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Comparative Well-to-Wheel Assessment of Conventional and Alternative Vehicles in Saudi Arabia, the UAE, Oman, and Yemen

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Abstract. This study investigates the well-to-wheel (WTW) environmental and water performance of conventional diesel ICE, hybrid electric vehicles, BEV, and FCV across Saudi Arabia, the UAE, Oman, and Yemen by using the GREET model. The climate change potential, respiratory effects, acidification, and water consumption per 100 km were evaluated. Clear country-dependent trends in vehicle performance can be seen. The FCVs show the smallest overall environmental impacts in Saudi Arabia, Oman, and Yemen, with values of 0.0089 Pt/100 km for climate change, 0.0075 Pt/100 km for respiratory effects, and 0.00046 Pt/100 km for acidification, while BEVs perform best in the UAE, reaching 0.0051 Pt/100 km for climate change, 0.0068 Pt/100 km for respiratory effects, and 0.00047 Pt/100 km for acidification due to its relatively cleaner electricity mix. Water consumption shows comparable variability, with the lowest value observed for Oman at 5.09 L/100 km and the highest for Yemen at 9.9 L/100 km, confirming that the environmental and water advantages of alternative vehicle technologies are strongly influenced by the country's energy and water resource characteristics.

Introduction

Among various sources, the transportation sector accounts for approximately a quarter of total energy-related CO_2 output and is one of the major sources of greenhouse gas (GHG) emissions globally [1] . However, the increasing number of vehicles and consumption of fuel make it more difficult to achieve global sustainability targets in this sector. Due to the increasing influence on the environment, governments and companies worldwide are searching for alternative propulsion technologies to reduce the use of fossil fuels and increase energy efficiency. Among these alternatives, hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs) have received considerable attention for their ability to reduce emissions from transportation [2] [3].

The benefit of new vehicle technologies regarding the environment differs per region. The use of electricity, energy, and transport policies, among other factors, influence the performance of a vehicle throughout its entire life cycle [4] [5]. For instance, in regions where fossil fuels are primarily used to generate electricity, the use of such electricity to charge battery electric vehicles may reduce the benefit of not emitting anything from the vehicle. This highlights the importance of conducting life cycle analyses, also known as cradle to grave (WTW) analyses.

The WTW framework examines the efficiency of energy use in a car throughout its entire life cycle. The WTW framework is divided into two broad areas: well-to-tank (WTT), which examines energy production and transport, and tank-to-wheel (TTW), which examines vehicle use [6]. TTW

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examines emissions from the tailpipe, while WTW examines total energy consumption and emissions. To gain a complete understanding of the environmental impact, WTW analysis must be incorporated into a larger life cycle assessment (LCA) that examines manufacturing and end of life impacts as well [7]. It is only by incorporating WTW analysis into LCA that we can compare the impacts of manufacturing versus emissions in use to gain a complete understanding of the sustainability of each technology [8] [9] .

The existing literature demonstrates that EVs significantly reduce emissions during operation but are more environmentally impactful during production due to the high energy required for producing lithium-ion batteries [7], [10]. For example, a study conducted by Ankathi et al. [10] and Dolganova et al. [8] indicates that battery production can account for approximately 10 to 394 kg CO_2-eq/kWh, depending on the type of battery chemistry and the mix of electricity. Moreover, Kurkin et al. [7] concluded that electric vehicles can require up to six times more natural resources than ICE vehicles, emphasizing the importance of material efficiency and recycling. On the other hand, in those situations where the electricity is supplied from renewable energy sources, large overall emissions reductions can be found for BEVs. For instance, Oliveri et al. [11] showed that adding solar power to logistics operations could cut BEV life-cycle impacts in half.

Thus, much of the electric vehicles' performance depends on how clean the electricity used is. BEVs outcompete gasoline powered cars in China only in those provinces where over half of the grid is powered by renewables up to 18.32 tons of CO_2 saved per vehicle. In Australia, with cleaner electricity grids, BEVs cut greenhouse gas emissions by as much as 80%. These findings suggest that it is not possible to reduce transport emissions without reducing carbon intensity in the production of electricity [4] [5].

While extensive research is being carried out in Europe, China, and North America, comparative studies of WTW emissions are very limited in the Middle East. Here, most of the electrical power comes from fossil fuels, but renewable projects are also emerging. The abundance of oil and gas resources, combined with increasing electricity consumption and rapidly growing renewable energy sources, turns the region into a unique location to assess the environmental impact of new vehicle technologies. Problems for electric vehicles in Jordan include a lack of charging infrastructure, high purchase costs, and low economic incentives. Similar issues exist in neighboring MENA countries, such as Morocco. Therefore, a study examined low-carbon alternative fuel vehicles in Morocco and demonstrated how these vehicles can reduce greenhouse gas emissions and achieve Net Zero goals. A study compares internal combustion engine vehicles, HEVs, BEVs, and FCVs with a lifecycle assessment over 15 years, taking into account well-to-wheel impacts in a region where fossil fuels are used for most of the electricity [12] . This therefore demonstrates the rationale for region-specific WTW analyses that could provide judgment on the environmental viability of alternative fuel vehicles, especially given Morocco's potential to achieve as much as a 42% cut in GHG emissions [13]. In the same direction, Solaymani and Botero [1] emphasize supply side policies (e.g., integrating renewables and clean hydrogen production) and demand side measures (e.g., tax, subsidy, and public awareness) for accelerating sustainable mobility.

These findings consequently leave a gap in understanding how vehicle technologies affect the environment, especially with unique energy setups within Middle Eastern countries. Furthermore, only a few studies combine modeling based on the GREET model with region-specific electricity data and broad environmental indicators such as the Eco-Indicator 99. Filling this knowledge gap becomes critical to help shape national policies on transport electrification and sustainable energy planning.

Therefore, this study aims to perform a new, straightforward comparison of well-to-wheel life cycle emissions for four vehicle technologies-diesel internal combustion engine, fuel cell vehicle, hybrid electric vehicle, and battery electric vehicle-across four Middle Eastern countries: Saudi

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Arabia, Yemen, Oman, and the United Arab Emirates. Using the GREET model as the base, the study merges national electricity data from Our World in Data with emission factors and eco-indicator metrics, which are processed through a mathematical model in Excel. It will seek to measure and compare greenhouse gas and pollutant emissions for each vehicle type under real regional energy conditions. The results should hence indicate how different country energy mixes affect environmental performances and inform guidance on sustainable transport and energy plans in the Arabian Peninsula.

Methodology

This study applies the WTW framework, part of the Environmental Life Cycle Assessment, comparing four vehicle technologies in the energy context of the United Arab Emirates, Saudi Arabia, Oman, and Yemen: diesel, hybrid diesel-electric, battery electric vehicle, and fuel cell vehicle. The WTW analysis provides a clear view of fuel production WTT and vehicle operation TTW together. A wider view of environmental impacts becomes possible that way. This perspective is important for new vehicle types like BEVs and FCVs, which do not emit much but can have great upstream impacts depending on the national grid of the country if it relies on fossil fuel electricity and natural gas-based hydrogen. The impacts have been estimated for 100 km of driving, considering climate change, respiratory effects, acidification, and eutrophication. Results from GREET models are used here, coupled with the factors of Eco-indicator 99 (Egalitarian); thus, all vehicle technologies have been compared consistently under the energy conditions of the country.

1. GREET Model Setup

By using the GREET1 model, and more precisely the Excel-based GREET1_2021 fuel-cycle module developed at Argonne National Laboratory. GREET calculates energy usage in MJ/km and emissions in kg/km for pollutants, including CO_2, CH_4, NOx, PM_{10}, $PM_{2.5}$, SOx, and total greenhouse gases. It examines feedstock, fuel production, and vehicle operation for four vehicle technologies. To adapt to regional contexts of energy supply, GREET's default U.S. electricity mix was updated to country-specific mixes for the UAE, Saudi Arabia, and Oman using 2024 data and to 2023 data for Yemen, where the 2024 data is not available. The mixes include coal, natural gas, oil, nuclear, solar, and wind:

Feedstock stage (extraction/collection/transport): $m_{i,v}^{\text{feed}}$ (kg/km)

Fuel stage (processing/refining/distribution): $m_{i,v}^{\text{fuel}}$ (kg/km)

Vehicle operation stage: $m_{i,v}^{\text{op}}$ (kg/km)

2. Data collection

The data for this analysis were collected from reliable national and international sources to represent the energy and transport context of each country during the most recent available year. Electricity generation mix data were obtained from *Our World in Data* and manually entered into the GREET electricity-generation module to replace the default grid composition with country-specific profiles. Data correspond to 2024 for Saudi Arabia, the UAE, and Oman, while for Yemen, 2023 energy mix data were used due to the unavailability of updated 2024 figures.

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Table 1:Electricity Generation Mix by Energy Source in Selected Gulf Countries [%] [14]

Energy Source	Yemen (%)	Saudi Arabia (%)	Oman (%)	UAE (%)
Coal	0	0	0	0
Oil	65.15	34.5	2.75	0.01
Natural Gas	17.92	63.34	93.06	68.42
Nuclear	0	0	0	22.97
Solar	16.94	1.81	3.92	8.6
Wind	0	0.35	0.28	0

Table 1 shows the electricity generation mix in Yemen, Saudi Arabia, Oman, and the UAE, expressed as the percentage contribution of each energy source. It highlights the dominance of oil and natural gas in most countries, the growing share of solar energy, and the presence of nuclear power in the UAE.

3. Well-to-Wheel and environmental impacts computation

First, after getting the data from GREET model of feedstock, fuel and vehicle operation of total energy and gas emissions for each type of vehicle. To refine the data and compute environmental impacts using the Eco-indicator 99 (Egalitarian) method, a separate excel sheet workbook was made.

The WTW framework was the first step in refining the data, and it provides a complete picture of the environmental performance of each vehicle type by integrating both upstream and operational stages. The total WTW impact is expressed as the sum of two main phases:

$$m_{i,v}^{\mathrm{WTW}} = m_{i,v}^{\mathrm{WTT}} + m_{i,v}^{\mathrm{TTW}} \quad (1)$$

The WTT phase includes all upstream processes required to supply the fuel or electricity to the vehicle. As was previously described in the GREET setup, the feedstock and fuel stages together constitute the upstream WTT phase and is expressed as:

$$m_{i,v}^{\mathrm{WTT}} = m_{i,v}^{\mathrm{feed}} + m_{i,v}^{\mathrm{fuel}} \quad (2)$$

The feedstock stage accounts for the extraction, collection, and transport of primary resources such as coal, natural gas, crude oil, or renewable inputs. The fuel cycle includes all phases involved in transforming the resources into usable energy carriers, such as diesel, hydrogen, or electricity. For battery electric vehicles, this involves the generation of electricity from the various power sources and transmission losses. For hydrogen fuel cell vehicles, this stage involves the generation of hydrogen either through natural gas reforming or renewable electrolysis.

The TTW phase is the operation phase which concentrates on the energy used and emissions generated during the driving of the vehicle. Which can be expressed as:

$$m_{i,v}^{\mathrm{TTW}} = m_{i,v}^{\mathrm{op}} \quad (3)$$

For conventional diesel and hybrid vehicles, this includes fuel consumption and emissions of greenhouse gases during driving. For battery electric vehicles, it indicates the amount of energy

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drawn from the power grid and the efficiency of the motor operation. For hydrogen fuel cell vehicles, this means the efficiency of the fuel cell and water vapor as the sole output.

To enhance the representation of real-world driving in the environmental assessment, the results of the GREET model, which were provided per kilometer of driving (MJ/km or g/km), were converted to a unit of 100 km . This scaling helped facilitate direct comparisons across diesel, hybrid, battery electric, and fuel cell vehicle technologies. Also, this adjustment maintains the proportionality of impacts while clearly presenting the cumulative environmental burden for a typical 100 km driving cycle in the UAE, Saudi Arabia, Oman, and Yemen.

$$M_{i,v}^{\text{stage, FU}} = m_{i,v}^{\text{stage}} \times 100 \quad \text{(g/100 km)} \tag{4}$$

Environmental impact numbers are calculated with Eco-indicator 99 (Egalitarian) factors. For each impact category the products of GREET's total pollutants from well-to-wheel and of matching factors were summed up. The total impact in each category was determined as:

$$I_{v,c}^{stage} = \sum_{i} \left(EF_{i,c} \times M_{i,v}^{stage,\, FU} \right) \tag{5}$$

Where:

- $EF_{i,c}$ represents the characterization factor in Pt/g for pollutant i.
- $m_{i,v}$represents the mass of pollutant i emitted by vehicle type v per 100 km of travel, as calculated from the GREET model.

Emissions considered under this study for climate change include CO_2, CH_4, N_2O, and CO. The breathing and health effects consider the pollutants as VOC, CH_4, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx, while acidification and eutrophication consider only NOx and SOx emissions.

Table 2:Eco-indicator 99 (Egalitarian) Characterization Factors [Pt/g] [15]

Ecosystem Quality		**Human Health**	
	Acidification/ Eutrophication	Climate Change	Respiratory Effects
CO2 (Pt/kg)		0.0040645	
CH4(Pt /kg)		0.0040645	0.00024774
N2O (Pt/kg)		1.3355	
VOC (Pt/kg)			0.024774
CO (Pt/kg)		0.0062323	0.014148
NOx (Pt/kg)	0.55682		1.7245
PM10 (Pt/kg)			7.2581
PM2.5 (Pt/kg)			13.548
SOx (Pt/kg)	0.10146		1.0568

All results were normalized and expressed in Pt/100 km. A lower score indicates less environmental impact and better overall sustainability. This makes the comparison of the four vehicle technologies for the four Gulf countries easy, taking into account different regional energy sources but using the same unit for comparison.

In the final step of the WTW framework, we add all the WTT contribution and the operational TTW contribution to yield the total environmental impact for each vehicle type and category. The final number $I_{v,c}^{\text{WTW}}$ in Pt/100 km, represents the full life-cycle environmental burden of each

vehicle technology for the studied region, allowing easy comparison across vehicle types under the same driving and energy assumptions.

$$I_{v,c}^{\mathrm{WTW}} = I_{v,c}^{\mathrm{WTT}} + I_{v,c}^{\mathrm{TTW}} \quad (6)$$

Results and Discussion

This section presents the key results of the WTW analysis for Saudi Arabia, the UAE, Oman, and Yemen. The results include three environmental indicators that comprise Climate Change, Respiratory Effects, and Acidification & Eutrophication, in addition to Water Consumption.

1. Analysis by Country
   a. Saudi Arabia

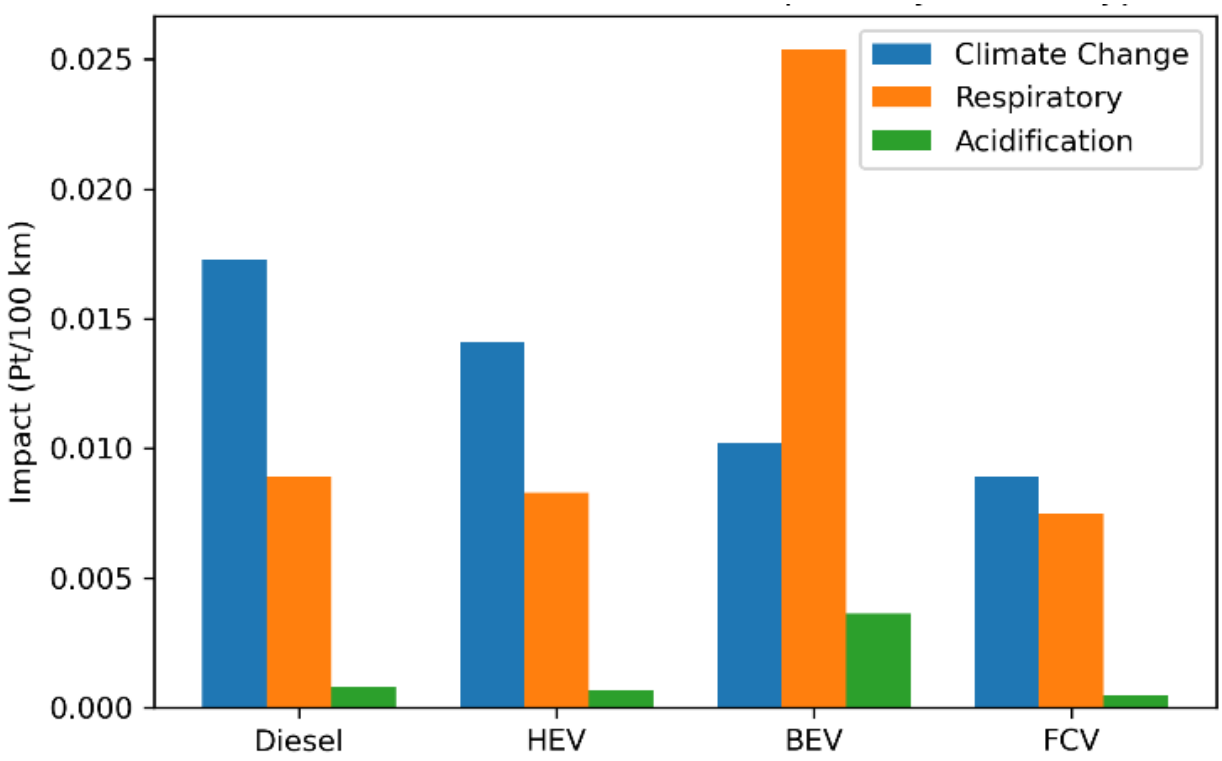


Figure 1: Saudi Arabia environmental impacts for each vehicle

FCVs have the smallest environmental impact for all measures within Fig. 1 with 0.0089 Pt/100 km for Climate Change, 0.0075 Pt/100 km for Respiratory Effects, and 0.00046 Pt/100 km for Acidification & Eutrophication. BEVs are not as good, particularly for respiratory effects, since the country relies on oil and gas for much of its electricity. In general, it seems FCVs are the most sustainable option for Saudi Arabia, as they go along with the country's hydrogen plans and the large supply of natural gas.

b. UAE

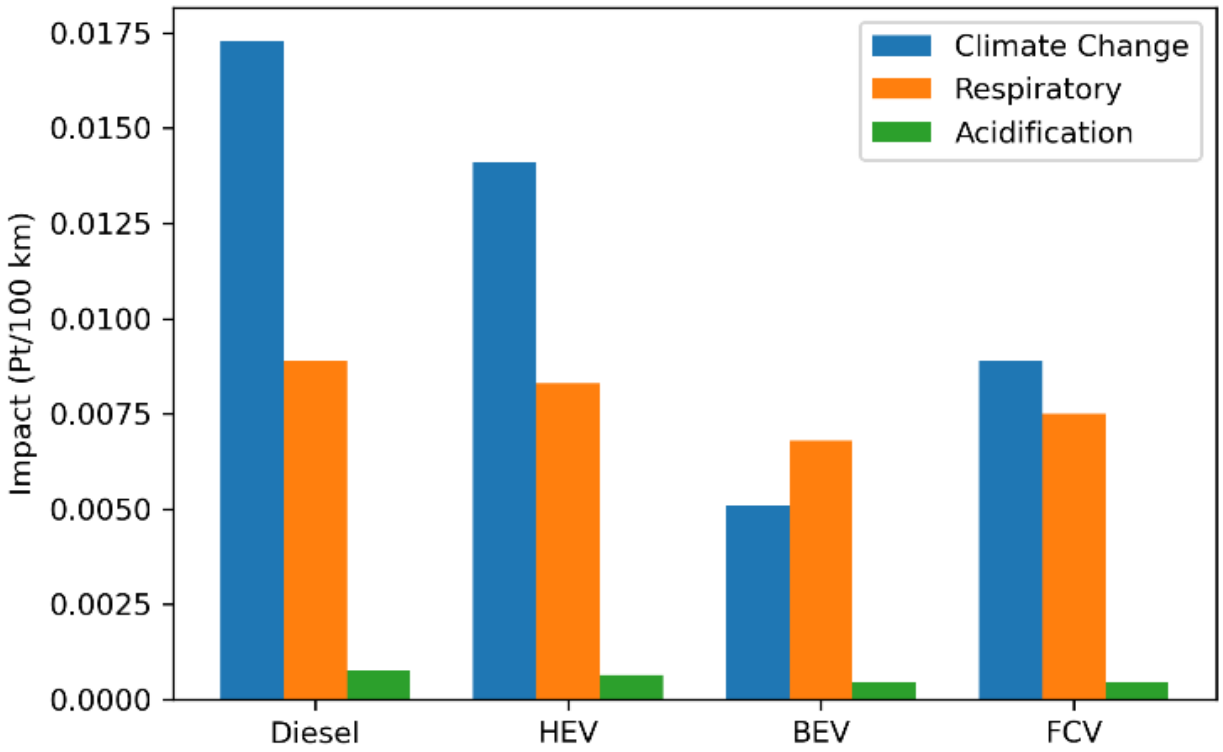


Figure 2: UAE environmental impacts for each vehicle

BEVs have the best environmental outcomes for all measures in Fig. 2 with 0.0051 Pt/100 km for Climate Change, 0.0068 Pt/100 km for Respiratory Effects, and 0.00047 Pt/100 km for Acidification. This is due to the cleaner electricity in the country, which is increasingly generated by solar power and natural gas. HEVs are decent, but FCVs have slightly higher impacts due to the methods of hydrogen production. Thus, BEVs are currently the environmentally friendliest option for the UAE, considering the growth of renewable energy capacity.

c. Oman

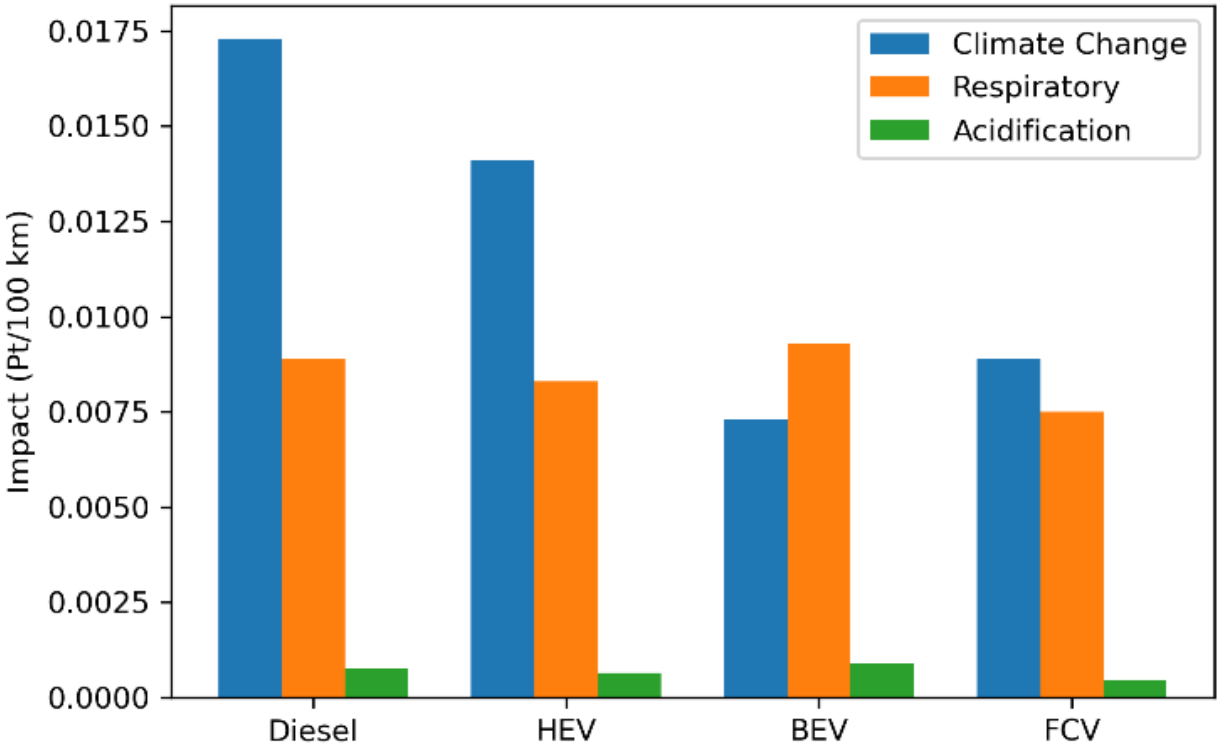


Figure 3: Oman environmental impacts for each vehicle

In Figure 3, FCVs provide the best overall environmental results in Oman: 0.0089 Pt/100 km for Climate Change, 0.0075 Pt/100 km for Respiratory Effects, and 0.00046 Pt/100 km for Acidification and Eutrophication. BEVs do a little better on Climate Change at 0.0073 Pt/100 km, but are worse in the other two categories, showing increased local air pollution. FCVs win overall because they stay low on all measures and help keep the air cleaner. This fits with Oman's natural gas-based electricity, which would lead to a moderately carbon-intensive production of hydrogen.

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d. Yemen

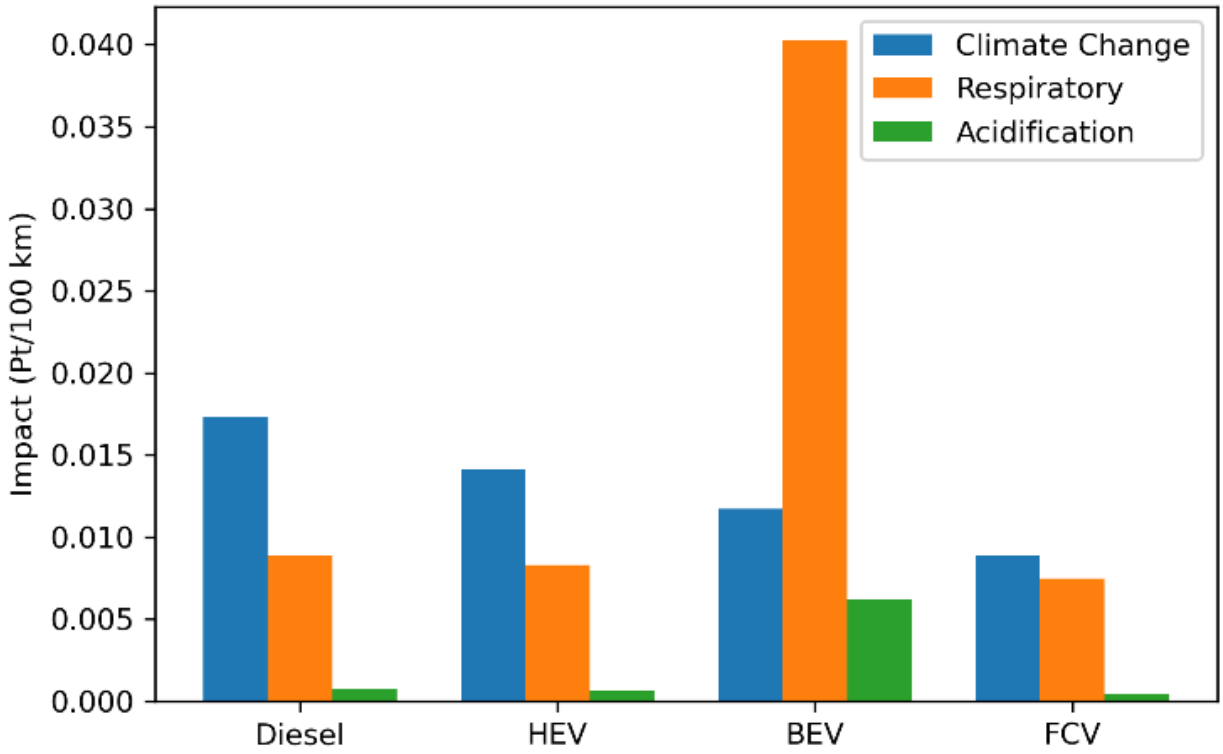


Figure 4: Yemen environmental impacts for each vehicle

In Fig. 4, FCVs again had the lowest environmental impacts of 0.0089 Pt/100 km for Climate Change, 0.0075 Pt/100 km for Respiratory Effects, and 0.0005 Pt/100 km for Acidification. BEVs emit the most: 0.0403 Pt/100 km for respiratory impacts, due to inefficient and fossil-dependent national power generation. Since Yemen has very minimal renewable capacity in place and a weak grid infrastructure, FCVs or HEVs are the most possible solutions to reduce its transport emissions in the short term.

2. Comparative Summary

Table 3: Summary of vehicle impacts for each country

Metric	Saudi Arabia	UAE	Oman	Yemen
Best Vehicle Type (to be adopted)	FCV	BEV	FCV	FCV
Climate Change (Pt/100 km)	0.0089	0.0051	0.0089	0.0089
Respiratory (Pt/100 km)	0.0075	0.0068	0.0075	0.0075
Acidification (Pt/100 km)	0.00046	0.0005	0.0005	0.0005
Water Use (L/100 km)	5.61	5.69	5.09	9.9

The findings of this analysis provide validation that the best car technology correlates linearly and varies according to the country's energy structure and the availability of water resources. It is evident from Table 1 that FCVs are rated as the best car solution for Saudi Arabia, Oman, and Yemen because of the low impact on all parameters, such as Climate Change 0.0089 Pt/100 km, Respiratory Effects 0.0075 Pt/100 km, and Acidification 0.00046-0.0005 Pt/100 km. BEV is rated as the best solution in UAE due to a cleaner energy mix from natural gas and solar resources that minimize climate change 0.0051 Pt/100 km damage to the environment as well as acidification 0.00047 Pt/100 km damage.

For the water usage, Saudi Arabia and Oman show moderate consumption with 5.61 L/100 km and 5.09 L/100 km respectively, but a relatively high demand for Yemen 9.9 L/100 km due to inefficient, fossil-based power. The UAE follows a similar water demand to that of Saudi Arabia 5.69 L/100 km, which represents a similar desalination-based power process. In general, FCVs have been found to be the best-balanced technology for fossil-based systems, while BEVs have been established as optimal for cleaner, renewable-based power grids. The findings indicate that we require more effective water-saving power techniques, hydrogen infrastructure, and renewable energy, all of which are to be pushed together with vehicle technology advancements to make use of Gulf projects in an environmentally viable manner.

Conclusion

The study analyzed how different types of vehicles affect the environment and water usage in Saudi Arabia, the UAE, Oman, and Yemen using the GREET model and each country's energy data. The best vehicle type depends on how each country produces electricity. FCVs had the lowest overall impacts in Saudi Arabia, Oman, and Yemen, while BEVs were the cleanest in the UAE because its grid relies more on clean, solar power. Water use was lowest in Oman and highest in Yemen due to differences in efficiency in generating the electricity.

In summary, the findings state that a sustainable transport system in the countries under study depends on integrating car use with the energy mix of the country. This involves the use of more renewable energy, developing the low carbon hydrogen energy sector, and improving the efficiency of hydroelectric and water-based power. The limitations of the study include the failure to examine the production of cars and the recycling of cars at the end of their life. For Yemen, only the 2023 electricity mix was available. Full life-cycle modelling, cost analysis, and regional hydrogen-supply scenarios are recommended for future work to develop a long-term, sustainable mobility plan for the Gulf region.

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