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# Relative costs of transporting electrical and chemical energy

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Transportation costs of energy resources are important when determining the overall economics of future energy infrastructure. The majority of long distance energy transmission occurs *via* merchant ships and pipelines carrying oil or natural gas. In contrast, future energy scenarios often envision vastly altered energy transportation scenarios including very high degrees of grid electrification and widespread installation of hydrogen pipelines. The unit cost of energy transportation varies by over two orders of magnitude. In particular, the costs of electricity and hydrogen transmission are substantially higher than the cost of oil and natural gas transportation. If carbon pricing is to be used to incentivize alternative energy systems, these differences in costs will need to be reduced and used when making meaningful technology comparisons.

### Broader context

Global energy consumption is expected to continue to grow for the foreseeable future with much of the increase centered in rapidly developing countries in Asia and Africa. The sources of primary energy will likely shift from coal and oil to more sustainable alternatives and the means by which energy resources are moved from sites of production to consumers may change significantly. The costs of energy transmission are estimated for several potential new energy infrastructure and supply alternatives that would be needed in a transition to a decarbonized energy system while meeting the growing demand. The costs of transporting energy per unit distance vary by over two orders of magnitude depending on the energy carrier and the method of transportation. Transporting energy dense liquid fuels is the least expensive means for moving energy resources.

## 1. Introduction

The large-scale transport of energy resources is an integral component of the global energy economy. Primary and secondary energy supplies are typically transported over long distances by merchant ships (tankers and cargo vessels), pipelines, or electrical wires. Oil and gas are always moved in part through pipelines, with large fractions transported over long distances by tankers and/or rail. Coal is moved in railcars and by ship. Fossil hydrocarbons are the primary sources for 80% of the world's energy;[1] however, alternative energy carriers, including hydrogen and redox-flow electrolytes, may become increasingly important in the future and the total system costs will include their transportation costs.

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Pipelines are used to supply gases (*e.g.* natural gas) and liquids (*e.g.* oil) and account for a major percentage of both domestic and international energy transport. In 2013, approximately 8.5 billion barrels of crude oil were carried inside $1.6 \times 10^5$ miles ($\sim 2.5 \times 10^5$ km) of oil pipelines in the United States,[2,3] and over 744 million cubic feet ($\sim 2.1 \times 10^7$ m$^3$) of natural gas traveled through over $3 \times 10^5$ miles ($\sim 4.8 \times 10^5$ km) of natural gas pipelines, many of which are also tied to the electrical system.[3,4] Over 7 billion barrels of refined products were also delivered by transmission pipelines.[2] Tankers are also used to transport oil and, increasingly, to transport liquefied natural gas (LNG). In 2005, over 60% of all petroleum consumed was transported in tankers.[5] Pipelines are used to transport the largest quantities of fuels over land and tankers are used for transport over water; generally the two are operated in integrated supply networks.

Electrical energy is transported from generation to load using conducting transmission wires. Over 4 trillion kilowatt-hours of electricity is generated and transmitted annually in the United States.[6] High-voltage alternating current (AC) is used for the majority of long distance electricity transmission. High voltage direct current (HVDC) transmission has efficiency advantages and has long been proposed as economically competitive.[7] Transmission lines are generally supported by above-ground towers and occasionally run in more costly underground conduits where they are less affected by weather and not visible to the communities.[8]

Strong interest in renewable energy generation has led to several proposed future energy transport scenarios, including debate over levels approaching 100% grid electrification[9,10] and widespread installation of hydrogen pipelines.[11,12] When considering future energy infrastructure alternatives, their differing energy transportation costs can become important differentiating factors. Transmission of renewable energy can feasibly occur through electrical wires; through hydrogen obtained by electrolysis or the direct conversion of sunlight into hydrogen; or through liquid fuels obtained from the conversion of sunlight into liquid biofuels or synthetic carbon-neutral gaseous or liquid fuels.

Herein we estimate the energy transmission costs for new infrastructure and additional energy supplies that would be needed in a transition to a decarbonized energy system while meeting growing demand. In contrast, the marginal costs for either additional energy supplies or transmission will be highly variable depending on the details of the energy system, geography, demand and generation/supply locations, and other factors that cannot be evaluated in general and require location, market and site-specific factors. Though not considered in this analysis, marginal costs will likely be a significant factor in the probability of new transportation systems displacing existing infrastructure though less important in developing markets with little or no existing system equipment. Costs for both power and energy transport are compared per unit distance, using expected operating lifetimes in determining depreciated costs and recognizing that they are often built and managed by different types of entities of that may amortize costs differently. Though we recognize that the needed energy transport distance and distribution costs will likely vary substantially between different energy resources, estimating those differences goes beyond the scope of this report. Furthermore, we recognize that in addition to technology cost, systems-based criteria are generally needed and used when making decisions for energy transmission.

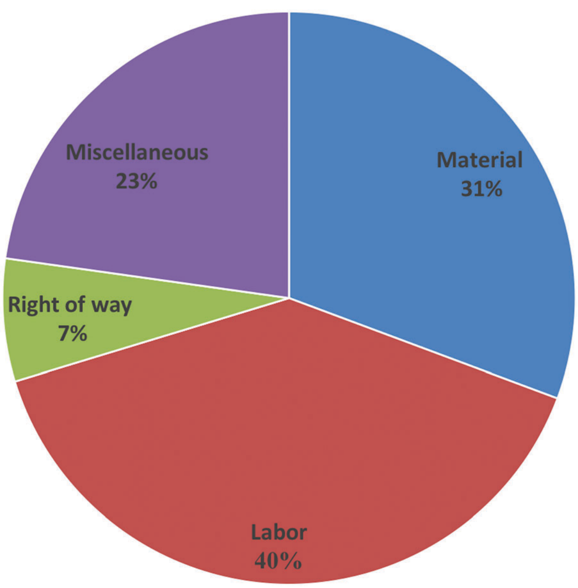


Fig. 1 Capital cost breakdown for oil pipelines.

## 2. Costs of energy transport

### 2.1 Oil pipelines

Oil carried over land primarily travels through 24″ to 48″ (~61 to 122 cm) diameter pipelines.[13] The project cost of constructing an oil pipeline (both crude and refined), is approximately 61 \$ per ft$^3$ (~2.2 \$ per dm$^3$), with an operating lifetime of 40 years.[13] The capital cost breakdown (Fig. 1) shows on average, an even distribution between material and labor costs, irrespective of pipeline diameter and length.[13] This breakdown was initially derived by Zhou *et al.* from the average cost data of 412 pipelines recorded between 1992 and 2008. These breakdowns are averages and have high project-to-project variability. The cost of transporting oil in pipelines is then estimated from the pipeline capital using the energy density of crude oil (38.5 GJ m$^{-3}$)[14] and is given in Table 1. Costs were calculated for fluid velocities ranging from 1–3 m s$^{-1}$, in accord with both current pipeline velocities (1.6 m s$^{-1}$ for the Trans Alaska Pipeline)[15] as well as proposed speeds for new constructions (2.5 m s$^{-1}$ for the Keystone Pipeline).[16] Based on the Worley Parsons estimation, the capital cost was assumed to account for 38%[17] of the total cost of transporting the oil, with the majority of the remaining costs associated with corrosion management and other pipeline maintenance. The energy efficiency of pipeline transportation was assumed to be near 100%, in agreement with previously calculated estimates.[18] This total cost estimate for oil transport in pipelines is comparable to previously published values.[19,20]

### 2.2 Natural gas pipelines

Natural gas is primarily moved and distributed through pipelines. Long-distance natural gas pipelines are generally maintained at high pressures, with 65–90 bar accounting for the higher end of typical natural gas pipeline velocities

Table 1 Cost of transporting oil in pipelines

| Fluid velocity (m s$^{-1}$) | Cost of pipeline (million \$ per mile) | Flow rate (m$^3$ s$^{-1}$) | Energy flow rate (GW) | Cost (\$ per km per kW) | Capital cost × 10$^{12}$ (\$ per km per J) | Total cost × 10$^{12}$ (\$ per km per J) |
|---|---|---|---|---|---|---|
| 1.00 | 2.3 | 0.66 | 25 | 0.06 | 0.04 | 0.12 |
| 2.00 | 2.3 | 1.31 | 51 | 0.03 | 0.02 | 0.06 |
| 3.00 | 2.3 | 1.97 | 76 | 0.02 | 0.01 | 0.04 |

 

Table 2 Cost of transporting natural gas by pipeline

| Pipe diameter (in) | Cost of pipeline (million \$ per mile) | Fluid velocity (m $s^{-1}$) | Pressure (bar) | Cost (\$ per km per kW) | Capital cost $\times 10^{12}$ (\$ per km per J) | Total cost $\times 10^{12}$ (\$ per km per J) |
|---|---|---|---|---|---|---|
| 20 | 1.4 | 25 | 65 | 0.09 | 0.11 | 0.30 |
| 36 | 2.9 | 25 | 65 | 0.06 | 0.07 | 0.19 |
| 20 | 1.4 | 25 | 90 | 0.06 | 0.08 | 0.22 |
| 36 | 2.9 | 25 | 90 | 0.04 | 0.05 | 0.13 |
| 20 | 1.4 | 10 | 65 | 0.14 | 0.28 | 0.75 |
| 36 | 2.9 | 10 | 65 | 0.16 | 0.18 | 0.47 |
| 20 | 1.4 | 10 | 90 | 0.10 | 0.21 | 0.54 |
| 36 | 2.9 | 10 | 90 | 0.15 | 0.13 | 0.34 |

according to a report by Argonne National Lab[12,21] and fluid velocities of ~10 m $s^{-1}$.[22] Natural gas is predominately methane with an energy density of approximately 47 MJ $kg^{-1}$ and gas properties reasonably well approximated as an ideal gas.[23] Due to wide differences between the composition of natural gas sources, natural gas liquids were not considered in this analysis. Notably, additional usage of transportation media for other, non-transportation related uses and value generation such as use of natural gas pipelines for storage, a common practice, were not taken into account.

The costs of construction and use of natural gas pipelines were estimated by taking the average cost from three separate reports[11,12,24] (Table 2). Although there has been much enthusiasm associated with the potential for cheaper, direct-reduced iron, the costs for these pipelines were based on historical steel prices. The individual contributions to capital cost for natural gas pipelines are similar to those of oil pipelines.[25] By analogy to oil pipelines, assuming that the capital cost accounts for 38% of the total cost, and assuming a lifetime of 40 years, the total cost per unit distance for transport of gas through pipelines is higher than the cost for oil pipelines by a factor of 5 to 10. These gas pipeline costs are also comparable to previously reported estimates.[26]

### 2.3 Hydrogen pipelines

Most hydrogen is transported today in pipelines and used as a chemical feedstock for commercial operations. To estimate of the cost of constructing long-distance hydrogen pipelines for energy transmission, the cost was assumed to be similar to that of commercially installed natural gas pipelines but with an across the board 10% increase, an estimate previously implemented by the Department of Energy (H2A). Current hydrogen pipeline pressures are ~10–30 bar[24] though pressures up to 100 bar have been envisioned with fluid velocities of approximately 15 m $s^{-1}$.[12] Hydrogen is assumed to behave as an ideal gas with an energy density of 120 MJ $kg^{-1}$.[23] Both the capital and total costs of energy transport *via* hydrogen in pipelines are estimated to be an order of magnitude greater than natural gas (Table 3), primarily due to the lower heat of combustion per mole as well as the lower pressures utilized in hydrogen pipelines.

### 2.4 Pipelines for alternative chemical fuels

In addition to transporting oil, large diameter pipelines may also be utilized for transporting chemical energy in the form of electrolytes for redox flow batteries or liquid organic hydrogen carriers (LOHC). The cost of transporting several redox flow systems and LOHCs can be estimated using their energy densities, which are typically much lower than the energy density of crude oil.[27–31] Large scale attempts to construct pipelines for the transfer of these materials have not yet been undertaken, so the costs of these pipelines were estimated by assuming similar diameters, materials and fluid velocities as oil pipelines, an estimate that is likely a lower bound for this cost. Table 4 shows the capital costs of transporting alternative chemicals in pipelines. The cost of transporting redox flow electrolytes is several orders of magnitude greater than for oil, due to the relatively low energy density. LOHCs benefit from substantially higher energy density than redox flow electrolytes, resulting in much lower costs of transportation.

### 2.5 Oil tankers

Oil is generally transported long distances over water in tankers that vary in carrying capacity from small 45 dry weight ton (DWT) ships to very large crude carriers (VLCC) with capacities of ~160–320 DWT. VLCC's account for the majority of crude oil

Table 3 Cost of transporting hydrogen in pipelines

| Pipe diameter (in) | Cost of pipeline (million \$ per mile) | Fluid velocity (m $s^{-1}$) | Pressure (bar) | Cost (\$ per km per kW) | Capital cost $\times 10^{12}$ (\$ per km per J) | Total cost $\times 10^{12}$ (\$ per km per J) |
|---|---|---|---|---|---|---|
| 20 | 1.6 | 15 | 15 | 2.2 | 2.8 | 7.4 |
| 36 | 3.2 | 15 | 15 | 1.4 | 1.8 | 4.7 |
| 20 | 1.6 | 15 | 30 | 1.1 | 1.4 | 3.7 |
| 36 | 3.2 | 15 | 30 | 0.69 | 0.88 | 2.3 |
| 20 | 1.6 | 15 | 100 | 0.33 | 0.43 | 1.1 |
| 36 | 3.2 | 15 | 100 | 0.21 | 0.26 | 0.69 |
| 20 | 1.6 | 10 | 30 | 0.74 | 0.94 | 2.5 |
| 36 | 3.2 | 10 | 30 | 0.46 | 0.58 | 1.6 |

Table 4 Cost of transporting energy as electrolytes for redox flow batteries or LOHC's by pipeline

| | Cost of pipeline (million $ per mile) | Fluid velocity (m s$^{-1}$) | Energy density of electrolyte (GJ m$^{-3}$) | Cost ($ per km per kW) | Capital cost × $10^{12}$ ($ per km per J) | Total cost × $10^{12}$ ($ per km per J) |
|---|---|---|---|---|---|---|
| Vanadium flow | 2.3 | 1.0 | 0.09 | 24 | 19 | 50 |
| Vanadium flow | 2.3 | 2.0 | 0.09 | 12 | 9.5 | 25 |
| High density vanadium flow | 2.3 | 1.0 | 0.15 | 15 | 12 | 30 |
| High density vanadium flow | 2.3 | 2.0 | 0.15 | 7.3 | 5.8 | 15 |
| Zinc-polyiodide | 2.3 | 1.0 | 0.60 | 3.6 | 2.8 | 7.5 |
| Zinc-polyiodide | 2.3 | 2.0 | 0.60 | 1.8 | 1.4 | 3.7 |
| Zinc-bromide | 2.3 | 1.0 | 0.25 | 8.6 | 6.8 | 18 |
| Zinc-bromide | 2.3 | 2.0 | 0.25 | 4.3 | 3.4 | 8.9 |
| Dodecahydro-*N*-ethylcarbazole/*N*-ethylcarbazole | 2.3 | 1.0 | 7.2 | 0.30 | 0.24 | 0.63 |
| Dodecahydro-*N*-ethylcarbazole/*N*-ethylcarbazole | 2.3 | 2.0 | 7.2 | 0.15 | 0.12 | 0.31 |
| Decalin/naphthalene | 2.3 | 1.0 | 6.8 | 0.32 | 0.25 | 0.67 |
| Decalin/naphthalene | 2.3 | 2.0 | 6.8 | 0.16 | 0.13 | 0.33 |

Table 5 Cost of transporting oil by tanker

| | Cost of tanker (million $) | Capacity (million bbl) | Barrel of oil equivalent (GJ per bbl) | Average speed (knots) | Cost ($ per km per kW) | Capital cost × $10^{12}$ ($ per km per J) | Total cost × $10^{12}$ ($ per km per J) |
|---|---|---|---|---|---|---|---|
| Panamax | 30 | 0.54 | 6.1 | 10 | 0.004 | 0.006 | 0.04 |
| | 30 | 0.54 | 6.1 | 20 | 0.002 | 0.003 | 0.02 |
| Aframax | 49 | 0.69 | 6.1 | 10 | 0.006 | 0.007 | 0.06 |
| | 49 | 0.69 | 6.1 | 20 | 0.003 | 0.004 | 0.03 |
| Suezmax | 52 | 1.3 | 6.1 | 10 | 0.003 | 0.004 | 0.03 |
| | 52 | 1.3 | 6.1 | 20 | 0.002 | 0.002 | 0.02 |
| VLCC | 94 | 2.0 | 6.1 | 10 | 0.004 | 0.005 | 0.04 |
| | 94 | 2.0 | 6.1 | 20 | 0.002 | 0.003 | 0.02 |



shipments across the globe although refined products such as gasoline are typically transported *via* smaller vessels.[32] The average lifetime of a tanker is estimated to be 25 years, the midway point of the average demolition age of crude tankers from 2000 to 2011.[33] The average speed was assumed to be ~10 knots[34] and the utilization percentage (fraction of time that the tanker carries cargo) was assumed to be 40%. The additional cost of loading and unloading of oil and compressed natural gas was not taken into account, as doing so would require the presupposition of a distance traveled. Table 5 summarizes the cost of energy transported as oil in tankers. While tankers vary quite significantly in size and cost, their capital costs are relatively similar and rather small (an order of magnitude less than the capital cost of oil pipelines).[35] The total cost of oil transportation was estimated by averaging the cost of several tanker route rates,[19,36] and was found to be comparable to that of oil pipeline transportation, implying that the variable costs constitute a very large portion of the total costs. The greater variable costs are likely due to high maintenance and personnel cost.

### 2.6 Liquefied natural gas tankers

Tankers typically transport liquid crude oil and its refined products, but ships (and trains) capable of carrying liquefied natural gas (LNG) are becoming increasingly important as abundant and relatively low-cost natural gas is offered to the global market. Several unique challenges make energy transportation as LNG more expensive than for oil in tankers, including the need for dedicated ports as well as highly trained personnel who are capable of handling the highly flammable liquefied natural gas. The costs were calculated by assuming that LNG tankers, relative to oil tankers, had similar lifetimes, speeds, utilization percentages, ratios of capital cost to total cost, speed and utilization percentages (Table 6). Additionally, 30% loss of LNG was assumed during the liquefaction and a 5% loss due to the use of the LNG as a fuel. The cost of LNG tankers was estimated from published data.[35,37] The total cost of energy transport as LNG in ships was found to be nearly equivalent to that of natural gas transmission in pipelines. This estimate is consistent with available data on the cost of LNG tanker transportation.[26,38]

### 2.7 Electrical transmission lines

High-voltage transmission lines are the backbone of the electrical energy grid, with more than $4.5 \times 10^5$ miles ($7.2 \times 10^5$ km) of domestic high-voltage transmission lines.[39] The cost of moving energy as electricity in transmission lines was estimated from reports analyzing the project cost of different types of power lines (Table 7).[7,8,40–42] The lifetime of the transmission lines was estimated to be 40 years, similar to the estimates by the Connecticut Siting Council.[36] The cost of electricity transportation ($ per J per km) is assumed for a joule of electricity and does not take into account energy lost during electricity generation. The total cost of energy transmission in electrical wires was found to be approximately an order of magnitude more expensive than the total cost of energy transmission in oil pipelines. The breakdown

 

Table 6 Transportation costs for liquefied natural gas (LNG) by tanker

| Cost of tanker (million $) | Capacity (thousand $m^3$) | Barrel of oil equivalent (GJ $m^{-3}$) | Average speed (knots) | Cost ($ per km per kW) | Capital cost × $10^{12}$ ($ per km per J) | Total cost × $10^{12}$ ($ per km per J) |
|---|---|---|---|---|---|---|
| 71 | 75 | 22 | 10 | 0.004 | 0.03 | 0.40 |
| 71 | 75 | 22 | 20 | 0.002 | 0.02 | 0.20 |
| 179 | 125 | 22 | 10 | 0.006 | 0.05 | 0.60 |
| 179 | 125 | 22 | 20 | 0.003 | 0.03 | 0.30 |

Table 7 Estimated cost of transporting electricity

| | Power (MW) | Current (A) | Cost of transmission line (million $ per mile) | Cost ($ per km per kW) | Capital cost × $10^{12}$ ($ per km per J) | Total cost × $10^{12}$ ($ per km per J) |
|---|---|---|---|---|---|---|
| 230 kV single | 400 | 1.7 | 1.4 | 3.6 | 1.8 | 3.5 |
| 230 kV double | 800 | 3.5 | 2.3 | 2.9 | 1.4 | 2.8 |
| 345 kV single | 750 | 2.2 | 2.0 | 2.7 | 1.3 | 2.6 |
| 345 kV double | 1500 | 4.4 | 3.2 | 2.2 | 1.1 | 2.1 |
| 400 kV double | 3190 | 8.0 | 4.7 | 1.5 | 0.72 | 1.4 |
| 400 kV double | 6380 | 16 | 8.5 | 1.3 | 0.65 | 1.3 |
| 400 kV double | 6930 | 17 | 8.5 | 1.2 | 0.6 | 1.2 |
| 500 kV Single | 1500 | 3.0 | 1.9 | 1.2 | 0.94 | 1.9 |
| 500 kV double | 3000 | 6.0 | 1.5 | 0.95 | 0.75 | 1.5 |
| 500 kV HVDC | 3000 | 6.0 | 0.77 | 0.48 | 0.38 | 0.75 |
| 600 kV HVDC | 3000 | 5.0 | 0.81 | 0.5 | 0.4 | 0.79 |

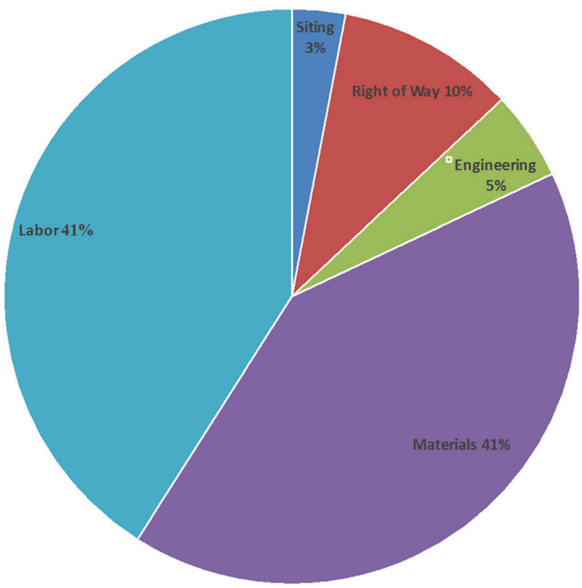


Fig. 2 Capital cost breakdown for electrical transmission lines.

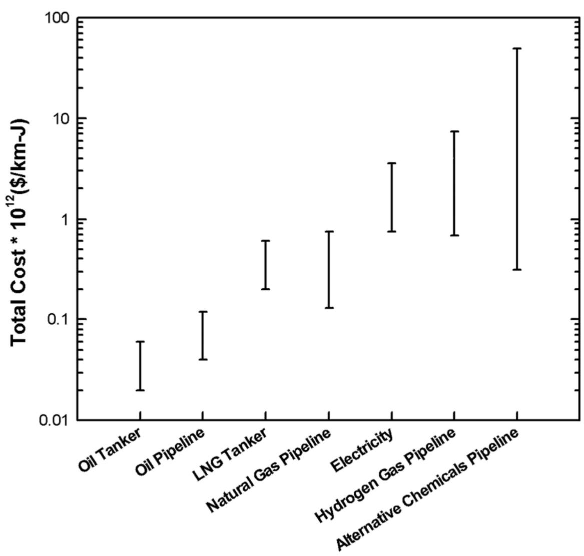


Fig. 3 Summary of the cost of transportation of energy resources in different forms.

of capital cost for electrical transmission lines is estimated in Fig. 2.[43] The cost of electricity transmission can be substantially higher if substations are needed, and right-of-way costs have the potential to further markedly increase the cost of electricity transmission, with some recent transmission lines having full project costs that are as much as a factor of ten higher than the costs in Table 7.[42]

# 3. Overall comparisons, comment, and conclusions

The total cost of large-scale energy resources supplied to consumers cannot be much more than $5–20 per GJ. In Fig. 3 the estimated costs of transportation of different energy resources are shown on a logarithmic scale. The costs are a combination of several major factors, including the end-station costs, maintenance costs and the cost of building and operating the transport system.

The costs of transporting energy per unit distance varies by over two orders of magnitude depending on the energy carrier and the method of transportation. The effect of this difference can be seen in Fig. 4, which shows the fraction of the delivered energy cost due to transport in, (i) oil pipelines, (ii) natural gas pipelines, and (iii) electrical transmission lines. Though all three are transported over land, the fraction of the cost, which

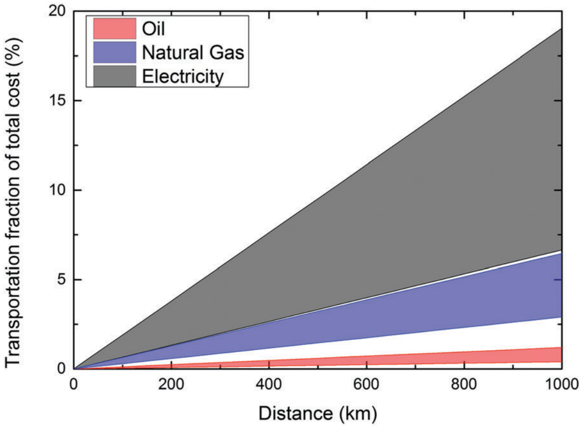


Fig. 4 Fraction of the delivered energy cost due to energy transport.

is due to transportation, varies substantially. Oil and natural gas have an inherent advantage in comparison to electricity and alternative transportable fuels such as electrolytes or hydrogen, by virtue of their relatively high energy densities. Intriguingly, while the transportation infrastructures are quite different, the average cost per mile for all three is within one order of magnitude (∼$1–10 million per mile), an amount similar to the average construction costs per mile of road.[44] Not surprisingly, larger diameter pipelines are more cost effective for liquids and gases due to the relatively small differential costs for the additional volume. Similarly, higher pressure pipelines are more cost effective based on capital investment alone; however, maintenance and compression costs at the source are not insignificant. Notably, even though electricity transportation is much more expensive on a per mile basis, transportation costs account for ∼10% of both oil and electricity total delivered costs,[20,45] because our current infrastructure is designed so that long distance land energy transportation is predominantly accomplished *via* oil pipelines not electrical wires. Due to their high energy densities, oil and natural gas, or carbon-neutral synthetic liquid fuels, have an inherent advantage in cost of energy transmission *vs.* distance with respect to electricity as well as with respect to alternative transportable fuels such as redox flow battery electrolytes or hydrogen.

In any given energy system, the energy transport distance will vary substantially between different energy resources, and the system design therefore prescribes the fraction of total energy costs ascribable to energy transport. Estimating those differences for a future specific energy system is beyond the scope of this work.

## Conflicts of interest

There are no conflicts to declare.

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