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Simulation and Energy Performance Assessment of the Ghazal Solar-Electric Commercial vehicle in Tehran, Iran

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A B S T R A C T

Nowadays, with increasing environmental pollution and damages that threaten the health of the community, a lot of research is being conducted on reducing the emission from transportation sector as one of the main sources of total worldwide emissions. It is confirmed that one of the ways to reduce emission is to switch from fossil-based fuels to more environmentally benign fuels. Among the options, electric vehicles (EVs) have proven themselves as one of the best options. In this research study, a solar-based EV which is developed and built at University of Tehran is studied. The environmental impacts assessment along with the energy consumption of this solar-electric vehicle is investigated

1. Introduction

Transportation refers to the movement of goods or people from a place to another place. Public transportation is carried out by road, air, rail, and sea via vehicles such as cars, buses, subways, and monorails. In some areas, passenger transportation in the city is carried out by using boats and cruises. Among the methods mentioned above, road transport is one of the most convenient transportation systems. The widespread use of this type of transportation method has also caused his problems. Among all these problems, transportation contributes a lot of environmental pollution that is in third place after industrial and residential areas [1].

The largest amount of this energy is supplied by fossil fuels (i.e., coal, oil and natural gas). Consumption of fossil fuels has led to global warming and among scientists, reducing the release of this gas is a top priority for preventing the rise of global warming and environmental preservation [2]. In addition, increased use of fossil fuels in transport vehicles such as cars, ships, and aircraft has also increased the level of environmental pollution [3]. Road transport accounts for over 20% of carbon dioxide emissions from the EU. 75 % of the produced carbon dioxide, which is the main gas of greenhouse gases, is the result of the fuel of passenger cars in this region [4-6].

According to the World Health Organization, air pollution and noise pollution are two of the most important environmental problems causing serious damage to the health of people in urban areas [7]. Noise pollution causes severe damage to health and quality of people's life and causes hearing impairment, vascular disease, and stress [8]. Air pollution means the presence of gases, harmful solids and liquid droplets remaining in the air. Particularly, transport contaminants are divided into two main categories.

The first category consists of carbon monoxide (produced by automobile fuel), sulfur dioxide (produced by the factories), nitrogen oxides and

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hydrocarbons, particular matters, toxic substances such as lead, benzene, formaldehyde etc. The second group contains ozone in the lower layers and other small pollutants. Because air pollution is a serious and high-risk factor for health through the development of respiratory infections, heart disease, and various cancers, urban air pollution is one of the worst toxic contamination problems in the 21st century [9]. The amount of contamination is usually defined as the weight of pollutant divided by a unit weight, volume, distance or duration of the pollution activity. The amount of air pollution is also measured by pollution monitoring stations [10-11]. A study by Tonoka in 2006 showed that 50% of world fossil fuel consumption and 25% of global carbon dioxide emissions are in transportation [12]. For example, the total British market annually produces about 1.7 million tons of carbon dioxide gas, where a recent study shows that about 40% of it is due to freight transportation [13].

Nowadays, various policies and strategies have been adopted to reduce air pollution in different countries. The rules for emissions in transportation (from Euro 1 to Euro 6) forced car companies to improve their internal combustion engine [14-15]. Reducing fuel consumption in transport is another approach that has been taken into consideration. The fuel efficiency of the automobile has always been improving in many different ways. Engine upgrades, different valves control, better lubrication to reduce friction, reduce rolling resistance and drag force, and use lighter materials to build are the solutions that are considered to reduce fuel consumption [16]. However, internal combustion engines appear to have reached their own economic-technology constraints, and alternative thinking has grown to solve the problem. Using vehicles that consume less carbon content fuels, such as hydrogen, electricity, CNG, LNG, and biodiesel can assist us to reduce emission in transportation. Among these alternative fuels, electric vehicles (EVs) with lithium batteries are perhaps the most popular option [17].

1.1. Electric Vehicle

From an environmental point of view, EVs do not produce any emission in the operating phase which makes them a good option to reduce regional pollution, especially in urban areas. However, it does not mean that EVs do not cause any harm to the environment, but transmit pollution to the outside of the urban area [18]. For example, 73% of the electricity needed by the EV, which is the main source of energy for the EV, is itself produced from the burning of fossil fuels such as coal and natural gas and gasoline [19].

So far, three models of EVs have been mass-produced. Hybrid EV is a type of vehicle that works both on fossil fuels and electrically. The second group of EVs is plug-in hybrid electric vehicles (PHEVs) and the last group of EVs with full batteries are called BEVs. Due to the limitations of technology, electric cars have still face some challenges such as short driving distance, high purchase cost, emission in the electricity production phase to charge the batteries [20]. The need for charging in EVs and refueling in Plug-in EVs is inevitable. In addition, the number of charging stations is limited. For example, there are only 10923 charging stations in Germany for charging electric cars [21]. Therefore, the existing routes for internal combustion engines are not always the best route for EVs. To solve the problem of charging for EVs, research was conducted to optimize the route to reduce pollution (The pollution-routing problem) [22-23]. On the other hand, in order to solve the problems of charging electric cars, a lot of research was done on the creation of static and dynamic charging infrastructure in the form of a conductive or contactless [24]. The successful implementation of Dynamic Charge Infrastructure, also known as Electric-Road, has great importance for the future of green transportation. Because it eliminates the cost and time of battery recharging limitations statically, it also increases the value of road infrastructure, which opens the door to more advanced materials and materials in the construction of roads that today have no economic justification. It also opens the way for research on intelligent infrastructures such as energy recovery from these roads or rehabilitated roads [25-27]. Another presented solution is the use of solar cells in EV to charge online batteries. Many efforts have been made to use solar energy as a clean and abundant resource of energy for driving cars.

1.2. Solar-Electric Vehicle

Due to the large difference in received energy from solar cells with fossil fuels, the use of solar-electric cars has so far been limited to the academic field [28]. Therefore, in order to achieve more energy levels, the battery is also used in conjunction with solar power. Places with ample solar energy, the solar-electric cars have the potential to charge their batteries online, whether they are moving or parked.

The remarkable fact is weather change leads to the change in the efficiency of the energy

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absorption system from the sun. The goal of solar-electric cars is to increase the energy received from the sun and optimize fuel consumption and lower its level so that it only depends on absorbed solar energy. World Solar Challenge racing is well known among universities and colleges for supporting alternative energy and energy efficiency. However, major engineering optimizations are needed to have a competitive vehicle. Several major developments in this competition are now being used in various industrial sectors. High-efficiency electric motors and controllers [29], low rolling resist Tires, MPPT, etc. are among them [30]. World Solar Challenge Racing is one of the most popular competitions in the world among universities, where teams from universities and colleges around the world participate every two years. The main goal of the competition is to travel 3022 kilometers from Darwin to Adelaide with solar power. Success in this race requires an efficient vehicle and a proper strategy [31]. As a result, the vehicle must be highly energy efficient. The main task of these cars is to focus on two issues: independence and reliability. To be independent, the car should receive the maximum amount of energy from the sun and consume the least amount of energy. In confidence, there are different items like car security, cell efficiency, aerodynamics, weight loss, and so on [32-36]. Therefore, to optimize the items, the appearance of solar-electric cars is usually different from commercial vehicles.

2. Persian Gazelle Solar-electric Car (PGSC)

The Persian Gazelle Design and Manufacturing Centre started the Persian Gazelle Solar-electric Car project, one of the greatest research centers projects in Iran, under the supervision of Prof. Abrinia since 2004. The Persian Gazelle Design and Manufacturing Center has designed and produced four types of Ghazal solar-powered EV as well as a BEV that called Arvin. Persian Gazelle I, 1-passenger EV was the first Iranian solar-electric car, which participated in the 2006 Taiwan competition. The Persian Gazelle team also participated with his second and third cars in the Australian World Solar Challenge in 2011 and 2015. The Persian Gazelle IV was the first family solar-electric car and first 4-passenger sedan in the Middle East, which is apparently close to commercial vehicles.

In the design process of this car, the initial designs were in various simulation software and optimized after various changes, to minimize its consumption. Due to the high priority of weight in energy consumption, carbon fiber is used as the main material for construction of the EV. On the other hand, solar cells with the highest efficiency are used to absorb the maximum possible energy from the sun. As a result, carbon fiber and high-efficiency cells have raised the price of these cars compared to other conventional cars. The designed car was entered the construction stage when several performance testes are applied to see its actual performance. In this research paper, to the main intention is to investigate the environmental impact assessment of these solar-electric cars in Iran. The specifications of the Persian Gazelle IV are listed in Table 1.

Table 1: Persian Gazelle IV specifications

Parameter	Sign	Unit	Value
Weight	m	kg	720
Drag Coefficient	C_D	-	0.17
Frontal area	A	m^2	1.78
Rolling coefficient	c_{rr}	-	0.007
Dimensions	-	m	4.5×1.8×1.12
Battery capacity	-	kWh	20

3. ANALYSIS and METHODOLOGY

In this study, we intend to compare some available EVs in the market with our solar-electric powered hybrid car, comparing the amount of energy consumed by them, their pollution and, finally, the effect on reducing environmental pollution.

To achieve our goal, we had to find a similar procedure to evaluate and compare the cars impartially. Based on the European rules, each car manufacturer should provide an emission document based on the specific driving cycle, which called New European Driving Cycle (NEDC). In order to find Persian Gazelle IV consumption theoretically, we modeled the car and its power unit, solar cells, and batteries.

3.1. Electric Drive

The electric drive consists of all energy transformations from the electricity produced by the battery or solar cells to the wheels. As seen in Figure 1, it includes batteries, controllers, power transmission systems and electric motors. The

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brushless dc electric motor which has a nominal efficiency of 92% is used for Persian Gazelle IV. Depending on the controller, an average controller efficiency is 97% estimated. However, mechanical losses are considered 2% [37]. Therefore, the overall efficiency of the energy drive system, as well as the assumptions made in previous studies [38], is 87.5%.

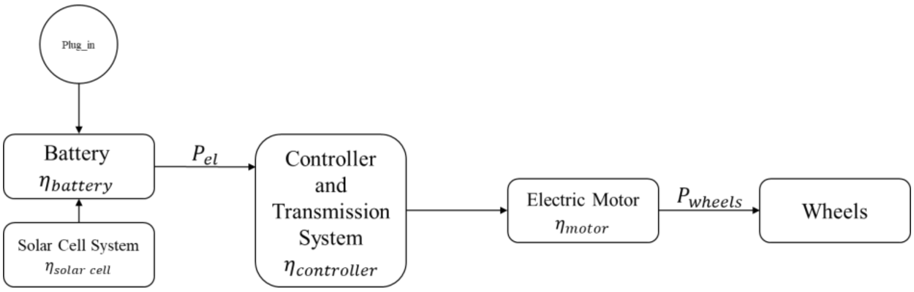

Figure 1. Modeling flow chart

During the driving cycle, the power of the car should withstand resistance forces depending on the speed of the vehicle. These forces include the aerodynamic force (air resistance), rolling resistance, acceleration, and the road slope. The power required in the wheels Pwheel will be equal to:

$$P_{wheel} = F_{res} \times V = (F_{air} + F_{RR} + F_{In} + F_g) \times V \qquad (1)$$

Here, “V” is the velocity of EV and “Fres” is the resistance force that is the sum of air resistance, rolling resistance, inertia resistance, and gravity resistance that are shown as “Fair”, “FRR”, “FIn”, and “Fg” respectively.

The aerodynamic forces, rolling resistance, inertia force, and gravity force on the vehicle are calculated using equations 2-5, respectively.

$$F_{air} = \frac{1}{2}\rho C_D\, A(V \pm V_{wind})^2 \qquad (2)$$

$$F_{RR} = k_1\, mg + k_2\, V^2\, mg \qquad (3)$$

$$F_{In} = ma \qquad (4)$$

$$F_g = mgsi\,n\,\theta \qquad (5)$$

In these equations, “m” represents the mass of the vehicle (kg), “V” is momentary speed (m/s), “a” is momentary acceleration (m/s2), “A” frontal area of the vehicle (m2), “ρ” air density (kg/m3), “k1” is the rolling resistance coefficient, “k2” is the speed speed-dependent roll coefficient, “CD” is the aerodynamic drag coefficient.

Considering the electric drive components and their efficiency (Figure 1), the power supplied by the battery or solar cell for the electric motor will be equal to:

$$P_{el} = \frac{P_{wheel}}{\eta_{controller} \times \eta_{motor}} + P_{aux} \qquad (6)$$

Paux is the electrical power consumed by other electrical equipment. One of the best ways to improve vehicle efficiency in driving cycles is the ability to charge the battery during braking (regenerative braking system). In this way, the lost energy of the vehicle is returned to the car during braking and is recharged in the battery.

3.2. Battery

Safety and energy capacity are the main features required for a battery. Among the wide range of commercial batteries, lithium-ion has been chosen as the technology suitable for this application because of its compliance with all the required features

The battery efficiency during charge and discharge, which is affected by internal losses, is calculated using a simple model that relates discharge efficiency to the current I intensity:

$$\eta_{discharge} = \frac{E-RI}{E} = 1 - \frac{R}{E}I \qquad (7)$$

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In the mentioned equation, the resistance R (Ω) and the open open-circuit voltage (E) are generally based on the battery charge (SOC), battery size, and cell array settings. Based on the modeling performed for instantaneous efficiency on high high-performance cycles ECE-EUDC and US06, the average discharge efficiency is 96% (η_(average-discharge)=96%) [42]. Also, a similar amount is considered for the charging process, which leads to the overall charge and discharges efficiency of 92%, which is considered constant in all models (Table 2).

Table 2. Li-ion characteristics.

Power density (W/kg)	400
Energy density (Wh/kg)	130
Efficiency (%)	92

3.3. Solar Cells

The power received from solar cells also depends on the angle of the sun with solar panels (φ), estimated ground radiation (I), panel efficiencies (η), and solar cell area (A), and can be calculated from the following equation:

$$P_s = I_i A_i \eta_s \sin(\varphi) \tag{8}$$

According to studies such as [43], it has been determined that the temperature of the cells and their cooling influences their efficiency. The most important climate point that affects the simulation of the car is the amount of sunlight and wind speed. Using climate and weather data for the past 50 years in the Australian region, wind speed and radiation levels have been achieved in different seasons (Figure 2). Sun radiation (I) is also calculated based on air mass and Lambert's law [44-45].

3.4. Driving Cycle

In order to better reflect the actual driving conditions, the European Driving Cycle (EDC) for measuring exhaust emissions from passenger cars was revised in the late 1980s. The result of this revision is the New European Driving Cycle (NEDC), which has been in force since 1996 (Figure 3). The NEDC consists of two sections. Part 1 (City) is made up of four identical city driving cycles with a maximum speed of 50km/h . This is supplemented by an overland cycle EUDC (Part 2) with speeds up to 120km/h.

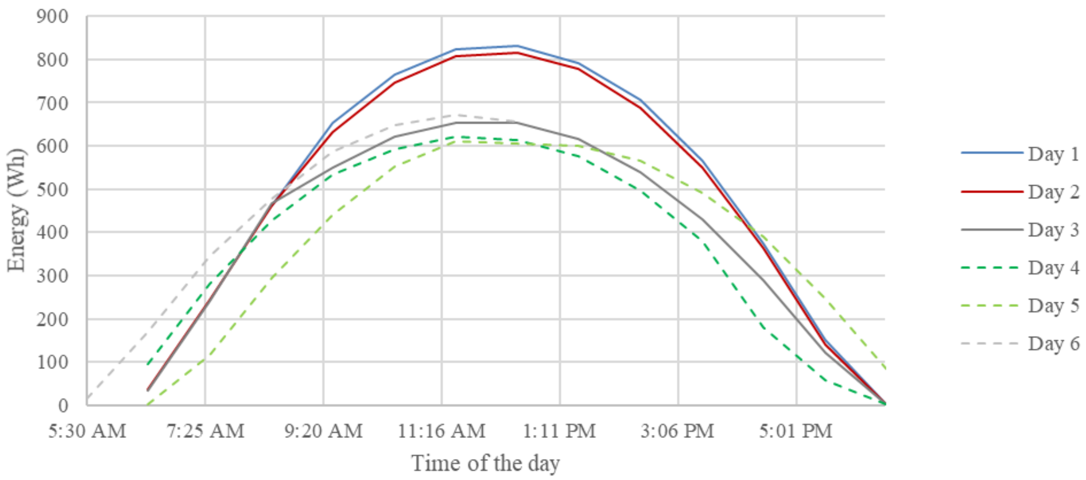

Figure 2. The energy absorbed by the sun in Australia on an autumn day.

For hybrid vehicles that do not have an external charging option, the charge balance of the internal battery is calculated and included in the fuel consumption and emission data. For plug-in hybrids, the consumption values are determined in two steps. First, an electrical range is determined, in which fully charged the battery, the test cycle is traversed purely electrically as often as possible. In the second step, the test cycle with empty electrical energy storage is traversed and determined which emissions the internal combustion engine causes. The calculation of consumption or emissions is based on the assumption that the vehicle first runs the battery completely empty and then travels 25 km with the

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combustion engine. The electrical consumption is assumed to be CO_2 neutral.

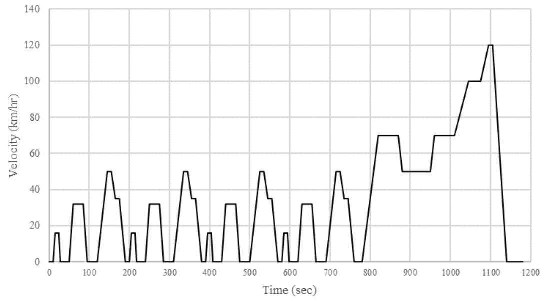

Figure 3. New European Driving Cycle.

calculated in the environmental conditions of Table 3.

Table 3. Environmental parameters.

Parameter	Sign	Unit	Value
Air density	ρ	kg/m^3	1.22
Wind velocity	V_{wind}	km/hr	8
Gravity	g	m/s^2	9.8
Road angle	θ	degree	0

4. RESULTS

In this research, the car is initially charged under sunlight, it starts to move on a driving cycle and along the path solar cells absorb the sunlight radiations to charge the batteries. Eventually, results related to driving time, average speed and emissions are compared with other EVs. Persian Gazelle IV solar-electric car consumption is

By moving the Persian Gazelle IV in a path with the conditions listed in Table 3 and with speed and acceleration in accordance with the NEDC, the performance of Persian Gazelle IV is evaluated. Figures 4, 5, and 6 obtain how the resistance forces are consuming the battery capacity along the path.

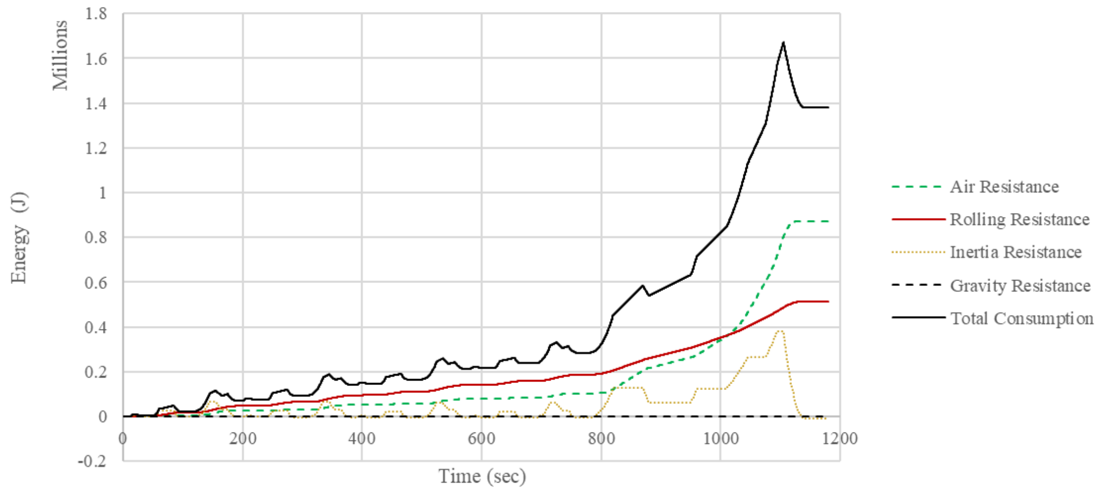

Figure 4. Energy consumption of Persian Gazelle IV during NEDC.

Figure 4 shows the energy consumption of each resistance as well as the total energy consumed by the Persian Gazelle IV during NEDC. As it is seen, in the second part of the cycle that car enters to the highway part, due to the speed of the car, the energy consumption of the car in the aerodynamics sector is growing sharply. In this way, the overall energy consumption, in comparison with the urban sector, is significantly increasing.

Figure 5 shows the power consumption and production of each term of aerodynamic force, rolling resistance, inertia force, gravity force, and total vehicle power. As indicated in the diagram, the mean power of Persian Gazelle IV in a NEDC is 2.25kW.

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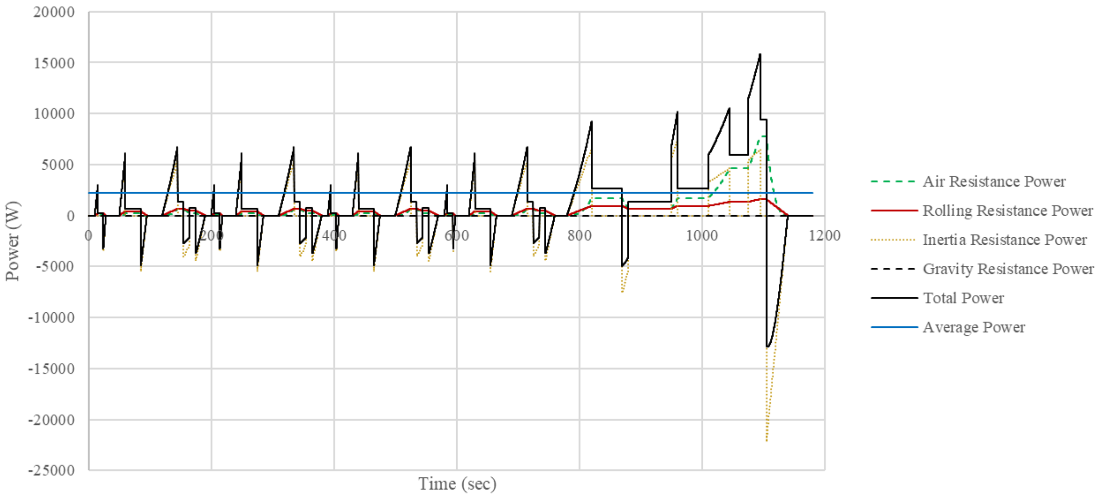

Figure 4. Energy consumption of Persian Gazelle IV during NEDC.

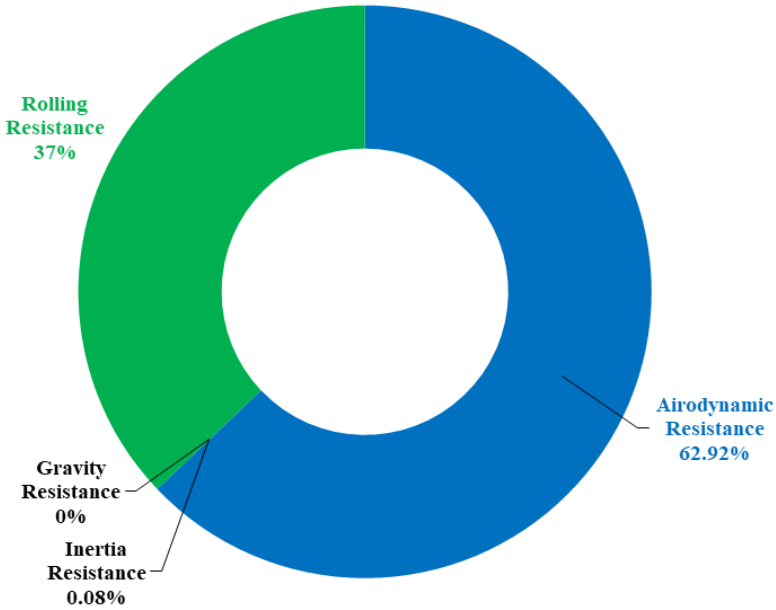

Figure 4. Energy consumption of Persian Gazelle IV during NEDC.

Figure 6 shows the energy consumption of each of the resistance parameters. Among forces, the aerodynamic force has a bigger contribution than other forces, given that a section of the route includes the highway and the car has been driven with high speeds.

Table 4 illustrates the comparison between solar-electric powered vehicle Persian Gazelle IV and several other well-known EVs. Other vehicle information in this table is also derived from the Guide on the fuel economy, CO2-emissions and power consumption published by DAT German Automobile Trust GmbH in 2018. In this table, the car's weight, battery capacity, energy consumption per 100 km of the NEDC cycle, and the number of NEDC cycles per charge are displayed.

As it can be seen, due to the lower average power consumption of the Persian Gazelle IV than other EVs, as well as the use of sunrays to save energy, this car can run more cycles for a full charge. Beside aerodynamic, the reason for the lower

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power consumption of the Persian Gazelle IV, compared to other cars, can be found in much less weight, which is about half of the rest of the vehicles, as well as the lack of utilization of comfort equipment which requires power (such as hydraulic steering, ventilation, etc.).

Table 4. Comparison of Persian Gazelle IV with other EVs during NEDC.

Name	Fuel Type	Mass (kg)	Battery Type	Storage Capacity (kWh)	Energy Consumption (kWh/100 km)	Number of cycles per one charge
					NEDC	
Persian Gazelle IV	Electric	720	L-ion	22	7.4	3
Hyundai IONIQ (AE)	Electric	1550	L-ion	28	11.5	2.4
Volkswagen e-up	Electric	1229	L-ion	18.7	11.7	1.6
Mitsubishi EV (I-MiEV)	Electric	1160	L-ion	16	12.5	1.3
Citroen C-Zero	Electric	1156	L-ion	15	12.6	1.2
Peugeot iOn	Electric	1140	L-ion	15	12.6	1.2
Volkswagen e-Golf	Electric	1615	L-ion	35.8	12.7	2.8
smart for two couple Series 453 60 kW electric drive	Electric	1085	L-ion	17.6	12.9	1.4
smart for two cabrio Series 453 60 kW electric drive	Electric	1115	L-ion	17.6	13.0	1.4
BMW i3 94 Ah (BEV)	Electric	1320	L-ion	22	13.1	1.7
smart for two Series 453 60 kW electric drive / EQ	Electric	1200	L-ion	17.6	13.1	1.3

5. CONCLUSION

In this research, the energy consumption of the solar-electric powered vehicle Persian Gazelle IV was analyzed and compared with other similar vehicles. It was simulated with the New European Driving Cycle. Due to its solar power absorption ability, weather data in Australia, where the car participated in a competition, was investigated and energy absorption was calculated from sunlight. In addition, the parameters involved in the energy consumption of Persian Gazelle IV each were studied separately and their part in consumption declared.

According to the results, it can be concluded that the energy consumption of the Persian Gazelle IV is 4.3 times in the second part of the NEDC cycle, which includes the highway cycle. This is also due to the high contribution of aerodynamic force to energy consumption at higher speeds.

In addition, aerodynamic, rolling, inertia and gravity forces were respectively the largest amount of automotive energy consumption. Due to the regenerative brake, that stored energy in negative accelerations in the NEDC, the inertial resistance force had a small contribution to consumption, as can be seen in studies equals zero and the gravity resistance is neglected because of the situations that NEDC required.

At the end, the consumption of Persian Gazelle IV was compared to other similar EVs. Due to the very low weight of the Persian Gazelle IV compared to other cars and the lack of use of comfort equipment such as hydraulic steering and aerodynamic design the consumption of Persian Gazelle IV compared to other vehicles is much lower.

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