Updated: 4/4/2024

Energy Transport Technologies

1.0 Introduction

In these notes, we focus mainly on various electric transmission technologies that are of high interest today because of their ability to obtain additional power transfer capability without increasing (and in some cases decreasing) the required right-of-way. We also make some comments about other forms of energy transport which may, in some cases, be considered as an alternative to electric transmission for transporting energy. The following technologies are described in these notes:

1. High temperature, low sag (HTLS) conductors
2. High surge impedance loading (HSIL) lines
3. Compact line design
4. Gas insulated conductors
5. Superconductors
6. Natural gas transmission
7. Rail (for coal and for agricultural commodities)
8. Hydrogen
9. Ammonia

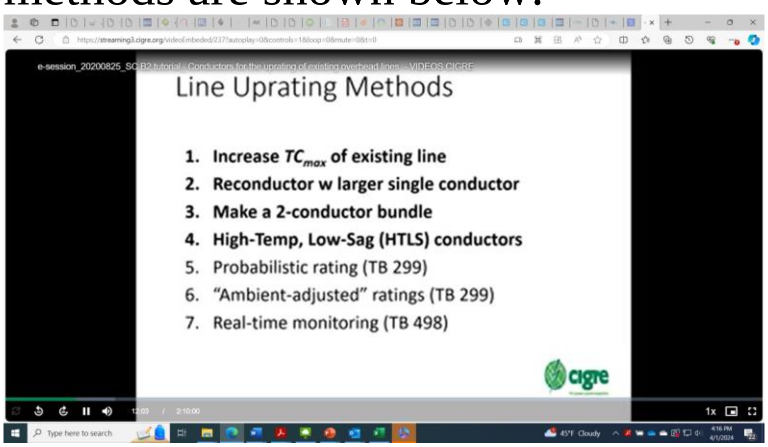
It would be useful to expand the list of transmission technologies available within a TEP or CEP code to include 1-3 and possibly others. To achieve this, one should start with the formulation given in [1, 2] and summarized in Section 3 of the EE 552 notes called "TransmissionPlanningOptimization."

2.0 High temperature, low sag conductors

This material on high-temperature low sag (HTLS) conductors was adapted from [3] and other sources. An excellent 2hr CIGRE video on HTLS is available at https://streaming3.cigre.org/videoEmbeded/237?autoplay=0&controls=1&loop=0&mute=0&t=0. I strongly recommend it. It covers the below:

The problem of uprating lines is of vary high interest because of the need for transmission motivated by renewables, and because of the difficulty of obtaining ROW to build new transmission. And so we look for methods of increasing transmission capacity that does not require additional ROW.

The video recommends consideration of three different uprating methods before deploying HTLS conductors. These methods are shown below.



Increasing the thermal rating of an existing line by use of a replacement conductor larger than the original, having lower resistance, increases both transverse ice and wind loads and tension loads on existing structures. A larger conventional conductor imposing greater loads on the existing structures may reduce the reliability of the existing line unless the structures are reinforced.

The method of HTLS conductors increases the thermal rating of an existing line by use of a replacement conductor having nearly the same diameter as the original conductor but capable of operation at higher temperature (within existing sag clearance and loss-of-strength constraints); HTLS may avoid the need for reinforcement of suspension structures. The idea of increasing thermal rating via increasing max. conductor temp., TCmax, is illustrated in Fig. 0 [4].

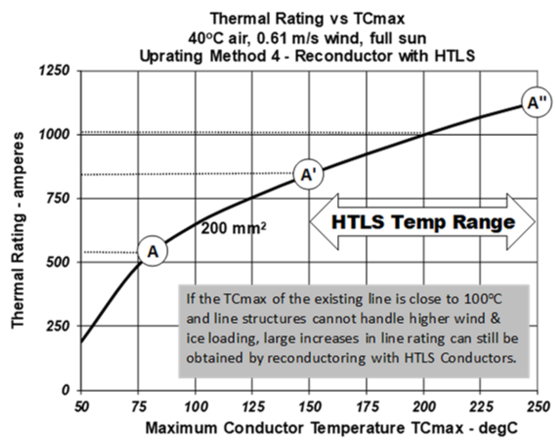


Fig. 0

A "High Temperature Conductor" is defined as a conductor that is designed for applications where continuous operation is above 100°C or the conductor is designed to operate in emergency conditions above 150°C. There are different types of HTLS conductors that can be used to increase the thermal rating of existing lines with minimum structural reinforcement. Several types of conductors that are commercially available are summarized in Table 1.

Table 1

	ACSS	Aluminium Conductor, Steel Supported[(1)(2)]
	ACSS/TW	Trapezoidal shaped strands, Aluminium Conductor, Steel Supported[(1)(2)]
	G(Z)TACSR	Gap Type Super Thermal Resistant Aluminium Alloy, Steel Reinforced
	KTACSR	High Strength Thermal Resistant Aluminium Alloy Conductor, Steel Reinforced(1)
	TACSR	Thermal Resistant Aluminium Alloy Conductor, Steel Reinforced[(1)]
	ZTACSR	Super Thermal Resistant Aluminium Alloy Conductor, Steel Reinforced[(1)]
	ZTACIR(3)	Super Thermal Resistant Aluminium Alloy Conductor, Invar Reinforced

(1) Additional suffices are allowed to describe the type of core (e.g. ACSS/GA)
(2) Originally known as SSAC
(3) Could also be known as STACIR

The five most attractive HTLS conductors, according to [5], are summarized below. The first three are also shown in the bolded boxes of Table 1 above.

1) ACSS (Aluminum Conductor, Steel Supported): Extra or ultra-high strength steel core, annealed[1] aluminum outer strands, typically trapezoidal, i.e., ACSS/TW. The trap design enables strands to fit tightly together (rel. to round), reducing empty spacing between them.

2) G(Z)TACSR (Gap-Type Conductor): Extra high strength steel core (Galvanized or Aluminum Clad Steel). Thermal (or Super Thermal) Resistant Aluminum outer strands, sometimes trapezoidal.

3) (Z)TACIR (Invar): Invar ("Invariant") Iron-Nickel Alloy Core. Thermal (or Super Thermal) Resistant Aluminum outer strands.

4) ACCC/TW (CTC Corp), Aluminum Conductor, Composite Core: carbon/glass fiber polymeric core, annealed alum. trap. outer strands.

5) ACCR (3M Corp.), Aluminum Conductor, Composite Reinforced: aluminum oxide fiber-reinforced metal matrix core. Thermal (or Super Thermal) Resistant Aluminum outer strands.

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[1] Annealing is a heat treatment process that changes the physical and sometimes also the chemical properties of a material to increase ductility and reduce the hardness to make it more workable.

The above are well-explained in App. B of J. Sleger's thesis here [16], as summarized here:

Table 2 summarizes advantages/disadvantages of HTLS conductors relative to ACSR conductors [6].

Table 2[2]

Conductor	Advantages	Disadvantages
ACSS	- Operating temperatures up to 250 °C - Lower sag increase at high temperatures. - Higher self damping capability - Reduced creep.	- Smaller tensile strength. - More expensive
ZTACIR	- Operating temperatures up to 210 °C - Lower sag increase for temperatures beyond the transition point.	- Smaller tensile strength. - For temperatures below the transition point the sag-temperature behaviour is similar to that of ACSR. - More expensive
GTACSR	- Operating temperatures up to 150 °C - Lower sag increase for all temperature ranges. - High self damping capability. - Higher tensile strength.	- More complex stringing procedures. - More expensive

To illustrate, ref [6] identified the "worst-case" span of a particular line which currently employs the HEN type of ACSR conductor. For this circuit, the sag limitation is 8.52m, which occurs at an ACSR operating temperature of 50° C. The operating temperature at which this same

[2] From https://www.britannica.com/science/tensile-strength, tensile strength is the "maximum load that a material can support without fracture when being stretched, divided by the original cross-sectional area of the material. Tensile strengths have dimensions of force per unit area and in the English system of measurement are commonly expressed in units of pounds per square inch, often abbreviated to psi. When stresses less than the tensile strength are removed, a material returns either completely or partially to its original shape and size. As the stress reaches the value of the tensile strength, however, a material, if ductile, that has already begun to flow plastically rapidly forms a constricted region called a neck, where it then fractures."

8.52m sag occurs for ZTACIR, ACSS, and GTACSR conductors having the same size and weight as the existing HEN ACSR conductor are shown in Fig. 1a, where we observe that ZTACIR and ACSS provide no significant increase in max operating temperature. GTACSR, on the other hand, is capable of operating at 80° C.

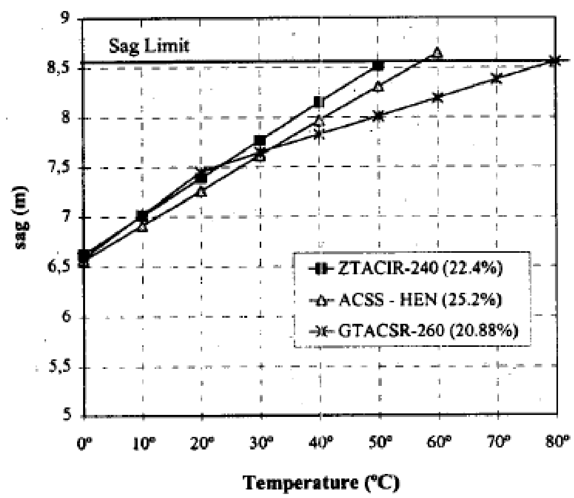


Fig. 1a

Figure 1b shows similar information from [5], where we once again see significant temperature gain for GTACSR (and several others).

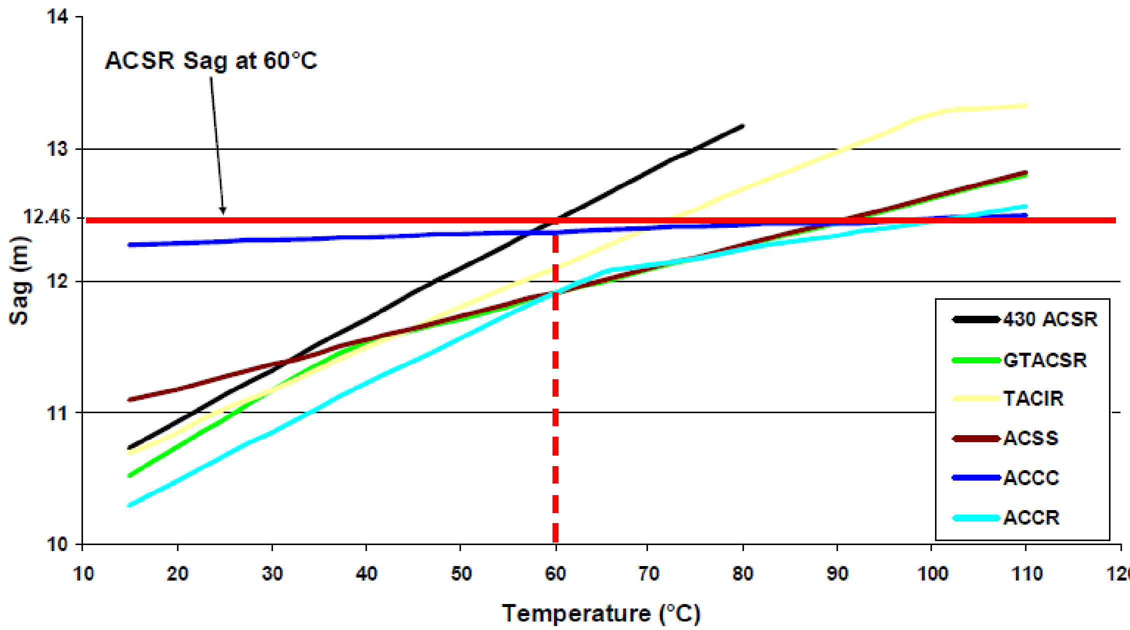


Fig. 1b

The relation between ampacity and operating temperature for the existing conductor (ACSR-HEN) and three HTLS conductors is shown in Fig. 2 [6]. Because it is at 50° C that the ACSR-HEN sags to the limiting 8.52 meters, its ampacity is 300 amperes. But the GTACSR does not reach the sag limitation of 8.52 meters until an operating temperature of 80 degrees C, a level corresponding to an ampacity of 640 amperes.

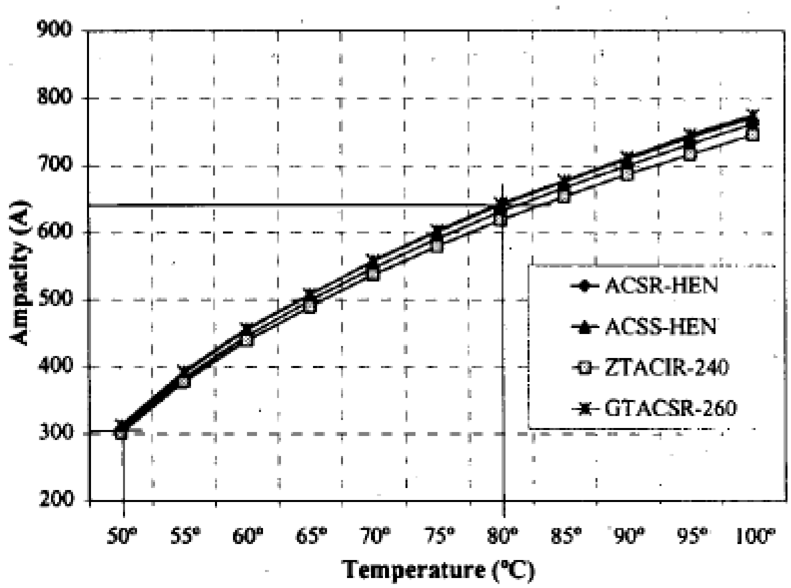


Fig. 2

So a rough way of estimating ampacity gain from HTLS conductors is to (a) identify the maximum allowable sag; (b) identify the corresponding steady-state temperature which causes that sag; (c) identify the current which results in that steady-state temp.

As of 2007, manufacturers indicated that there was approximately 10,000 km of ACSS in use in the US, and a survey indicated about 41,000 km of some kind of HTLS conductor in use worldwide, with most of it in Japan.

A GTACSR conductor is shown in Fig. 1c from a Japanese vendor [7], illustrated in Fig. 1d. From [7],

> "Extra high strength steel core is in the center and (Super) thermal-resistant aluminum alloy is supplied in conductor part. To maintain the gap between the steel core and aluminum inner layer, the inner layer wires are trapezoid shaped. The thermal-resistant

grease is filled to the gap to avoid friction between the steel core and aluminum inner layer. The aluminum layer and steel core move independently."

Fig. 1c: GTACSR conductor

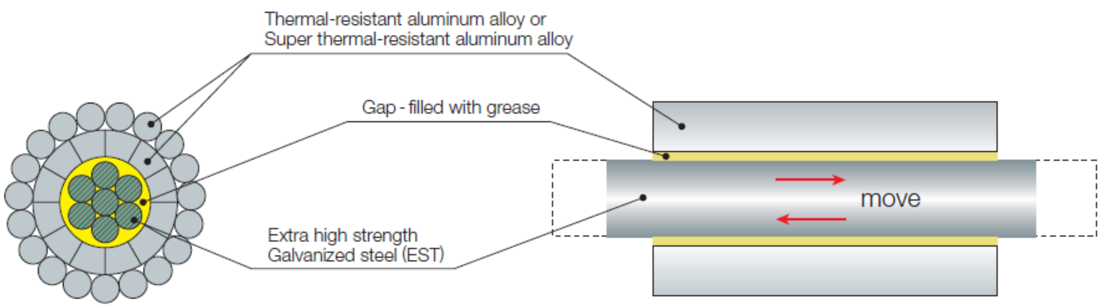


Fig. 1d: GTACSR conductor

Reference [7] explains the "thermal resistance" as:

"Thermal-resistant aluminum alloy (TAI) and Super thermal resistant aluminum alloy (ZTAI) improve its thermal-resistant characteristics by adding zirconium. ZTAI and TAI can keep its tensile strength in high temperature condition. TAI can withstand up to 150ºC and can carry 1.6 times current of Hard drawn aluminum (1350). ZTAI can withstand up to 210ºC and can carry 2.0 times current of Hard drawn aluminum (1350). Both TAI and ZTAI maintain nearly the same mechanical and electrical characteristics as Hard drawn aluminum (1350).

Reference [7] illustrates the above as in Fig. 1e, showing that ZTAI and TAI are equivalent to Al in conductivity and tensile strength and much better in maximum operating temperature.

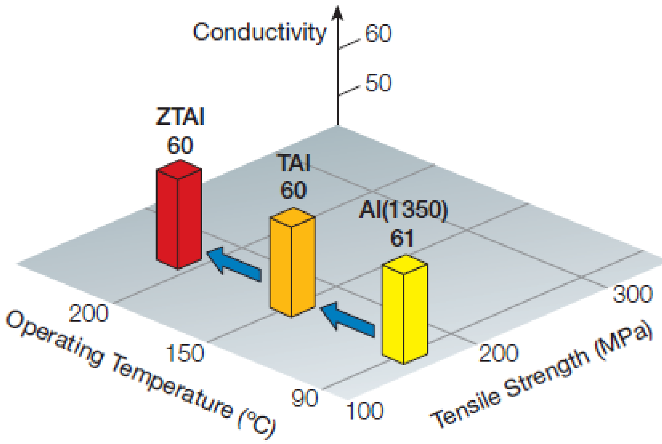


Fig. 1e

However, there is a cost to this additional current-carrying capacity. Reference [8] provides the following comments about HTLS conductors:

> "The main purpose of high temperature low sag conductors is to improve the thermal rating of a line. A typical HTLS conductor can handle 1.6 to 3 times the current of a similar conventional conductor [3]. This increase in current is proportional to the increase in thermal rating. However, this increase in current comes at a dollar cost of up to 6.5 times that of a conventional conductor (see Table I). Comparing the alternatives of a single HTLS circuit versus a double circuit conventional line, HTLS may have higher I^2R losses as a consequence of the higher current and slightly higher resistance. HTLS conductor operating temperatures can be in the range 80° to 250° C [4], and consequently the conductor resistance can be higher than that seen for conventional conductors. As an example, [4] quotes a lower conductivity of HTLS conductors in the range of 60 to 63% of that for conventional aluminum conductors (i.e., the resistance increase over conventional conductors is 1.59 to 1.67). As a further example, 3M ACCR has 0.1116 Ω/mi at 75°C and 0.1613 at 210°C [6]."

This same reference [8] provides the following table, which shows that the additional ampacity does cost money.

Table 3: Increase in current and cost for HTLS conductor compared to conventional conductors

Conductor type	Relative ampacity*	Relative cost*	Manufacturer
ACCC	2.0	2.5-3.0	CTC Cable [5]
ACCR	2.0-3.0	5.0-6.5	3M [6]
ACSR	1.6-2.0	2.0	J-Power [7]
ACSS/TW	1.8-2.0	1.2-1.5	Southwire [8]
ACSS/AW	1.8-2.0	1.2-1.5	Southwire [8]
ACIR/AW	2.0	3.0-5.0	LS Cable [9]

*Compared to conventional conductors [3], for typical commercially available HTLS conductors

As a final comment in this section, there is an ISU faculty working to produce a new conductor that is lighter, stronger, with the same conductivity as traditional ACSR for AC purposes but more conductive for DC purposes [9, 10, 11]. This may be a very attractive alternative for HVDC design.

HTLS conductors are useful when a circuit is current-limited. We have seen, however, that circuits are typically current-limited only for relatively short lines. Longer lines (beyond about 50 miles) may be more limited by reactive/voltage or angular instability issues. In this case, increasing the line's surge impedance loading can provide a more effective means of increasing power transfer capability. This is the topic of the next section.

3.0 High surge impedance loading conductors

High surge impedance loading (HSIL) conductors can achieve significant increase in surge impedance loading (SIL) values for a given voltage level. The table below [12] quantifies the difference between the SIL of a conventional circuit and that of an HSIL circuit (but upper values of HSIL lines seem too large to me – need to check it).

Voltage Level (kV)	Conventional Line (MW)	HSIL Line (MW)
69	9 - 12	10 - 40
138	40 - 50	50 - 120
230	120 - 130	130 - 440
500	900 - 1020	950 - 2000

We observe that we can more than double the capacity in most cases. How is this done?

Let's reconsider the formula for SIL:

$$P_{SIL} = \frac{V_{LL}^2}{Z_C} \qquad Z_C = \sqrt{\frac{z}{y}} = \sqrt{X_L X_C}$$

We observe that if we can make Z_C small that, for a given voltage level, P_{SIL} will become large. Thus, according to the St. Clair curve, at a given line length, we will be increasing the power transfer capability. So…. how can we design the line so as to make Z_C small?

Recall that X_L and X_C are given by

$$X_L = \underbrace{2.022\times10^{-3} f \ln\frac{1}{R_b}}_{X_a} + \underbrace{2.022\times10^{-3} f \ln D_m}_{X_d} \ \Omega/\text{mile} = 2.022\times10^{-3} f \ln\frac{D_m}{R_b}$$

$$X_C = \underbrace{\frac{1}{f}\times1.779\times10^{6}\ln\left(\frac{1}{R_b^c}\right)}_{X'_a} + \underbrace{\frac{1}{f}\times1.779\times10^{6}\ln(D_m)}_{X'_d} \ \Omega\text{-mile} = \frac{1}{f}\times1.779\times10^{6}\ln\left(\frac{D_m}{R_b^c}\right)$$

Substitution into the expression for Z_C yields

$$Z_C = \sqrt{X_L X_C} = \sqrt{(2.022\times10^{-3} f \ln\frac{D_m}{R_b})(\frac{1}{f}1.779\times10^{6}\ln\left(\frac{D_m}{R_b^c}\right))}$$

$$= \sqrt{(3.5971\times10^{3}\ln\frac{D_m}{R_b})(\ln\left(\frac{D_m}{R_b^c}\right))}$$

We see that there are two ways to make Z_C small:

1. Make D_m small.
2. Make R_b and R_b^c large.

Let's investigate both of these.

3.1 Phase position

Recall the expression for D_m is given by

$$\boldsymbol{D_m \equiv \left(d_{ab}^{(1)} d_{ab}^{(2)} d_{ab}^{(3)}\right)^{1/3}}$$

where $d_{ab}^{(k)}$ is the distance between phases a and b when in position k, with k=1,2,3 corresponding to the three positions of the phases caused by trans-positioning.

So we see clearly that in order to make D_m small, we need to reduce $d_{ab}^{(k)}$, k=1,2,3. This means that we need to reduce the distances between phase positions.

3.2 Bundling

Bundling is useful to mitigate corona losses and interference at voltages above 230 kV. Recall the expressions for bundle GMRs R_b, R_b^c are given by

$$\begin{aligned}
R_b &= \left(r' d_{12}\right)^{1/2}, && \text{for 2 conductor bundle} \\
&= \left(r' d_{12} d_{13}\right)^{1/3}, && \text{for 3 conductor bundle} \\
&= \left(r' d_{12} d_{13} d_{14}\right)^{1/4}, && \text{for 4 conductor bundle} \\
&= \left(r' d_{12} d_{13} d_{14} d_{15} d_{16}\right)^{1/4}, && \text{for 6 conductor bundle} \\
R_b^c &= \left(r d_{12}\right)^{1/2}, && \text{for 2 conductor bundle} \\
&= \left(r d_{12} d_{13}\right)^{1/3}, && \text{for 3 conductor bundle} \\
&= \left(r d_{12} d_{13} d_{14}\right)^{1/4}, && \text{for 4 conductor bundle} \\
&= \left(r d_{12} d_{13} d_{14} d_{15} d_{16}\right)^{1/6}, && \text{for 6 conductor bundle}
\end{aligned}$$

where *r* is the radius of a single conductor, and *r'* is the Geometric Mean Radius (GMR) of an individual conductor, given by

$$r' = re^{-\frac{\mu_r}{4}}$$

To make R_b and R_b^c large, we can do two things.

- Increase *r*, the radius of the conductor

- Increase the distance $d_{1,k}$, for $k=1,\ldots,n$ where n is the number of conductors in the bundle; this means expanding the bundle geometry.

3.3 Example

In our previous notes, we computed X_L and X_C for a 765 kV AC line, single circuit, with a 6-conductor bundle per phase, using conductor type Tern (795 kcmil). The bundles had 2.5' (30'') diameter, with phase separation of 45', as shown in Fig. 3 below.

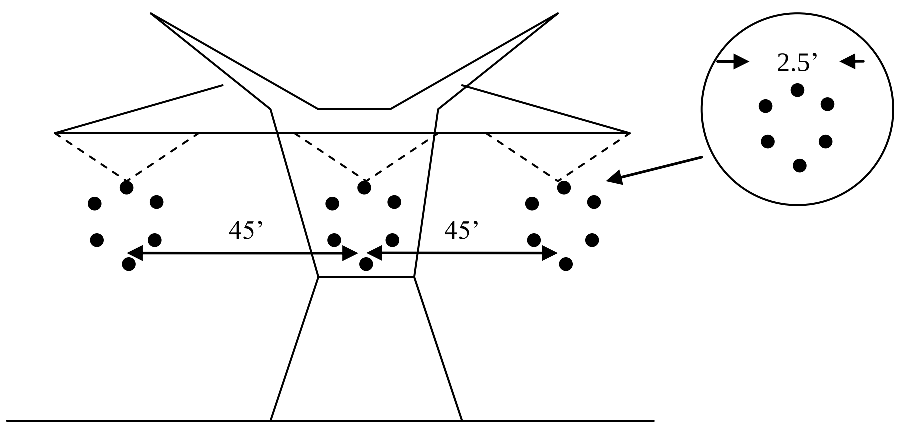


Fig. 3

For this data, we obtained:

$X_L=X_a+X_d$=0.0205+0.4619=0.4929 ohms/mile

$X_C=X'_a+X'_d$=0.0343+0.1128=0.1471Mohms-mile.

$y=1/-jX_C$=6.7981E-6 Mhos/mile

Z_C=sqrt(0.4929/6.7981E-6)=
269.27 ohms

P_{SIL}=(765E3)^2/269.27= 2173.4 MW

Let's perform three separate calculations in order to observe the effect on $P_{SIL.}$

Effect of phase position:

Let's decrease the distance between phases from 45' to 36', a 20% decrease.

Get per-unit length inductive reactance:

Since we are not changing the bundle geometry, the inductive reactance at 1-foot spacing remains the same, which is X_a=0.0205.

From Table 3.3.12, we find

36' phase spacing: X_d=0.4348

So $X_L=X_a+X_d$=0.0205+0.4348=0.4553 ohms/mile.

Now get per-unit length capacitive reactance.

Again, since we are not changing bundle geometry, the capacitive reactance at 1 foot spacing remains the same, which is X_a'=0.0307.

From Table 3.3.13, we find

36' phase spacing: X'_d=0.1062

So $X_C=X'_a+X'_d$=0.0307+0.1062=0.1369E6ohms-mile

So $z=jX_L$=j0.4553 Ohms/mile, and

$y=1/-jX_C=1/-j(0.1369\times10^6)=j7.3046\times10^{-6}$ mhos/mile

The surge impedance is

$$Z_C = \sqrt{\frac{z}{y}} = \sqrt{\frac{\text{j}.4453}{\text{j}7.3046 \times 10^{-6}}} = 246.904\text{ohms}$$

Then the SIL is

$$P_{SIL} = \frac{V_{LL}^2}{Z_C} = \frac{\left(765 \times 10^3\right)^2}{246.904} = 2.3703\text{e} + 009$$

The SIL for this circuit is **2370 MW**.

With a 45' phase distance, we obtained an SIL of **2173 MW**, and so we see that the 20% decrease in distance (from 45' to 36') gained us an additional 9.1% in SIL.

<u>*Bundle geometry*</u>*: Effect of increasing bundle to 36''*

We will maintain our 36' phase distance and now increase the diameter of our 6-conductor bundle from 30'' to 36''.

Get per-unit length inductive reactance:

From Table 3.3.1,

36'' bundle: X_a=-0.011

From the previous calculation above

36' phase spacing: X_d=0.4348

So $X_L=X_a+X_d$=-0.011+0.4348=0.4238 ohms/mile.

Now get per-unit length capacitive reactance.
From Table 3.3.2, we find
36'' bundle: X_a'=-0.0035

From the previous calculation above
36' phase spacing: X'_d=0.1062
So $X_C=X'_a+X'_d$=-0.035+0.1062=0.1027E6ohms-mile

So z=jX_L=j0.4238 Ohms/mile, and
y=1/-jX_C=1/-j(0.1027×10^6)=j9.737×10^{-6} mhos/mile

The surge impedance is

$$Z_C = \sqrt{\frac{z}{y}} = \sqrt{\frac{\text{j}.4238}{\text{j}9.737\times10^{-6}}} = 208.6\text{ohms}$$

Then the SIL is

$$P_{SIL} = \frac{V_{LL}^2}{Z_C} = \frac{\left(765\times10^3\right)^2}{208.6} = 2.8055\text{e}+009$$

The SIL for this circuit is **2805 MW**.
With a 30'' bundle (and 36' phase distance), we obtained an SIL of **2370 MW**, and so we see that the 20% increase in bundle radius gives us an additional 18.3% increase in SIL.

Overall, the two changes we have made have increased from **2173 MW to 2805 MW**, 24.8%.

Effect of conductor size:
We previously used a conductor type Tern having 795 kcmil (this characterizes the aluminum portion of the conductor) or 431 sq mm (this characterizes the entire conductor). Let's increase the radius by 20% which means we need to choose a conductor having an area of $1.2^2(431)=621$ sq mm. The Finch conductor (1590 kcmil) has area of 636 sq mm, which is close. Let's try it.

Note that the conductor radius only affects the reactance quantities at 1 ft spacing X_a and X_a'.

Get per-unit length inductive reactance:

From Table 3.3.1,
36'' bundle: X_a=-0.014

From the previous calculation above
36' phase spacing: X_d=0.4348

So $X_L=X_a+X_d$=-0.014+0.4348=0.4208 ohms/mile.

Now get per-unit length capacitive reactance.
From Table 3.3.2, we find
36'' bundle: X_a'=-0.0044

From the previous calculation above

36’ phase spacing: X'_d=0.1062
So $X_C = X'_a + X'_d$=-0.044+0.1062=0.1018E6ohms-mile

So $z = jX_L$=j0.4208 Ohms/mile, and
$y = 1/-jX_C = 1/-j(0.1018\times10^6) = j9.823\times10^{-6}$ mhos/mile

The surge impedance is

$$Z_C = \sqrt{\frac{z}{y}} = \sqrt{\frac{\text{j.4208}}{\text{j}9.823\times10^{-6}}} = 206.97\text{ohms}$$

Then the SIL is

$$P_{SIL} = \frac{V_{LL}^2}{Z_C} = \frac{\left(765\times10^3\right)^2}{206.97} = 2.8276\text{e}+009$$

The SIL for this circuit is **2827 MW**.

With a 431 sq mm conductor (Tern), 36’’ bundle diameter, and 36’ phase distance, we obtained an SIL of **2805 MW**, and so we see that the 20% increase in conductor radius gives us less than a 1% increase in SIL. Higher SIL is typically not achieved by increasing conductor type; choice of conductor type is typically driven by other issues, including ampacity (for short lines), and ruling span (ruling span is the span length in which tension in the conductor, under changes in temperature and loading, most nearly agree with the average tension in a series of spans of varying lengths between dead-end towers [13])[3].

Overall, the three changes we have made have increased from **2247 MW to 2827 MW**, 25.8%.

Bundle geometry: Effect of decreasing bundle to 24"
Here, we return to the Tern 795 kcmil conductor.

From Table 3.3.1,
24'' bundle with 6 conductors: X_a=0.0031

From the previous calculation above
36' phase spacing: X_d=0.4348

So $X_L=X_a+X_d$=0.0031+0.4348=0.4379 ohms/mile.

Now get per-unit length capacitive reactance.
From Table 3.3.2, we find
24'' bundle: X_a'=0.0065

From the previous calculation above
36' phase spacing: X'_d=0.1062
So $X_C=X'_a+X'_d$=0.0065+0.1062=0.1127E6ohms-mile

[3] The text by Gonen, "Electric Power Transmission System Engineering: Analysis and Design," 1988, Wiley, explains further on pg. 640-641: "When a line consists of spans of unequal length, each span should theoretically be tensioned according to its own length. However, this is not possible with suspension insulators since the insulator strings would swing so as to equalize the tension in each span. It is impractical to dead-end and erect each span separately. However, it is possible to assume a uniform tension between dead-end supports by defining an equivalent span, which is called a ruling span, and basing all the calculations on this equivalent span."

So $z=jX_L=j0.4348$ Ohms/mile, and
$y=1/-jX_C=1/-j(0.1127\times10^6)=j8.8731\times10^{-6}$ mhos/mile

The surge impedance is

$$Z_C = \sqrt{\frac{z}{y}} = \sqrt{\frac{\text{j.4379}}{\text{j}8.8731\times10^{-6}}} = 222.15\text{ohms}$$

Then the SIL is

$$P_{SIL} = \frac{V_{LL}^2}{Z_C} = \frac{\left(765\times10^3\right)^2}{222.15} = 2.6344\text{e}+009$$

So we see SIL decreased from 2805 MW to 2634 MW when we decreased the bundle diameter from 30” to 24”.

3.4 Other comments about HSIL

The ability to reduce phase distance GMD D_m and increase bundle GMR R_b and R_b^c are of course limited by the fact that we cannot allow the phases to overlap. In addition, there are other factors which limit the minimum D_m and maximum R_b and R_b^c. There factors include:

- Inter-phase & phase to ground insulation coordination
- Galloping
- Ruling Span (tension)
- Live-line maintenance (walkout clearance, working space under crossarm)
- Audible Noise (AN) and Radio frequency Interference (RI) at the edge of right of way

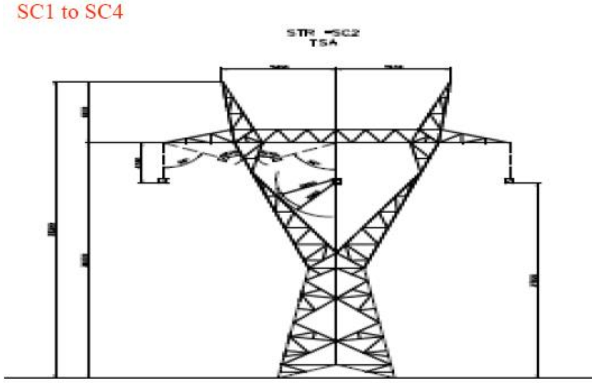
- Electric field at the surfaces of sub-conductors & Electromagnetic field effects at the edge of ROW
- Wind & snow loading clearance requirements
- Conservation of eco-sensitive Right-of-Way
- Overall transmission cost including capital, maintenance+operation costs

Below are some actual data based on a 500KV Single Circuit (SC) Design Requirement for a 330km (205 mile) circuit in Alberta [14]. Comments:

- "MMC" should be "MCM", which stands for "1000 cmils" where "cmil" is a unit of area of a circular conductor given by d^2 where d is the diameter of the conductor in mils, where 1 mil is 1/1000 of an inch).
- It is interesting to inspect the variation in SIL and in $/MW-Km for the different designs.
- The highest SIL occurs for designs SC11, 12, 13, because the phase separation is least (7 ft).
- It is unclear why SC15 has greater SIL than SC14, given SC15 has larger phase spacing than SC14.

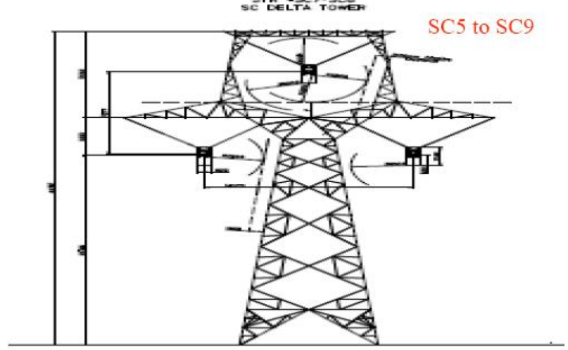
Tower designation	Tower Type	Phase spacing H[m]	Bundle Conductor MMC	# of bundle	SI Ω	SIL MW		Cost $/MW-Km	Live Line Maintenance
SC1	T I string	14.05	1590	3	274	912		931	Limited
SC2		14.05	1033	4	253	988		982	Limited
SC3		14.05	795	4	251	958		967	Yes
SC4		14.05	1033	4	253	988		929	Yes
SC5	Δ v string	14.3	1590	3	254	947		1015	Yes
SC6		14.3	1033	4	243	1029		989	Yes
SC7		14.3	1033	4	243	1029		1007	Yes
SC8		13.3	1033	4	239	1046		893	Yes
SC9		13.3	1033	4	241	1037		890	No
SC10	∇ V string	13.3	1590	4	227	1011		913	Yes
SC11		7	1272	3	202	1233			No
SC12		7	1033	4	208	1202			No
SC13		7	477	6	193	1296		938	No
SC14		7	1272	4	228	1096		978	No
SC15		14.4	1272	4	202	1233		903	No
SC16	T v	7	1033	4	248	1008		878	Limited
SC17	Tv&I string	12	1033	4	237	1056		903	Yes
SC18		10	1590	3	255	980		874	Yes

SC1 to SC4



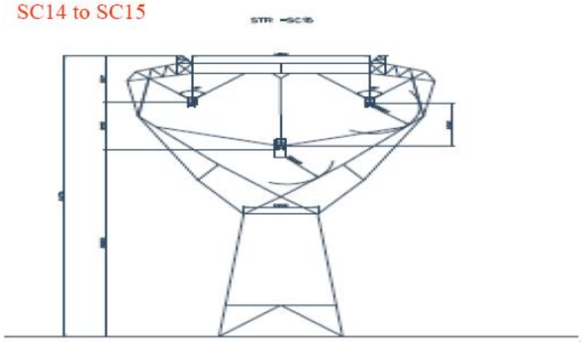
TSA - TOWER
SURGE IMPEDANCE -247Ω
(4-SDC-636)

SC5 to SC9



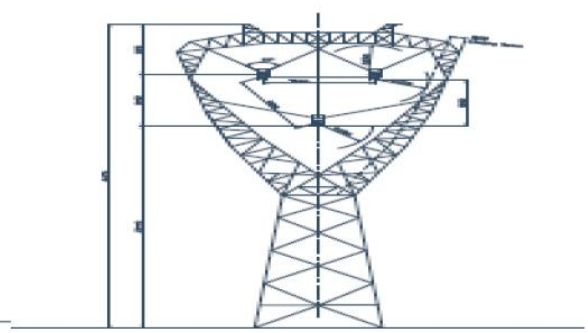
FULLY FUNCTIONAL
SURGE IMPEDANCE -243Ω
(4-ACSR-1033-CURLEW)

SC14 to SC15

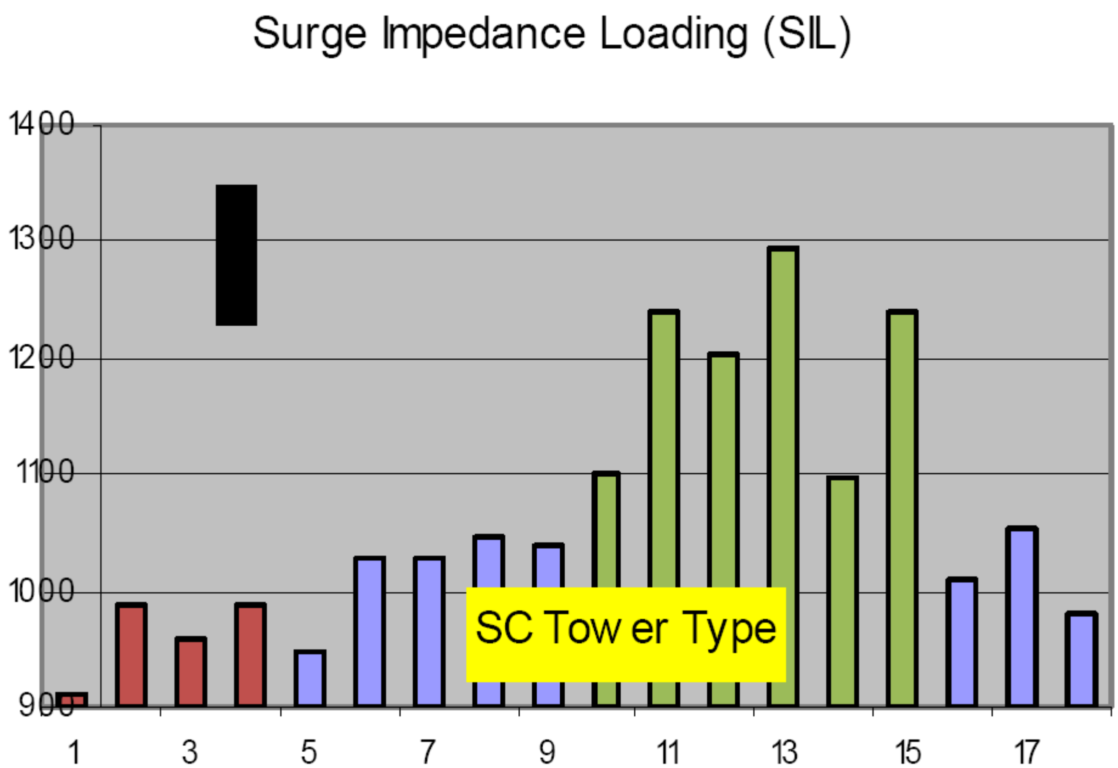


SURGE IMPEDANCE - 228 Ω
(4-ACSR-1272-PHEASANT)

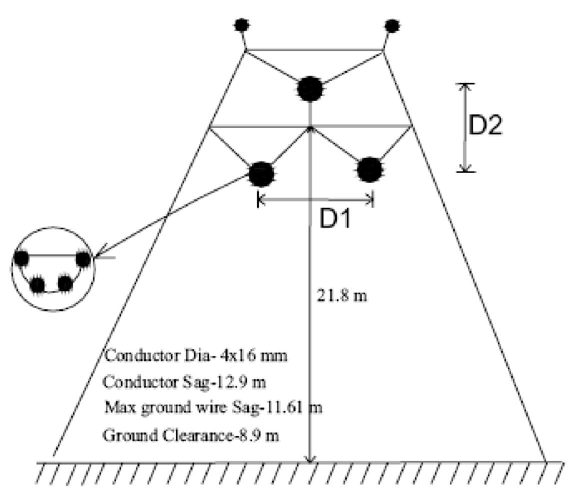
SC10 to SC13



NON-FUNCTIONAL
SURGE IMPEDANCE - 202 Ω
(4-ACSR-1272-PHEASANT)



A final comment here is that we have only discussed symmetrical bundles. There is some advantage to be gained from non-symmetrical bundles of the sort illustrated below [15].



The topic of HTLS conductors has additional issues of interest, including sag calculation, computation of conductor ampacity, and specifics of each HTLS technology. These are covered in Appendix B of J. Slegers MS thesis [16], which has been posted to the course website.

4.0 Compact line design

We observe in the previous section that making our phases as close together as possible, to minimize the geometric mean distance between phases, D_m, increases SIL. We also observed that increasing the GMRs of the bundles R_b and R_b^c, increases SIL.

To increase the GMRs of the bundles, however, we need to have bundles. If we only have a single conductor, we cannot use this approach. For high voltage distribution (34.5 kV) or lower voltage transmission (69 kV, 115 kV, 138 kV, 161 kV, and even 230 kV), it is often the case that the additional cost of bundling (additional conductors and other) cannot be economically justified because the additional power increase is not very much (note the increase in the 69 kV circuit in the table at the beginning of these notes is only from about 12 MW to about 40 MW).

Yet, the additional cost of decreasing phase distance may not be too high, requiring only redesigned conductor supports and new insulators. And so we may use an increased surge impedance line (ISIL), rather than HSIL, in such an application. Such a design is often referred to as a *compact line design*. Compact line designs are very attractive because they often require less right-of-way (ROW).

The below is from [8], "To determine the minimum allowed phase spacing for a transmission line, a number of variables need to be taken into consideration including:

- The permissible sag
- The phase to phase voltage
- Altitude above sea level
- Span length
- Wind levels
- Icing levels
- Insulator configuration
- Lightning surges
- Tension vs. sag towers
- Environmental issues
- Maintenance issues"

Table II NESC minimum conductor spacing for specific operating voltages at elevations under 1500 ft [12]

Voltage	Minimum Conductor Spacing*
500 kV	13.6 ft
345 kV	9.4 ft
230 kV	7.1 ft

*For higher elevations, add 3% spacing for every 1000 ft above 1500 ft

Note the asterisk in the above table which indicates that spacing needs to increase with higher elevation. This is because the air is less dense at higher elevations and as a result, is a poorer dielectric insulator.

It has been suggested that collection circuits for wind farms, which are typically 34.5 kV, can significantly benefit from using compact line design, because:

- It can be less expensive than going underground;
- Right of way is typically very important for farmland as farmers do not want to have to deal with overhead wires as they are using their farm equipment in the field;

- The increased SIL provides for increased turbine density per dollar expended for collection circuit (turbine density is also heavily, perhaps mostly, influenced by the need to avoid energy reduction from wake-related interference between turbines).

There can be other interesting situations, one of which is below, which illustrates a need to site transmission in a location that is highly constrained.

> Version "A" routing began at an existing steel terminal pole on the XXX-YYY No. 2 line. The line then traveled to a 90 deg wood pole and turned left to traverse the common fence between the two substations -- passing underneath three 230-kV transformer-bank feeders. Finally, it turned a 90 deg angle into Bay No. 3 to connect to the XXX substation 230-kV bus. The length of this route was 593 ft. This version required a compact 230-kV line design because of the limited clearance between the transformer-bank feeders and this proposed route. In addition, phase-to-ground clearances were critical.

EPRI publishes an excellent reference [17] on compact line design, which is free for EPRI members and $2375 otherwise. They usually provide reports to students for much less but not sure if they will do so here.

The topic of compact line design has additional issues of interest, including phase spacing and conductor motion, corona, audible noise, radio interference, and electromagnetic field issues. These are covered in App. C of J. Slegers' MS thesis [16], which has been posted to the course website here.

5.0 High phase order transmission

The first part of this section is adapted from [18].

Figure 4 below illustrate the voltage phasor relationships between line-to-neutral and line-to-line quantities associated with three-phase transmission and six-phase transmission, respectively.

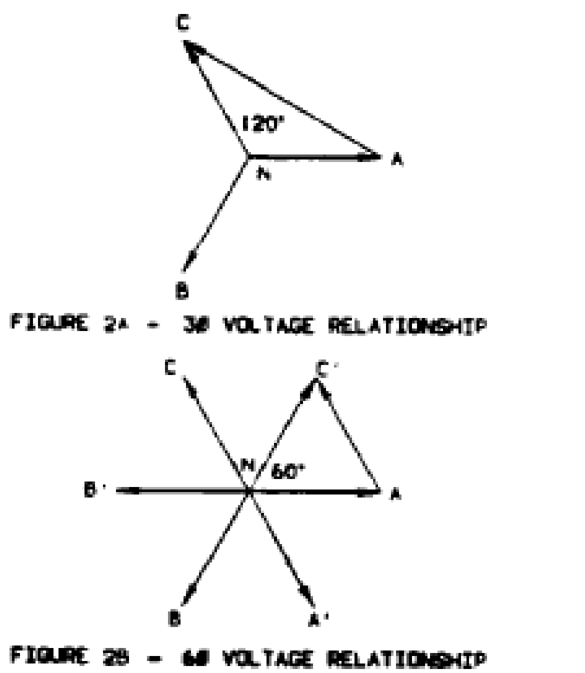


Fig. 4

Assume that the 3-phase system has a line-to-neutral voltage of V_{an}=66kV, which means it has a line-to-line voltage of $V_{AC}=\sqrt{3}(66kV)=115kV$, consistent with the top diagram of Fig. 4 which has a 120° phase separation, as is usual for 3-phase systems.

Now let's assume that we will utilize the same phase-to-neutral voltage level in the six-phase system. In this case, we observe from the lower diagram of Fig. 4 that the phase separation is 60 degrees, rather than 120 as in the three-phase system. Thus, the phasor relationships between line-to-neutral and line-to-line are such that $V_{AN}=V_{AC}$, implying that our phase-to-phase voltage will also be 66 kV as well.

What is the implication of this?
If we are limited on right-of-way, then we would like to bring the phases closer together. However, one limitation associated with doing so is that we must maintain a minimum separation between phases in order to avoid flashover. But the minimum separation depends on the voltage between the phases, i.e., the line-to-line voltage. Therefore, in applying six-phase transmission, we have reduced the line-to-line voltage by (115-66)/115=43%. This means that we can obtain the same per-phase power transfer capability,

$$P_{1,max}=V_{an}I_{max}$$

but utilize significantly less ROW (here it is assumed that the same conductor would be used for both three-phase and six-phase transmission and that the conductor ampacity is the limiting influence for power transfer capability).

Of course, the three-phase transmission would obtain $3P_{1,max}$ whereas the six-phase transmission would obtain $6P_{1,max}$, and so we get double the power transfer capability with the six-phase transmission. This is not so attractive as it may seem, since we are also utilizing twice the number of conductors and so the $/MW-mile may not be much different.

Figure 5 [19] illustrates the difference in possible tower designs for a 230 kV (V_{an}=133 kV) circuit and a three-phase circuit having V_{an}=80 kV, where I_{max} is the ampacity of any one conductor, so that in the two designs, the maximum power transfer is

$$P_{3\varphi}=3(133E3)(I_{max})=399E3\times I_{max}$$

$$P_{6\varphi}=3(80E3)(I_{max})=480E3\times I_{max}$$

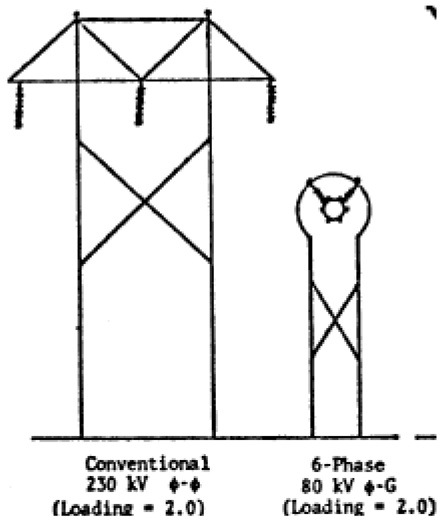


Fig. 5

In addition, because the geometry of the 6-phase circuit is more compact, we obtain a lower surge impedance and thus a higher SIL than we do for the 3-phase circuit.

We can also consider even higher order phase designs than 6. Although we will find that the ampacity increases directly with number of phases, the SIL does not, as indicated by Fig. 6 below.

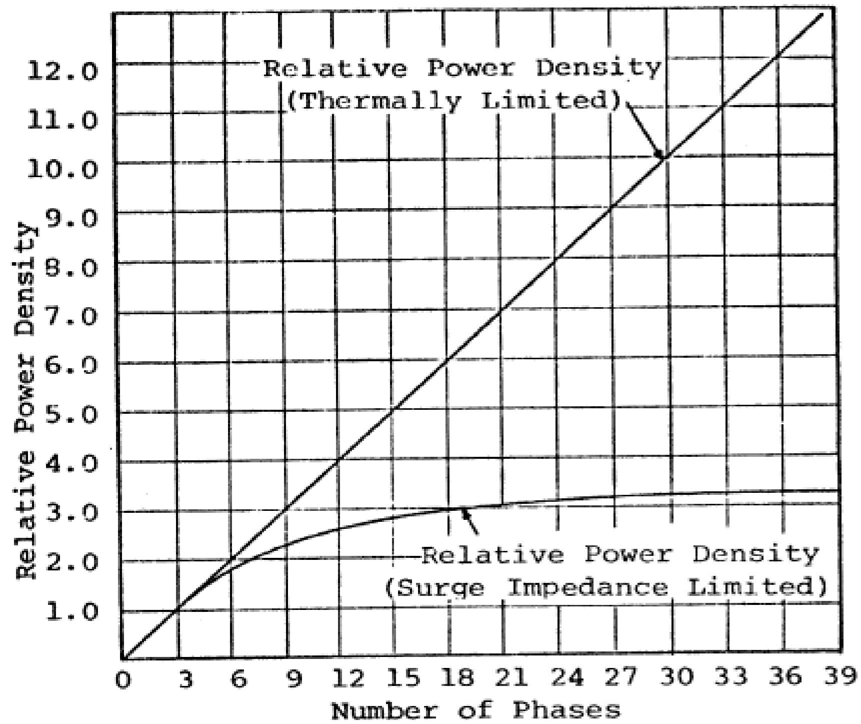


Fig. 6

The reason the surge impedance Z_C decreases with number of phases (and SIL increases) is because as the number of phases gets large, (i) the configuration more and more closely approximates a "circle," and there is less and less flux interior to the "circle," therefore less flux linking the conductors, reduced inductance, and reduced inductive reactance; (ii) distance between phases reduces, increased capacitance, and reduced capacitive reactance.

The reason this causes saturation (i.e., the surge impedance-limited curve, Fig. 6, falls off with number of phases) is because there is a limiting case of infinite phases which would configure a perfectly hollow conductor such that there is almost no flux in the interior, and capacitance reaches a maximum. This limiting case is nearly obtained at about 24 phases, after which we see very little reduction in surge impedance Z_C (and very little increase in SIL).

6.0 Compact HVDC

There has been some recent work on "Compact HVDC," as indicated in the below figure [20]. This technology is useful for converting an AC transmission line to an HVDC transmission line with much more capacity, but with no additional right-of-way requirements. I am not very familiar with it (yet) and simply refer you to [20].

7.0 Gas insulated transmission lines

Gas **i**nsulated transmission **l**ines (GIL) is of interest today because it provides the potential to achieve significant power transfer capability underground. There is a good book on the subject [21]. There are three main features to GIL:

- It uses a combination of sulfur-hexaflouride[4] (SF_6) and nitrogen (N_2) as the insulating medium, which gives it the ability to achieve much higher voltages within the relatively constrained space required of underground facilities. Actually, SF_6 is the insulating medium; N_2 is added in order to reduce the amount of SF_6 which is required to insulate a very long transmission circuit.

[4] SF_6 has been used in the electric power industry for many years but mainly in high voltage circuit breakers, high voltage transformers, distribution voltage switchgear, and gas insulated power substations. Its use in GIL has been relatively more recent. It should be noted that SF_6, although an excellent insulator (has a dielectric strength twice that of air), is a greenhouse gas.

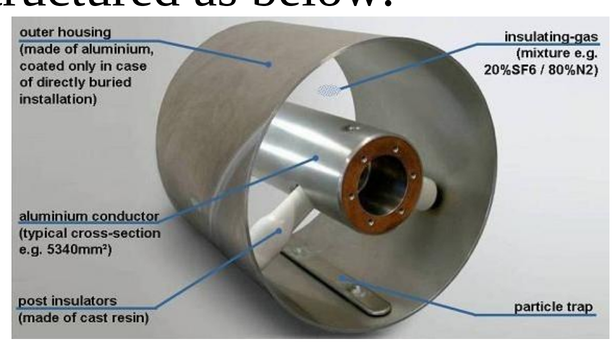
This distinguishes it from conventional underground transmission.

- Because it is underground, there is no need to be concerned for strength as is the case for overhead; therefore the conductor can be manufactured based purely on its conductivity properties (aluminum alloys are used). Relative to overhead lines, then, GIL is able to significantly diminish losses. These losses not only decrease production costs but in addition they decrease heating which is a significant issue for underground where there is no natural cooling available. The table below compares.

TABLE 1 COST OF LOSSES FOR OHL AND GIL (ENERGY COSTS: $.10/KWH X 8,600 H X 12,800 KW)

		OHL	GIL
Transmitted Power	mW	1400	1400
Losses per circuit meter	W/m	580	180
Losses per 32 circuit meters (20 miles)	mW	18.56	5.76
Difference between GIL and OHL	mW	12,800	
Cost of additional losses of the OHL per year (USD)		$10,908,000	

Each pipe is structured as below.



It can be directly buried underground as below.

Or it can be built in underground tunnels, as was done at the Geneva Airport in Switzerland. The capability of this double circuit GIL is 2250 MVA at 300 kV rated voltage.

Another double circuit GIL in Wehr (Germany) at 420 kV is shown below.

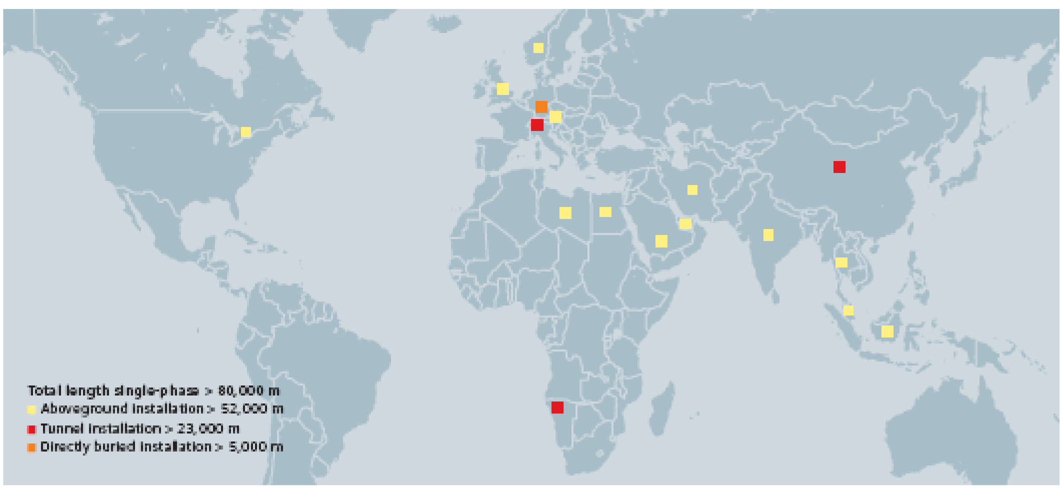
Below is a photograph of a GIL installation in Saudi Arabia.

Siemens advertises that it can manufacture GIL up to 800 kV having transmission capacity between 500 to 4000

MW. I have not yet been able to find cost data on this type of transmission, but it is clear that it is significantly more expensive than overhead transmission. Benefits accruing from the higher investment cost include the lower losses, lower capacitance (and therefor no line charging problem typical of underground AC), high MW transfer capacity, and high reliability. It can be particularly attractive where high reliability is needed, e.g., airports and nuclear plants.

There are various manufacturers of GIL, including Hitachi ABB, Siemens, GE, and others [22].

Below is an indication of where GIL has been deployed as of 2013.



A recent installation is described below [23].

Oct 17, 2013
Energy Sector / Power Transmission

Siemens completed the construction of a high-voltage gas-insulated transmission line (GIL) for China Three Gorges Project Corporation at the country's second largest hydropower plant "Xiluodu". It is located in the southwest of China on the Jinsha Jiang River at the Xiluodu dam. The project consisted of the installation of a total of seven three-pole systems, each with a length of 620 meters. **The single-tube tube length is 12.5 kilometers, making this the world's longest GIL.**

This system features a second world record – designed for a power capacity of 3900 megavolt ampere (MVA) at a voltage of 550 Kilovolt (kV) and a rated current of 4500 ampere (A), this is the world's highest-capacity connection using GIL.

In order to transport electricity from the dam to the population centers in the eastern part of the country, power must first travel from the turbines in the power plant cavern to the overhead transmission lines, a distance of about 460 meters. Seven three-pole GIL systems, which are inserted vertically in four shafts to the right and left of the dam, each transmit 3900 MVA of power safely and efficiently to the overhead power lines.

Using a GIL instead of a high-voltage cable has the added advantage of its special design that eliminates any risk of fire. GIL tubes are not flammable. In the event of a malfunction, they do not represent a fire load and thus pose no hazard to operating personnel. The tunnel of the insulated high-voltage lines can also be used as ventilation and service shafts for personnel. Optimal values for electromagnetic compatibility, increased earthquake resistance, a leak-proof design due to welding style, and the fact that GIL's do not age, round out the system's broad benefits. Additionally, the GIL tubes are welded over their entire length. This not only increases operational reliability but also gives the GIL tube flexibility, so it can adapt to any changes in the tunnel wall that occur over time.

The welding of the GIL's aluminum tubes is an innovative high-tech process that requires clean-room conditions. The latest welding and ultrasound methods ensured the required quality was achieved, and allowed rapid installation of the gas-insulated lines.

The individual GIL modules, each of which is about 11.5 meters long, were welded directly to each other in a vertical position inside the installation shafts, and then pushed upward, section by section, in the tunnel. Various branch-offs and horizontal sections extend the overall length of the individual three-phase systems to 620 meters.

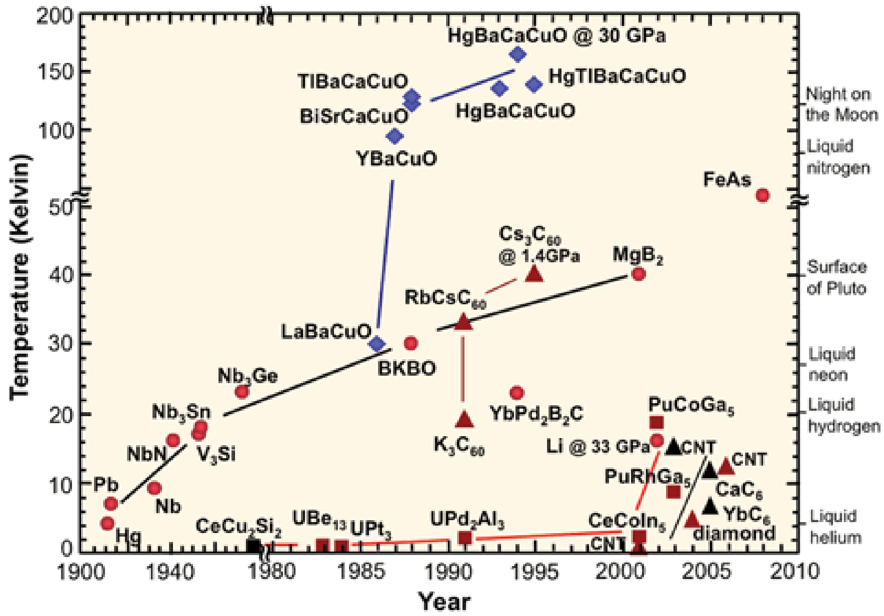
"In the Xiluodu project, we completed the world's longest vertical GIL installation," says project manager Mathias Schreiber, Siemens Energy. "This is also the first time technical figures such as 550 kilovolts of operating voltage and 3900 MVA transmission power per system have been involved. We're proud that we completed this massive project in such a short time under complex installation conditions at the job site."

After the first of the seven GIL systems passed high-voltage testing in March 2013, three more systems were commissioned in July. As a result, the China Three Gorges Corporation, both a utility company and the power plant operator, was able for the first time to send hydro-generated electricity to a distant consumer location and sell it there. The final two GIL systems were completed in September 2013.

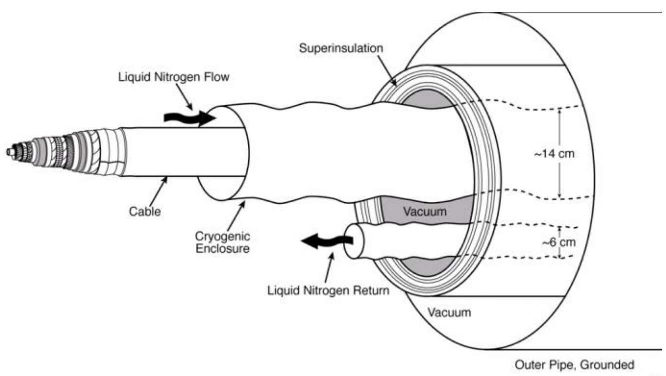
8.0 Superconducting transmission

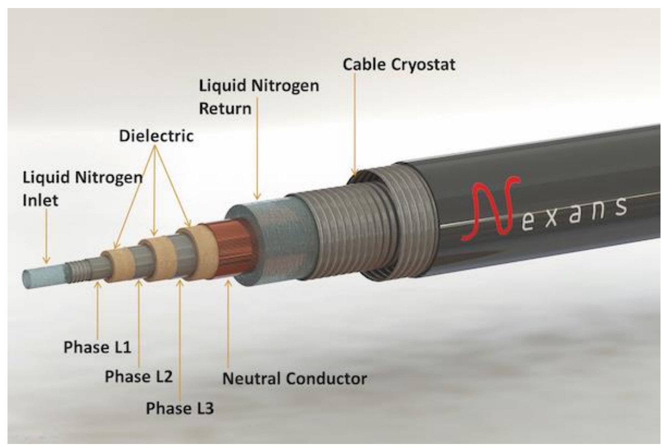
Some of this material is adapted from [24]. Superconductors are materials that exhibit zero resistance to DC and extremely high current densities when operating at very low temperatures. The earliest superconducting materials discovered required cooling to almost 0 degrees Kelvin. A very high-level history is as follows:

1911: "Superconductivity" discovered where certain materials, if cooled to 0°K (-273°C), have 0 resistance.
1986: "High-temperature superconductivity" discovered where a ceramic, copper oxide material superconducted at approximately 40°K. In 1986, a ceramic "high temperature" superconductor (HTS) material was discovered that required cooling to only about 90°K, something that can be done with liquid nitrogen. Additional materials have been identified since then, below.



This was the beginning of development of the “superconducting pipe” as illustrated in the two figures below.



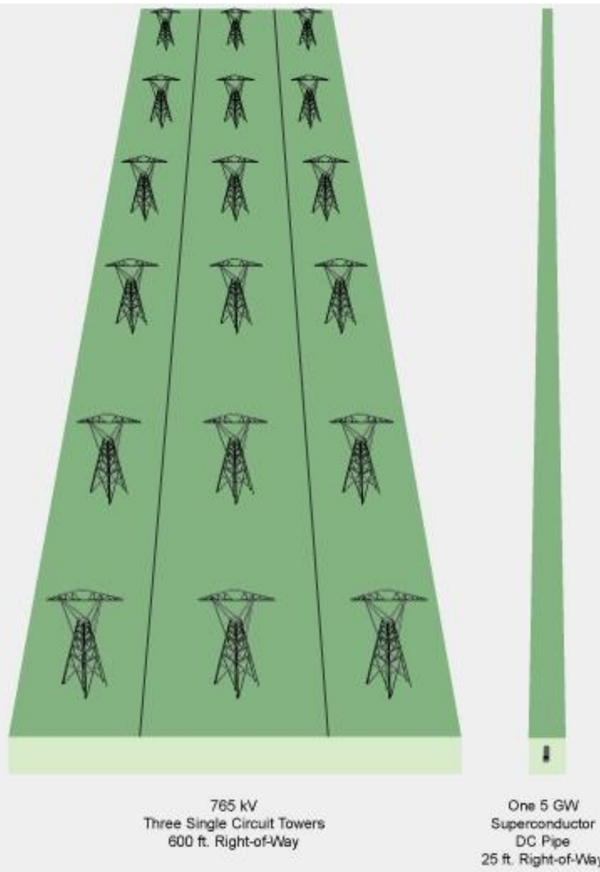


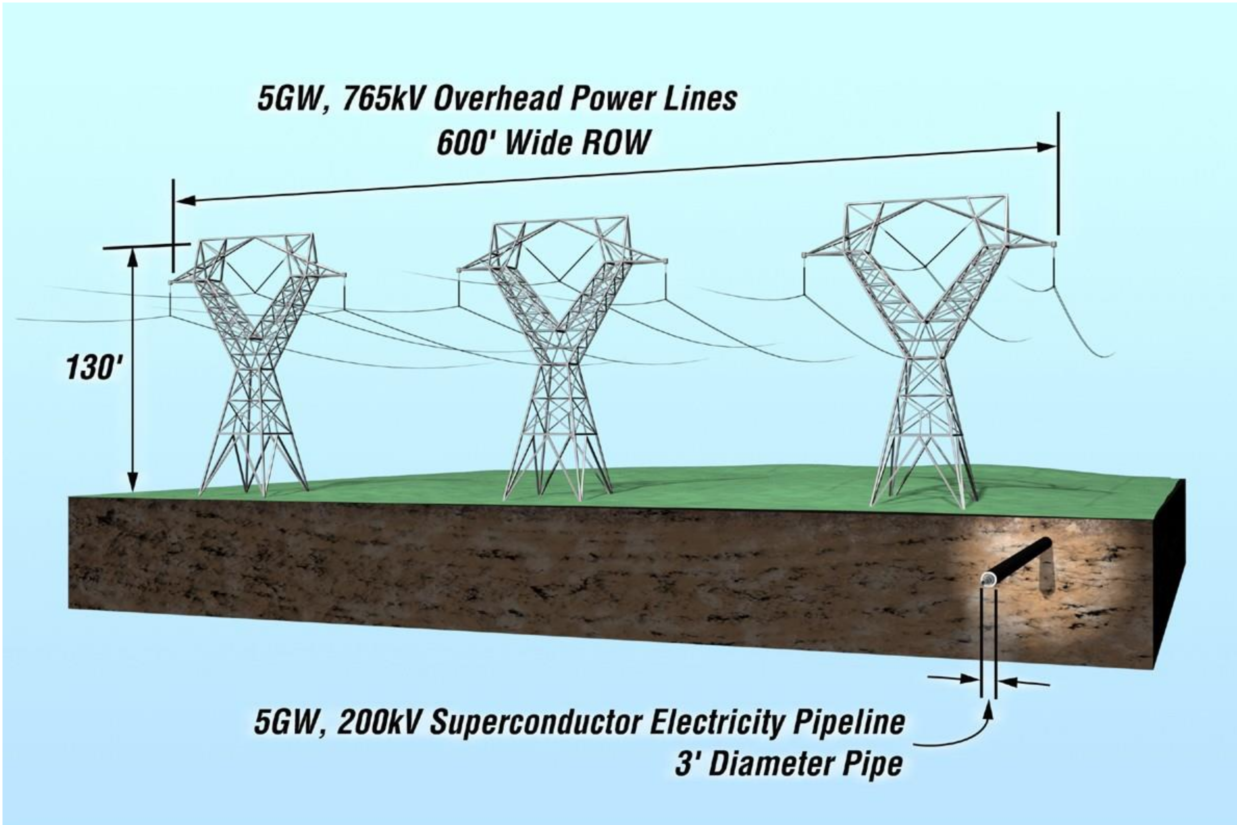
Although superconducting transmission does not incur “joule” (I^2R) losses, they do require a pumping system for the nitrogen. This pumping system requires some energy which can be considered to be losses. A disadvantage of superconductors is that these losses are always incurred, even at no-load. An important advantage of superconductors is that that the losses do not increase with power transfer (MW), as do losses for standard electric transmission.

Some interesting benefits of this technology, when used as a 200 kV DC "superconducting pipeline" are summarized in the figures below.

	Metric	DC Superconductor Cable	765 kV Transmission Lines
Performance	Efficiency [1]	3%	9-14%
	Storm/Security Risk	Low	High
	Precise Control for Efficient Markets	Yes	No
	Cost Allocation Method	Easy	Difficult
	Requires Rebuild of Underlying Grid	No	Yes
	"Black Start" Capability	Yes	No
Siting	Right of Way	25 ft wide	600 ft wide
	Aesthetics	Good	Bad
	Electromagnetic Field	None	High
	New Land Required	No	Yes
Cost	Efficiency Savings [2]	$230 million/yr.	n/a
	CO2 Emission Savings	3 million tons/yr.	n/a
	Cost Per Mile [3]	$8M for 5 GW pipe $13M for 2 pipes	$9-10M/mile minimum

1 Cooling & converters for cable; line & substation losses for 765 kV
2 Based on $0.065/kW-hr
3 $14M/mile superconductor costs based on fully redundant cable system; 765 kV figure based on Midwest ISO and does not include likely cost of upgrading underlying infrastructure





Type of Transmission Line	345kV AC	500kV AC	765kV AC	800kV DC	Superconductor Electricity Pipeline
Right of Way Requirement	1350'	1000'	600'	270'	25'

SUITABLE TRANSMISSION SOLUTIONS

TRANSMISSION LINE POWER AND DISTANCE REQUIREMENTS		Overhead Solutions: AC	Overhead Solutions: Point-to-Point HVDC	Overhead Solutions: Multi-terminal VSC HVDC	Underground Solutions: AC	Underground Solutions: Point-to-Point HVDC	Underground Solutions: Multi-terminal VSC HVDC	Underground Solutions: Multi-Terminal Superconductor Pipeline
Low Power (<1GW)	Short (<100 mile) lines	✓		✓	✓	✓	✓	
Low Power (<1GW)	Moderate (100-400 mile) lines	✓	✓	✓		✓	✓	
Low Power (<1GW)	Long (>400 mile) lines	✓	✓					
Moderate Power (1-5GW)	Short (<100 mile) lines	✓						
Moderate Power (1-5GW)	Moderate (100-400 mile) lines	✓	✓	✓		✓	✓	
Moderate Power (1-5GW)	Long (>400 mile) lines		✓			✓		✓
High Power (>5GW)	Short (<100 mile) lines	✓						
High Power (>5GW)	Moderate (100-400 mile) lines		✓					✓
High Power (>5GW)	Long (>400 mile) lines		✓					✓

Unique fit of Superconductor Electricity Pipelines for Long Distance, High Power, Multi-terminal transmission

Below is a cost comparison between a 1000-mile superconducting DC underground system and an EHV AC system.

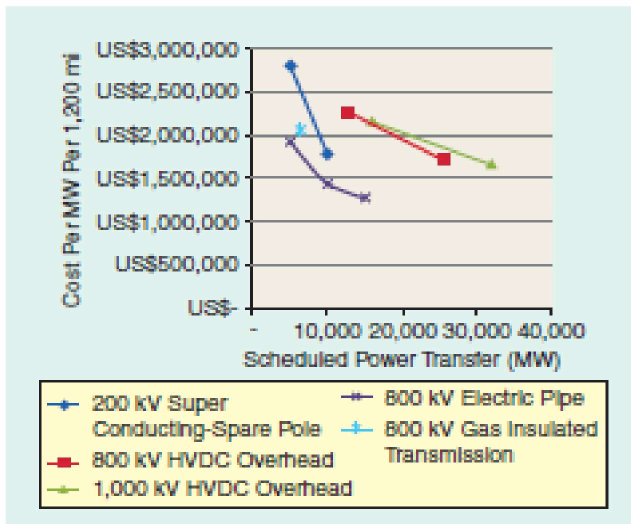
- 5GW, 1000mile (1609km) Superconductor DC Cable System
  - US$8 Million/mile
  - US$13 Million/mile fully redundant
  - Costs include DC terminals, refrigeration, installation
  - Doubling capacity to 10GW line increases cost by 1/3
- Cost Competitive with EHV AC
  - US$3.2 - $5.5 Million/mile
  - 3 lines needed for same capacity

Below are some cost-comparisons made by several US ISOs. Although the costs were given in 2024 dollars, the estimates were made in 2013.

TABLE 4-3. COST PER MILE ASSUMPTION (US $2024, MILLIONS)

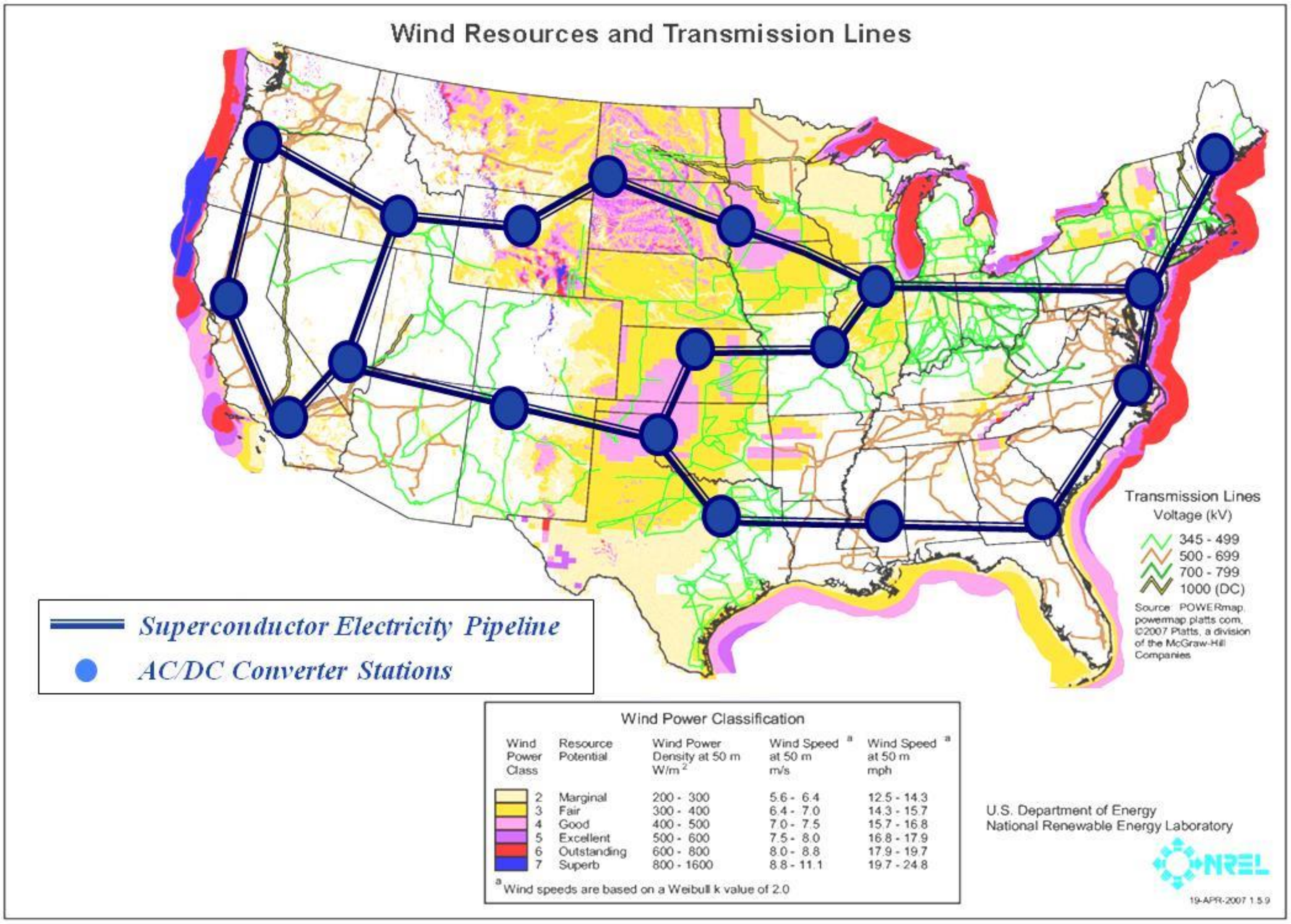
REGION	345 kV	345 kV AC (double circuit)	500 kV	500 kV AC (double circuit)	765 kV	400 kV DC	800 kV DC
MISO	3.2	3.9	5.6	9.4	7.1	3.8	6.0
SPP	1.9	3.2	3.0	4.3	4.5	3.8	6.0
PJM	7.2	12.0	9.2	15.4	16.0	3.8	6.0
ISO-NE/ NYISO	5.5	9.1	7.0	11.7	16.0	3.8	6.0

The Midwest Independent Transmission System Operator (MISO) has investigated relative costs for various HVDC options. Representative results are shown below [25]. Each point in this figure indicates, for a specific HVDC transmission technology, the cost per MW necessary to build 1200 miles of transmission to obtain the corresponding power transfer given by the point's horizontal coordinate.



Cost/MW per 1200 miles for various HVDC options

A superconducting macrogrid system was proposed for the US, as shown below.



There was a project proposed in 2010 to connect the three US interconnections, called the Tres Amigas Superstation Project, which would utilize superconducting pipes, as shown below. The indication of a 2016 completion date was not met; indeed, the project is now defunct.

Tres Amigas president: Completion date still 2016

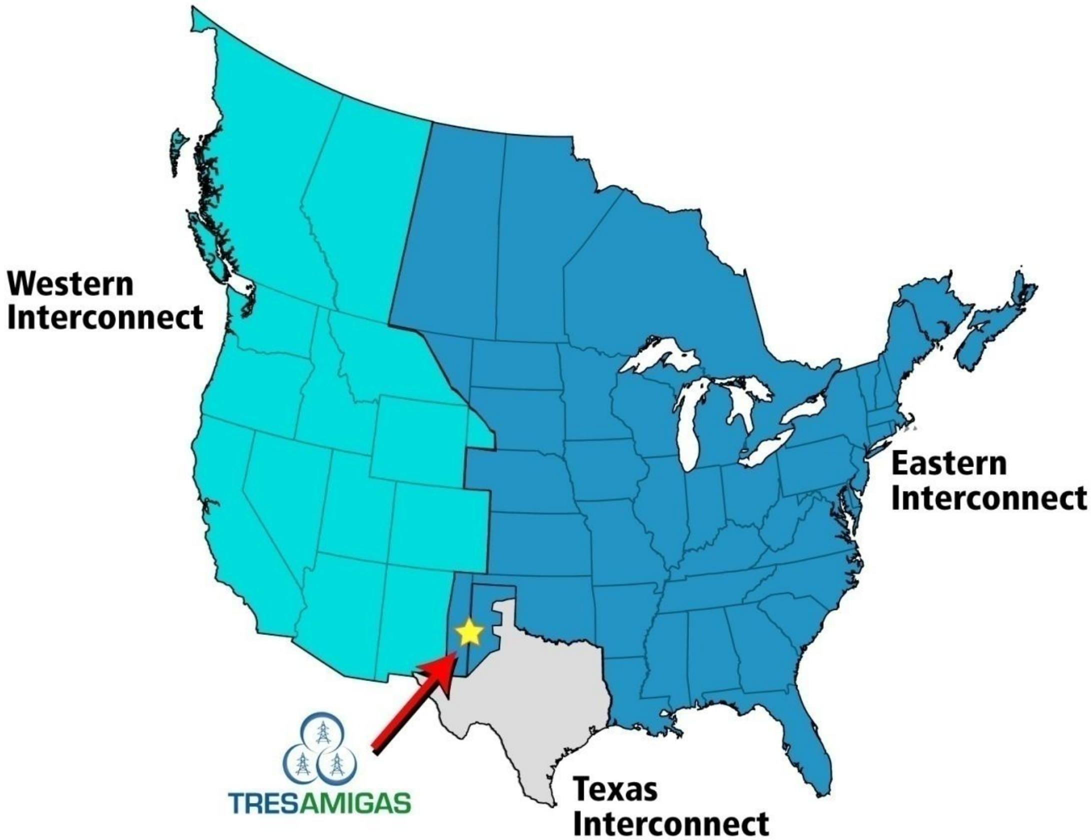
October 15, 2013

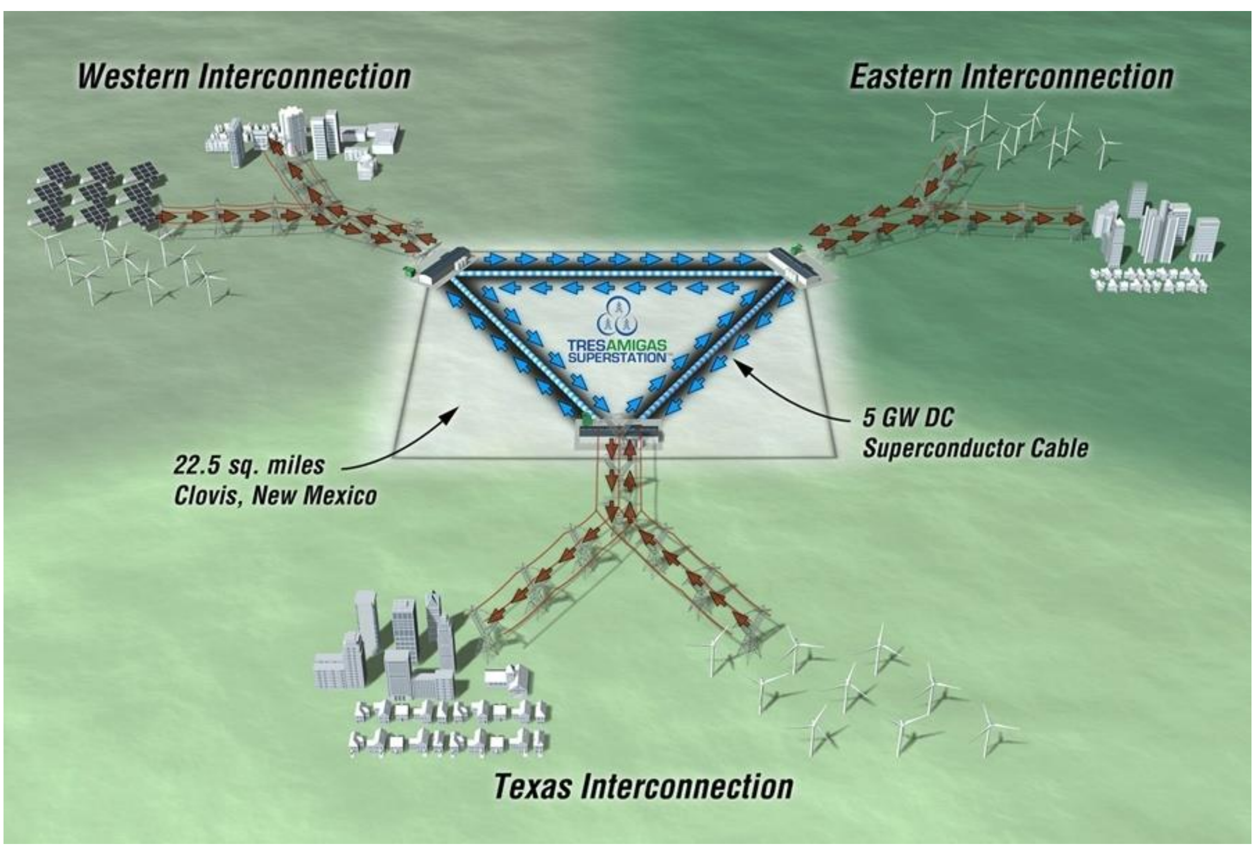
By Alisa Boswell

CMI staff writer

aboswell@pntonline.com

The president of Tres Amigas told Pure Energy Expo attendees Tuesday that although the project's groundbreaking date was moved back numerous times, the company has made great strides with the project in 2013.…


Western
Interconnect
Eastern
Interconnect
Texas
Interconnect
TRESAMIGAS


Western Interconnection
Eastern Interconnection
TRESAMIGAS SUPERSTATION
5 GW DC
Superconductor Cable
22.5 sq. miles
Clovis, New Mexico
Texas Interconnection

9.0 Other forms of bulk energy transportation

There are four other forms of bulk energy transportation available today that should be considered when designing very high-capacity infrastructure that can be considered national in scope. We mention them here but only provide brief comments about them. They are

- Natural gas pipelines
- Rail and barge (mainly for coal)
- Hydrogen
- NH_3
- Agricultural commodities

8.1 Natural gas pipelines

There has recently been and a significant increase in natural gas infrastructure investment. This is caused by an increase in economically attractive US natural gas supply and its downward pressure on natural gas prices, the lower carbon content per unit energy (relative to coal), the relatively high efficiencies of natural gas combined cycle units, the need for increased regulating and ramping reserves via combustion turbines (motivated by growing penetrations of variable generation), the pressure to retire coal plants, and the continued dependence on natural gas for supply for heating needs. At the same time, there has been large renewable growth, particularly wind, with its need for electric transmission given the most favorable wind resources are generally far from load centers.

The information below roughly compares electric transmission investment cost to gas transmission investment cost, resulting in

- a "pre-combustion" comparison of \$101.4/(mmbtu/hr×mile) for gas to \$139.0/(mmbtu/hr×mile) for electric, or
- a "post-combustion" comparison of \$730,000/GW-mile for gas to \$1,000,000/GW-mile for electric.

PIPELINES INVESTMENT COST

NATURAL GAS CHARACTERISTICS	
Energy Content (MMBTU/MMcf)	1,027

PIPELINE CHARACTERISTICS	
Diameter (inch)	42
Transmission Capacity (MMcf/day)	1,800.0
Transmission Capacity (MMcf/hour)	75.00

COMPRESSOR STATION CHARACTERISTICS	
Distance between stations (miles)	50
Power (HP per station)	25,000

PIPELINE INVESTMENT COSTS	
Pipeline Investment Cost (*) (\$ per inch - mile)	155,000
Pipeline Investment Cost (\$ per mile)	6,510,000

This is high.

COMPRESSOR STATION COSTS	
Compressor Station Inv. Cost (*) (\$ per HP)	2,600
Compressor Station Inv. Cost (\$ per mile)	1,300,000

(*) Source: North America Midstream Infrastructure through 2035: Capitalizing on Our Energy Abundance. The INGAA Foundation. March 18, 2014

$$6{,}510{,}000\,\$/mile + \$1{,}300{,}000\,\$/mile = \$7{,}810{,}000\,\$/mile$$

$$\frac{7{,}810{,}000\,\$/mile}{75\,mmcf\ /hr} = 104{,}133\,\$/(mmcf\ /hr \times mile)$$

$$\frac{104{,}133\,\$/mmcf\ /hr \times mile)}{1027\ mmbtu\ /mmcf} = 101.4\,\$/(mmbtu\ /hr \times mile)$$

PIPELINE SYSTEM INVESTMENT COSTS	
Pipeline System Investment Cost (\$ per mile)	7,810,000
Pipeline System Investment Cost (\$ per (MMcf/hr x mile))	104,133
Pipeline System Investment Cost (\$ per (MMBTU/hr x mile))	101.40

TRANSMISSION LINES INVESTMENT COST

CONVENTIONAL COMBINED CYCLE PLANT CHARACTERISTICS	
Heat Rate (MMBTU/GWh)	7,196

This calculation provides a "pre-combustion" value to enable comparability with natural gas, i.e., flow on transmission lines is energy after conversion losses, whereas flow on gas pipelines is energy before conversion losses.

$$\frac{1{,}000{,}000\,\$/GWmile}{7196\ MMBTU\ /GWhr} = 139.0\,mmbtu\ /hr \times mile$$

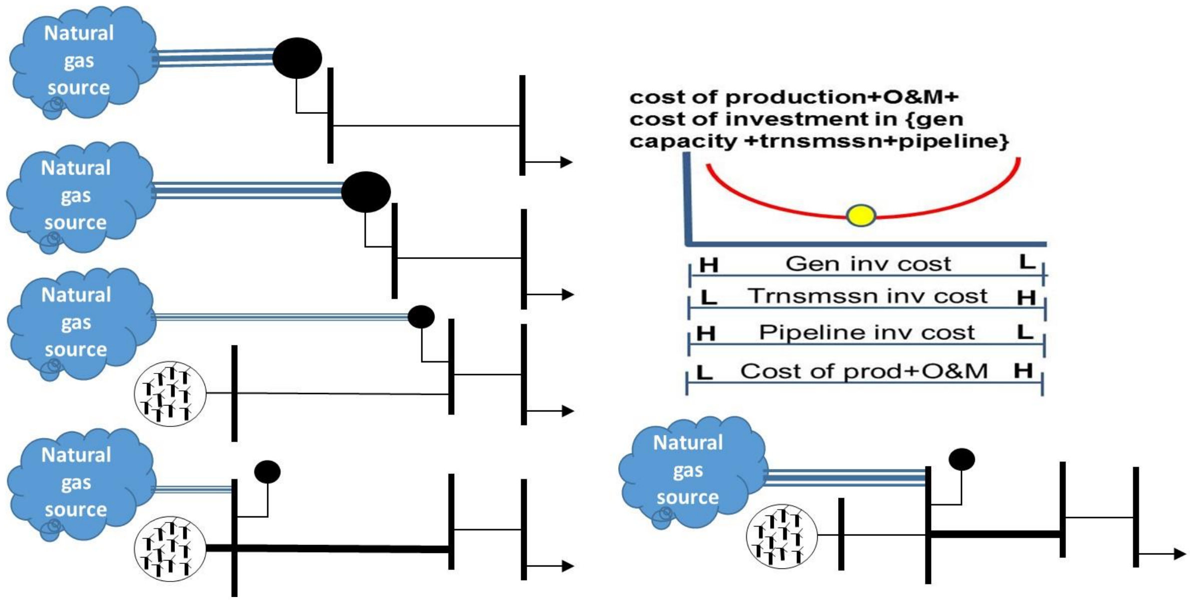
TRANSMISSION LINE INVESTMENT COSTS	
Transmission Line Investment Cost (\$ per GW - mile)	1,000,000
Transmission Line Investment Cost (\$ per (MMBTU/h x mile))	139.0

This is low. Could be \$1.5M/gw-m

You can also obtain "post-combustion" values: 101.4*7196=730,000\$/GW-mile

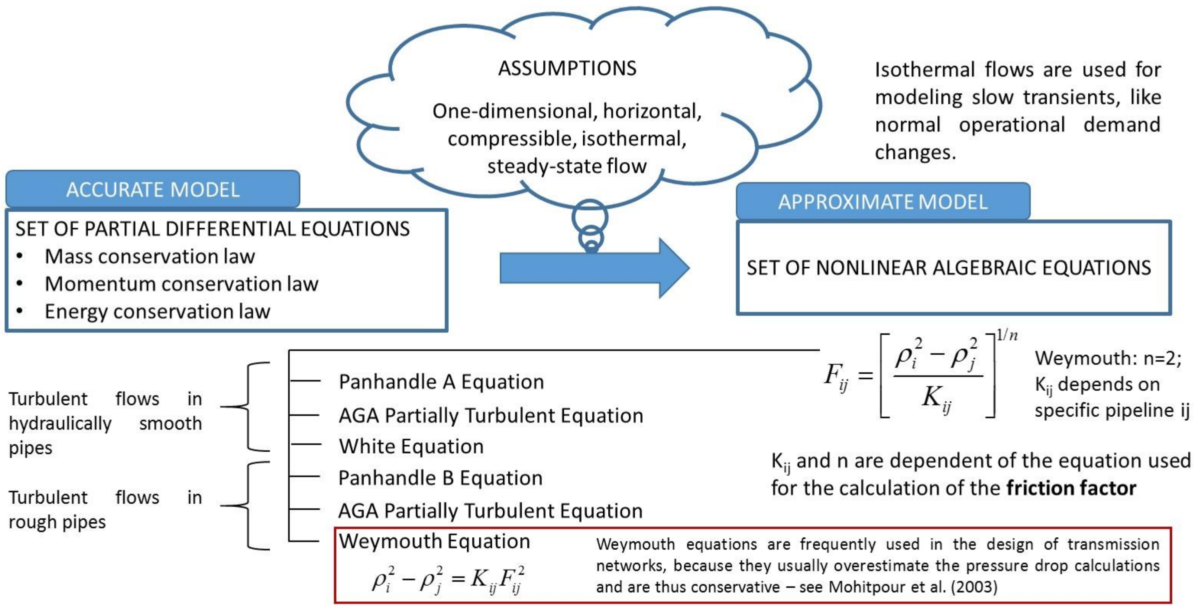
Similar analysis, but of a specific case, done by BPA and AGA, is here:
www.northwestchptap.org/NwChpDocs/Transmission_and_N_Gas_Comparing_Pipes_and_Wires_032304.pdf

The significance of trading off gas transmission against electric transmission is illustrated in the figure below.



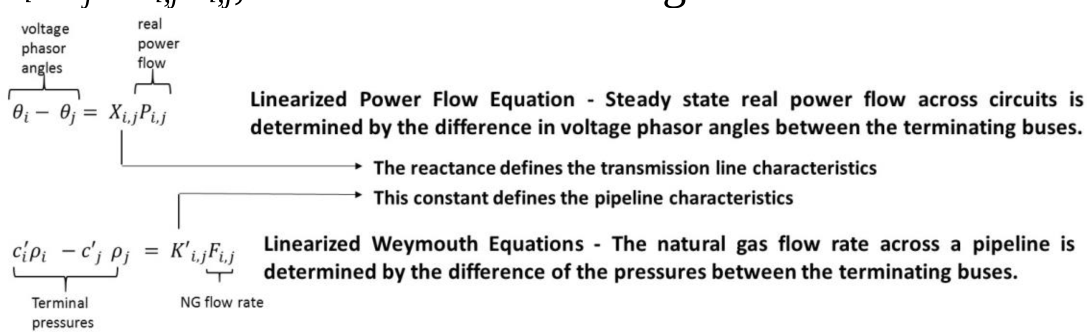
So how to co-optimize gas transmission, electric transmission, and natural gas-fueled generation? We make some comments in response to this question, but these comments should be considered in the context of the EE 552 notes on TEP and CEP. A good paper addressing this co-optimization problem is [26].

The Weymouth equations, under some assumptions, describe the physical laws governing gas flow in a pipeline. These equations are given by $\rho_i^2 - \rho_j^2 = K_{i,j}F_{i,j}^2$ where ρ_i and ρ_j are the pressures at stations i and j, respectively, $F_{i,j}$ is the gas flow between those stations, and $K_{i,j}$ is the friction factor. The figure below illustrates the basis for the Weymouth equations.



One approach to including these equations in gas/electric co-optimization is to linearize them, resulting in
$c'_i\rho_i - c'_j\rho_j = K'_{i,j}F_{i,j}$.

This equation has the same form as the linearized power flow equations of the electric system, which is given by
$\theta_i - \theta_j = X_{i,j}P_{i,j}$, as illustrated in the figure below.



Thus, we may deploy disjunctive representation to them, and effectively solve the co-optimized gas/electric problem as a linear mixed integer programming model, just as we do when using the disjunctive representation of electric transmission. We have tried this but found that, whereas the linearized power flow equations are relatively accurate for real power (MW) flows, the linearized gas flow equations are quite sensitive to operating conditions through parameters c'_i and c'_j. Therefore, ways to represent gas flows more accurately are of interest. One way is to represent each gas pipeline with a piecewise linear model, and iterate using successive linearizations.

8.2 Rail and barge

Rail and barge provide energy transport for two forms of energy: coal and agricultural commodities.

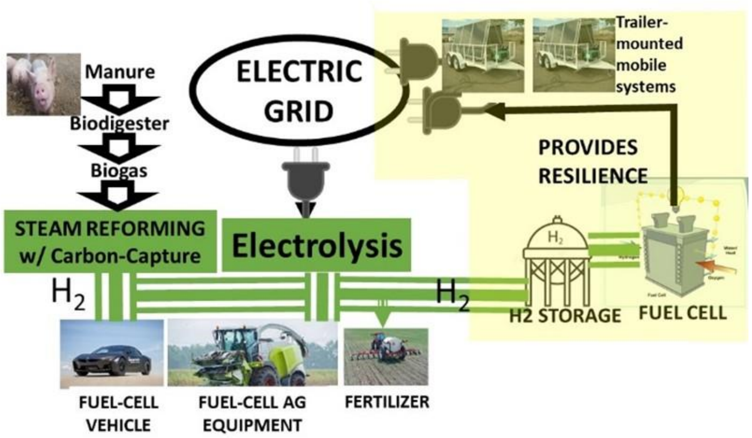
8.3 Hydrogen

Both hydrogen and anhydrous ammonia are combustible and therefore can drive an internal combustion engine. In addition, both can supply a fuel cell. Neither one produces greenhouse gas.

There are three basic problems with hydrogen.

- It is highly reactive and therefore poses some safety concerns
- It must be stored at a low temperature and high pressure to maintain reasonable volumes.
- Its production requires energy, and so, by conservation of energy, hydrogen production must result in a net loss. Furthermore, if the energy used to produce hydrogen is derived from a CO_2-emitting process, then there is no overall environmental benefit.

There are two basic ways to produce H_2: steam reforming and electrolysis, both of which are illustrated in the figure below where manure is used in a biodigester to create biogas (methane) which is then converted to H_2 using steam reforming. In steam reforming, high-pressure/high-temperature steam is generated from water, and combined with biogas to create produce H_2 and CO. In electrolysis, an electric current splits water into H_2 & O. The resulting H_2 can be transported or stored and/or used in various applications.



8.4 Ammonia

Anhydrous ammonia (NH_3) is perhaps more attractive than hydrogen because it is less reactive and does not incur the same storage problems. Some are today proclaiming NH_3 as a better alternative to hydrogen. Of course, production of NH_3 also requires energy. One approach to appropriate use of hydrogen or NH_3, then, is to use energy that would otherwise go unused in its production, i.e., convert wind or solar to hydrogen or NH_3, a sort of storage mechanism, and then use the hydrogen or NH_3 to produce electricity through a fuel cell when that electricity is needed.

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