3. Energy uses for 1 *kg* gaseous $H_2$ delivery and distribution [27]

| subprocess step | energy in *kWh* required |
|---|---|
| compression at distribution terminal | 2.58 |
| compression at refueling station | 1.21 |
| pre-cooling | 0.63 |
| entire process | 4.42 |

The *GHG* emissions associated with $H_2$ delivery and distribution include the *GHG* emissions associated with the electricity used to liquify or compress $H_2$ in order to be transported to the refueling station, the *GHG* emissions associated with the gasoline fuel burned by the trucks during

$H_2$ transportation and the emissions associated with the $H_2$ refueling station processes before $H_2$ is dispensed into the *FCV* onboard storage tank.

In table 3, we note that the electricity used in all subprocesses involved in 1 *kg* gaseous $H_2$ delivery and distribution is 4.42 *kWh*. We use the *CA* electricity grid resource mix to compute the *GHG* emissions for 1 *kg* gaseous $H_2$ delivery and distribution which are 0.9 *kg* $CO_2e$. Then we add the *GHG* emissions due to the $H_2$ transportation from the production plant to the refueling station. We assume that the distance between the production plant and the refueling station is 100 *mi*. In this sense the *GHG* emission due to the 1 *kg* $H_2$ transportation are 0.15 *kg* $CO_2$e [27]. We conclude that *GHG* emissions for gaseous 1 *kg* of $H_2$ delivery and distribution are 1.06 *kg* $CO_2$e.

In table 4, we observe that the electricity used in all processes involved in the liquid $H_2$ delivery and distribution is 12.63 *kWh* /*kg* $H_2$. We note that the electricity used for liquid $H_2$ delivery and distribution is 3 times above the gaseous $H_2$ delivery and distribution. The $H_2$ liquefaction is an energy intensive process hence the 12 *kWh* required to liquify 1 *kg* of $H_2$.

Table 4. Energy uses for 1 *kg* liquid $H_2$ delivery and distribution [27]

| subprocess step | energy required in *kWh* |
|---|---|
| liquefaction at distribution terminal | 12 |
| compression at distribution terminal | 0.08 |
| compression at refueling station | 0.55 |
| entire process | 12.63 |

We also use the *CA* electricity grid resource mix to compute the *GHG* emissions for 1 *kg* liquid $H_2$ delivery and distribution which are 2.59 *kg* $CO_2e$. In analogy with the gaseous $H_2$ gaseous delivery and distribution, we add the emissions due to the $H_2$ transportation from the distribution terminal to the refueling station. We conclude that the total *GHG* emissions for 1 *kg* liquid $H_2$ delivery and distribution are 2.74 *kg* $CO_2e$.

We note that the *GHG* emissions for 1 *kg* liquid $H_2$ delivery and distribution are nearly 3 times above than for 1 *kg* gaseous $H_2$ delivery and distribution. As previously mentioned the $H_2$ liquefaction comprises major part of the *GHG* emissions.

The average fuel economy of *Toyota Mirai XLE* taking into account the efficiency of the *tank-to-wheels* process is 0.88 *kg* $H_2$ / 100 *mi* [29].

## 3.3 Concluding remarks

Analogously to the *EV w-t-w* efficiency study, we evaluate the energy uses and *GHG* emissions in terms of a selected *EV-Tesla Model* 3 *LR*. We assess the case of electricity supply from the electricity resource mix of the selected *US states*: *CA*, *FL*, *IL* and *NY*. We note that *NY* has the least *GHG* emissions associated with each unit of electricity. We ignore the temporal variation of the electricity grid resource mix and assume the average value of the *GHG* emissions, since, over the long run, the *EV* is likely to be charged at different times a day. In this sense, the *GHG* emissions associated with the electricity used to charge the *EV* will tend to the average *GHG* emissions value associated with the production of each unit of electricity from the electricity resource grid mix.

In analogy with the *FCV w-t-w* efficiency evaluation, we assess the energy uses and *GHG* emissions in terms of a selected *FCV-Toyota Mirai XLE*. We evaluate the energy uses and *GHG* emissions in selected $H_2$ production methods and gaseous and liquid $H_2$ delivery and distribution. We observe that $H_2$ produced by electrolysis that uses solar, wind, or nuclear energy for generation of electricity has the fewest *GHG* emissions among the selected $H_2$ production methods. We also note that the energy uses for 1 *kg* liquid $H_2$ delivery and distribution are nearly 3 times above than for 1 *kg* gaseous $H_2$ delivery and distribution. We also note that the *GHG* emissions for 1 *kg* liquid $H_2$ delivery and distribution are twice larger than for 1 *kg* gaseous $H_2$ delivery and distribution.

# CHAPTER 4

# *EV* AND *FCV* ECONOMIC AND ENVIRONMENTAL COMPARATIVE ANALYSIS

In previous chapters, we evaluated the efficiency, energy uses and *GHG* emissions associated with each subprocess involved in the *EV* and *FCV* *w-t-w* processes. The *EV* and *FCV* *w-t-w* processes comprise a sequence of subprocesses, each of which incurs a loss of energy and consequently has economic and environmental impacts.

In order to make the results concrete in terms economic and environmental impacts, in this chapter we do our comparative analysis in terms of 100-*mi* travel of a selected *EV-Tesla Model* 3 *LR* and *FCV-Toyota Mirai XLE*.

Firstly, we calculate and compare the fuel costs i.e. the amount of energy in *kWh* that *Tesla Model* 3 *LR* and *Toyota Mirai XLE* use to travel 100 *mi*. Subsequently, we present the *GHG* emissions produced by the 100 *mi*-travel by *Tesla Model* 3 *LR* and *Toyota Mirai XLE*. In the case of *Tesla Model* 3 *LR* we present and compare environmental results in four selected *US states*: *CA*, *FL*, *IL* and *NY*. Next we examine and compare the environemntal results from *Toyota Mirai XLE* fueled by $H_2$ colors and gaseous and liquid $H_2$ delivery and distribution. Consequently, this report provides an comparative analysis of the environmental impacts produced by the 100-*mi* travel by *Tesla Model* 3 *LR* and *Toyota Mirai XLE*.

We recall that the transportation sector generates the largest share of *GHG* emissions in the *US*. More than 90 *%* of the fuel used for transportation is petroleum-based, which mainly includes gasoline and diesel fuel. In this sense, one of the contributions of this report is to analyze the role of *EV*s and *FCV*s in the *GHG* emissions reduction in the *US* transportation sector. On this basis, this report provides an environmental comparative analysis between *Tesla Model* 3 *LR*, *Toyota Mirai XLE* and *Mitsubishi Mirage* 2021.

## 4.1 Comparative fuel economy evaluation

We recall that the fuel economy of *Tesla Model* 3 *LR* is 25 *kWh* /100 *mi*. In this sense, this report considers two major loss associated with the energy loss during the distribution and transmission of the electricity and the loss associated with the *charger-to-wheels* process. The efficiency of the transmission and distribution grids to deliver the electricity from the generation sources to the *EV* charger is 95 *%* whereas the *charger-to-wheels* process in the *Tesla Model 3 LR* has an efficiency of 75 *%*. In this sense, the total electricity generated so as the *Tesla Model* 3 *LR* travels 100 *mi* is 35.08 *kWh*.

In the previous chapter, we evaluated that the fuel economy of *Toyota Mirai XLE* which is 0.88 *kg* $H_2$ / 100 *mi* taking into account the efficiency of the *tank-to-wheels* process. In addition, electrolysis for 1 *kg* $H_2$ production uses an overall energy requirement of 51.2 *kWh*. Then, the electricity used in all processes involved in 1 *kg* $H_2$ the gaseous delivery and distribution is 4.42 *kWh* while for 1 *kg* $H_2$ liquid delivery and distribution is 12.63 *kWh*. Therefore, we compute the total energy in *kWh* that it is needed for 0.88 *kg* $H_2$ production by electrolysis, delivery and distribution in both $H_2$ liquid forms. As a result, the electricity used in 0.88 *kg* of $H_2$ production, gaseous delivery and distribution is 48.95 *kWh* while in the 0.88 *kg* production, liquid delivery and distribution is 56.17 *kWh*. In this sense, the total electricity used for gaseous $H_2$ production by electrolysis, gaseous delivery and distribution so as the *Toyota Mirai XLE* travels 100 *mi* is 48.95 *kWh* while for liquid $H_2$ delivery and distribution is 56.17 *kWh*.

In light of our evaluation we conclude that *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis for gaseous delivery and distribution uses 40 *%* more electricity than *Tesla Model* 3 *LR* and 60 *%* more electricity for liquid $H_2$ delivery and distribution.

## 4.2 Comparative environmental impact evaluation

The electricity resource generation mix of each *US* state has major impacts on its corresponding *GHG* emissions for a 100-*mi* travel by an *EV*.

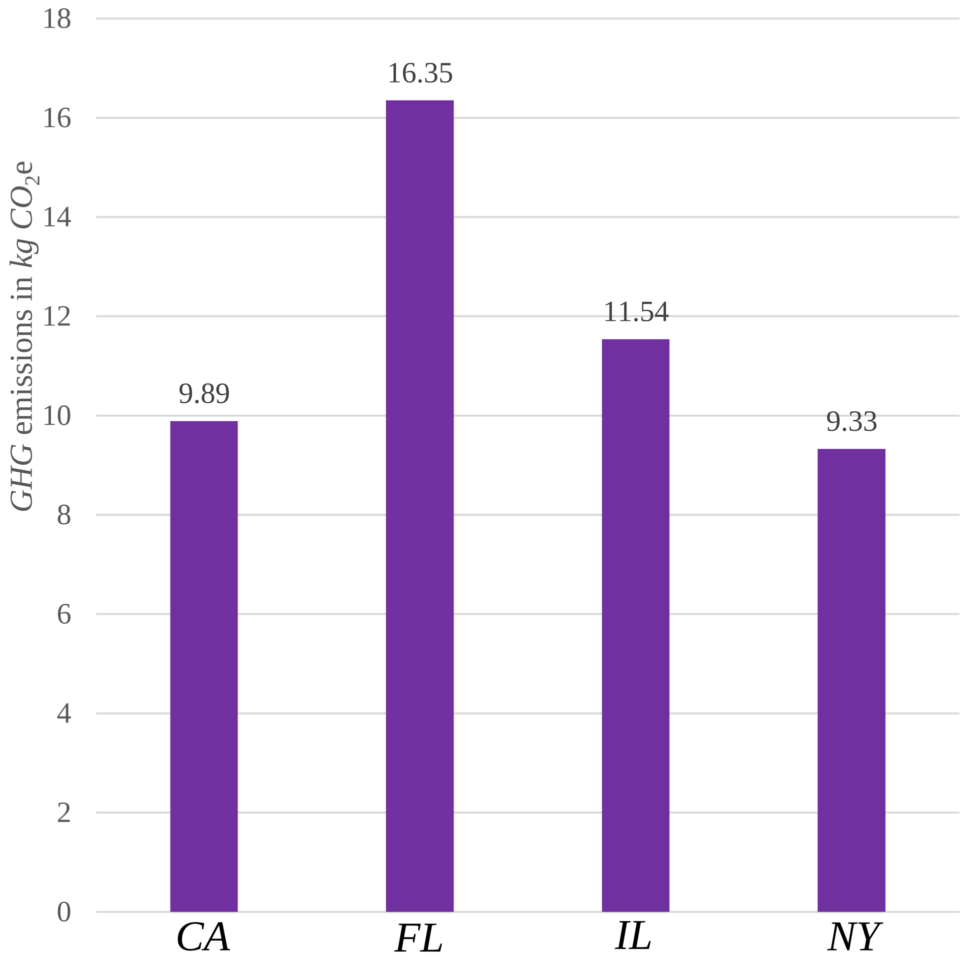


Figure 8: *GHG* emissions produced by 100-*mi* travel by *Tesla Model* 3 *LR* in selected *US states*

In figure 8, we note that among the selected *US states*, *NY* that the lowest *GHG* emissions while the largest are in *FL* under the assumption that the *EV* is charged with electricity produced by the state´s resource mix. We also observe that *GHG* emissions produced by 100-*mi* travel by *Tesla Model* 3 *LR* in *CA* are close to those in *NY* while The *GHG* emissions in *IL* are between those in *CA* and *FL*.

We illustrate the *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by $H_2$ colors and gaseous $H_2$ delivery and distribution. We note that there exist significant differences in the *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by $H_2$ colors. We note that *Toyota Mirai XLE* powered by the coal gasification, brown $H_2$, has the largest *GHG* emissions followed by *SMR*, gray $H_2$. However, we also observe that when *SMR* and combined with *CCUS*, blue $H_2$ and coal gasification and combined with *CCUS*, blue´ $H_2$, there is a significant decrease in *GHG* emissions. Indeed, coal gasification and combined with *CCUS* has more than 5 times fewer *GHG* emissions while *SMR* and combined with *CCUS* has more than twice fewer *GHG* emissions. Also, *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis has very few *GHG* emissions. Therefore, among *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses solar energy for electricity generation, green $H_2$, has the largest *GHG* emissions while wind energy for electricity generation, green´ $H_2$, and nuclear energy for electricity generation, green´´ $H_2$, have comparable *GHG* emissions.

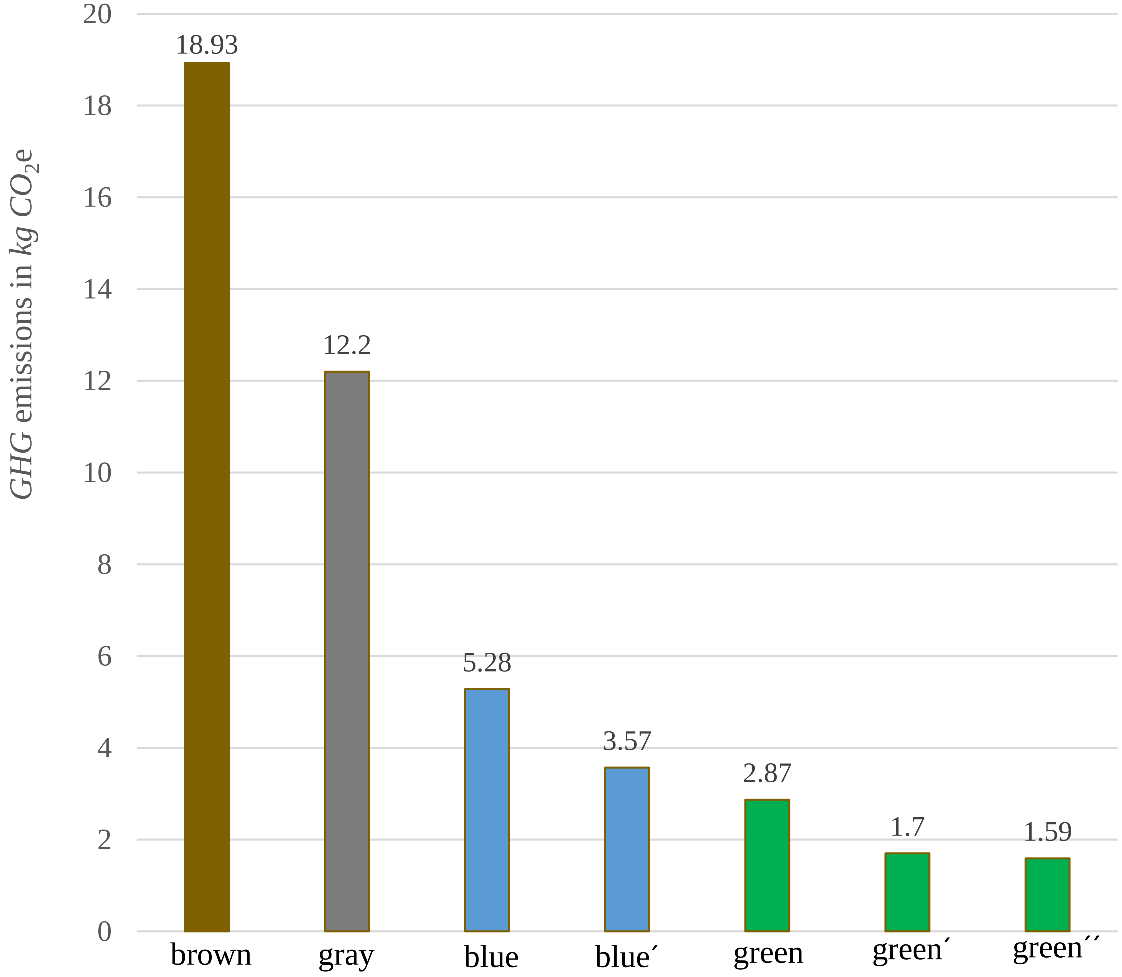


Figure 9: *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by $H_2$ colors and gaseous $H_2$ delivery and distribution

We illustrate in figure 10 the *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by $H_2$ colors and liquid $H_2$ delivery and distribution. In analogy with the gaseous $H_2$ delivery and distribution, we note that there exist significant differences in the *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by $H_2$ colors. In comparison to the gaseous $H_2$ delivery and distribution, there are no major differences in the *GHG* emissions when *Toyota Mirai XLE* is fueled by $H_2$ produced by *SMR* and the coal gasification. However, we note than when *Toyota Mirai XLE* is fueled by $H_2$ produced by electrolysis that uses solar, wind, or nuclear for electricity generation the *GHG* emissions are twice above for liquid $H_2$ delivery and distribution than for gaseous $H_2$ delivery and distribution. We use the same $H_2$ color code than in the case of gaseous delivery and distribution

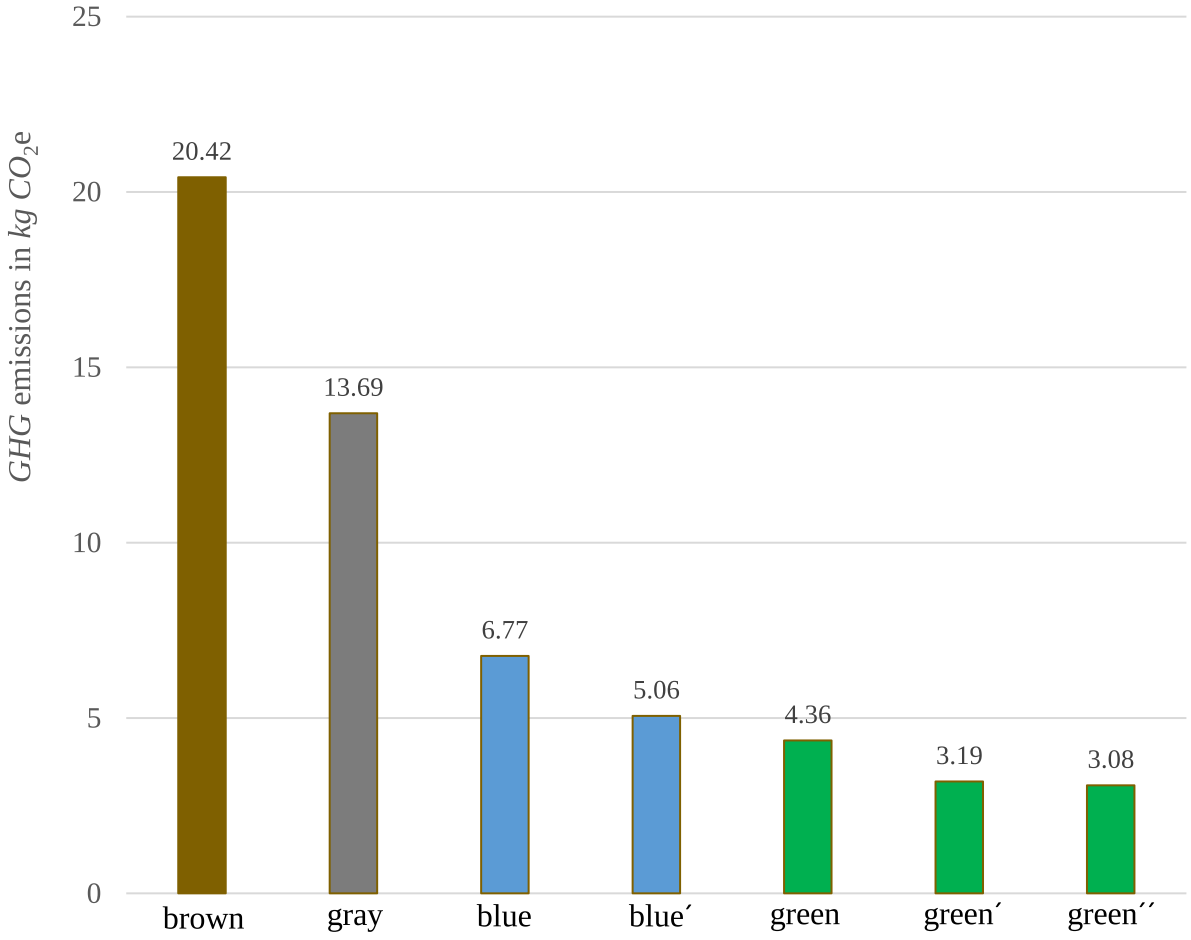


Figure 10: *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by $H_2$ colors and liquid $H_2$ delivery and distribution

Table 5. *GHG* emissions produced by 100-*mi* travel by *Tesla Model* 3 *LR* in selected *US states*

| *US state* | *GHG* emissions in *kg* $CO_2e$ |
|---|---|
| *CA* | 9.89 |
| *FL* | 16.35 |
| *IL* | 11.54 |
| *NY* | 9.33 |

Table 6. *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by selected $H_2$ production methods and gaseous $H_2$ delivery and distribution

| $H_2$ production method | *GHG* emissions in *kg* $CO_2$e |
|---|---|
| *SMR* | 12.82 |
| *SMR* with *CCUS* | 5.28 |
| coal gasification | 18.93 |
| coal gasification with *CCUS* | 3.57 |
| electrolysis that uses solar energy for generation of electricity | 2.87 |
| electrolysis that uses wind energy for generation of electricity | 1.7 |
| electrolysis that uses nuclear energy for generation of electricity | 1.59 |

Table 7. *GHG* emissions produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by selected $H_2$ production methods and liquid $H_2$ delivery and distribution

| $H_2$ production method | *GHG* emissions in *kg* $CO_2$e |
|---|---|
| *SMR* | 13.69 |
| *SMR* with *CCUS* | 6.77 |
| coal gasification | 20.42 |
| coal gasification with *CCUS* | 5.06 |
| electrolysis that uses solar energy for generation of electricity | 4.36 |
| electrolysis that uses wind energy for generation of electricity | 3.19 |
| electrolysis that uses nuclear energy for generation of electricity | 3.08 |

In table 5, we summarize the environmental results produced by 100-*mi* travel by *Tesla Model* 3 *LR* in selected *US states*. In table 6 and 7, we summarize the environmental results produced by 100-*mi* travel by *Toyota Mirai XLE* fueled by $H_2$ colors and gaseous and liquid $H_2$ delivery and distribution.

We observe that *Toyota Mirai XLE* fueled by coal gasification in both gaseous and liquid $H_2$ delivery and distribution has more *GHG* emissions than *Tesla Model* 3 *LR* in each of the selected *US state*. Also, *Toyota Mirai XLE* fueled by *SMR* has more *GHG* emissions than *Tesla Model* 3 *LR* in each of the selected *US* except *FL*. However, when the $H_2$ production based on fossil-fuel-produced electricity and combined with *CCUS*, there is a significant decrease in *GHG* emissions. As such, the *Toyota Mirai XLE* fueled by blue and blue´ $H_2$ has fewer *GHG* emissions than *Tesla Model* 3 *LR* in each of the selected *US* state.

We note that *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis has much fewer *GHG* emissions than *Tesla Model* 3 *LR* in each of the selected *US* state. Indeed, we note that for gaseous $H_2$ delivery and distribution, *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for electricity generation has 6 times fewer *GHG* emissions than *Tesla Model* 3 *LR* powered by *CA* and *NY* electricity grid resource mix and 7 and 10 times fewer *GHG* emissions than *Tesla Model* 3 *LR* powered by *IL* and *FL* respectively.

Similarly, for liquid $H_2$ delivery and distribution *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for electricity generation has 3 times fewer *GHG* emissions than *Tesla Model* 3 *LR* powered by *CA* and *NY* electricity grid resource mix and 3.5 and 4 times fewer *GHG* emissions than *Tesla Model* 3 *LR* powered by *IL* and *FL* respectively.

In Appendix B, we evaluate the *GHG* emissions of *Mitsubishi Mirage* 2021 and determine that value for 100-*mi* travel by *Mitsubishi Mirage* 2021 *is* 22.27 *kg* $CO_2$e. We note that *Tesla Model* 3 *LR* has considerably fewer *GHG* emissions in each of the selected *US state*. Also, we note that *Toyota Mirai XLE* powered by any blue or green $H_2$ has significant fewer *GHG* emissions that *Mitsubishi Mirage*. In this sese, *Toyota Mirai XLE* powered by blue $H_2$ has on average 4 times fewer *GHG* emissions. Also, we note that for gaseous $H_2$ delivery and distribution *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for electricity generation has 14 times fewer *GHG* emissions than *Mitsubishi Mirage* 2021.

## 4.3 Concluding remarks

We conclude that *Toyota Mirai XLE* powered by $H_2$ produced for electrolysis and gaseous $H_2$ delivery and distribution uses 40*%* more electricity than *Tesla Model* 3 *LR* and 60 *%* more electricity for liquid $H_2$ delivery and distribution. We note that *Toyota Mirai XLE* powered by $H_2$ except from $H_2$ production fossil fuels-based has fewer *GHG* emissions than *Tesla Model* 3 *LR* in each selected *US state*. Particularly, *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis has the fewest *GHG* emissions. In comparison to *Mitsubishi Mirage, Tesla Model* 3 *LR* has considerably fewer *GHG* emissions in each selected *US* state while *Toyota Mirai XLE* powered by electrolysis that uses nuclear energy for electricity $H_2$ has on average 10 times fewer emissions.

# CHAPTER 5

# CONCLUDING REMARKS

The transportation sector in the *US* has become the biggest *GHG* emitting sector due to the use of mostly petroleum-based fuel. In particular, the light-duty vehicles account for 60 % of the *GHG* emissions in the transportation sector in the *US*. This report provides *EV* and *FCV* comparative analysis in terms of efficiency and economic and environmental impact. To make our results concrete, we provide our comparative analysis in terms of selected *EV-Tesla Model* 3 *LR* and *FCV-Toyota Mirai XLE*.

The *w-t-w* structure was originally introduced to evaluate *ICEV* efficiency; the process is applied, with small modifications, to assess *EV* and *FCV* efficiency. The *w-t-w* process involves a sequence of subprocesses, each of which incurs a loss of energy and consequently impacts the overall efficiency of the process. The *EV w-t-w* process can be decomposed in two components: *well-to-charger* subsystem and *charger-to-wheels* subsystem. We describe in detail the *EV w-t-w* process which starts at the well and its energy conversion to generate electricity that charges the *EV* battery which supplies the electric motor that moves the wheels of the *EV*. Similarly, we explain the *FCV w-t-w* process which can be decomposed in two components: *well-to-tank* and *tank-to-wheels*. In this sense, we describe in detail the chain of processes through each energy changes from the $H_2$ production to *FCV* onboard storage tank

We evaluate the energy uses and *GHG* emissions associated with each subprocess involved in the *EV* and *FCV w-t-w* processes. Analogously to the *EV w-t-w* efficiency assessment, we evaluate the energy uses and *GHG* emissions in terms of a selected *EV-Tesla Model* 3 *LR*. We evaluate the case of electricity supply from the electricity resource mix of the selected *US states*: *CA*, *FL*, *IL* and *NY*. In analogy with the *FCV w-t-w* efficiency evaluation, we assess the energy uses and *GHG* emissions in terms of a selected *FCV-Toyota Mirai XLE*. We evaluate the $H_2$ produced by selected methods: *SMR* with and without *CCUS*, the gasification of coal with and without *CCUS* and electrolysis that uses wind, solar or nuclear energy for generation of electricity. We also assess the gaseous and liquid $H_2$ delivery and distribution.

## 5.1 Summary of contributions

We conclude that the *EV w-t-w* efficiency is 38.5 *%* in terms of a selected *EV-Tesla model* 3 *LR* and electricity supply generation by a combined cycle natural gas (*CCNG*). We also conclude that the *FCV w-t-w* efficiency is 12.8 *%* in terms of a selected *FCV-Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis that uses nuclear energy for generation of electricity and liquid $H_2$ delivery and distribution.  We stress that we do not generalize the ratio between the efficiencies of both *w-t-w* processes since we used a selected case for the *EV* and *FCV w-t-w* processes.

We assess the case of electricity supply to charge the *EV* from the electricity resource mix of the selected *US states*: *CA*, *FL*, *IL* and *NY*. We note that *NY* has the least *GHG* emissions associated with each unit of electricity. We ignore the temporal variation of the electricity grid resource mix and assume the average value of the *GHG* emissions since over, the long run, the *EV* is likely to be charged at different times a day. In this sense the *GHG* emissions associated with the electricity used to charge the *EV* will tend to the average *GHG* emissions value associated with the production of each unit of electricity from the electricity resource grid mix.

In analogy with the *FCV w-t-w* efficiency evaluation, we assess the energy uses and *GHG* emissions in terms of a selected *FCV-Toyota Mirai XLE*. We evaluate the energy uses and *GHG* emissions in selected $H_2$ production methods and gaseous and liquid $H_2$ delivery and distribution. We observe that $H_2$ produced by electrolysis that uses solar, wind or nuclear energy for generation of electricity has the fewest *GHG* emissions among the selected $H_2$ production methods. We also note that the *GHG* emissions for 1 *kg* liquid $H_2$ delivery and distribution are nearly 3 times above than for 1 *kg* gaseous $H_2$ delivery and distribution the energy uses and *GHG* emissions in the gaseous and liquid $H_2$ delivery and distribution.

We conclude that *Toyota Mirai XLE* powered by $H_2$ production by electrolysis for gaseous $H_2$ delivery and distribution uses 40 *%* more  electricity than *Tesla Model* 3 *LR* and 60 *%* more electricity for liquid $H_2$ delivery.

We note that the lowest *GHG* emission impacts produced by the 100-*mi* travel by *Tesla Model* 3 *LR* are in *NY* while the highest are in *FL* under the assumption that the *EV* is charged with electricity produced by  t notable reduction in *GHG* emissions by *Toyota Mirai XLE* powered by state´s resource mix. We note that *Toyota Mirai XLE* powered by $H_2$ except from $H_2$ production fossil fuels-based has fewer *GHG* emissions than *Tesla Model* 3 *LR* in each selected *US state*. However, we also observe that when *SMR* and combined with *CCUS* , blue $H_2$ and coal gasification and combined with *CCUS*, blue´ $H_2$, there is a significant decrease in *GHG* emissions. As such, *Toyota Mirai XLE* powered by any blue $H_2$ has fewer emissions than *Tesla Model* 3 *LR*. We also notice an increase in the *GHG* emissions impact of *Toyota Mirai XLE* for the liquid $H_2$ delivery and distribution. *Toyota Mirai XLE* fueled by $H_2$ produced by electrolysis has the fewest *GHG* emissions. Indeed, *Toyota Mirai XLE* powered by $H_2$ produced by electrolysis that uses nuclear or wind energy for electricity generation and gaseous $H_2$ delivery and distribution have 6 times fewer *GHG* emissions than *Tesla Model* 3 *LR* powered by *CA* and *NY* electricity grid resource mix and 7 and 10 times fewer *GHG* emissions than *Tesla Model* 3 *LR* powered by *IL* and *FL* electricity grid resource mix respectively.

In comparison to *Mitsubishi Mirage, Tesla Model* 3 *LR* has considerably fewer *GHG* emissions in each selected *US* state while *Toyota Mirai XLE* powered by $H_2$ produced by electrolysis that uses nuclear or wind energy for electricity generation and gaseous $H_2$ delivery and distribution has 10 times fewer *GHG* emissions.

This report developed the basis to effectively affirm that *EV*s and *FCV*s reduce significantly the *GHG* emissions emitted by *ICEV*s. In this sense, the implementation on large scale of *EV*s and *FCV*s will be necessary to decarbonize the transportation sector in the *US*.

## 5.2 Directions for future research

The implementation of *EV* and *FCV* on large scale will be necessary to reduce significantly the *GHG* emissions in the transportation sector. The deployment of renewable and nuclear energy resources is necessary in order to have fewer emissions associated with the electricity grid resource mix. This will imply fewer emissions associated with both *ZEV*s. The lack development of large-scale batteries makes $H_2$ as a key component in the decarbonization of the industry and electrification of transportation. There is a massive amount of energy that is wasted during off-peaks at renewable power plants. A further study needs to focus on the feasibility to build $H_2$ production plants next to renewable power plants and compute the amount of green $H_2$ could be produce by the renewable energy that is wasted at off-peaks.

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# APPENDIX A: ACRONYMS

| | |
|---|---|
| *WHO* | World Health Organization |
| *GHG* | Greenhouse gas |
| $CO_2$ | carbon dioxide |
| $CO_2$e | carbon dioxide equivalent |
| *GWP* | global warming potential |
| *IEA* | Internation Energy Agency |
| *ZEV*s | zero emissions-vehicles |
| *EV*s | electric vehicles |
| *FCV*s | fuel cell vehicles |
| $H_2$ | hydrogen |
| *CA* | California |
| *FL* | Florida |
| *IL* | Illinois |
| *NY* | New York |
| *w-t-w* | well-to-wheels |
| *SMR* | steam methane reforming |
| *CCUS* | carbon capture utilization and storage |
| *ICEV*s | internal combustion engine vehicles |
| *PEM* | Polymer electrolyte membrane |
| *CCNG* | combined cycle natural gas |
| *EIA* | U.S. Energy Information Administration |
| *NASA* | National Aeronautics and Space Administration |
| *IMF* | International Monetary Fund |
| *UN* | United Nations |
| *EPA* | U.S. Environmental Protection Agency |
| *NASEM* | National Academies of Sciences, Engineering, and Medicine |
| $CH_4$ | methane |
| $N_2O$ | nitrous oxide |

# APPENDIX B: *GHG* EMISSION IMPACT EVALUATION OF THE *MITSUBISHI MIRAGE*

We compute the *GHG* emissions produced by 100-*mi* travel by *Mitsubishi Mirage*. In this sense, we convert the atmospheric impact of methane ($CH_4$) and nitrous oxide ($N_2O$) based on its *GWP* to $CO_2$e. $CH_4$ and $N_2O$ have a *GWP* of about 25 and 298 respectively using a 100-*year* time horizon. A gasoline passengers car releases 0.0051 $g\ CH_4 / mi$ and 0.0015 $g\ N_2O / mi$ [30].

$$0.0051\ \frac{g\ CH_4}{mi} \times 25 = 0.1275\ \frac{g\ CO_2e}{mi}$$

$$0.0015\ \frac{g\ NO_2}{mi} \times 298 = 0.447\ \frac{g\ CO_2e}{mi}$$

Therefore, the sum of *GHG* emissions associated with $CH_4$ and $N_2O$ released by a passenger car are 0.5745 g $CO_2$e / *mi*. In this sense, in a 100 *mi*-travel *GHG* emissions associated with $CH_4$ and $N_2O$ released by a passenger car are 57.45 g $CO_2$e

Now we add the $CO_2$ emissions produced by 100-*mi* travel by *Mitsubishi Mirage*. $CO_2$ emissions from a gallon of gasoline: 8,887 grams $CO_2$ / *gal* [31]. *Mitsubishi Mirage* has a fuel economy of 40 *mpg*.

$$8{,}887\frac{g\ CO_2}{gal} \times \frac{1\ gal}{40\ mi} \times 100 = 22{,}220\ \frac{g\ CO_2}{100\ mi}$$

$CO_2$e represents the amount of a *GHG* whose atmospheric impact is standardized to that of 1 unit mass of $CO_2$. In this sense, we can add all the emissions. As a result, *GHG* emissions produced by 100-*mi* travel by *Mitsubishi Mirage* are 22,270 $g\ CO_2$e i.e. 22.27 $kg\ CO_2$e