Chapter 6

Costs of Transporting Electrical and Chemical Energy

6.1 Introduction

The transport of energy is an integral component of the global energy economy. Primary and secondary energy supplies are typically transported for long distances by merchant ships (tankers and cargo vessels), pipelines, or electrical wires. Fossil hydrocarbons are the predominant energy supplies that are used and transported today, however, transport of energy from renewable sources, including hydrogen and redox-flow electrolytes, may become increasingly important in the future.

Oil, natural gas, and coal are the primary sources for 80% of the world's energy.[1] 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.

Pipelines account for a major percentage of both domestic and international energy transport, and are used to supply gases (e.g. natural gas) and liquids (e.g. oil). In 2013, approximately 8.5 billion barrels of crude oil were transported across 160,000 miles of oil pipeline in the United States,[2, 3] and over 744 million cubic feet of natural gas were transported in over 300,000 miles of natural gas pipelines.[3, 4] 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 fuels over land and tankers over water, so the two methods are often to supplement each other.

Electrical energy is transported from generation to load using conducting transmission wires. Over 4 trillion kilowatthours of electricity is annually generated and transmitted 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) has efficiency advantages and has long been proposed as a potentially economically competitive mode of transmission.[7] Transmission lines are generally supported by tall above ground supports and occasionally are placed underground, where they are less affected by weather but incur additional costs.[8]

Strong interest in renewable energy has led to several proposed future energy transportation scenarios, including 100% grid electrification[9] and widespread installation of hydrogen pipelines.[10, 11] When considering future energy infrastructure alternatives, it is important to include their differing energy transportation costs. Herein we summarize and compare the estimated costs for building and transporting different energy sources across new infrastructure. Costs are compared on a dollar per unit power per unit distance basis, and on a dollar per unit of energy per unit distance basis, using expected operating lifetimes.

6.2 Costs of Energy Transport

6.2.1 Oil Pipelines

Oil that is transported over land primarily moves through 24” to 48” diameter pipelines.[12] The project cost of constructing an oil pipeline, as estimated by averaging the construction cost of large numbers of pipelines, is approximately 61 $\$/ft^3$, with an operating lifetime of 40 years.[12] The capital cost breakdown (Figure 6.1) shows, on average, an even split between material and labor costs, irrespective of pipeline diameter and length.[12] It is important to note that these breakdowns are averages and have high variability between projects. The cost of transporting oil in pipelines can therefore be estimated using the energy density of oil, 38.5 GJ/m^3.[13] (Table 6.1). Costs were calculated for fluid velocities ranging from 1- 3 m/s, which correspond to average pipeline velocities. The capital cost was assumed to account for 38%[14] of the total cost of transporting the oil, with the majority of the remaining costs associated with corrosion and pipeline maintenance. This total cost estimate for transporting oil in pipelines is comparable to published values.[15, 16]

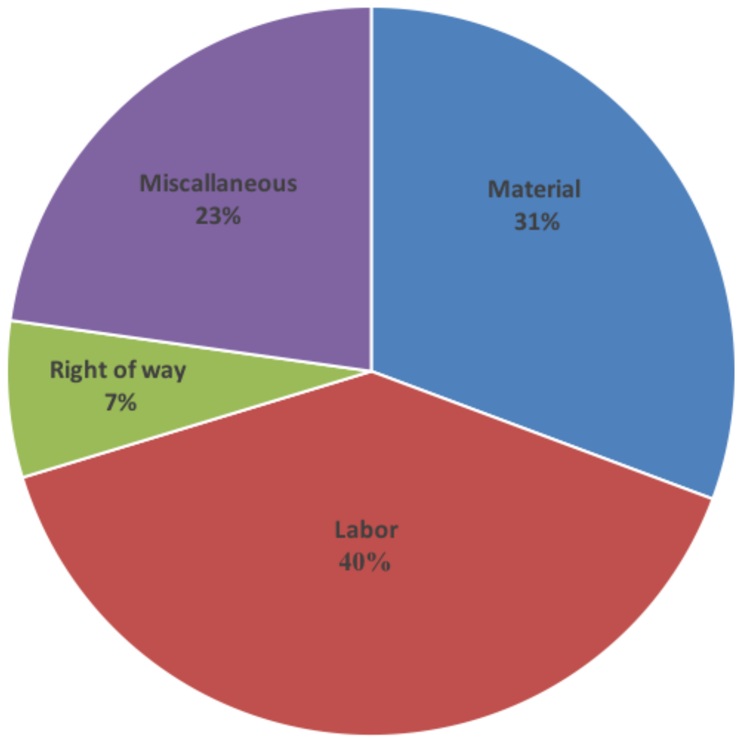

Figure 6.1: Capital cost breakdown for oil pipelines

Pipe Diameter (in)	Cost of pipeline (million $/mile)	fluid velocity (m/s)	Energy density of oil (GJ/m3)	Flow rate (m3/s)	Energy flow rate (GW)	Cost ($/km kW)	lifetime (years)	Capital Cost ($/1000 km-GJ)	Total Cost ($/1000 km-GJ)
36	2.3	1.00	38.50	0.66	25.28	0.06	40	0.04	0.12
36	2.3	2.00	38.50	1.31	50.56	0.03	40	0.02	0.06
36	2.3	3.00	38.50	1.97	75.83	0.02	40	0.01	0.04

Table 6.1: Cost of transporting oil in pipelines

6.2.2 Natural Gas Pipelines

Most natural gas is transported in pipelines. Long-distance natural gas pipelines are usually maintained at high pressures (~65-90 bar)[11, 17] with fluid velocities of ~10 m/s.[18] Natural gas is predominately methane, which is reasonably treated as an ideal gas with an energy density of approximately 47 MJ/kg.[19] The costs of construction and use of natural gas pipelines were estimated from three separate reports[10, 11, 20] (Table 6.2). The capital cost of natural gas pipelines has similar a cost breakdown to that of oil pipelines.[21] 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 similar, but higher, than the cost for oil pipelines. These cost estimates are also comparable to previous reports.[22]

Pipe diameter (in)	Cost of pipeline (million $/mile)	Fluid velocity (m/s)	Pressure (bar)	Heat of Combustion (MJ/kg)	Cost ($/km kW)	Lifetime (years)	Capital Cost ($/1000 km-GJ)	Total Cost ($/1000 km-GJ)
20	1.44	10	65	47	0.22	25	0.28	0.75
36	2.91	10	65	47	0.14	25	0.18	0.47
20	1.44	10	90	47	0.16	25	0.21	0.54
36	2.91	10	90	47	0.10	25	0.13	0.34

Table 6.2: Cost of transporting natural gas by pipeline

6.2.3 Hydrogen Pipelines

Hydrogen pipelines are used primarily to transport hydrogen as a chemical feedstock for commercial operations. To estimate of the cost of constructing long-distance hydrogen pipelines for energy purposes, the cost was assumed to be similar to that of commercially installed natural gas pipelines. This is an optimistic assumption as the transportation of hydrogen would likely require more expensive steel due to hydrogen embrittlement.[10] The hydrogen pressure was assumed to be ~10-30 bar[20] and the fluid velocity was assumed to be approximately 15 m/s.[11] Hydrogen is assumed to behave as an ideal gas with an energy density of 120 MJ/kg.[19] Both the capital and total costs of transporting energy via hydrogen in pipelines are estimated to be an order of magnitude greater than natural gas (Table 6.3), primarily due to the lower heat of combustion per mole as well as the lower pressures utilized in hydrogen pipelines.

Pipe diameter (in)	Cost of pipeline (million $/mile)	Fluid velocity (m/s)	Pressure (bar)	Heat of Combustion (MJ/kg)	Cost ($/km kW)	Lifetime (years)	Capital Cost ($/1000 km-GJ)	Total Cost ($/1000 km-GJ)
20	1.44	15	15	120	2.02	25	2.57	6.75
36	2.91	15	15	120	1.27	25	1.61	4.24
20	1.44	15	30	120	1.01	25	1.28	3.38
36	2.91	15	30	120	0.63	25	0.80	2.11

Table 6.3: Cost of transporting hydrogen in pipelines

6.2.4 Pipelines for Alternative Chemicals

In addition to transporting oil, large diameter pipelines may also be utilized for transporting chemical energy in the form of redox flow battery electrolytes 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 oil.[23-27] The costs of these pipelines were calculated by assuming similar diameters, materials, and fluid velocities to oil pipelines. Table 6.4 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 significantly higher energy density than redox flow electrolytes, resulting in much lower costs of transportation.

	Pipe Diameter (in)	Cost of pipeline (million $/mile)	fluid velocity (m/s)	Energy density of electrolyte (GJ/m3)	Cost ($/km kW)	Lifetime (years)	Capital Cost ($/1000 km-GJ)	Total Cost ($/1000 km-GJ)
Vanadium Flow	36	2.28	1	0.09	23.94	40	18.91	49.77
Vanadium Flow	36	2.28	2	0.09	11.97	40	9.46	24.89
High density Vanadium Flow	36	2.28	1	0.15	14.60	40	11.53	30.35
High density Vanadium Flow	36	2.28	2	0.15	7.30	40	5.77	15.17
Zinc-polyiodide	36	2.28	1	0.6	3.59	40	2.84	7.47
Zinc-polyiodide	36	2.28	2	0.6	1.80	40	1.42	3.73
Zinc-bromide	36	2.28	1	0.25	8.55	40	6.75	17.78
Zinc-bromide	36	2.28	2	0.25	4.28	40	3.38	8.89
Dodecahydro-N-ethylcarbazole/N-ethylcarbazole	36	2.28	1	7.24	0.30	40	0.24	0.63
Dodecahydro-N-ethylcarbazole/N-ethylcarbazole	36	2.28	2	7.24	0.15	40	0.12	0.31
Decalin/naphthalene	36	2.28	1	6.82	0.32	40	0.25	0.67
Decalin/naphthalene	36	2.28	2	6.82	0.16	40	0.13	0.33

Table 6.4: Cost of transporting energy as redox flow battery electrolyte by pipeline

6.2.5 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 shipments across the globe.[28] The average lifetime of a tanker is estimated to be 25 years,[29] the average speed was assumed to be ~10 knots[30] and the utilization percentage (fraction of time that the tanker carries cargo) was assumed to be 40%. Table 6.5 summarizes the cost of energy transport 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).[31] The total cost of oil transportation was estimated by averaging the cost of several tanker route rates,[15, 32] 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.

Name	Cost of tanker (million $)	capacity (million bbl)	barrel of oil equivalent (GJ/bbl)	average speed (knots)	Cost ($/km kW)	Lifetime (years)	Capital Cost ($/1000 km-GJ)	Total Cost ($/1000 km-GJ)
Panamax	30	0.54	6.1	10	0.004	30	0.006	0.04
Aframax	49	0.69	6.1	10	0.006	30	0.007	0.06
Suezmax	52	1.26	6.1	10	0.003	30	0.004	0.03
VLCC	94	1.96	6.1	10	0.004	30	0.005	0.04

Table 6.5: Cost of transporting oil by tanker

6.2.6 Liquefied Natural Gas Tankers

While tankers typically transport liquid crude oil and its refined products, ships (and trains) capable of carrying liquefied natural gas (LNG) are increasingly used, taking advantage of abundant and relatively low-cost natural gas. 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, and ratio of capital cost to total cost. Additionally, a 30% loss of LNG was assumed during the liquefaction. The cost of LNG tankers was estimated from published data.[31, 33] 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.[22, 34]

Cost of tanker (million $)	capacity (thousand m^3)	barrel of oil equivalent (GJ/m^3)	average speed (knots)	Cost ($/km kW)	Lifetime (years)	Capital Cost ($/1000 km-GJ)	Total Cost ($/1000 km-GJ)
71	75	22	10	0.004	30	0.03	0.26
179	125	22	10	0.006	30	0.05	0.4

Table 6.6: Transportation costs for liquefied natural gas (LNG) by tanker

6.2.7 Electrical Transmission Lines

High-voltage transmission lines are the backbone of the electrical energy grid, with more than 450,000 miles of domestic high-voltage transmission lines.[35] 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 6.7).[7, 8, 36-38] The total cost of energy transmission via electrical wires was found to be approximately an order of magnitude more expensive than the total cost of energy transmission via oil pipelines. The breakdown of capital cost for electrical transmission lines is estimated in Figure 6.2.[39] 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 6.7.[38]

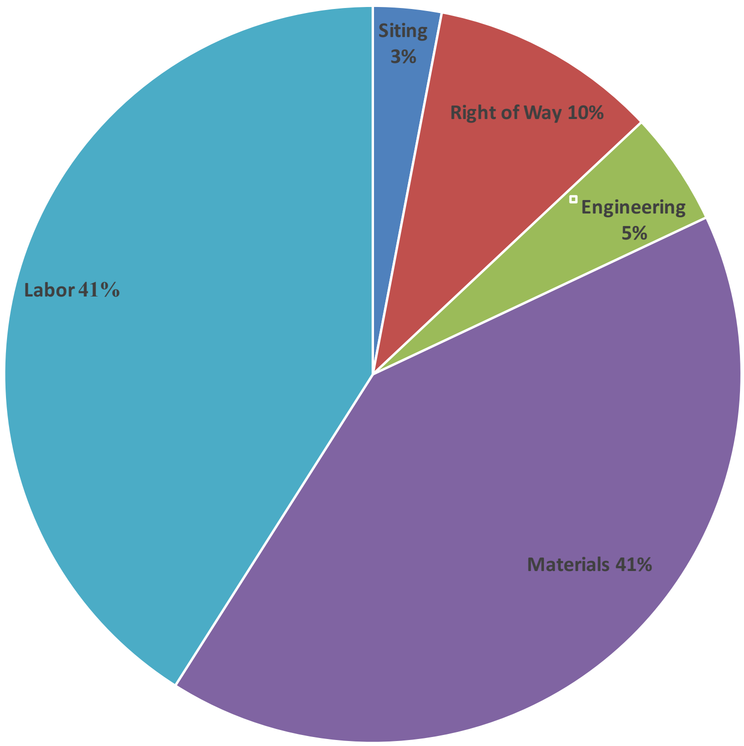

Figure 6.2: Capital cost breakdown for electrical transmission lines

Type	Power (MW)	Current (A)	Cost of transmission line (million $/mile)	Cost ($/km kW)	Lifetime (years)	Capital Cost ($/1000 km-GJ)	Total Cost ($/1000 km-GJ)
230 kV single	400	1.74	1.44	3.60	40	1.77	3.53
230 kV double	800	3.48	2.30	2.88	40	1.41	2.83
345 kV single	750	2.17	2.02	2.69	40	1.32	2.64
345 kV double	1500	4.35	3.23	2.15	40	1.06	2.11
400 kV double	3190	8	4.65	1.46	40	0.72	1.43
400 kV double	6380	16	8.45	1.32	40	0.65	1.30
400 kV double	6930	17.33	8.45	1.22	40	0.60	1.20
500 kV Single	1500	3	1.92	1.19	40	0.94	1.88
500 kV double	3000	6	1.54	0.95	40	0.75	1.51
500 kV HVDC	3000	6	0.77	0.48	40	0.38	0.75
600 kV HVDC	3000	5	0.81	0.50	40	0.40	0.79

Table 6.7: Estimated cost of transporting electricity

6.3 Overall Comparison, Comment and Conclusion

Figure 6.3 compares the estimated costs of transporting energy resources in different forms. The costs are a combination of many factors, including the end-station costs, maintenance costs and the cost of building and operating the transport system. The cost of transporting energy per unit distance varies by over two orders of magnitude depending on the energy carrier and the method of transportation. Due to their high energy densities, oil and natural gas have an inherent advantage in comparison to alternative transportable fuels such as redox flow battery electrolytes or hydrogen.

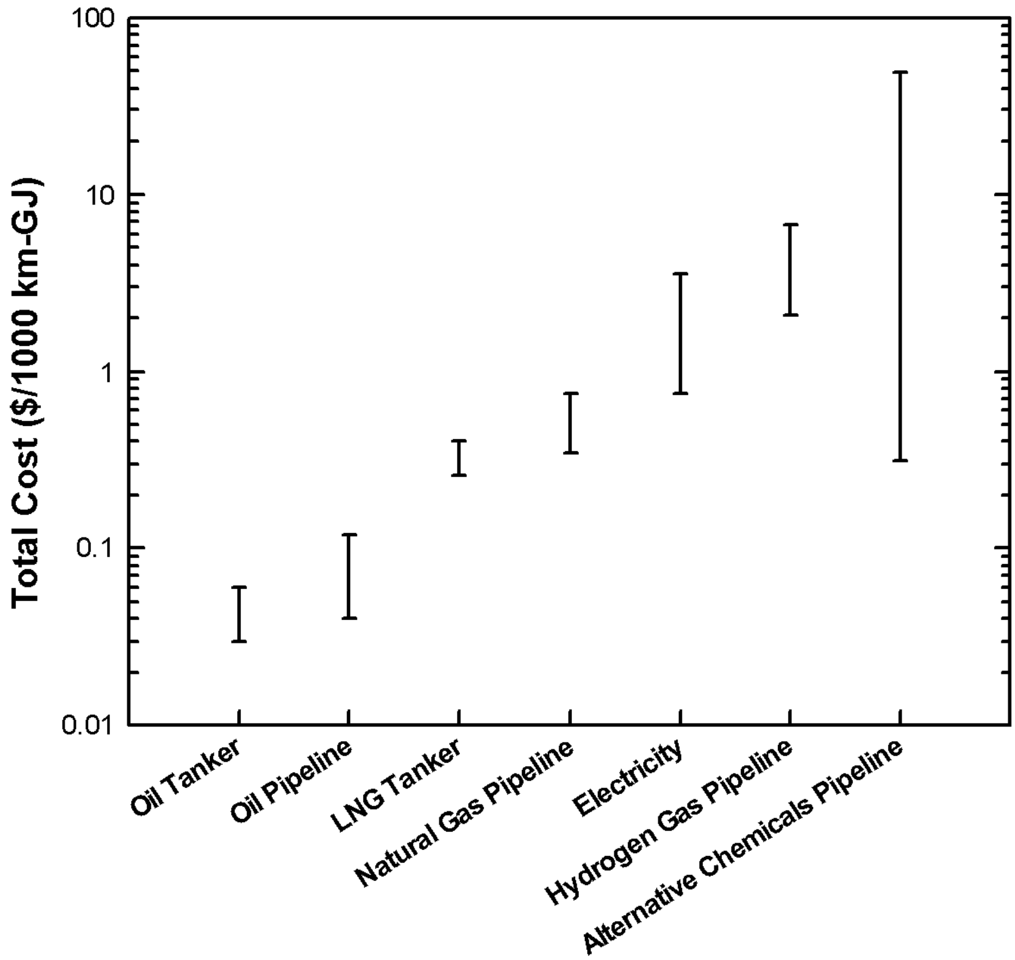

Figure 6.3: Summary of the cost of transportation energy resources in different forms.

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