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Towards sustainable transportation: The development of hyperloop technology in Saudi Arabia

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Abstract

Saudi Arabia aims to achieve the principles of sustainable development goals (SDG) in all aspects of life in accordance with its ambitious vision 2030, especially in the field of sustainable passengers and freight transportation. Hyperloop technology can be considered as an excellent sustainable solution for the future of transportation in Saudi Arabia as a result of the availability of auxiliary ingredients, such renewable energy resources and the necessary infrastructure required enhancing the future mobility technology. Hyperloop can reduce the travel time between Saudi cities at a cost equivalent to ticket prices compatible with forms of mass passenger transportation. Accordingly, the Hyperloop technology can be more efficient in terms of energy consumption through the application of renewable energy resources, which makes this technology very attractive to the Saudi Arabia. The present paper discusses the feasibility of Hyperloop technology in Saudi Arabia in technical and economic perspectives including basic performance and cost analysis. Moreover, the integration of different renewable energy recourses, such as solar and hydrogen energy is also discussed. Three major energy systems were reviewed in depth: electrical energy derived from typical fossil fuels and two renewable energy systems based on solar energy, which can be utilized as a primary source of energy or to produce green hydrogen. The overall estimated cost of the three distinct power supply systems was compared using 2022 prices as a benchmark. In comparison to the electrical system and the solar-hydrogen system, the overall cost of the Hyperloop-hydrogen system is the most expensive power supply system. It is expected that the use of Hyperloop technology in Saudi Arabia will be a motivating factor in achieving the Kingdom's Vision 2030 in the transportation sector and as a catalyst for high technology through its requirements for artificial intelligence programs and computer-based operational systems. It can also achieve a significant increase in Gross Domestic Product (GDP) by providing jobs and opportunities for young Saudi men and women in the high-technology sector.

Keywords: Hyperloop Technology; Hyperloop Economic; Renewable Energy Resources; Sustainable Infrastructure; Sustainable Transportation; Saudi Arabia

1 Introduction

The Hyperloop is considered as a theoretical high-speed ground transportation technology riding on a cushion of air and combining pressurized capsules with reduced pressure tubes [1]. It is designed to connect cities sustainably, efficiently, and safely in a fixed guideway using tube-based infrastructure [2]. In this case, the Hyperloop system is built to reduce energy use travel time and costs while its travel speeds between cities could reach to 1,200 km/hr using electricity being provided by sources of renewable energy [1].

In Hyperloop systems, two different types of propulsion technology are included; namely, linear motor and axial compressor. First, the linear motor is to generate thrust through the interactions of magnetic fields on the capsule and

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the infrastructure. Second, the axial compressors are to compress air in front of the capsule and bring it out of the back at higher energy, generating thrust [3]. The successful development of the Hyperloop requires a fusion of advanced technologies that is used on transport modes of magnetic levitation, high-speed rail (HSR), and aviation, as well as its integration of safe into the existing transport modes [2].

In general, the current state progress of Hyperloop is focused on the components of the system such as the vehicle (capsule or pod), its infrastructure, and the communication system. First, the capsule or pod includes an aerodynamic fuselage, the electric subsystem, and the interior (e.g seats). Second, the infrastructure of Hyperloop system contains the tube, the stations, and the sub-structure [2]. In this case, the infrastructure depends on the type of propulsion and levitation systems. It includes the pressure maintenance system and the power substations (to offer a significant reduction of air drag that will help the capsule to reach its maximum speed of 1,200 km/hr) [2]. The Hyperloop's tube ensures minimum air leakage, as well as it encloses and maintains the environment of low-pressure. Finally, the communication system commonly exchanges data, creates an autonomous environment, and coordinates operations to ensure comfort and safety [2].

Regarding to the power system of Hyperloop technology, there are two concepts being identified. First, the energy-autonomous pod is used through storing huge amounts of on-board energy, which could reduce the infrastructure costs. In this case, the power supply can be provided by the on-board rechargeable batteries to the capsule's system, as the power for each capsule may be supplied for acceleration/deceleration, control, levitation, and other services [2]. On the other hand, there are several advantages demonstrated through the connection the power system of an infrastructure-side to the electrical grid, including reduced energy consumption, better efficiency, decreasing the potential of collision, cost saving on the construction of the tube, higher synchronized control of propulsion and manufacturing tolerances of the guideway [2]. For the Hyperloop project, Elon Musk's goal has a new alternative transport technology that will be faster, safer, more convenient, lower cost, sustainable self-powering, immune to weather, and not disruptive to other transport modes [4]. This type of transport is belonged to sustainable transportation that can be defined as any mode of green transportation and has a low environmental impact. It's also about balancing our current and future transportation needs. Walking, cycling, public transportation, carpooling, car sharing, and green automobiles are all examples of sustainable mobility.

2 Literature reviews

Hyperloop is regarded as the fifth mode of transportation. It consists mainly of a capsule for passengers or freight levitating inside a low air pressure tube with a passive levitation technology. An eco-friendly version of the Hyperloop is powered by a skin of solar-powered modules and wind turbines. This concept does not pollute the planet unlike conventional transportation. According to the Chinese architecture firm MAD, this technology is the modern version of the futuristic transportation system, as seen in Figure 1.

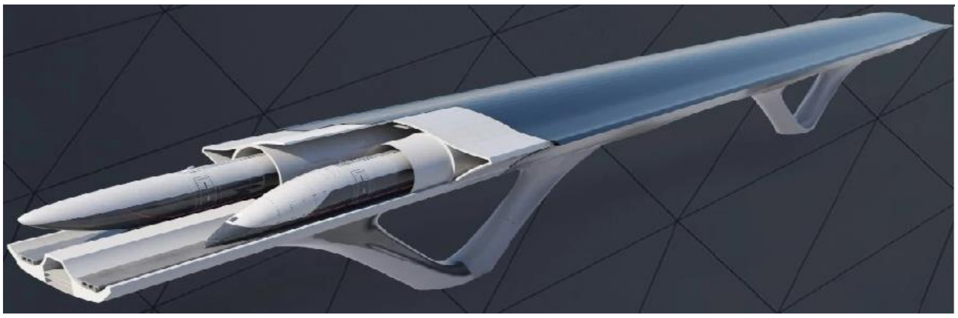

Figure 1 The solar powered Hyperloop system (MAD)

According to the designers, the tunnels used are equipped with bendable solar panel skin modules that can power the Hyperloop along with solar powered LEDs installed along its surface that function as interactive information boards, as seen in Figure 2. Moreover, bladeless wind turbine forests can be built alongside the tunnel of the Hyperloop system, with the goal of generating power for the transportation network that help lowering the project's energy costs. Hyperloop can be regarded as a long-term, self-powered, high-speed, safe, and promising method of transportation, but its shortcomings will necessitate certain revisions and upgrades in the future.

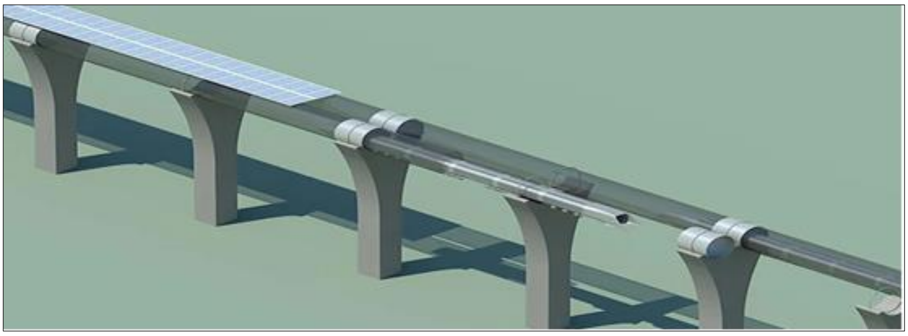

Figure 2 Solar arrays powered Hyperloop system

2.1 Alternatives for the Power Supply of Hyperloop

Different options for power supply of Hyperloop have been previously discussed and assessed. Regarding to the previous technical specifications related the first prototype and the commercial system of Hyperloop, the different options for power supply are analysed.

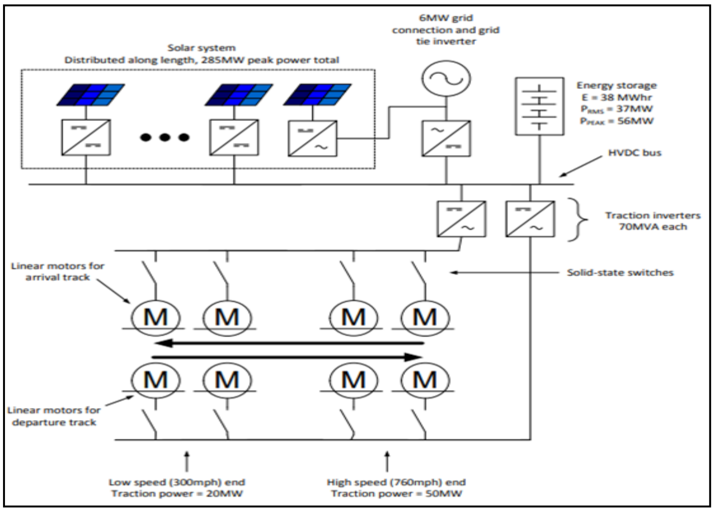

Figure 3 Power supply system for Hyperloop [2]

As seen in Figure 3, the power supply system, as proposed by Elon Musk (2013), is mainly consists of a source of energy connected to an energy storage system, which is used for driving a system of linear motors for arrival and departure purposes. The primary energy of the system can be obtained from either conventional or renewable energy sources.

2.2 The Direct Connection to the Electric Grid

One of the rail systems that is considered closely similar to the Hyperloop system is the MAGLEV rail system [5], However it is designed for a speed up to 500 km/h. Maglev is a rail transportation system that use two sets of magnets: one to resist and push the vehicle off the track, and another to propel the elevated train forward using the absence of friction, as seen in Figure 4. In order to identify the issues connected with Hyperloop technology-based railway systems, comprehensive dynamic simulation experiments have been carried out [5]. Rather than determining the economic consequences or practicality of Hyperloop technology, the previous research [5] focuses on assessing reliability-related impacts. Electric power requirements were established based on the many physical and mechanical assumptions of a hypothetical Hyperloop deployment.

The study instances and their effects on regional and interconnection wide grid operations were based on these electric power requirements. Moreover, the potential grid impacts of a full-scale Hyperloop system at four United States locations were performed. The findings of this study clearly showed that continuous power pulses for intercity transportation applications are sufficiently large in magnitude and ramp rates to cause system voltage disturbances, which may violate generally used design standards for voltage fluctuations and flicker in some circumstances. In addition to that, the simulation findings clearly showed that compensation devices will be required for both active and reactive power in Hyperloop technologies to address or anticipate the pulsing demand. Other technologies, including as energy storage systems, may have unique characteristics to absorb the grid's pulses by balancing and reducing the rapid power demands during pod acceleration and storing electric energy during regenerative braking.

Figure 4 The Maglev transport system [4]

2.3 Renewable Energy applied for Energy Storage Systems

Solar panels would be mounted on the tubes' tops, generating enough energy to power the entire Hyperloop system through the energy storage systems. The solar panel may be 14 feet (4.25 meters) broad and stretch for more than 350 miles (563 km). With such a large area of solar arrays, energy production would be 0.015 hp/ft^2 (120 W/m^2), with peak solar activity producing up to 382,000 hp (285 MW). This energy would be stored and then it can be used to power an electric fan in reverse or driving a linear motor.

Solar PV is usually the most cost-effective technique to supply big amounts of electricity. Although the cost of solar PV electricity has decreased dramatically, further reductions are required in order for this technology to be affordable to the general public. Solar PV has issues surrounding the uncertainty of how much of sun's rays it will receive, as weather can change from time to time. This would make calculating how much energy to store for future use challenging. During the night, while there is still a demand for electricity, sunlight is clearly unavailable. Furthermore, peak radiation availability may not coincide with peak electrical consumption. For this reason, a technique for effective energy storage and recovery is required. It's possible also that the location will be an issue. The amount of solar radiation available varies by location. Solar radiation is substantially higher in some areas, such as the Southwest, than in others, such as the Northeast. This means that solar energy production is reliant on specific places where the devices must be built.

On average, the solar panels in Musk's Hyperloop idea can create roughly 21 megawatts of power. When the system is cruising, however, it requires an average power of 6 megawatts. The energy storage system will employ the same lithium ion technology as the Tesla Model S to provide this power. The energy storage device will assist balance out changes in solar energy output and ensure service continuity during the night by acting as a buffer. We see no reason why the storage system wouldn't function with an average generation of 21 megawatts and an average output of 6 megawatts.

2.4 Different Energy Storage Devices

Energy storage devices have been used in the railway industry before, usually to avoid energy waste during braking or to limit the use of infrastructure. Light trains and trams with energy storage devices on board are becoming more widespread, making them more efficient than stationary options. However, using stationary energy storage devices is more cost-effective and reduces the maximum power demands on the grid [6, 7]. Three energy storage technologies were chosen from among the many available on the market, based on their maturity level and the qualities of high power, low energy, and quick reaction. These energy storage elements are: batteries, supercapacitors, and flywheels [8, 9]. In the following section, a new energy storage technology; namely the hydrogen technology, is discussed.

2.5 Energy Storage via Hydrogen Technology

Transportation energy especially that sourced from fossil fuels is becoming increasingly problematic around the world. Many of these concerns can be addressed by using hydrogen as a transportation fuel. Hydrogen, which is made from renewable resources, has the potential to reduce greenhouse gas emissions to zero, with the usage of some fossil fuels even lowering emissions. Noise and air quality issues would also be addressed. Although progress is being made, and many governments see hydrogen as an important component of a long-term energy strategy, adoption is being hampered by social and economic concerns as well as inexperienced technology. Support from policymakers, industry, and the general public is required to ensure that expectations are satisfied.

Road transport is still one of the biggest roadblocks to reducing greenhouse gas emissions effectively. Despite the fact that the climate aim is explicit, there is still debate regarding whether alternative low-carbon drive technologies for road transport are preferable. While ambiguity is a major source of debate, it has largely been overlooked in comparisons of the three main options: battery electric vehicles, hydrogen-based fuel cells, and internal combustion engines powered by decarbonized fuels, as seen in Figure 5.

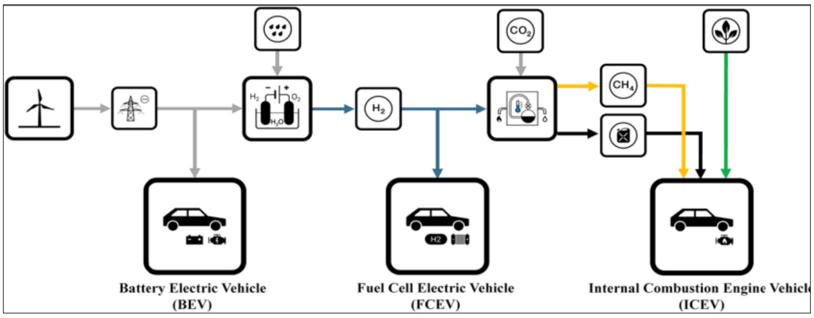

Figure 5 Different technology options for low-carbon transport systems [10]

Hydrogen based fuel cell electric transport systems differ from battery electric systems in terms of electricity supply. The former system produces the demanded power from hydrogen via a fuel cell. This electricity is then used to operate an electric motor. The hydrogen system contains an additional step, since electricity is used firstly to produce an energy carrier; hydrogen; through electrolysis. Accordingly, the overall efficiency is comparably low, between 25 and 30% [11].

The proposed system for Hydrogen based fuel cell used as alternative fuel train for regional transportation can be seen in Figure 6. This system can also be easily applied for Hyperloop technology in the near future.

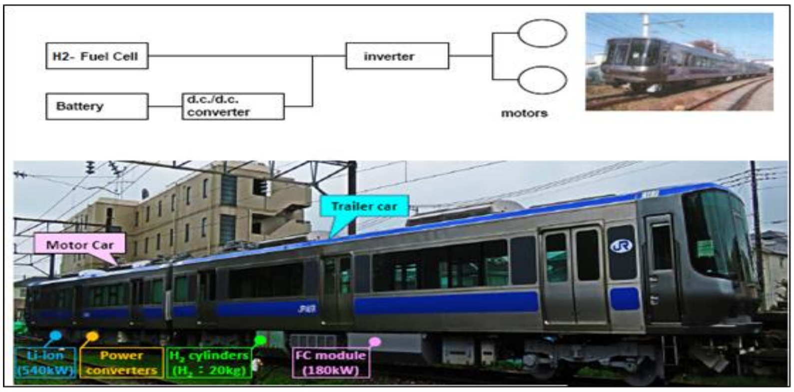

Figure 6 Hydrogen based fuel cell used as alternative fuel train

3 Methodology

In order to generate more electricity for operating the Hyperloop system than it consumes, the integration of three different renewable energy recourses is considered. However, the economic consideration of Hyperloop is one of potential benefits beside environmental factor, time saving, reduced congestion, and induced demand or grid complementarities. Hyperloop will have not positive economic impacts on the transport sector, but also on the environment and society. The unit cost used in this paper is assumed, as the power will increase with the passenger capacity.

3.1 Cost of Electrical Power

The interface of Hyperloop system with the grid may require energy storage since the system is powered by electricity. In this case, the electrical energy needed to support one moderately Hyperloop system for passenger travel might be in a range of 500 to 600 MWh/day (Megawatt-hour/day) over a 24-hour period, while it could be up to 1,900 MWh/day for freight. The power of peak demand might be in the range of 100 to 600 MW (Megawatt) for passenger travel and up to 2,000 MW for heavier freight systems. As a result, the annual energy savings of one 300-mile Hyperloop passenger system with a 15,000 passengers per day were estimated to be around 2.8 trillion Btu (British thermal unit) in 2030, or approximately 0.01% of national transportation energy demand. In comparison with other freight transport modes, the Hyperloop would be at least eight times less energy efficient in terms of energy used per ton-mile shipped than transport by rail and water, and at least three times than transport by truck [12].

3.2 Cost of Solar Power

Apart from being very convenient, and fast, is also an earth-friendly transport mode, using a low power due to running on renewable resources like solar energy. The solar panels placed on the tube can generate energy more than the operating requirement of the Hyperloop system, as well as producing an extremely low carbon footprint, which is accounting to be 2 to 3 lesser than railways and 5 to 6 times lesser than air travel [13]. In this case, the solar panels can be mainly installed on the tube of Hyperloop's vacuum, giving a 240 MW rated from the 340 km long and 6 m wide of 2 square-km footprint [14].

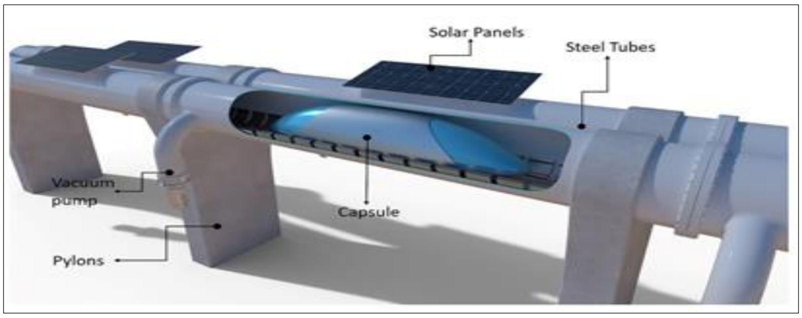

Figure 7 The solar-Hyperloop-system

The energy of Hyperloop system generated by solar panels batteries might be on average 57 MW/year, which is accounted three times higher than the total power consumption for the Hyperloop line between Los Angeles and San Francisco that has an average of 21 MW [15].

3.3 Cost of Hydrogen Power

A Hydrogen might be considered as one solution to produce the power of Hyperloop system, as it is recently proposed for both public high-speed transportation systems and freight transport through the burning hydrogen with oxygen and based on hydrogen fuel tanks, a fuel cell and a battery pack. The Hydrogen supply from the storage tanks as fuel through a reaction with oxygen, using a hydrogen fuel cell or within a hydrogen internal combustion engine.

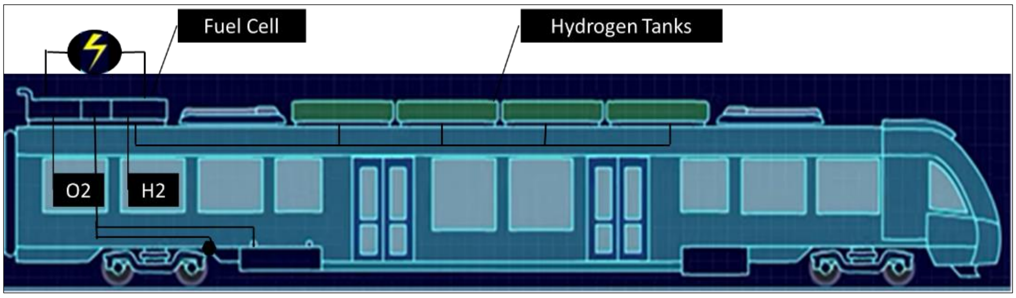

Figure 8 The hydrogen-Hyperloop-system

4 Results and discussion

4.1 Solar Energy Supply Model

For this study, the operator costs of constructing Hyperloop system between two main cities in Saudi Arabia was determined based on secondary data obtained by [16] with respect to many components of capsule and tube. For example, the elements of capsule are structure and doors, compressor and plumbing, interior and seats, batteries and electronic, propulsion, suspension and air bearing, and components assembly. In this case, the data used to calculate the cost for year 2022 is based on data from 2015 with taken the consumer price index into account, as it equal to $99.42 and $109.11 for years of 2015 and 2022, respectively. However, the total cost of providing 40 Hyperloop capsules is $59 million at 2022 prices, compared to $54 million at 2015 prices based on the index value of 1.097 shown in Table 1.

Table 1 Estimated cost of Hyperloop capsule

Element	Cost ($million)	Consumer Price Index in January 2015	Consumer Price Index in January 2022	Index	Cost ($million)
Capsule structure and doors	9.8	99.42	109.11	1.10	11
Interior and seats	10.2	99.42	109.11	1.10	11
Compressor and plumbing	11	99.42	109.11	1.10	12
Batteries and electronics	6	99.42	109.11	1.10	7
Propulsion	5	99.42	109.11	1.10	5
Suspension and air bearings	8	99.42	109.11	1.10	9
Components Assembly	4	99.42	109.11	1.10	4
Total	54	99.42	109.11	1.10	59

The cost of constructing Hyperloop tube is categorized into several components such as tube, pillars and tunnel construction, propulsion, solar panels and batteries, station and vacuum pumps, and permits and land. However, the total cost of constructing Hyperloop tube is $5,937 million at 2022 prices, compared to $5,410 million at 2015 prices. In this paper, the type of power used to operate the Hyperloop system is mainly considered and the total operating cost of tube needs to be calculated with respect to power system individually. For using the power system of solar panel and batteries, the total operating cost of Hyperloop tube is $5,937 million at 2022 prices, compared to $5,410 million at 2015 prices and the cost of solar panels and batteries is accumulated of 3.9% out the total tube cost, as it is increased from $210 million to $230 million in 2022 as shown in Table 2.

Table 2 Estimated cost of Hyperloop tube

Element	Cost ($million) in 2015	Consumer Price Index in January 2015	Consumer Price Index in January 2022	Index	Cost ($million) in 2022
Tube construction	650	99.42	109.11	1.10	713
Pillar construction	2,550	99.42	109.11	1.10	2,799
Tunnel construction	600	99.42	109.11	1.10	658
Propulsion	140	99.42	109.11	1.10	154
Solar panels and batteries	210	99.42	109.11	1.10	230
Station and vacuum pumps	260	99.42	109.11	1.10	285
Permits and land	1,000	99.42	109.11	1.10	1,097
Total	5,410	99.42	109.11	1.10	5,937

It can be seen from the above tables that; the total cost of the Solar-Powered-Hyperloop-System is about $6,000 million according to the estimated cost in 2022. The cost of the solar energy power supply is about $230 million with a ratio of 3.8% from the total cost.

4.2 Electrical Energy Supply Model

Electric train grid effect studies are the most closely tied to a Hyperloop (or the MAGLEV technologies). Given that each train engine (locomotive) for intercity train routes has a rated power capacity of 1-2 MW, 10 or more trains running within a traveling corridor can result in electric power requirements of 10-20 MW.

Early research on the integration of transportation systems with the electric grid examined many aspects of generalizing the design and operation of train electrification systems [17]. Some researches, on the other hand, compared the power usage and impact of electric vehicles and light rail transit [18]. In the United States and around the world, industrial loads with similar load characteristics (e.g., arc-furnace installations) have been successfully connected to the transmission grid utilizing dynamic transmission.

By considering the consumption tariffs announced recently by Saudi Electricity Company [19], shown in Table 3 below, the New Electricity Tariffs for all categories of consumption as approved by the Council of Ministers' Decree dated 12/12/2017, which has been applied since 1/1/2018.

Table 3 The Saudi consumption tariffs [19]

<table>
<tr><th>Consumption categories</th><th>Residential</th><th>Commercial</th><th>Agricultural & Charities</th><th>Governmental</th><th>Industrial</th><th>Private educational facilities, private medical facilities</th></tr>
<tr><td>Unit</td><td>(Halalah / kwh)</td><td>(Halalah / kwh)</td><td>(Halalah / kwh)</td><td>(Halalah / kwh)</td><td>(Halalah / kwh)</td><td>(Halalah / kwh)</td></tr>
<tr><td>1-6000</td><td>18</td><td>20</td><td>16</td><td rowspan="2">32</td><td rowspan="2">18</td><td rowspan="2">18</td></tr>
<tr><td>More than 6000</td><td>30</td><td>30</td><td>20</td></tr>
</table>

The maximum Saudi consumption tariffs is about $0.09, i.e., $0.0864 for each kWh. Consequently, the estimated cost for the electric power requirements of 10-20 MWh is about $86.4. The pump-down phase's power consumption was estimated to be around 80 kW/mile. There will be no operations during that time. As a result, the compressors would be the only source of electricity. Tube leakage makes up a significant amount of the total load; especially low-pressure operation will result in leaks due to diffusion, desorption, permeation, microcracks, and tolerances in mechanical component fabrication and assembly. For heavy freight, the average power draw to counterbalance leakage was projected to be 48 kW/mile, for small freight, 36 kW/mile, and for passengers, 31 kW/mile [20]. For a long-distance of 1000 mile, the cost will be about $4.5 thousands for electricity cost.

According to the last estimation of the High-Speed-Electrical-Train made in Egypt (2022) [21], the total cost of a single train consists of 6 passengers areas is about $40 million. It can be seen that, the cost of electricity for Hyperloop, even when the infrastructure of electrical grid is added, is lower than that for a solar energy system. However, the environmental effects by using the electrical grid are much larger than that of using solar energy as a power supply system. Consequently, the total cost of the Electrical-Hyperloop system can be estimated as $5,800 million including the cost of Hyperloop capsule and tube.

4.3 Hydrogen Energy Supply Model

The Hydrogen is considered as a new alternative renewable energy recourse for Hyperloop system, which is mainly based on generating energy through the combination of Hydrogen stored on the capsule's roof and Oxygen in the air. In this case, the estimated cost of Hyperloop tube is recalculated. In electrical terms, the energy density of hydrogen is equal to 33.6 kWh of usable energy per kg, versus diesel which only holds about 12–14 kWh per kg. What this really means is that 1 kg of hydrogen, used in a fuel cell to power an electric motor, contains approximately the same energy as a gallon of diesel.

It is expected that the cost of the Hydrogen-Hyperloop system is increased over the Solar-Hyperloop system according to the cost of electrolyzer used for hydrogen production. Since 1920, alkaline electrolysis cells (AECs) have been used to produce hydrogen for industrial purposes. Although the yearly market volume in 2019 was only 140 Megawatts electric (MWel), the cumulative installed water electrolysis capacity since 1956 is expected to be over 20 Gigawatts electric (GWel). The installed capacity is predicted to be 1, 5, or 17 Terawatts electric (TWel) by 2050 [22].

The current cost of the kW/h produced from hydrogen is about $0.068, which nearly equals three times the cost of kW/h produced from the solar energy. This is due to the cost of electrolyzes systems. In this case, the total energy cost of Hyperloop system, using the electric is $5.8 thousands, compared to the energy used by solar panels of $6.0 thousands.

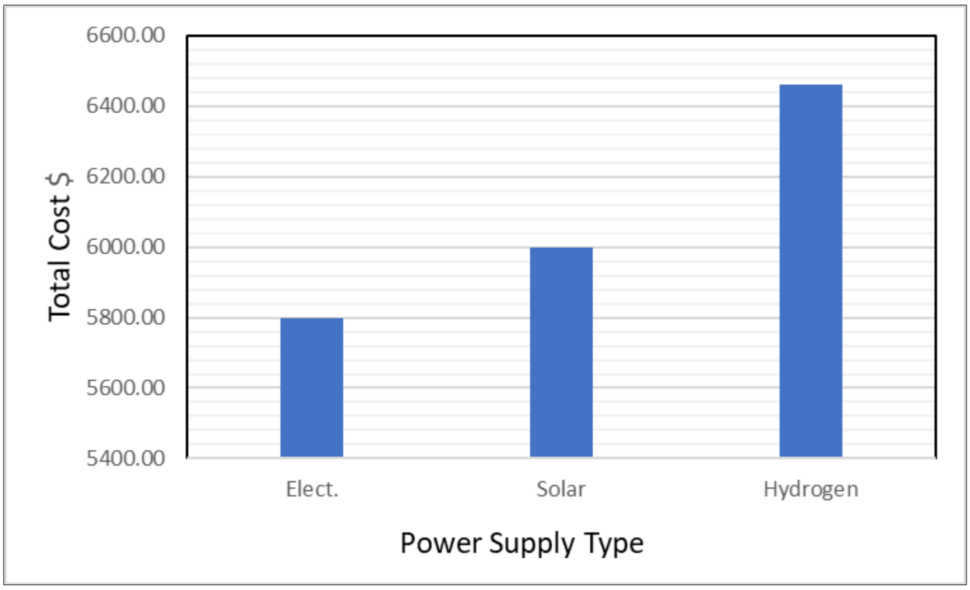

Figure 9 The total cost of 3-different energy-Hyperloop-system

As a result, the total energy cost of Hydrogen-Hyperloop-System can be estimated as $690 million. This leads to a total Hyperloop cost of $6,460 million in 2022 prices as shown in Figure 9, including the cost of Hyperloop capsule and tube.

5 Conclusion

The present paper discusses the possibility of the application of Hyperloop system in Saudi Arabia as a sustainable transportation strategy that aligned with 2030 Saudi vision. The concept of the hyperloop system was discussed in details with emphasis on the cost estimation of hyperloop-infrastructure for a specified distance between two Saudi's cites. The total cost includes the cost of the hyperloop-tube, capsule and power supply system. Three different energy systems were discussed in details; namely electrical energy produced from traditional fossil fuels and two renewable energy systems based on solar energy where the solar energy can be used as a main source of energy or it can be used for of green hydrogen. The green hydrogen can be used-in connection with-fuel cell system to operate the hyperloop. The total estimated cost of the three different power supply systems were compared according to the estimated cost of 2022 prices. The total cost of the hyperloop-hydrogen system is the much expensive power supply system in comparison with the electrical system and the solar-hydrogen system.

By 2030, the cost of green hydrogen would have dropped by one-third, and by 2050, it would have dropped by two-third from the currently cost. Although green hydrogen can quickly become more economically viable than hydrogen produced via traditional energy, a comparison with battery-electric transport vehicles, which are favoured for lower energy supply costs and thus are currently the preferred choice of local transportation organizations, is necessary.

More efficiency and cost specifics of hydrogen-based and battery-electric road transportation should be discussed in our future research. In larger-scale applications, such as Hyperloop, aircraft or heavy-duty road transport, where battery weight is a factor, hydrogen is likely to be more competitive. Heavy-duty trucks, on the other hand, are currently in short supply.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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