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# Comparison of the Overall Energy Efficiency for Internal Combustion Engine Vehicles and Electric Vehicles

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***Abstract*** **– The tremendous growth in the transportation sector as a result of changes in our ways of transport and a rise in the level of prosperity was reflected directly by the intensification of energy needs. Thus, electric vehicles (EV) have been produced to minimise the energy consumption of conventional vehicles. Although the EV motor is more efficient than the internal combustion engine, the well to wheel (WTW) efficiency should be investigated in terms of determining the overall energy efficiency. In simple words, this study will try to answer the basic question – is the electric car really energy efficient compared with ICE-powered vehicles? This study investigates the WTW efficiency of conventional internal combustion engine vehicles ICEVs (gasoline, diesel), compressed natural gas vehicles (CNGV) and EVs. The results show that power plant efficiency has a significant consequence on WTW efficiency. The total WTW efficiency of gasoline ICEV ranges between 11–27 %, diesel ICEV ranges from 25 % to 37 % and CNGV ranges from 12 % to 22 %. The EV fed by a natural gas power plant shows the highest WTW efficiency which ranges from 13 % to 31 %. While the EV supplied by coal-fired and diesel power plants have approximately the same WTW efficiency ranging between 13 % to 27 % and 12 % to 25 %, respectively. If renewable energy is used, the losses will drop significantly and the overall efficiency for electric cars will be around 40–70 % depending on the source and the location of the renewable energy systems.**

***Keywords*** **– Electric car; internal combustion engine; overall energy efficiency.**

## 1. INTRODUCTION

Transportation is one of the major energy-intensive sectors in the world and contributes up to 27 % of global primary energy demand [1]. Thus, the transportation sector significantly contributes to the Earths' GHG emissions, which is the primary driver of climate change. Additionally, the dramatic increase in transportation sectors results in rising of air pollution and has adverse effects on human health and the economy [2]. Improving energy efficiency in the various aggregate energy-consuming sectors plays a vital role in controlling the energy demand, as well as restricting the negative environmental impact [3]–[5].

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Developing countries are experiencing the highest growth rate in transportation energy consumption [6]. As vehicles play a substantial role in human society, it is essential to investigate the energy efficiency of vehicles in order to deal with energy management issues. In aiming to understand vehicle energy efficiency and compare the efficiency of different vehicle models, the WTW efficiency should be recognised. WTW examination has been extensively applied to gauge vehicle energy consumption. WTW concerns the efficiency of the energy chain of vehicles "from cradle to grave". The aim of this paper is to compare the WTW efficiency of conventional internal combustion vehicles (gasoline, diesel and natural gas) to electric vehicles.

WTW efficiency of the electric car indicates that optimum use of natural gas combined-cycle power plants will improve the overall efficiency of the electric cars [7].

An investigation compared the energy performance of internal combustion engines to electric motorcycles using dynamometric essays real data. The results indicate that electrical driven efficiency (47.06 %) is three-time greater than liquid-fuelled engines (15.32 %). This research motivated further comprehensive evaluation of the overall energy chain to gain an accurate estimation of energy performance [8].

The examination of electric vehicles energy efficiency, $CO_2$ emissions and cost, while considering the impact of EV on electricity need and stability of electricity grid showed the significance of including all energy chain processes (WTW) in the assessment of electric vehicles performances [9].

A comparison for the energy consumption of conventional cars and their equivalent electric car models in mountainous roads in Andorra. The simulation model used a protoplasmic path to analyse the energy performance of diesel and electric vehicles. The results show that electric vehicles have more potential when it comes to saving energy [7], [10], [11].

In this paper, the overall energy efficiency of cars using ICE and an EV powered by varied types of power plants, including gas, coal and diesel are compared. The assessment is performed according to WTW efficiency methodology.

## 2. METHODOLOGY

To be able to calculate the overall energy efficiency, the efficiency of each energy conversion or transmission were determined in the first step then all the efficiencies attained from the previous step were multiplied to find the overall energy efficiency. One individual component with a low efficiency rating has a multiplicative effect on the rest of the system and the overall efficiency.

Our method approach to analysing the overall efficiency (WTW) is to break it down into well to tank efficiency and tank to wheel efficiency. The efficiency of all the individual components are multiplied together to find the overall efficiency. The tank to wheel efficiency $\eta_{TTW}$ is defined as tracking the following stage for liquid fuels, natural gas compressors and electricity:

$$\eta_{\text{Liquid fuel}} = \eta_{\text{Crude oil extraction}} \cdot \eta_{\text{Fuel conversion}} \cdot \eta_{\text{Distribution}}\ ; \quad (1)$$

$$\eta_{\text{Natural gas compressor}} = \eta_{\text{Natural gas extraction}} \cdot \eta_{\text{Fuel conversion}} \cdot \eta_{\text{Compressor}}\ ; \quad (2)$$

$$\eta_{\text{Electricity}} = \eta_{\text{Resoures extraction}} \cdot \eta_{\text{Powerplant}} \cdot \eta_{\text{T\&D}} \cdot \eta_{\text{Charging}}\ , \quad (3)$$

where

$\eta_{\text{Crude oil extraction}}$, $\eta_{\text{Natural gas extraction}}$ and $\eta_{\text{Resource}}$ – extraction are the energy sources mining or forming efficiency;

$\eta_{\text{Fuel Conversion}}$ Efficiency of crude oil refinery;

$\eta_{\text{Distribution}}$ Energy consumed in fuel transportation to oil station;

$\eta_{\text{Compressor}}$ Efficiency of natural gas compressors at the refuelling station;

$\eta_{\text{Powerplant}}$ Efficiency of electrical generation power plants;

$\eta_{\text{T\&D}}$ Electrical grid transport and distribution efficiency;

$\eta_{\text{Charging}}$ Efficiency of transfer of the electricity to EV in the station.

The tank to wheel efficiency $\eta_{\text{TTW}}$ of internal combustion vehicles, natural gas compressor vehicles and electric vehicles are defined based on literature and manufacturer's data.

Additionally, the overall efficiency was estimated using renewable energy sources to charge the EV. For the main sources of renewable energy (wind and solar) the overall efficiencies calculations will assume the following; for solar, only the losses from the inverter and the charger if the PV is installed near the building (roof PV systems). In case of PV or wind farm, it will assume the losses from the transmission lines for electricity come from farms that are located far away from the charging station.

## 3. DATA COLLECTION

### *3.1 Extraction, Processing and Distribution Efficiency*

The energy chain starts by extracting the crude oil, converting it in a refinery plant and then distributing it to the desired service, such as a power plant or oil station. The efficiency of each step of this process is detailed in Table 1. The efficiency average of each stage was taken to determine the TTW efficiency.

TABLE 1. PRIMARY ENERGY EXTRACTION, PROCESSING AND DISTRIBUTION EFFICIENCY

| **Fuel stock** | **Extraction** | **Processing** | **Distribution** |
|---|---|---|---|
| Natural gas | 99 % [12]–[14]<br>96 % [15] | 96–99 % [12]–[14]<br>94 % [15] | 96–98 % [16]<br>93.3-99 % [12] |
| Coal | 97 % [17] | 97 % [15] | 98 % [18] |
| Crude oil: | | | |
| Gasoline<br>Diesel | 95.0 % [12]<br>93 % [15] | 88 % [12]<br>95.0 % [12] | 99 % [12] |

### *3.2 Power Plant Efficiency*

Most power plants depend on coal and natural gas as fuel stock to generate electricity. The coal-based and natural gas-fired power plant account of almost 40 % and 20 % of the world's electricity generation, respectively. Natural gas is considered as an efficient fossil fuel to generate electricity with efficiency reaching around 34 % in the sample cycle turbine, to 50.1 % in the gas turbine based combined cycles plant. Comparatively, the coal-based power plants deliver overall efficiencies in the range 32–42 %. Diesel power plants, high capability industrial engines, have an efficiency of 35 % to 42 % as shown in Table 2.

The power plant has a significant interest in the determination of electric vehicles efficiency; electricity is the primary power source of an electric vehicle. For that, the power plant performance of fossil fuels was intensively reviewed and is summarised in Table 2. In this research, the efficiency ranges shown in Table 2 were used, taking into consideration that some of the energy used came from inside the power plant itself.

TABLE 2. POWER PLANT EFFICIENCY

| **Fuel Type** | **Technology** | **Efficiency** | **Efficiency Range** |
|---|---|---|---|
| Natural gas | Simple-cycle turbines | 34 % [19] | 34–51 % |
| | Combined-cycle | 50 % [19] | |
| | | 36–50 % [20] | |
| | | 47 % [21] | |
| | | 42 % [22] | |
| | | 34–46 % [23] | |
| Coal-fired | | 34 % [24] | 32–42 % |
| | | 37 % [25] | |
| | | 41 % [26] | |
| | | 32–42 % [18] | |
| | | 34–40 % [23] | |
| Diesel motor generators | | 40 % [27] | 32–40 % |
| | | 32 % [15] | |

The natural gas is supplied directly into a refuelling station in the compression phase. The compressor efficiency is based on the assumption that a refuelling station is detected to range between 91 % and 97 % [7]. In this research, the compressor efficiency was assumed to be 94 %.

Generate electricity from renewable energy sources has the advantage of being free of energy loses until it reaches the inverter due to being extracted from totally uncharged sources. The efficiency of PV and wind inverter ranges from 90 % to 95 % [28], [29].

### *3.3 Electrical Grid and Charging Stations Efficiency*

The electricity generated at the power plant transfer and distributed through the electrical grid to reach the charge station. The station charger is used to supply electricity to the EV. It found that electrical grid efficiency was 92 % [30] and a charging efficiency is 95 % [31].

### *3.4 Vehicle Tank to Wheel (TTW) Efficiency*

To determine the TTW efficiency of electric vehicles, every EV component should be analysed. Table 3 shows the efficiency of EV components. TTW efficiency of EV is taken in a range that goes from 50 % to 80 % based on values of EV components found in literature reviewed.

TABLE 3. EV COMPONENTS EFFICIENCY

| EV components | Efficiency | Efficiency range |
|---|---|---|
| AC/DC converter | 96 % [32] | 90–96 % |
| | 90 % [33] | |
| Battery input | 96 % [32], [34] | 90–99 % |
| | 95 % [35] | |
| | 99 % [35] | |
| | 90 % [9] | |
| Battery output | 95 % [32] | 93–98 % |
| | 96 %[34] | |
| | 93 % [35] | |
| | 98 % [35] | |
| DC/AC converter | 96 % [32] | 96–98 % |
| | 97 % [34] | |
| | 98 % [33] | |
| Electric motor | 90 % [32] | 81–95 % |
| | 92 % [34] | |
| | 95 % [33] | |
| | 81 % [35] | |
| | 89 % [35] | |
| Electric generator | 85 % [32] | 82–95 % |
| | 92 % [34] | |
| | 95 % [33] | |
| | 82 % [35] | |
| | 88 % [35] | |
| Mechanical transmission | 98 % [32] | 89–98 % |
| | 98 % [34] | |
| | 97 % [33] | |
| | 89 % [35] | |

The TTW efficiency of ICEV is dependent on various factors like speed, load conditions, vehicle weight, driver behaviour and the road conditions. The TTW efficiency of the ICEV found at a range of 14–33 % for gasoline ICEVs [10], [36], [37], 28–42 % for diesel ICEVs [10], [37]–[39] and 14 % to 26 % for NGCV [39].

Higher energy consumption results in higher emissions especially if the wasted energy is high, these will result in higher environmental impacts due to the larger amount of emissions. The greenhouse effects measurements of various human activities are significant in establishing effective climate change mitigation strategies. The greenhouse effects of burnable fossil fuels involve combustion emissions and all of emissions from the fuel production chain until combustion. It is vital to be able to evaluate the full influence of these different emissions and to present the results in an inclusive way even for biofuels [40], [41].

Promoting for lower energy consumption and using more efficient car type can be implemented by several agencies, corporations, non-profit organizations, or other groups and institutions aimed to improve environmental quality. The relevant public forces causing environmental change: firstly; science and technology secondly; governance, then markets and the economy, and finally the public behaviour which is useful analytic to begin developing the future strategies [42].

## 4. Discussion and Results

Considering WTW efficiency breakdown, the Tank to Wheel efficiency of liquid ICEV (gasoline and diesel) and CNGV determine the following Eq. (1) and (2) respectively. The average efficiency values of extraction, refinery and distribution fuel was taken as shown in Table 1. For the gasoline and diesel cases, as shown in Fig. 1 and Fig. 2 respectively, the liquid fuel derived from the oil station is then pumped to the vehicle. The TTW efficiency of ICE gasoline and diesel burned is mentioned in section 4.5. Hence, the total WTW efficiency of gasoline ICEV ranges between 11–27 % and diesel ICEV ranges from 25 % to 37 %.

In CNGV case, the natural gas is compressed through a compressor then fed to the vehicle. The overall process is shown in Fig. 2. The CNGV WTW efficiency is found to be between 12 % to 22 %.

For electric vehicles, the stock fuel is extracted and processed and then supplied to the power plant. The power plant electricity generating efficiency depends on the fed fuel and technology types. The electricity reached the EV after being transferred by the distribution grid and the charger station. The WTW efficiency of EV described and explained in Fig. 4. The power plant efficiency has a significant consequence on WTW efficiency. The EV fed by a natural gas power plant shows the highest WTW efficiency which ranges from 13 % to 31 %, while the EV supplied by coal-fired and diesel power plants have approximately the same WTW efficiency ranging between 13 % to 27 % and 12 % to 25 %, respectively.

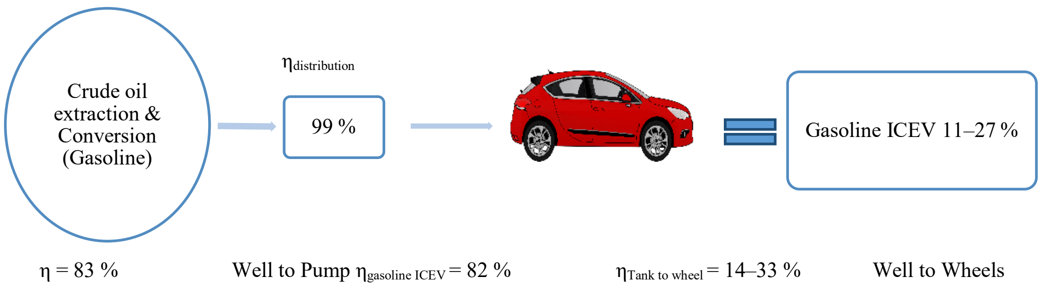


Fig. 1. WTW efficiency of gasoline ICEV.

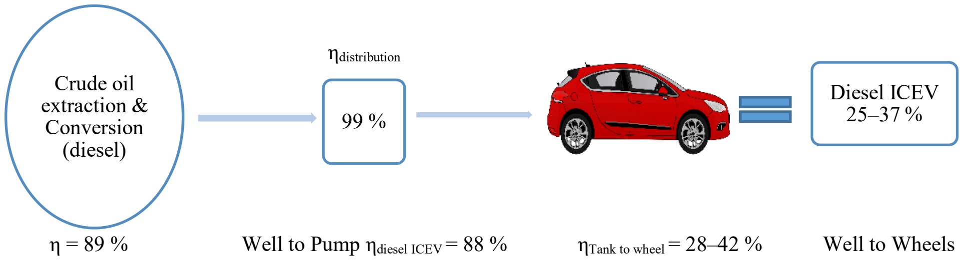


Fig. 2. WTW efficiency of diesel ICEV.

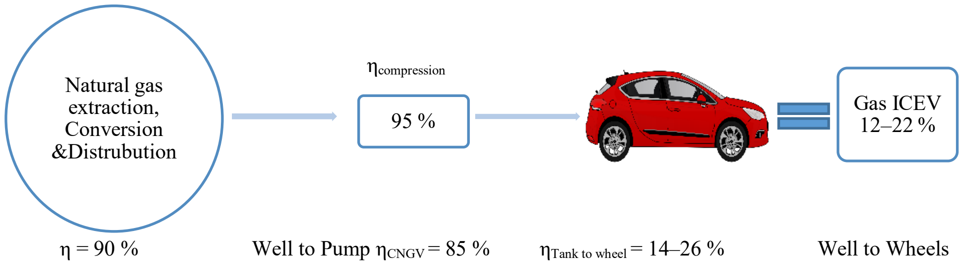


Fig. 3. WTW efficiency of CNGV.

A significant improvement in the WTW efficiency of EV is retrieved through the use of electricity generated by solar or wind systems. The overall efficiency of EV charged from PV or wind farms ranged between 39 % to 67 %, while using the roof PV system increased total efficiency due to low transmission losses, thus, the WTW efficiency of EV charged from PV roof systems can reach a range of 42 % to 72 % as shown in Fig. 5.

Fig. 6 shows different overall efficiencies for different cars. In general, renewable energy sources have the highest overall efficiencies followed by diesel engines, then electric cars, and gasoline cars, and the lowest overall efficiencies of gas cars.

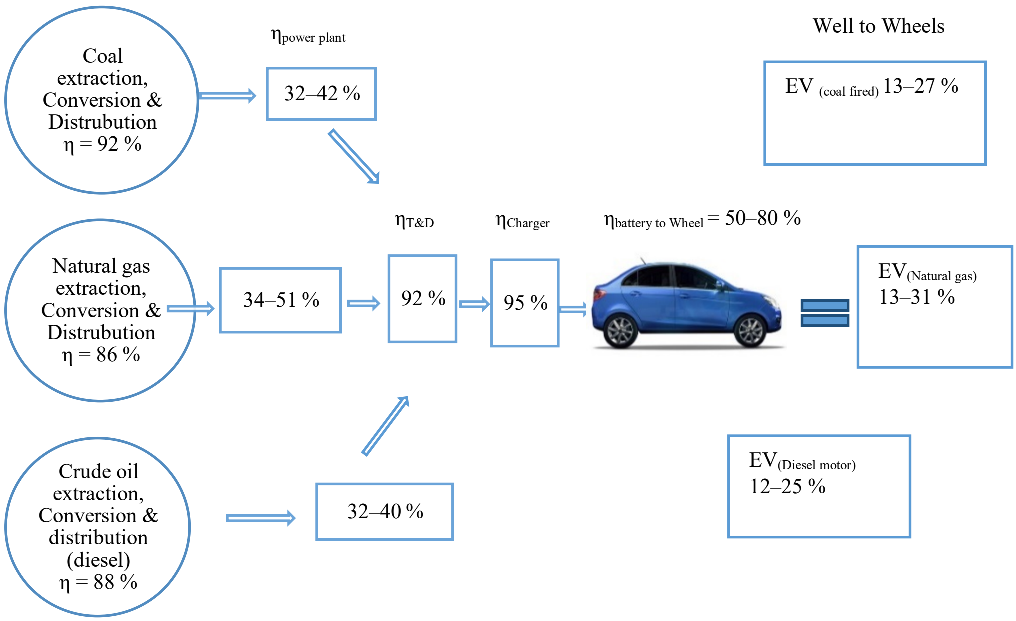


Fig. 4. WTW efficiency of EVs powered from fossil fuels power plants.

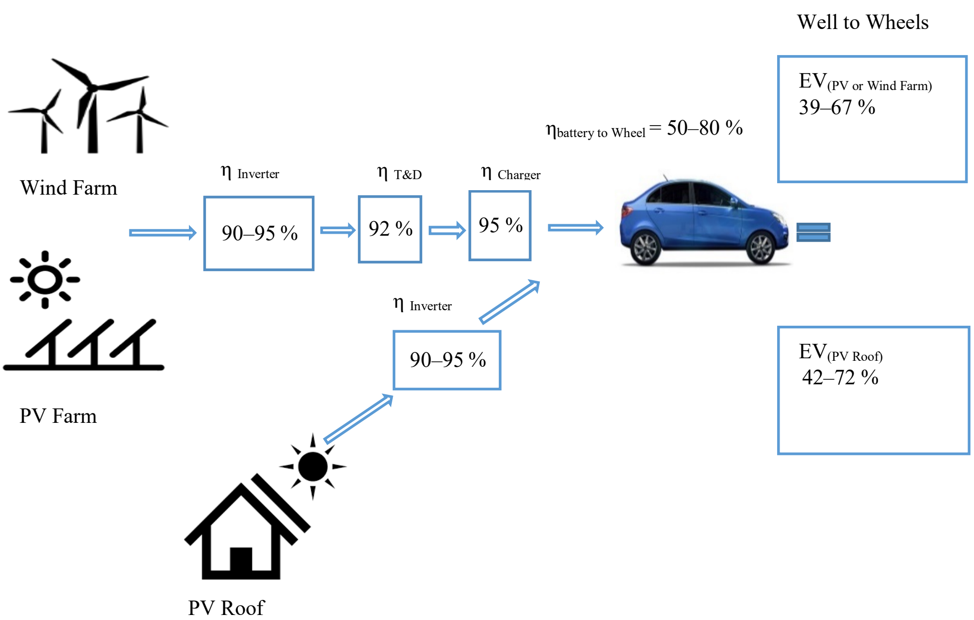


Fig. 5. WTW efficiency of EVs from renewable energy sources.

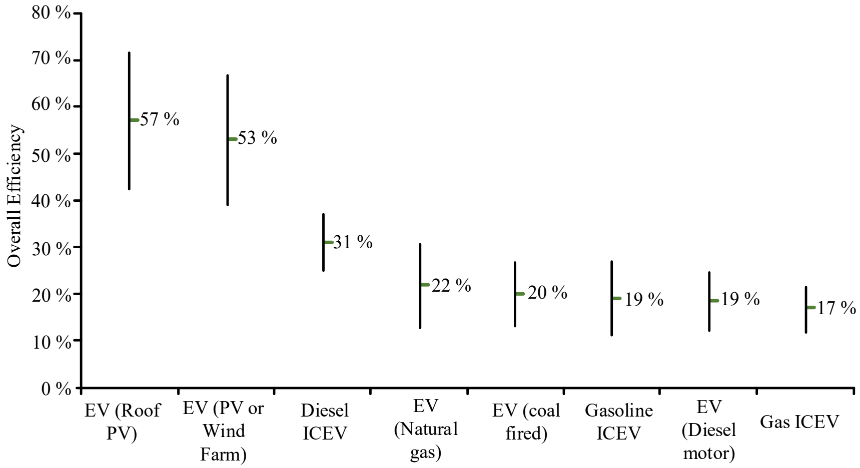


Fig. 6. Overall efficiencies for different cars powered from different sources.

## 5. CONCLUSION

This paper compared the Well to Wheel efficiency of conventional, internal combustion vehicles (gasoline, diesel, and natural gas) to electric vehicles. The final results showed that the power plant efficiency has a significant consequence on WTW efficiency. The EV fed by a natural gas power plant shows the highest WTW efficiency which ranged from 13 % to 31 %, While the EV supplied by coal-fired and diesel power plants have approximately the same WTW efficiency range, between 13 % to 27 % and 12 % to 25 %, respectively. While the total WTW efficiency of gasoline ICEV ranged between 11 % to 27 %, diesel ICEV ranged from 25 % to 37 % and CNGV ranged from 12 % to 22 %. While a significant improving in WTW efficiency of EV retrieve through used electricity generated by Solar or wind systems. The overall efficiency of EV charge from PV or wind farm ranged between 39 % to 67 %, while the using roof PV system will increase the total efficiency due to low transmission losses, thus the WTW efficiency of EV charged from PV roof reach range of 42 % to and 72 %.

In general, diesel cars are more efficient than electric cars powered by fossil fuels but further investigations are needed to examine the life cycle emissions from cradle to grave of both systems. The overall efficiency for gasoline cars is similar to electric cars powered from coal and diesel power plants. CNGV powered cars were the least overall efficient among the different fuelled cars, due to lower efficiency for CNGV cars.

Finally, powering the electric cars from renewable energy sources will significantly improve the overall system efficiency but further investigations are needed to study the influence of the storage systems for renewable energy systems on the overall efficiencies. Also, more investigation needed to analyse the hybrid-electric vehicles and the life-cycle of the vehicles, including their manufacturing, recycling and disposal.

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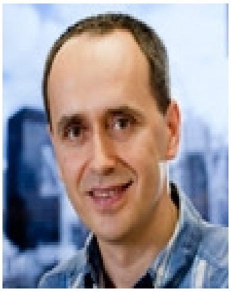

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