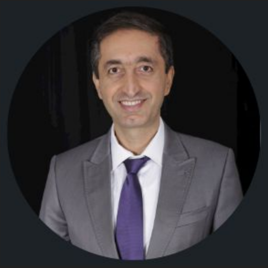

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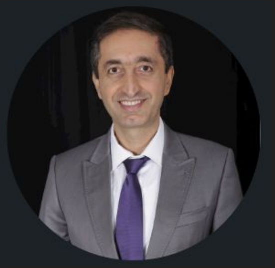
16 Types of Hydrogen Storage



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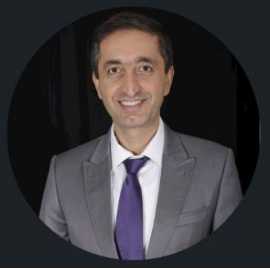
Hydrogen Storage

In recent years, hydrogen (H2) has become a critical element in the decarbonization strategies of many countries. This is because it can serve as a fuel, feedstock, energy carrier, and storage. Additionally, green hydrogen, which is produced from water using renewable energy sources and hydrogen electrolysers, can be generated anywhere in the world.



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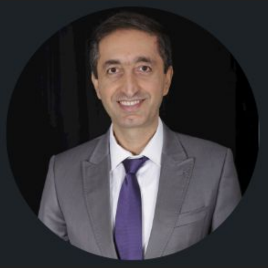
1) Compressed gaseous hydrogen

1.1) Storing hydrogen in a form of high pressure gas is the most mature hydrogen storage technology.

You need to store gaseous hydrogen at high pressure (350-700 bar) in high pressure storage vessels.

1.2) Energy required to compress hydrogen to 700 bar = 6 kWh/kg.



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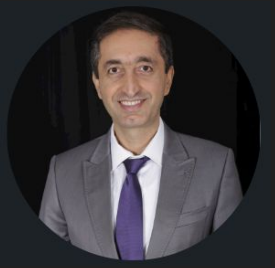
1) Compressed gaseous hydrogen

1.3) High pressure gaseous hydrogen (700 bar) offers moderate volumetric density = 42 kg/m3).

1.4) For hydrogen vehicles either hydrogen fuel cell (FCEV) or hydrogen internal combustion engine (H2ICE), the fuelling time is less than three (3) minutes for 0.2 m3 of hydrogen tank which is enough to drive more than 500 km.



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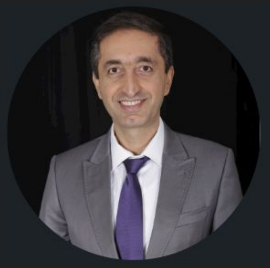
2) Liquefied hydrogen

2.1) Liquid hydrogen offers highest volumetric density = 70.8 kg/m3.

2.2) Kawasaki Heavy Industries and Victorian government successfully built and tested first liquefied hydrogen carrier that delivered liquid hydrogen from Australia to Japan in February 2022.



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2) Liquefied hydrogen

2.3) Liquefaction energy requirement = 10-13 kWh/kgLH2 and high rate of the boil-off and potential product loss due to the boil-off are the liquid hydrogen storage challenges.

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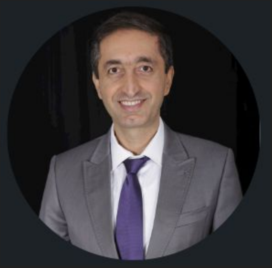
3) Synthetic fuels

3.1) Green hydrogen + captured carbon → Synthetic fuels (green methane, gasoline or diesel)

$(2n + 1)\ H_2 + n\ CO \rightarrow C_nH_{(2n+2)} + n\ H_2O$ (Fischer-Tropsch process)



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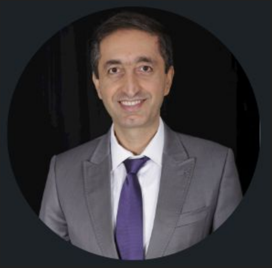
3) Synthetic fuels

3.2) The advantage of producing the above Synthetic fuels is that the storage, transport and usage of them are already in place.

3.3) the disadvantages of Synthetic fuels are high price of Fischer-Tropsch process and need for carbon management and storage.



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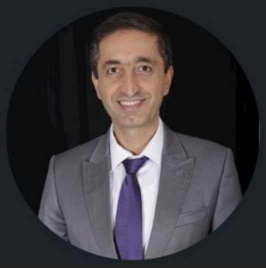
4) Compressed and liquefied synthetic natural gas (SNG)

4.1) Captured CO_2 + $4H_2$ (green hydrogen) → CH_4 +$2H_20$ (Sabatier reaction)

4.2) Storage and delivery of compressed and liquefied natural gas is in place and the technology is mature.



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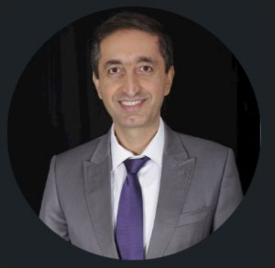
4) Compressed and liquefied synthetic natural gas (SNG)

4.3) SNG then dehydrogenated (hydrogen is ‘extracted’ from SNG)

4.4) The challenges of this option are high temperatures (250-350 °C) and high pressures (around 30-30 bar) and also the need to use a nickel, aluminium oxide catalyst, which needs high energy demand, high costs.



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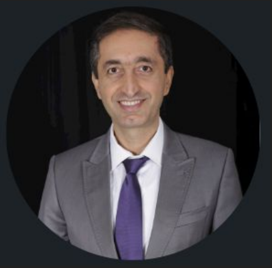
5) Ammonia

5.1) Ammonia has high volumetric hydrogen density (107.7-120 kg/m3 for liquid ammonia) and high gravimetric hydrogen content (17.65 wt% for liquid ammonia).



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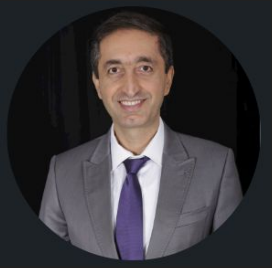
5) Ammonia

5.2) Ammonia less energy for liquefaction because it requires to be cooled down to -33 °C, while SNG and H2 need to be cooled down to -252.8 °C.



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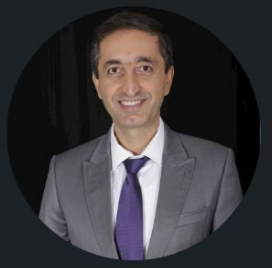
5) Ammonia

5.3) Ammonia (NH3) compare to methanol (CH3OH) does not contain carbon (C) atoms and therefore carbon management is not required.



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5) Ammonia

5.4) The disadvantage of using Ammonia as hydrogen carrier is that they required energy intensive dehydrogenated process:

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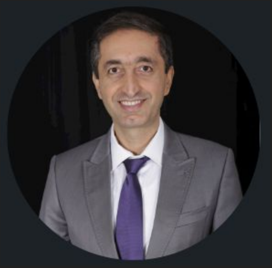
6) Methanol

6.1) Methanol has high volumetric hydrogen density (95.04-99 kg/m3) and high gravimetric hydrogen content (12.1 wt%).



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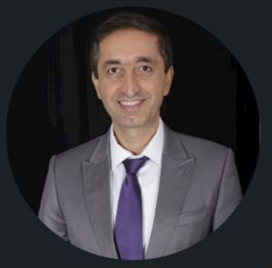
6) Methanol

6.2) Methanol is liquid at normal atmospheric pressure and temperature and does not require any additional energy for that.



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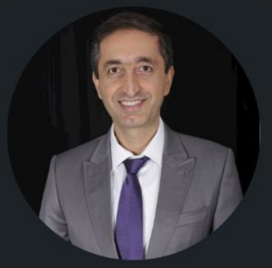
6) Methanol

6.3) The disadvantage of using methanol as hydrogen carrier is that they required energy intensive dehydrogenated process:

$CH3OH \rightleftharpoons CO + 2H2; CO + H2O \rightarrow CO2 + H2$

$CO + 2H2 \rightleftharpoons CH3OH; CO2 + 3H2 \rightleftharpoons CH3OH + H2O$



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7) Formic Acid (CH2O2) and Isopropanol (C3H8O)

7.1) They have high volumetric hydrogen density (around 53 kg/m3 for formic acid and 25.9 kg/m3 for isopropanol) and high gravimetric hydrogen content (4.3 and 3.3 wt% for formic acid and isopropanol, respectively) for hydrogen storage.

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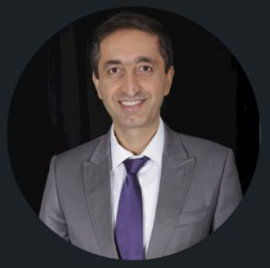
7) Formic Acid (CH2O2) and Isopropanol (C3H8O)

7.2) As isopropanol and formic acid molecule contain carbon, they required energy intensive dehydrogenated process and carbon management.



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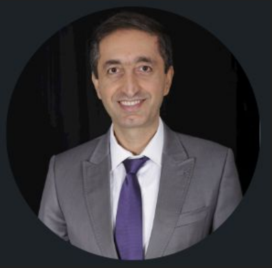
8) Liquid organic hydrogen carriers (LOHCs)

8.1) Liquid organic hydrogen carriers (LOHCs) are organic material that can absorb and release hydrogen through chemical reactions.



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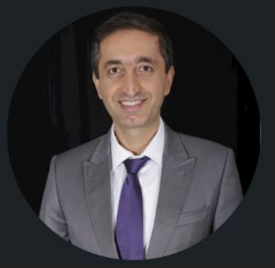
8) Liquid organic hydrogen carriers (LOHCs)

8.2) Currently the most promising LOHCs are toluene/ methylcyclohexane (MCH) (C_7H_8/ C_7H_{14}), naphthalene/ decalin ($C_{10}H_8$/ $C_{10}H_{18}$), benzene/ cyclohexane (C_6H_6/ C_6H_{12}), and dibenzyltoluene (DBT)/ perhydro-dibenzyltoluene (PDBT) ($C_{21}H_{20}$/ $C_{21}H_{33}$).



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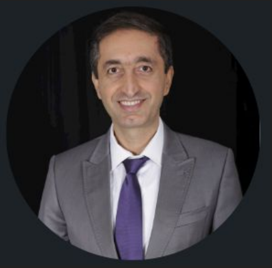
8) Liquid organic hydrogen carriers (LOHCs)

8.3) LOHCs gravimetric hydrogen content is between 6.19 and 7.29 wt% which is not attractive is some of the hydrogen application.



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9) Metal hydrides

9.1) Metal hydrides are used for storing hydrogen in a solid form.

9.2) Metal hydrides have the greatest volumetric hydrogen densities among all the storage options.

9.3) Metal hydrides gravimetric hydrogen content is less desirable, therefore, they offer heavier storage per unit of H2 stored.

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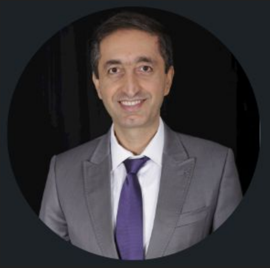
9) Metal hydrides

9.4) Elemental metal hydrides including magnesium hydride (MgH_2) and aluminium hydride (AlH_3) have good hydrogen storage capacity (up to 7.6 wt% for MgH_2 and 10.1 wt% for AlH_3) and low cost.

9.5) Intermetallic hydrides including AB_5, AB_2, AB types and $LaNi_5H_6$ need less temperatures and pressures for hydrogenation/dehydrogenation compare to Elemental metal hydrides.



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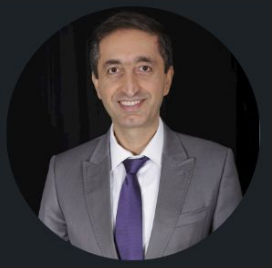
9) Metal hydrides

9.6) Complex metal hydrides including lithium borohydride ($LiBH_4$) and lithium amide ($LiNH_2$) have sluggish de/re-hydrogenation kinetics and undesirable operating temperatures, which effect their widespread usage.



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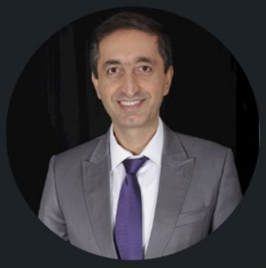
10) Carbon Porous materials

Carbon-based porous hydrogen storage include carbon fibre 21, nanotubes, aerogel, templated and activated carbon and which have the potential for commercialisation.



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11) MOF Porous materials

Metal-organic frameworks (MOFs) are organic-inorganic hybrid and crystalline porous materials, and their structures, pore environment, and their function can be set for specific conditions of hydrogen storage. They have high surface area and large pores and their gravimetric hydrogen content is attractive (up to 10 wt%).

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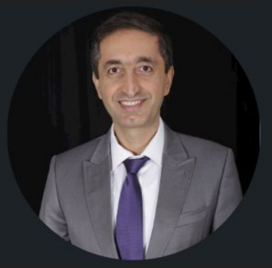
Reference for methods 1-11

Hydrogen storage for a net-zero carbon future, Rahmat Poudineh , Aliaksei Patonia, The Oxford Institute for Energy Studies, April 2023

https://www.oxfordenergy.org/publications/hydrogen-storage-for-a-net-zero-carbon-future/



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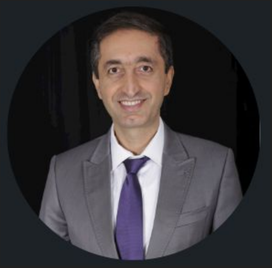
12) Hydrilyte®

12.1) Hydrilyte® is a substance made up of metal hydride particles that are suspended in mineral oil. The metal used in Hydrilyte® is widely available, which makes it easier to produce and export in large quantities. Hydrilyte® is non-toxic and non-reactive, making it easy and cost-effective to handle during the transportation of hydrogen.



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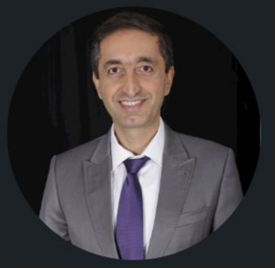
12) Hydrilyte®

12.2) Additionally, the process of storing and releasing hydrogen using Hydrilyte® does not require the use of catalysts, which helps to reduce the overall cost of the plant and ongoing maintenance.

https://carbon280.com/hydrilyte-tech



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13) Vallourec’s Delphy Solution

Conscious of the limitations of existing hydrogen storage solutions, Vallourec’s teams devised the Delphy system. Delphy can store between 1 and 100 metric tons of hydrogen on its site of production or use. It functions using a series of long pressure vessels, made out of pipe assemblies in which pressurized hydrogen is injected to be stored.

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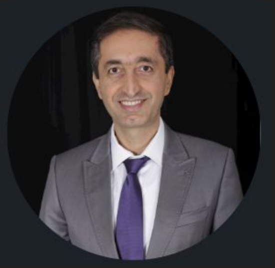
13) Vallourec’s Delphy Solution

Pipe strings are housed underground in excavated cavities between 5 and 10 meters in diameter and up to 100 meters deep.

https://www.vallourec.com/news/vallourecs-delphy-solution-is-a-game-changer-for-hydrogen-storage/



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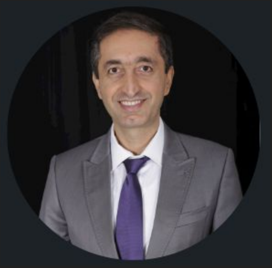
14) Natural Hydrogen

Naturally occurring hydrogen, trapped underground in geological formations, is emerging as a potential game-changer for hydrogen storage. This eliminates the need for complex and energy-intensive processes like electrolysis (green hydrogen) or carbon capture (blue hydrogen).



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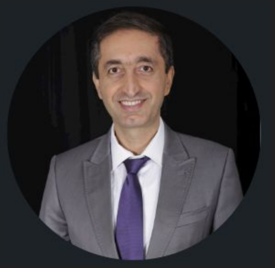
14) Natural Hydrogen

Exploiting natural hydrogen could offer a readily available, low-cost storage solution if further research can pinpoint sufficient reserves and develop safe extraction methods.



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15) Line Packing and Salt caverns

Line packing with hydrogen

To calculate the kgH2 stored in the pipeline, we only need to consider the volume of the pipeline, the density of the hydrogen, and the flow in the pipeline.

kgH_2 stored = ρH x Volpipe,

$\rho H_2 = P\ MWH_2 / ZR0\ T$,

Volpipe =($\pi D^2 /4$) x Lpipe

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15) Line Packing and Salt caverns

The flow in the pipe causes pressure drop due to friction.

$\Delta P = 1/2.\ \rho u^2\ f\ L/D$,

f= friction coefficient for a pipe (depends on the Reynolds number ($Re = u\rho D/\mu$) of the pipe flow and roughness).

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15) Line Packing and Salt caverns

The mass flow M(kg/sec) in the pipe is

$M=u\rho A$

$P\,dP/dx = \frac{1}{2} (M^2 /A^2) f/D (ZRT)$,

$R=R0/gmMWH_2$

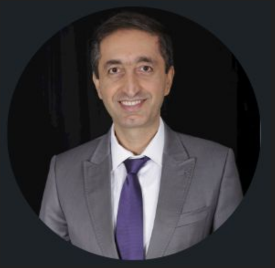
Integrating, one obtains the equation for pressure drop in the pipe.

$P1^2-P2^2 = CL$,

$C=f (M^2 /A^2D) (ZRT)$, $\rho2/\rho1 =P1/P2$

$Paver = 2/3 (P1^3-P2^3 /P1^2 -P2^2)$

The line-pack flexibility can be calculated using the above formulas.



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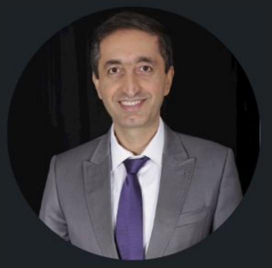
15) Line Packing and Salt caverns

For pipeline transported hydrogen:

- Line Packing is ideal for short-term storage.

- Salt caverns: suitable for long-term storage with high cost-effectiveness.



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15) Line Packing and Salt caverns

Key findings:

1- In pipelines with 36" and 48" diameters and 100 km length, 150-300 tonnes of hydrogen can be stored per day at a levelized cost of $0.05/kg or less. However, varying peak pressure to meet customer demand may reduce the lifetime of the pipeline.

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15) Line Packing and Salt caverns

Key findings:

2-A typical salt cavern case for storing 500 tonnes of hydrogen costs around \$18M (\$36/kgH2). Storing hydrogen in the cavern for 120 days has a levelized cost of \$1.2/kg and only costs \$0.15/kg if stored for 15 days regularly.

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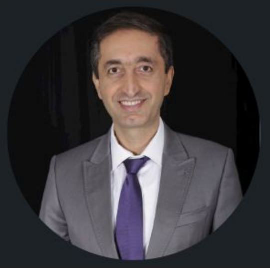
15) Line Packing and Salt caverns

Levelized storage cost range ($/kgH2)

Line packing → 1 day or less, 100-300 (tonnes of H2) = 0.05 $/kgH2;

Salt cavern → 2-4 months, 500-1000 (tonnes of H2), 0.6-1.2 $/kgH2.



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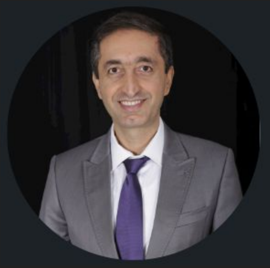
Reference for item 15

Burke, A., Ogden, J., Fulton, L., & Cerniauskas, S. (2024). Hydrogen Storage and Transport: Technologies and Costs. UC Davis: Hydrogen Pathways Program. Retrieved from

https://escholarship.org/uc/item/83p5k54m



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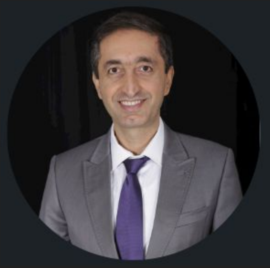
16) Decommissioned Wellbores

Wellbore decommissioning marks the end of an oil or gas well's life, requiring operators to safely seal the wellbore. Repurposing near-decommissioned wellbores for pipe storage creates a hydrogen energy storage system from excess renewable electricity. This approach could integrate green hydrogen into local economies while managing decommissioning cost.

Reference for item 16

Alireza Salmachi, Tara Hosseini, Raheel Ahmed Shaikh, Alex Dinovitser, Derek Abbott, Techno-economic assessment of hydrogen pipe storage in decommissioned wellbores sourced from surplus renewable electricity, International Journal of Hydrogen Energy, Volume 47, Issue 56, 2022, Pages 23710-23720, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2022.05.160



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Thank you

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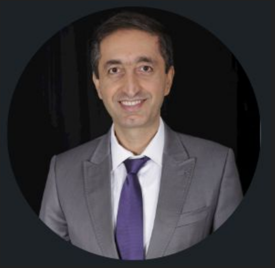

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