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GAS PIPELINE VERSUS LIQUID HYDROGEN TRANSPORT – PERSPECTIVES FOR TECHNOLOGIES, ENERGY DEMAND AND TRANSPORT CAPACITY, AND IMPLICATIONS FOR AVIATION

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Abstract

Distance-dependent energy demand as well as transport capacity of different (future) hydrogen (H_2) distribution options – in gaseous form (GH_2) through repurposed natural gas or new pipelines as well as in liquid form (LH_2) via ship and truck – are analyzed based on technology perspectives, key scaling properties and performance potentials. As central result of thermodynamic analysis, the energy demand based breakeven distance for GH_2 pipeline transport versus LH_2 shipping and trucking is typically reduced by about 35 % to maximally several hundred kilometers, if GH_2 transport proceeds through large *repurposed* instead of *new* steel pipelines. This stems from the underlying differences in pipe's inner layer condition and resulting friction-induced pressure losses leading to enhanced energy demand for recompression along the transport path. Moreover, in reflection of the trade-off between energy demand and transport capacity and hence sensible transport range, a 10 % reduction in load capacity for repurposed pipelines is found to balance additional energy demand and differences in breakeven distance compared with new steel pipelines. Techno-economic consequences regarding the envisioned *European Hydrogen Backbone* including perspectives of composites technology for GH_2 pipelines are discussed together with implications for favorable transport scenarios for the aviation sector, which for reasons of energy density typically requires the provision of liquid hydrogen for use as energy carrier on-board future aircraft.

1. INTRODUCTION

Green hydrogen (H_2), as a scalable, versatile clean-burning energy carrier derived from renewably generated electricity, holds promise for sustainably meeting future global energy demands in various sectors from transportation including aviation over industrial energy and heating. In aviation, H_2 offers opportunities for emission savings and reduced high-altitude climate impact either by direct use for electrochemical conversion by a fuel cell and / or within combustion-based concepts or as a feedstock for synthetic fuels.

While the system transition to a hydrogen economy offers important synergy effects through sector coupling, it also affects aviation-related considerations and demands for a holistic picture of benefits, challenges and implications.

For example, for reasons of energy density, apart from possible niche applications, H_2 has to be used in liquid form as an energy carrier on board aircraft, with projected demand exceeding hundred times the current global liquefaction capacity (cf. Figure 1). However, for most other sectors, H_2 may not only be utilized, but correspondently also be transported in gaseous form (e.g. via gas pipelines). This, for instance, also applies for the usage of H_2 as feedstock for the production of drop-in sustainable aviation fuels like power- or sunlight to-liquid [1]. Accordingly, the *European Hydrogen Backbone*, a masterplan for a continent-wide network of H_2 infrastructure by a group of thirty-one energy operators, based on repurposed natural gas pipelines for gaseous hydrogen (GH_2) transport to start operation in 2030 with extension to full size by new pipelines planned until 2040 [3], will likely take a prominent role in future large-scale hydrogen provision.

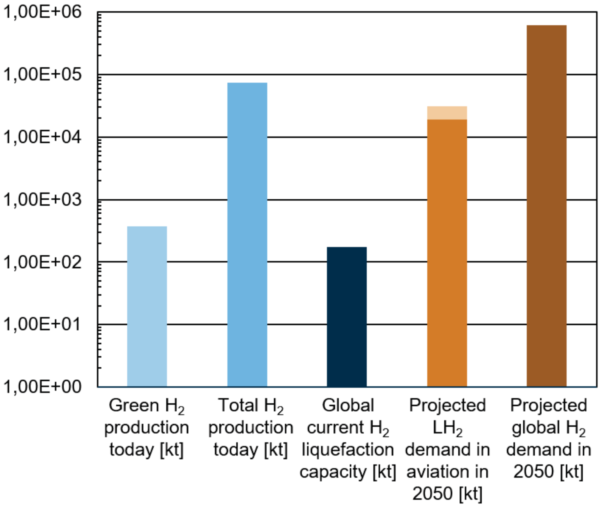

Figure 1: Comparison of current annual (Green) hydrogen production and liquefaction capacities and projected demands in 2050 based on data from Ref. [4-6] .

However, in the aviation context, significant disadvantages can arise for liquefaction of electrolysis-derived H_2 in proximity to an airport as compared with e.g. directly at location of production adding to those for long-distance GH_2 pipeline transport compared with LH_2 shipping and trucking (cf. Figure 2) [7]. Besides availability and cost of renewable energy sources, economy of scale effects are a decisive factor [5] typically in favor of central (and potentially locally combined) hydrogen production and liquefaction at beneficial geographical locations.

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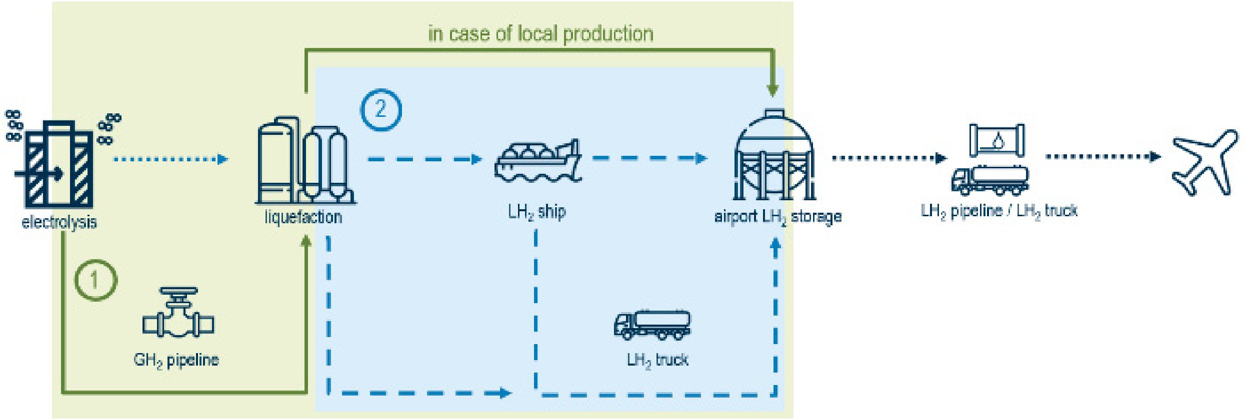

Figure 2: The (L)H_2 life cycle with different considered transportation options 1) electrolysis-derived H_2 is first transported in gaseous form via GH_2 pipelines and then liquefied in close proximity to the airport; 2) electrolysis-derived H_2 is liquefied off the airport (e.g. directly at location of production) and then transported in liquid form by ship and / or truck (dotted: not explicitly considered in this work). Figure adapted from Ref. [2].

Economy of scale effects are of particular relevance for liquefaction, as the prospective average specific energy consumption of the latter can be halved when existing, very small plant designs are compared with potentials for future very large ones (with respective specific energy consumption per kg LH_2 of 14 and 6-7 kWh/kg) [5]. Hence, while centralized solutions take advantage of economies of scale, longer transport distances may significantly enhance H_2 distribution costs. The latter can be minimized by locating production (and liquefaction) at or very close to the point of use.

When it comes to the techno-economic assessment of different H_2 transportation modes, technology-dependent scaling properties and future perspectives regarding energy demand and resulting distance dependence as well as transport capacity can have a key impact on overall cost and their structure. For instance, according to current estimates, total GH_2 pipeline transport cost mainly depend on capital investments in (steel) pipelines and compressor stations directly followed by operational expenditures (OPEX), governed by energy demand for recompression to compensate for friction-induced pressure losses along the transport path [3]. Note that in contrast to the pipelines, compressors in use for the natural gas infrastructure cannot be repurposed for H_2 compression even for blends with >40 % GH_2 owing to the low molecular weight of H_2.

However, while repurposed natural gas pipelines are estimated to decrease eventual capital costs by 75–90 % [3, 8], it has recently been noted that besides transport capacity, differences in pipe's inner layer condition, i.e. surface roughness of used, modified and new pipelines, can have a significant impact on friction-caused pressure loss [8, 9]. The latter turns out to be the most decisive parameter besides transport capacity and technical equipment used determining energy consumption for required re-compression of GH_2 transported in pipelines, e.g. in evenly distributed compressor stations along the way [8]. Since energy consumption for compression is a main driver of OPEX [3], the lower CAPEX of repurposed pipelines needs to be balanced against increased OPEX compared with newly built pipelines of much lower surface roughness.

When it comes to the transportation of LH_2 in cryogenic storage tanks, land-based trucking for low to intermediate distances is already realized today [10], while commercial operations for maritime transport over large distances by means of large LH_2 carrier ships are expected to start in the mid-2020s [11, 12]. For both transportation options, boil-off is a significant source of energy loss, typically amounting to up to a few per thousand per day [10, 12]. For both options, a promising future perspective for reducing energy losses is the re-use of H_2 boil-off gas, for instance as a near-term perspective for Kawasaki's large LH_2 carrier for on-board electricity generation or ultimately as main engine fuel, e.g. for fuel-cell based propulsion [10, 12].

For the development of optimized Green Hydrogen supply chains, the correlation of the distribution of global and European renewable energy and Green Hydrogen production potentials and future hydrogen consumers is important [13], accounting also for the interplay between H_2 network and electricity grid expansion to balance intermittencies of renewables [14]. Moreover, cross-sector synergy potentials and distinctions need to be analyzed and placed in context with high-leverage technology options and their potentials along the Green Hydrogen life cycle. These can then be incorporated in the likely development of a parallel infrastructure for H_2 transportation and distribution both in gaseous and liquid form.

For strategic decision-making in aviation, it is hence important to understand perspectives and implications including energy demand and transport capacities of potential future large-scale H_2 distribution via pipeline networks such as of the *European Hydrogen Backbone* compared with maritime and land-based LH_2 transport and the dependence on transport distance, taking account of future technology options and associated scaling properties. In this work, in order to comparatively assess perspectives with a focus on energy demand – to be met by renewable energy sources – for GH_2 pipeline transport, the significant influence of varying pipe's inner layer conditions as well as applied load capacity on pressure loss are accounted for considering future new as well as repurposed pipelines compared with LH_2 transport options. The paper is structured as follows. In Section 2, different technology options for GH_2 transport as well as key metrics and trade-offs are discussed covering besides conventional steel-based pipelines also emerging composites technology solutions including allegedly less investment intensive pipe-within-pipe technology [15]. In Section 3, different equipment (e.g. compressor types used) for recompression of GH_2 in compressor stations at appropriate distances required to compensate for pressure losses are considered. Section 4 analyzes basic scaling properties relevant for assessing energy demand for both GH_2 pipeline and LH_2 transport, for the former based on thermodynamic modeling and for the latter accounting for reduction potentials of boil-off both for LH_2 shipping and trucking. Respectively in sections 5 and 6, the distance-dependent energy demand and transport capacity are quantitatively compared for different transportation modes and technology solutions. Based on the results, in Section 7, techno-economic consequences regarding the envisioned *European Hydrogen Backbone* are discussed together with implications for favorable transportation scenarios for aviation as important basis for in-depth (scenario-based) techno-economic assessment, which goes beyond the scope of this work.

2. PIPELINE TECHNOLOGIES, KEY METRICS, PERSPECTIVES AND TRADE-OFFS

General requirements on pipeline technology include durability with respect to H_2 embrittlement and corrosion, safety endangered by mechanical failure and H_2 leakage, preservation of H_2 purity levels and cost-effectiveness, which is influenced by the preceding metrics. Furthermore, as the pressure in the pipe and the flow rate is proportional, the higher the pressure, the higher is the transport capacity of the pipeline. According to Barlow’s formula, the maximum operating pressure of a thin-walled line pipe is proportional to its material strength and wall thickness and inversely proportional to its outer diameter under static load [8]. Commonly employed high-grade steels offer economic thin-walled solutions enabling high operating pressures. Yet, in order to reduce the risk of material failure, the European Industrial Gases Association recommends the use of API 5L steel grade X52 or lower, non-susceptible to irreversible hydrogen embrittlement that can cause H_2-induced cracking (cf. Ref. [8] and references therein). In order to enhance corrosion resistance and durability, multiple protective layers such as internal and external coating are applied. Typically, operating pressures range between 16 and 100 bar, for pipe diameters between 40 and 140 cm (16 to 56'') at flow velocities between 10 and 80 m/s depending on the pipeline design [8, 16, 9].

Repurposing existing natural gas pipelines is discussed as effective means for decreasing capital expenditures (CAPEX) by up to 75-90 % compared with the construction and installation of new ones [3, 8], while at the same time enabling fast realization of high-capacity hydrogen distribution.

Moreover, efforts are going on for replacing traditional pipeline materials like steel by composite materials such as currently already employed in the oil and gas industry. The successful adaption for use in hydrogen pipelines has been recently established as codified Fibre-Reinforced Polymer (FRP) pipe up to 6'' in diameter in ASME B31.12 ("Hydrogen Piping Code") for gaseous hydrogen transmission up to 170 bar and a design life of 50 years (cf. Ref. [15] and references therein). Such composite pipelines can exhibit significantly higher strength and lower weight than steel, which enables to reduce both weight and cost of hydrogen pipelines (estimates stating about 20 % cost saving potential [15]) and according to Barlow’s formula in addition higher-pressure operation and hence improved flow capacity. Moreover, they are more flexible and hence spoolable for delivery to installation sites, reducing installation cost by up to 25 % [17], while also offering enhanced resistance to corrosion and increased durability. Another difference lies in the possibility of manufacturing longer sections owing to their continuous structure, leading to a smaller number of joints and welds than for steel-based pipelines and hence among other things a lower risk of leaks. In addition, manufacturing pipelines from steel is a carbon-intensive process. Alternative to on-going efforts to lower emissions generated from steel (“green steel”), expanded use of composite pipes instead of steel-based ones could offer significant opportunity to reduce carbon emissions in pipeline manufacturing.

For guaranteeing safe and reliable operation, advanced sensors and monitoring systems are under development to ensure mechanical integrity and leak tightness of pipes as well as valves, used to control, regulate, or direct flow of gas in a pipeline [15].

Another technology option is provided by recently patented pipe-within-pipe technology [15]. It includes flexible FRP pipes recently rated for H_2 use by the American Society of Mechanical Engineers (ASME) that are reported to offer a 50-year useful life at 170 bar and to be operable up to 1600 km. These lines could be used inside virtually any existing oil and gas pipeline, water pipe, sewer line, storm drain, or other pipelines, which typically run underground under major cities in the world. By incorporation inside an optional slightly larger diameter one (“safety pipe”) running an inert gas in between to constantly sweep for H_2 molecules, this could in addition enable the safe delivery of fuel cell grade GH_2 (preserving purity levels ≥ 99.7) without inferring with continued commercial use of the pipeline for other purposes. While the flexibility of use of this readily deployable technology option seems attractive, in case excavation of existing pipelines would be required, significant cost penalties could arise [18, 8].

Another discriminative metric relevant in the context of energy demand for compression and hence OPEX is the absolute pipe roughness. For reference, for high-pressure Fiberspar™ Line Pipes (with thermoplastic inner and outer layer as pressure barrier and for wear resistance, respectively) used in the oil and gas industry values of $k=0.0015$ mm are reported [19]. The surface is significantly smoother than new, coated steel line pipes with values between 0.07 and 0.18 mm. For repurposed lines cleaned after long operation and with mild incrustation, significantly higher values between 0.15 and 1.5 mm emerge [8]. In Section 4, implications for energy demand for compression are analyzed and discussed.

In summary, durability, safety, ease of installation, flow capacity and cost-effectiveness (regarding both CAPEX and OPEX) are key metrics for comparing different pipeline technologies. Furthermore, preserved H_2 purity level is a relevant measure especially when it comes to future fuel cell-based usage of hydrogen. For example, the effort required for recovering high-purity hydrogen is amongst the technical barriers for economic blending of hydrogen into natural gas pipelines [3].

3. COMPRESSORS

Optimized design and positioning of compressor stations, which are among the most important components of a future H_2 pipeline infrastructure, are key pre-requisites for energy-efficient, high capacity and ecological operation [8]. Against this background, among the key benefits of centrifugal compressors with respect to positive displacement ones lie in their superior isentropic efficiency and their ability to compress larger volume flows. However, the low molecular weight of hydrogen and current restriction in maximal achievable pressure ratios of the order of 1.5 typically lead to the requirement of multi-stage compression [8]. For later reference, Table 1 summarizes the assumed characteristic parameters for reciprocating and centrifugal compressors – constituting an example for each of the two most common compressor classes, i.e. positive displacement and dynamic compressors, respectively.

Table 1: Parameters for the considered compressor types

Parameter	Value	Unit
Mechanical-electrical efficiency	0.96	%
Maximal compression power per compression unit	32	MW
Isentropic efficiency (reciprocating / centrifugal compressor)	0.6 / 0.8	%
Compression ratio Π_{max} per unit (reciprocating / centrifugal compressor)	2.0 / 1.2	-

4. ANALYZIS OF ENERGY DEMAND FOR DIFFERENT H_2 TRANSPORTATION MODES

In this section, technology-specific energy demand and relevant scaling relations are analyzed that enable a quantitative comparison of different H_2 transportation modes on an energy-basis, namely GH_2 pipeline transport and LH_2 transport by means of ship and / or truck.

At the injection point of GH_2 pipeline systems, typically initial compressor stations are required, to compress the electrolysis-derived H_2 to operating pressures for pipeline transport to enable high-capacity distribution [8, 20]. For example, for compression from 30 to 80 bar, centrifugal and reciprocating compressors require 1.3 and 1.7 % of the LHV of H_2, respectively, for characteristics as specified in Ref. [8].

Similarly, for liquefaction, with perspectives for specific energy consumption of 6-7 kWh/kg [5] for large liquefaction plants – corresponding to 18-21 % of the LHV of H_2 – a significant fraction falls onto the pre-compression. For example, based on data from Ref. [8] up to about 15 % emerge for operating pressures of 80 bar of the liquefaction plant, depending also on compressor characteristics. Accordingly, provision of pipeline-transported GH_2 at elevated pressures would also benefit liquefaction, as specific energy demand for pre-compression could be reduced accordingly.

Moreover, some electrolysis types can operate at elevated pressure, coming along with the potential to provide GH_2 at an output pressure higher than ambient at reduced energy demand compared with downstream compression by external compressors owing to the higher molar mass of H_2O than H_2 [21]. This could be exploited beneficially both for saving (parts of) the specific energy demand for initial compression for GH_2 pipeline transport and for pre-compression for H_2 liquefaction, with reduction potentials of the same order of magnitude: up to about 2 and 3 % of the LHV of H_2, respectively. Accordingly, in the following we will focus on the technology-discriminative energy demand and its dependence on distance both for re-compression by intermediate compressor stations to balance pressure losses upon GH_2 pipeline transport and for LH_2 shipping and trucking.

4.1. Gas Pipeline Transport

In the following we will focus on the energy demand and its distance dependence of intermediate re-compression stations that typically need to be placed after pipeline sections carrying GH_2 every 100 to 600 km and constitute key components of a H_2 pipeline system [8].

As mentioned before, the energy demand for compensating friction-induced pressure losses in GH_2 pipelines is mainly influenced by the pipe's inner layer condition as well as by transport capacity and equipment, materials and coatings employed [8, 9]. In the following, we quantitatively examine the relation between surface roughness, pressure losses, compressor types as well as chosen compression ratios, stages, and compressor positioning to the required energy demand for re-compression for repurposed steel line pipes with mild incrustation compared with new ones (dip-galvanized). These results are then used in Section 5, for an analysis of the break-even distance on an energy-basis of GH_2 and LH_2 transport scenarios.

The equation system that describes a frictional non-isothermal compressible gas flow in pipeline applications and defines the pressure drop $\Delta p = p_{in,pipe} - p_{out,pipe}$, relating the initial pressure at the inlet $p_{in,pipe}$ to that of the outlet pressure $p_{out,pipe}$ for a horizontal pipeline section of length l with hydraulic diameter d can be found in Ref. [8] (Eqs. (10) - (35)). The pressure drop depends on the materials used, most notably on absolute surface roughness k of the pipe's inner layer. Firstly, the heat input resulting from frictional losses can cause an increase in gas temperature, which goes along with a decrease in the gas density and an acceleration of the gas flow. In addition, the temperature of the transported gas along the pipeline and hence the outlet temperature $T_{out,pipe}$ of a specific pipeline section depends on the heat transfer characteristics of all material layers composing the pipeline buried in soil and defining the heat exchange with the surrounding media [8].

However, owing to its fundamentally different properties, the effect of gas expansion can lead to a decrease in temperature along the pipeline, i.e. $T_{out,pipe} < T_{in,pipe}$, resulting from a negative Joule-Thompson coefficient μ of GH_2. Note that this contrasts for instance natural gas for which μ is always positive in the range that is relevant for pipeline transport [8, 22]. However, it is beneficial in terms of required compression work for GH_2 recompression, which is proportional to T_{out} as discussed in the following.

The specific compressor work in *J/kg* required for recompressing the GH_2 at the outlet of the pipeline section with pressure $p_{out,pipe} = p_{1,comp}$ and temperature $T_{out,pipe} = T_{1,comp}$ to the pressure $p_{in,pipe} = p_{n+1,comp} > p_{1,comp}$ by means of a compressor with n stages is given by [8, 23]

(1) $w = \sum_{i=1}^{n} w_{i,i+1}$, where

$$(2) \quad w_{i,i+1} = \frac{\bar{\kappa}}{\bar{\kappa}-1}\frac{R_u}{M}\frac{T_{1,comp}}{Z_1}\left[r_{i,i+1}^{\frac{\bar{\kappa}-1}{\bar{\kappa}}} - 1\right]$$

denotes the specific compression work for a given compression stage with Z_1 being the corresponding compressibility factor, R_u denoting the universal gas constant R_u = 8.3145 *J/mol/K*, M the molar mass of H_2 and $r_{i,i+1}$ the pressure ratio between the intermediate pressures $p_{i,comp}$ and $p_{i+1,comp}$ of the given compression stage

$$r_{i,i+1} = \left(\frac{p_{i+1,comp}}{p_{i,comp}}\right)$$

and with $\bar{\kappa}$ denoting the average real isentropic exponent

(3) $\bar{\kappa} = \frac{\kappa_i(p_i,T_i)+\kappa_{i+1}(p_{i+1},T_{i+1})}{2}$.

Due to construction limitations, all compressor types are limited in their maximal pressure ratio per stage Π_{max}, with centrifugal compressors exhibiting a significantly smaller permissible ratio than reciprocating ones as mentioned before [8]. Accounting for a given or maximally allowed pressure ratio as characteristic for the compressor type, the required number of compression stages n for equal efficiency of compression stages is defined by [8, 23]

(4) $\Pi_{tot} = {\Pi_{max}}^n$ with

(5) $\Pi_{tot} = \left(\frac{p_{n+1,comp}}{p_{1,comp}}\right) = \left(\frac{p_{in,pipe}}{p_{out,pipe}}\right)$.

Cooling between consecutive stages brings the gas back to temperature T_1 as universal start temperature of any compression stage [23]. The heat that needs to be removed is given by the product of the mass flow and the difference in specific enthalpies of the different consecutive states.

Finally, the required power consumption P_{el} is proportional to the mass flow $\dot{m}$ and the specific compression work w defined by Eqs. (1) - (3) and inversely proportional to the total efficiency η_{tot} [8, 23]

(6) $P_{el} = \dot{m}\frac{w}{\eta_{tot}}$ with

(7) $\eta_{tot} = \prod_i \eta_i$.

In Figure 3, the pressure drop Δp resulting from thermodynamic analysis is plotted as a function of pipeline section length both for repurposed and new steel pipelines, considering centrifugal compressors and pipelines with characteristics as summarized in Table 1 and Table 2, respectively. It is observable that significantly increased pressure drop emerges for the former compared with the latter. Based on Eqs. (4) - (5), the requirement of enabling single stage compression for balancing the pressure drop for a maximal pressure ratio of Π_{max} =1.2 cannot be full-filled for the new and repurposed pipelines as off distances of about 150 km and 80 km, respectively, under the assumptions summarized in Table 2. As concerns cost-effectiveness of operation, a key trade-off occurs between transport capacity and energy demand for recompression, especially for repurposed old steel-based pipelines of high surface roughness [8]. This is reflected in Figure 4, in which we compare the resulting P_{el} based on the pressure loss Δp (cf. Figure 3) for varying surface roughness and a section of 125 km length as a function of load capacity based on Eqs. (1) - (6). According to Eqs. (4) - (5), this requires up to two compressor stages for the repurposed

Table 2: Parameters assumed for the thermodynamic analysis of high-pressure GH_2 transmission via pipelines

Parameter	Value	Unit
Length *l* of each pipeline section	125	km
Nominal diameter *d*	122	mm
Mass flow $\dot{m}$	360	t/day
Transport capacity	13	GW
Maximal / reference operating pressure ($p_{in,max}$ / $p_{in,pipe}$)	100 / 80	bar
$T_{in,pipe}$	10	°C
Absolute roughness (new / repurposed pipelines)	0.07 / 1.5	mm

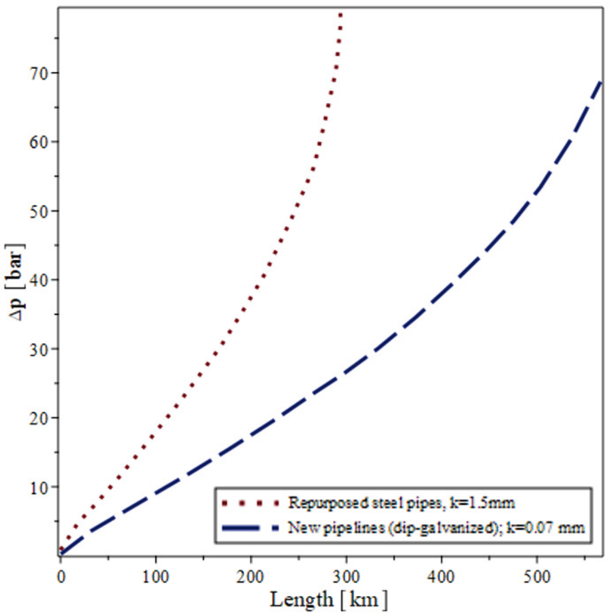

Figure 3: Pressure drop as a function of pipeline section length with varying surface roughness as characteristic for repurposed and new steel pipes, respectively. Based on data from Ref. [8]

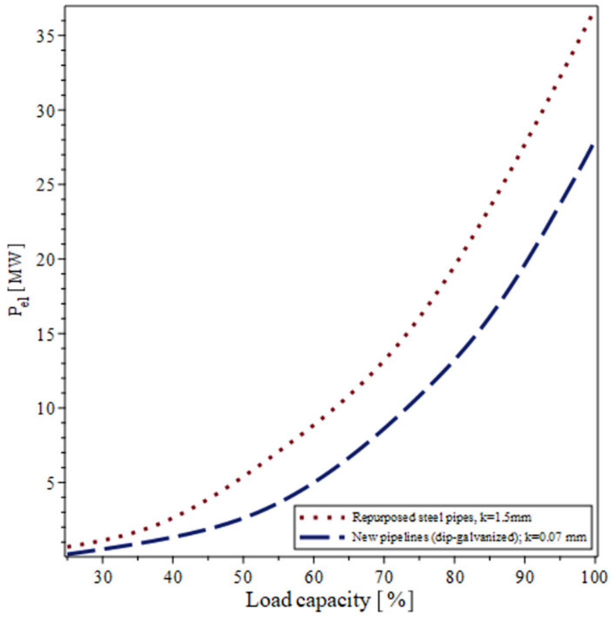

Figure 4: Electrical power demand for recompression after GH_2 transport in a pipeline section of length of 125 km with varying surface roughness as characteristic for repurposed and new steel pipes, respectively.

and only one for the new ones. As becomes apparent, reducing the load, i.e. sacrificing GH_2 transport capacity per pipe, tends to balance pressure losses and hence penalties in energy consumption. For instance, a 10 % reduction in load capacity for repurposed pipelines leads to equal electrical energy demand as for new ones (cf. Figure 4).

Further important trade-offs result between CAPEX and OPEX in dependence on the pipeline system set-up with significant implications on life cycle balance [8, 20]. For example, the use of two parallel-aligned pipes with one subsequent compression unit can enhance the transport efficiency with respect to schemes with a single pipeline of equal transport capacity and with multiple intermediate recompression units, yet at the expense of significantly higher material demand and consequently associated CO_2 emissions and capital expenses [8]. Similarly, for fixed transport capacity, it is energetically preferred to operate several parallel pipelines at reduced capacity as compared with a single pipeline at full load capacity [3], yet again with important trade-offs between OPEX and CAPEX and life cycle emissions [8].

4.2. Liquid Hydrogen Transport

As both the energy density per unit mass and per unit volume of LH_2 are several times higher than that of high-pressure GH_2 even at several hundreds of bar, for use on-board aircraft as energy carrier, hydrogen typically needs to be utilized in its liquid form. This requires compressing and deep cooling H_2 to under 21 K and storing and transporting it in insulated cryogenic tanks [5].

This section concerns with perspectives in energy demand and hydrogen loss (boil-off) for land-based and maritime LH_2 transportation, respectively by truck and by ship. In both cases, H_2 fuel-cell propulsion is assumed.

Based on data from Ref. [10], for the LH_2 truck results an energy demand per kg pf H_2 of $6.66 \cdot 10^{-4}$ kWh/ (km kg) (only outward journey considered) and a boil-off of up to 0.5 % per day. Typical transport capacity of cryogenically stored LH_2 amounts to 4t per truck.

For transport of LH_2 via ship, data from Ref. [12] for a fuel-cell powered carrier by C-Job Naval with initial LH_2 delivery planned in 2027 between Scotland and Germany is used for estimating the energy demand. Assuming an overall efficiency of 50 %, we find an energy demand of $1.46 \cdot 10^{-4}$ kWh / (km kg) for the LH_2 ship, if only the outward journey is considered. The prospective transport capacity amounts to in total 2625 t to be stored in three spherical LH_2 tanks, each with a LH_2 capacity of 875t. Boil-off is expected to range between 0.1-0.2 % per day [24].

As a promising future perspective for reducing energy losses both for land-based and maritime LH_2 transportation, implications of using H_2 boil-off gas as main engine fuel are assessed in the next section. Note that for instance Kawasaki's large LH_2 carriers with commercial operations planned in mid-2020s are to use boil-off gas for on-board electricity generation [11].

5. COMPARATIVE ASSESSMENT OF PERPECTIVES FOR ENERGY DEMAND FOR DIFFERENT TECHNOLOGY OPTIONS

This section quantitatively compares the energy demand and its distance dependence for different H_2 transportation modes.

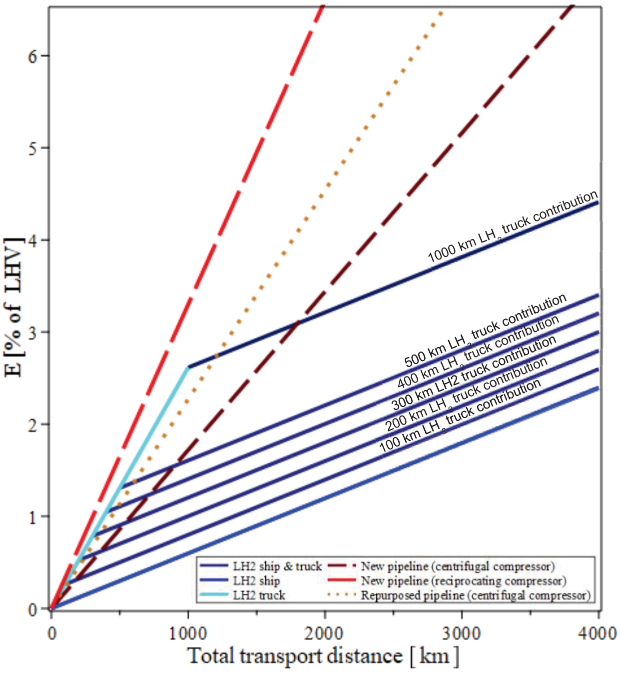

Figure 5: Comparison of energy consumption for hydrogen transport as a function of total transport distance for different transportation modes.

In Figure 5, the transmission energy demand of GH_2 via new as well as repurposed steel pipelines resulting from thermodynamic analysis for parameter values summarized in Table 1 and Table 2 is compared to that of LH_2 transport via ship and / or truck as a function of total transport distance. The required GH_2 recompression to compensate for pressure losses upon GH_2 transport is assumed at regular distance intervals complying with respective maximum pressure ratios of centrifugal and reciprocating compressors as specified in Section 3.

It is observed that the choice of compressor type has a significant impact on the result: in case reciprocating compressors are used for recompression of GH_2, pipeline transport is energetically disfavored irrespective of transport distance and LH_2 transportation mode. When centrifugal compressors are employed instead, transport via GH_2 pipeline usage is energetically preferred to land-based transport by LH_2 truck, but inferior to purely maritime LH_2 transport by ship. As indicated by Figure 5, hence the breakeven distance on an energy-basis for LH_2 transport via ship and subsequently via truck and for GH_2 transport via pipelines decreases with increasing proportion of the total transportation distance that is accounted for by truck. For example, it amounts to about 900 and 1800 km for new pipelines, for a contribution to the total distance of 500 and 1000 km by LH_2 truck, respectively.

As a further key result, the breakeven distance is reduced by a factor 1.5 to 600 and 1200 km respectively, if repurposed steel GH_2 pipelines are considered as a result of enhanced surface roughness and hence friction-induced pressure losses.

As summarized in Table 3, for long-distance transportation significantly higher energy demand results for transportation in GH_2 pipelines, e.g. for new / repurposed

Table 3: Perspectives for energy demand of long-distance H_2 transportation for different transportation modes in terms of Lower Heating Value (LHV) of H_2 of 33.3 kWh/kg

Transportation mode	Transport distance [km]	Energy demand [% of LHV of H_2]
GH_2 pipeline transport (new / repurposed)		
	4,000	6.9 / 9.1
	10,000	17.2 / 22.7
LH_2 transport (truck / ship)	4,000 (500 / 3,500)	3.4[1] / 1.9[2]
	10,000 (1,000 / 9,000)	8.0[1] / 4.4[2]

[1] no re-use of boil-off; [2] future re-use of boil-off for propulsion

by a factor of 3.5 / 4.7 for 4000 km transport distance, assuming LH_2 transport by ship / truck of 3500 km / 500 km, respectively. For repurposed pipelines, for very large distances of 10^4 km, even higher energy demand than expected for future large-scale liquefaction plants would emerge, taking values as high as ~23 % of the LHV of H_2.

Note that alternatively, a capacity reduction in repurposed pipelines by roughly 10 % would enable to reduce pressure losses and hence lead to similar energy consumption per unit length as for new steel pipelines, as discussed in the last section.

While from an energy-based perspective, this would lead to the same breakeven distances with LH_2 transportation as for new pipelines, yet, it would require sacrificing transport capacity and presumably negatively affect levelized transport cost for H_2 as discussed in the next section.

While a detailed thermodynamic modeling goes beyond the scope of this work, it is to be expected that the significantly lower surface roughness of composite pipelines, e.g. with thermoplastic coatings (cf. Section 2), will reduce energy consumption for recompression per unit length as compared with steel pipelines. For example, Ref. [9] finds for Medium Density Polyethylen (MDPE) pipelines a reduction in pressure loss per unit length by a factor 1.06 for hydrogen flow velocity of 30 m/s and a pipe diameter of 1 m.

The latter, increases both for higher flow velocities (to a factor of 1.21 at ~80 m/s) and for lower pipe diameter (by a factor of 16 for a tenth of diameter, i.e. 0.1m), as interactions with the pipe walls carry higher relative weight [9]. While standardization efforts are still ongoing, composite pipes also promise further techno-economic benefits beyond energy-efficient GH_2 transportation discussed in Sections 2 and 7.

As concerns LH_2 transport both via ship as well as via truck, future re-use of boil-off gas as main engine fuel bears the potential, to reduce the energy consumption as indicated in Table 3. This results in breakeven distances of ~820 / 1100 and 420 / 560 km for new / repurposed pipelines, for a contribution to the total distance of LH_2 transportation of 500 and 1000 km by truck, respectively.

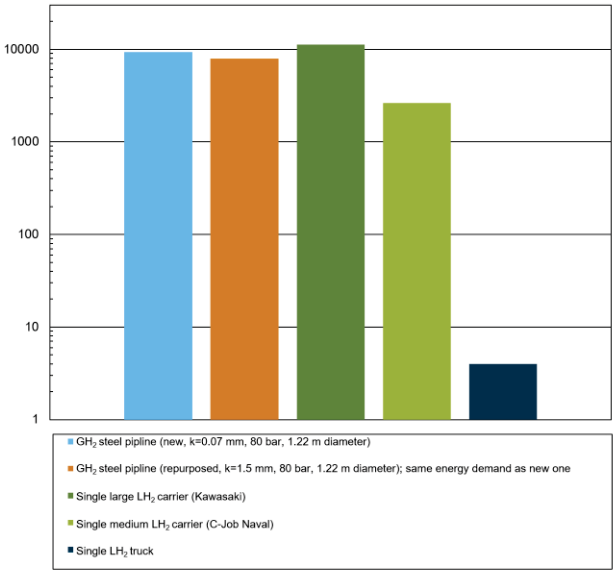

Figure 6: Comparison of typical H_2 transport capacities in tons per day considering different transportation modes (log scale). Based on data from Refs. [11, 12, 5].

As discussed in the last section, transport capacity could in principle be traded for energy consumption for GH_2 pipeline transport and hence for sensible transport range. For instance, a capacity reduction by 10 % to 11.7 GW enhances the breakeven distances to ~1150 / 2300 and 700 / 1400 km for new / repurposed pipelines, for a contribution to the total distance of LH_2 transportation of 500 and 1000 km by truck, respectively.

It should be noted that additional boil-off losses associated with fuel transfer (e.g. from LH_2 carrier to LH_2 truck or subsequent storage tanks at the airport) or further transportation steps such as transportation of GH_2 e.g. by truck after pipeline transport or after liquefaction as well as due to leakage have not been assessed in this work. Furthermore, only the outward trip of LH_2 ships and trucks are considered. In principle, for return journeys an additional energy penalty emerges. Yet, for lower payload, the energy consumption for propulsion is reduced [10] and it is likely that by means of logistic optimization, the distance traveled by LH_2 trucks in empty state will be minimized. While this seems more challenging for LH_2 ships, in general, their energy consumption (per km and kg LH_2 transported) is an order of magnitude lower than for trucks such that energy consumption for an “empty” return journey in comparison generally carries less weight. A more detailed techno-economic assessment goes beyond the scope of this study and is left for future work.

6. COMPARATIVE ASSESSMENT OF TRANSPORT CAPACITY FOR DIFFERENT TECHNOLOGY OPTIONS

This section concerns with technology-dependent transport capacity both for GH_2 pipeline as well as LH_2 transport via truck and ship, respectively. Figure 6 compares expected transport capacities per day for different GH_2 and LH_2 transportation options, assuming equal energy demand for new and repurposed pipelines. It becomes evident that prospectively, similar amounts of hydrogen, respectively in gaseous and liquid form, can be transported per day via large-diameter GH_2 pipelines of steel and via future high-capacity LH_2 carriers. As discussed in Section 2, the flow capacity of GH_2 pipelines depends on the allowed operating pressure, which tends to be higher for composite than for steel pipelines. Hence, increased transport capacities are expected for the former without penalizing the energy demand for recompression, as the surface roughness is significantly lower. In contrast to repurposed steel-based pipelines, hence for *new* composite pipelines, higher transport capacities than for large LH_2 ships could emerge.

Furthermore, it becomes evident from Figure 6 that transport capacity by truck severely falls back with respect to that of other transport options (similarly to energy-efficiency of transport as discussed in the last section). Especially for large airports with prospective demands in 2050 of up to ~1550 t of LH_2 per day [7], alternative options limiting the number of required LH_2 trucks for supply are prioritized. This could potentially also include (short-distance) LH_2 pipeline transport [7] for supply scenarios with electrolysis- derived GH_2 being first distributed via pipelines and subsequently liquefied in proximity of the airport.

7. DISCUSSION OF TECHNO-ECONOMIC IMPLICATIONS

This section concerns with a high-level discussion of selected techno-economic implications of the results discussed in the last section with a focus on the aviation perspective as important basis for an overall techno-economic assessment, which goes beyond the scope of this study and will be analyzed elsewhere.

In general, the key finding of 35 % increased energy demand for recompression of GH_2 for transportation within large *repurposed* instead of *new* pipelines resulting from enhanced friction-induced pressure losses at the same transport capacity has implications for the total investments of the H_2 backbone and respective cost structures. Current cost estimates find up to roughly 45-47% of the latter to be provided by total OPEX that are largely influenced by compressor operating cost (averaging over new and repurposed pipelines assuming *equal* OPEX) [3]. Hence, an increase in compressor OPEX of up to 35% for repurposed pipelines constituting 60% of the network could yield up to ~10% increase in overall investments. Moreover, this would in total result in a larger dependence on (renewable) energy availability and cost and corresponding geographical variation.

As a key trade-off between energy demand and transport capacity, a 10 % load reduction (from 13.0 to 11.7 GW) for large repurposed pipelines was found to be exploitable for balancing the additional energy consumption as compared with new pipelines of the same diameter with 13 GW transport capacity. On the one hand, in comparison to energy consumption for LH_2 shipping and trucking this could increase the breakeven distance by a factor 1.5, thereby presumably significantly enhancing the sensible distance range for GH_2 transport in selected application scenarios. Moreover, a load reduction could positively influence pipeline maintenance cost as higher mass flow rates are likely to influence the onset and propagation of cracking and embrittlement in steel pipes over a given time span [9]. On the other hand, as total OPEX are governed by energy costs for compression, besides sacrificing transport capacity, this would probably still negatively affect the levelized costs for GH_2 transport. The reason is that (besides the total investment costs) these are proportional to the inverse of the total H_2 transport capacity over the network lifetime, which would decrease by 10% for 60% of the network (repurposed pipelines), i.e. by O(10) %.

As mentioned before, in contrast to most other sectors, H_2 typically needs to be provided in its liquid form to be used as an energy carrier on-board aircraft for reasons of energy density. Especially for very large distances of GH_2 pipeline transport, the last section demonstrated energy penalties comparable with those for liquefaction of electrolysis-derived H_2, especially when transport via repurposes and not new pipelines is considered. For aviation applications, hence decisive factors for scenarios that could beneficially rely on the provision of GH_2 and subsequent liquefaction in the proximity of an airport are the availability of sufficiently inexpensive renewable energy as well as the exploitability of economy of scale effects, especially to minimize specific energy consumption for liquefaction together with transport distance. As seen in the last section, transport capacities of large GH_2 pipelines extend to about 360 t/h (i.e. 9360 t/day) per pipe. For exploiting economy of scale effects for liquefaction to optimize specific energy consumption, plant (unit) sizes at least of the order of 100 t/day (with potential modularization of unit operations to reach higher liquefaction capacities) are required [5] and could hence rely on GH_2 grid-based supply. Yet, compared with liquefaction e.g. directly at location of production, typically with guaranteed availability of inexpensive renewable energy, and subsequent LH_2 shipping and / or trucking, only for GH_2 pipeline transport distances below typically 900 km / 600 km for new / repurposed pipelines of equal transport capacity energetically favored scenarios can result. As mentioned before, significantly enhanced energy consumption for transport in repurposed pipelines quantified in this study (cf. Section 5) tend to severely restrict the sensible transport distances and hence geographical locations with corresponding application potential for liquefying the transported GH_2 in proximity to an airport, at least from an energy-based view point.

Moreover, as discussed in the last section, from an energy perspective, GH_2 pipeline transport over large distances can add significant penalties with respect to transport via LH_2 ship and truck. Furthermore, from the point of view of energy cost, for long distances both for transportation and for liquefaction in proximity to the airport (instead of e.g. directly at the location of production) significant disadvantages can arise, unless sufficient quantities of inexpensive renewable energy are available. Overall, only for several hundred kilometers of transport distance, in a grid composed of both repurposed and new pipelines, GH_2 transport via pipeline can energetically be favored compared with LH_2 transportation as mentioned before.

Another aspect, especially of relevance for large airports with prospective demand in 2050 of up to ~1550 t of LH_2 per day [7], relates with the potential to avoid trucking of LH_2 after all (e.g. relying on LH_2 pipelines between liquefaction plant and airports in close proximity). Both regarding specific energy demand (including energy transfer losses) as well as H_2 transport capacity, the latter is significantly inferior to all other H_2 transportation modes. Hence, high-capacity GH_2 pipeline supply could hence enable to avoid this limiting factor for specific application scenarios in aviation.

8. CONCLUSIONS

The planned *European Hydrogen Backbone* is envisioned to distribute H_2 on the continent in gaseous form primarily using existing, repurposed natural gas pipelines until 2030 with ~40% extension by new pipelines until 2040 to a full network length of 56,000 km. In this study, GH_2 transport in *repurposed* and *new* pipelines has been quantitatively compared to LH_2 shipping and trucking. Different technology options and their perspectives especially regarding resulting energy demand and transport capacity have been assessed, to derive implications for aviation, discriminating between transport of electrolysis-derived GH_2 in pipelines to the site of liquefaction in proximity of use versus liquefaction e.g. directly at location of production with subsequent LH_2 shipping and trucking.

For long-distance transportation, in general, the energy demand for GH_2, proportional to distance, was found to be significantly enhanced as compared with LH_2 transport. This mainly relates with the demand of energy-intensive GH_2 re-compression every (several) hundred kilometers of transport distance owing to friction-induced pressure drop along the pipeline. Moreover, since for long-distance LH_2 transportation, the energetically favored transport by ship exhibits a larger share in total transport distance than the LH_2 truck, LH_2 transport benefits from increased efficiency.

As a further key result, the breakeven distance in energy demand for GH_2 versus LH_2 transport was found to decrease by ~35 % typically to only a few to several hundred kilometers, if transport proceeds through large *repurposed* instead of *new* steel pipelines. This stems from an increase in electrical power demand for re-compression per unit pipeline length due to enhanced surface roughness and thus pressure drop for repurposed pipelines.

While for LH_2 transportation by ship and truck, future re-use of boil-off as main engine fuel was found to offer perspectives for limiting energy losses to a few percent of the LHV of H_2 even for very large transport distances of 10^4 km, for GH_2 pipeline transport roughly four times larger values resulted. These are comparable with those expected for liquefaction in future large-scale plants (together reaching roughly 40 % of the LHV of H_2), reflecting the demand to severely limit GH_2 transport distance for economic viability.

As a key trade-off between energy demand and transport capacity, a 15% load reduction (from 13.0 to 11.7 GW) for large repurposed GH_2 pipelines was found to be exploitable for balancing the additional energy demand compared with new pipelines of the same diameter with 13 GW transport capacity – leading to equal energy-based breakeven distance with respect to LH_2 transport.

In any case, levelized cost for GH_2 transport, proportional to total investments and to the inverse of total transport capacity over network lifetime, are estimated to be enhanced by up to 10 % (accounting for higher energy demand or alternatively reduced transport capacity of repurposed as compared with new pipelines).

For establishing scenarios in aviation that could still profit from the *European Hydrogen Backbone*, decisive factors include:

- Transport distance as a key driver of pipeline OPEX with energy-based breakeven distance with respect to LH_2 transport of few hundreds to order of thousand kilometers (mainly influenced by surface roughness of pipelines and transport capacity)
- Availability of high-capacity GH_2 grid connection yielding typically up to ~10^4 t / day, thereby limiting / avoiding further fuel transfer and transportation losses and enabling the provision of sufficient GH_2 for large-scale liquefaction plants in close proximity of use to exploit important economy of scale effects to optimize specific energy demand for liquefaction. In addition, possible capacity bottlenecks and energy penalties could be diminished / avoided arising from LH_2 trucking (4t / day / truck) such as for the supply of large airports with expected future demands of more than 1500 tons of LH_2 per day, e.g. potentially by further relying on (short-distance) LH_2 pipeline transport
- Geographic location of airport: availability of sufficient inexpensive renewable energy (which is typically a given for liquefaction e.g. directly at favorable production locations) and required distance to be covered by energetically disfavored land-based LH_2 transportation as alternative to GH_2 pipeline transport

Taken together, for aviation applications, the development of an infrastructure for LH_2 supply parallel to that for GH_2 grid-distribution seems mandatory. From an energy-demand perspective, especially the quantified disadvantages of planned transport in repurposed natural gas pipelines (making up ~60% of the envisioned *European Hydrogen Backbone*) severely restrict energy-based breakeven distances – especially for future re-use of boil-off for LH_2 carriers and trucks – and affect overall cost structures. Yet, techno-economic perspectives for new *composite* pipelines for GH_2 transport are promising. Potentials for reducing total investments for GH_2 transport arise for both OPEX (mainly due to lower compression energy demand per unit length due to lower surface roughness than steel-based pipelines) and CAPEX (especially due to ease of pipeline installation due to flexibility) at enhanced capacity, with first successful adaptions in use from the oil and gas industry.

The derived results for an energy-based quantitative comparison of different (future) hydrogen transport technologies provide an important basis for the development of optimized Green Hydrogen supply chains requiring in-depth scenario-based techno-economic and ecological assessment, which goes beyond the scope of this work.

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