Cable Train: In-Situ Manufacturing of Trackside Underground Cable HVDC Transmission Systems

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HVDC in a Renewable Future

- Ideal for connecting to remote renewables → cost of converters offset by eliminating capacitive, inductive, skin effect, dielectric charging losses
- Connection of asynchronous AC grids
- Less materials and less ROW required compared to equivalent AC systems
- VSC more robust to geomagnetically induced current (GIC)
- In 2016, a study by NOAA scientists found that a large-scale, optimized HVDC grid could enable the U.S. to use wind and solar generation to eliminate up to 80% of CO2 emissions while meeting its energy needs at the same cost of electricity as in 2012 [6].

- How can we build these HVDC lines faster and cheaper!?

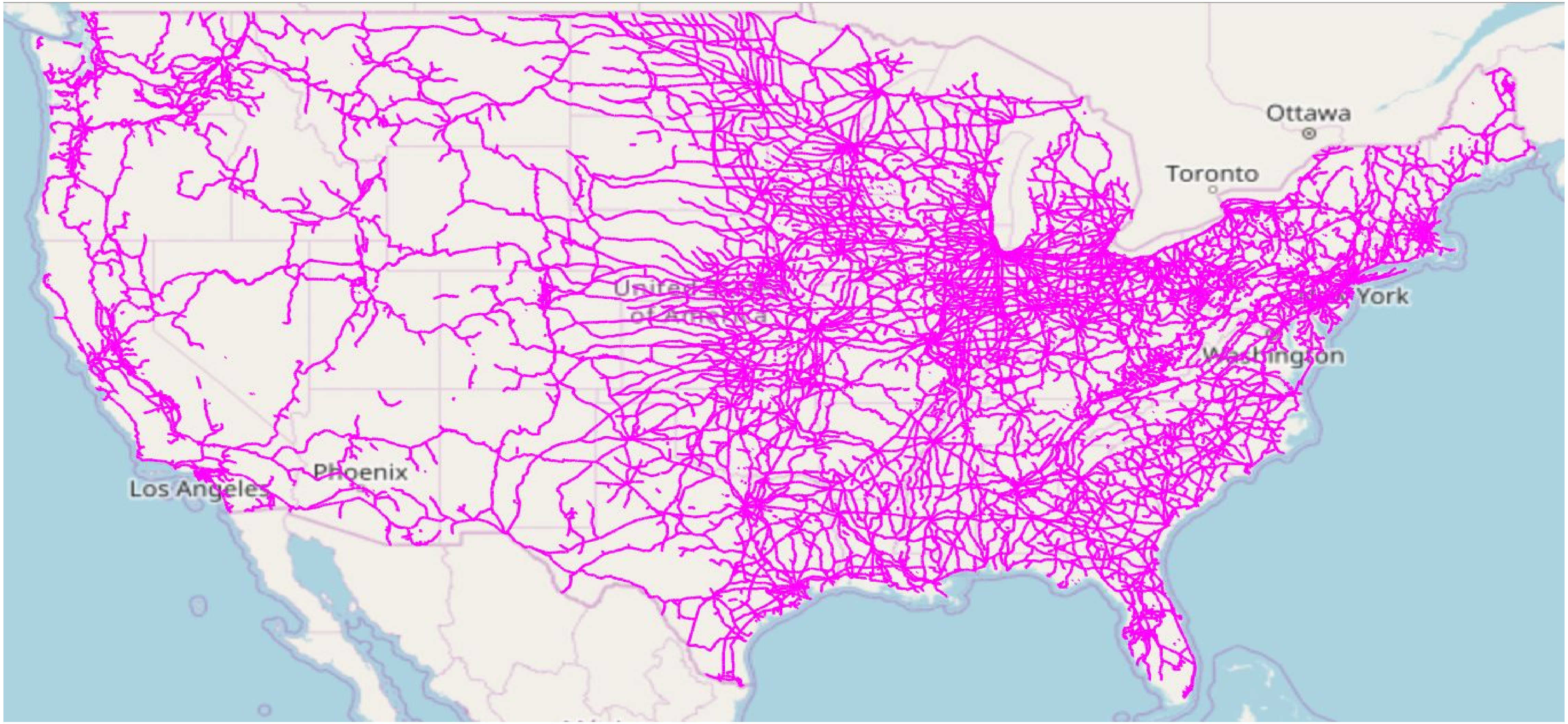
Limitations in overland HVDC construction

- Much of the best wind and solar resources in the U.S. are landlocked
- Overhead lines (OHL) are traditionally used because they are several times cheaper than underground cable (UGC)

$$\text{Cost(UGC)/Cost(OHL)} = 4 \rightarrow 14$$

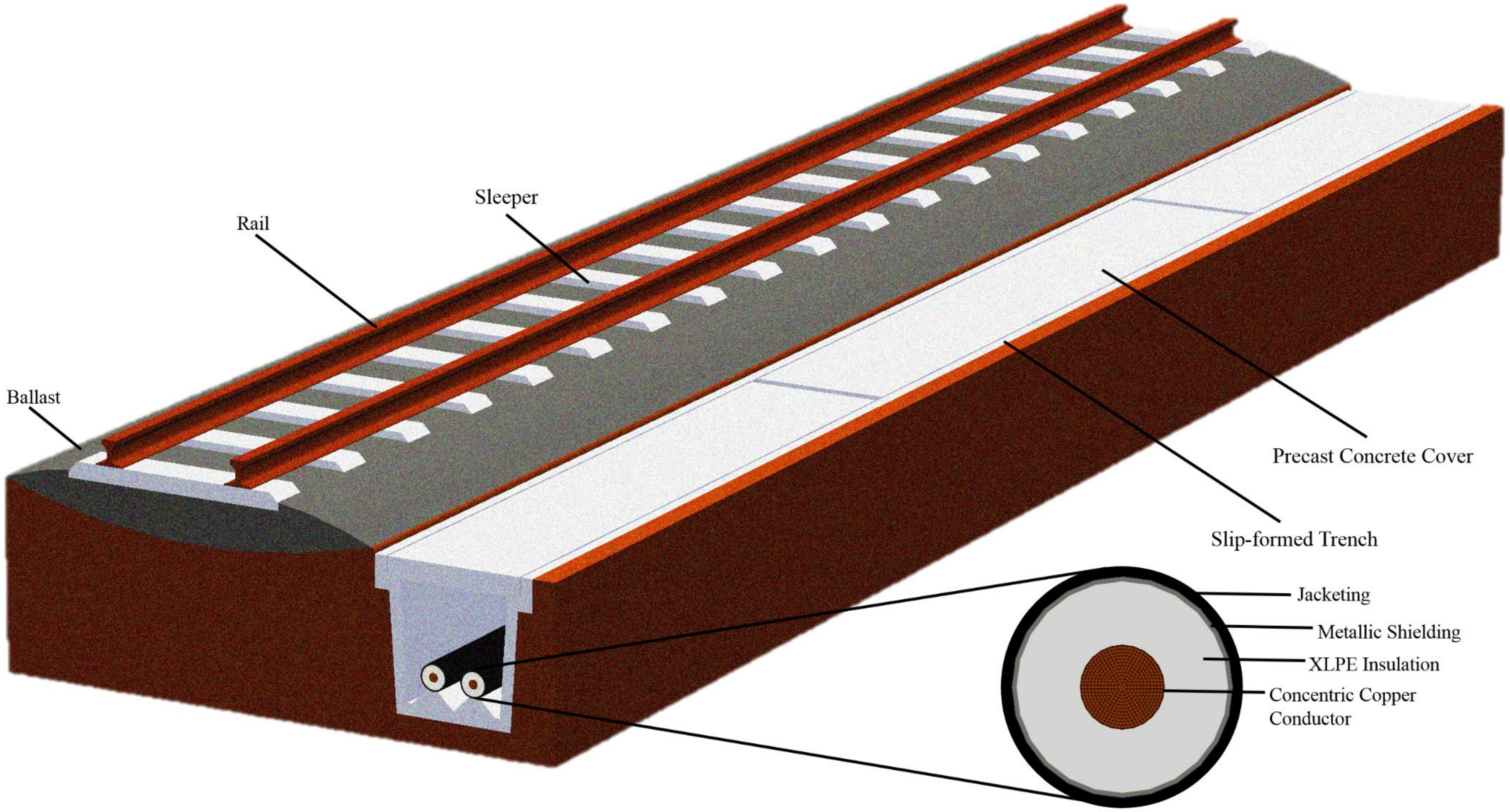
- However, external stakeholders have stopped OHL HVDC projects in their tracks…
  - Visual pollution
  - External Magnetic Fields (EMF)
- UGC is invisible, electromagnetically shielded, low loss, less vulnerable to damage, etc.
- What's more expensive: building a UGC system in 3 years or building an OHL system in 10+ years?
- Can we make Cost(UGC)/Cost(OHL) → 1?

Co-location on railroads



"Trackside UGC"

- Why not "trackside OHL"?
  - ROW
  - Structures hazardous
  - EMF not compatible with other services
  - Pylons potential obstacles to future development



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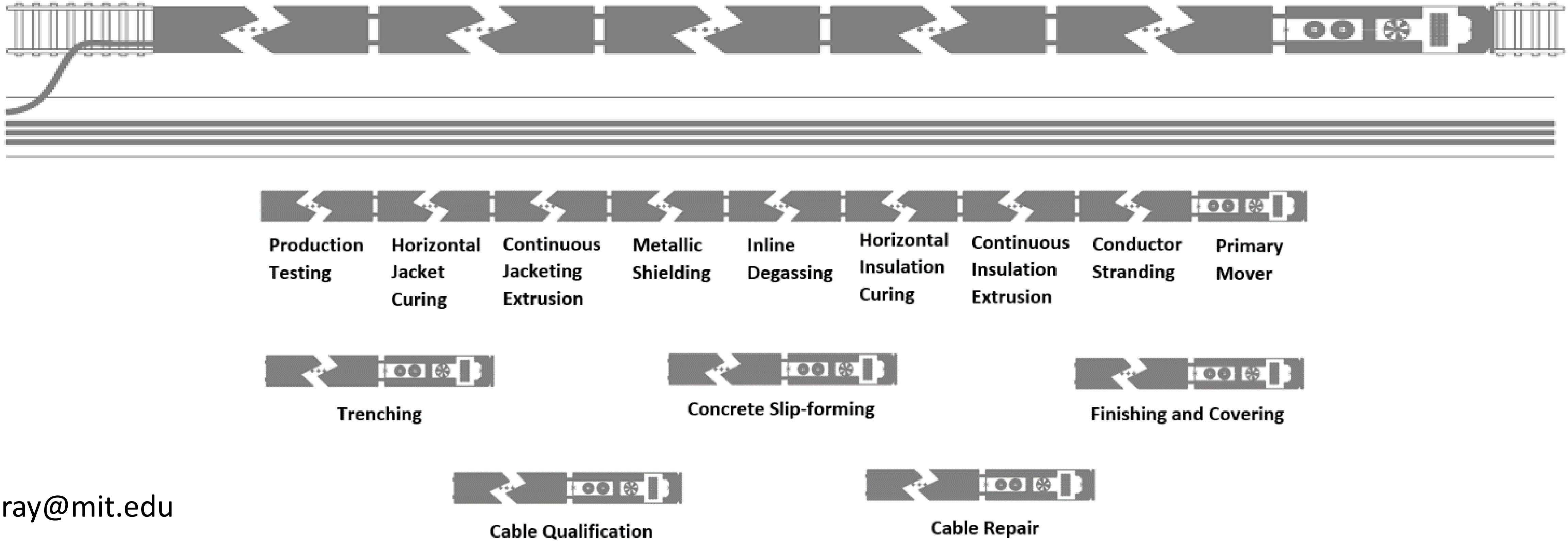
Check out the SOO Green Renewable Rail project on a Canadian Pacific Railway route!

Sure, there are MANY innovative ways to deliver and install long lengths of HVDC cable in trackside space, but…

…can we do more with the opportunities railroads provide?

In-situ manufacturing with a “Cable Train”?

- Fully exploit the mobility afforded by railroads
- Eliminate joints → decrease initial cost and system failure rate
- Replace cost of reel transportation with the cost of moving raw materials



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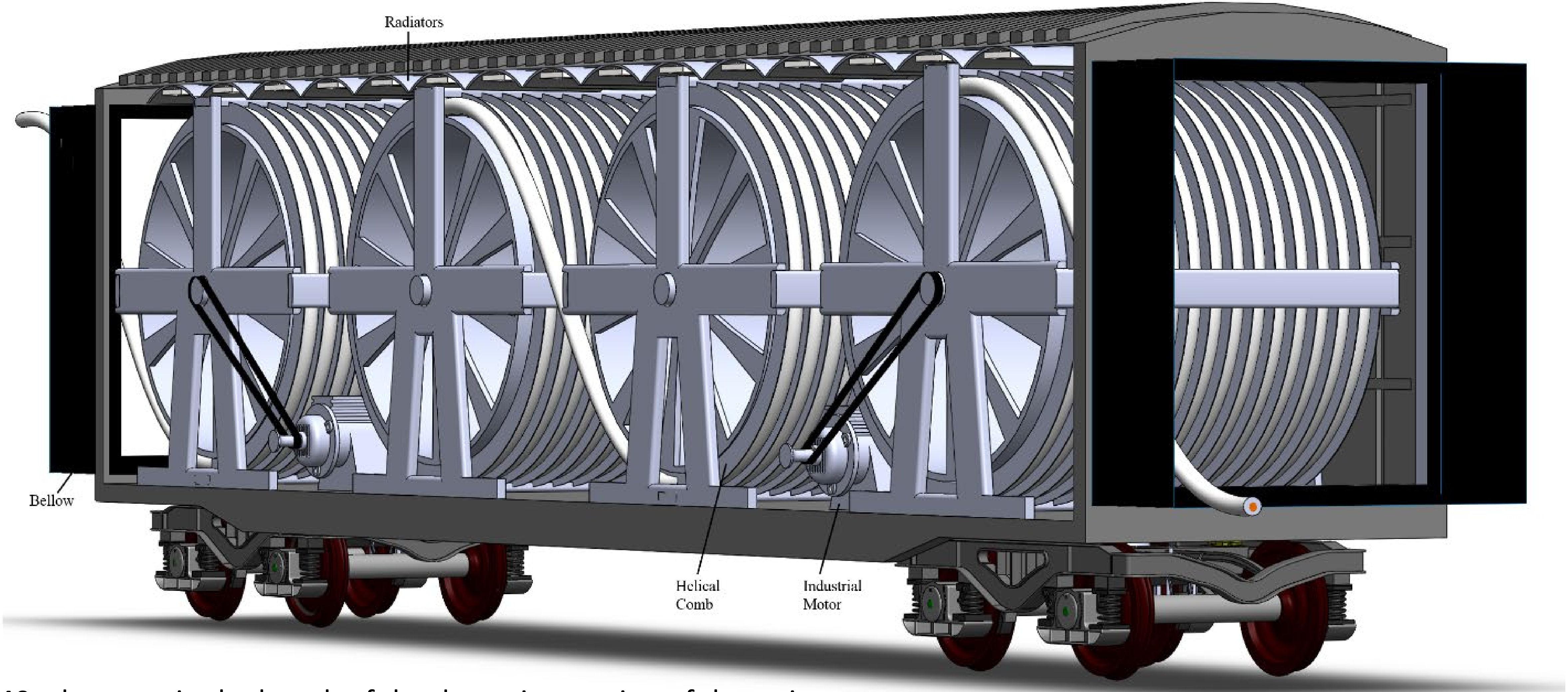
Challenges

- Continuous Extrusion → redundant barrels
- Horizontal Curing → Long Land Die (LLD)
- Inline Degassing → we needed to solve this
- Manufacturing standards → new (and old) inline sensing
- Stranding, taping, shielding → nothing a little buffer can't fix

- Yes we are talking about a HIGHLY synchronized process → but it's nothing that hasn't already been accomplished by submarine cable manufacturing…

Critical Module – Inline Degassing Car



40x decrease in the length of the degassing section of the train.

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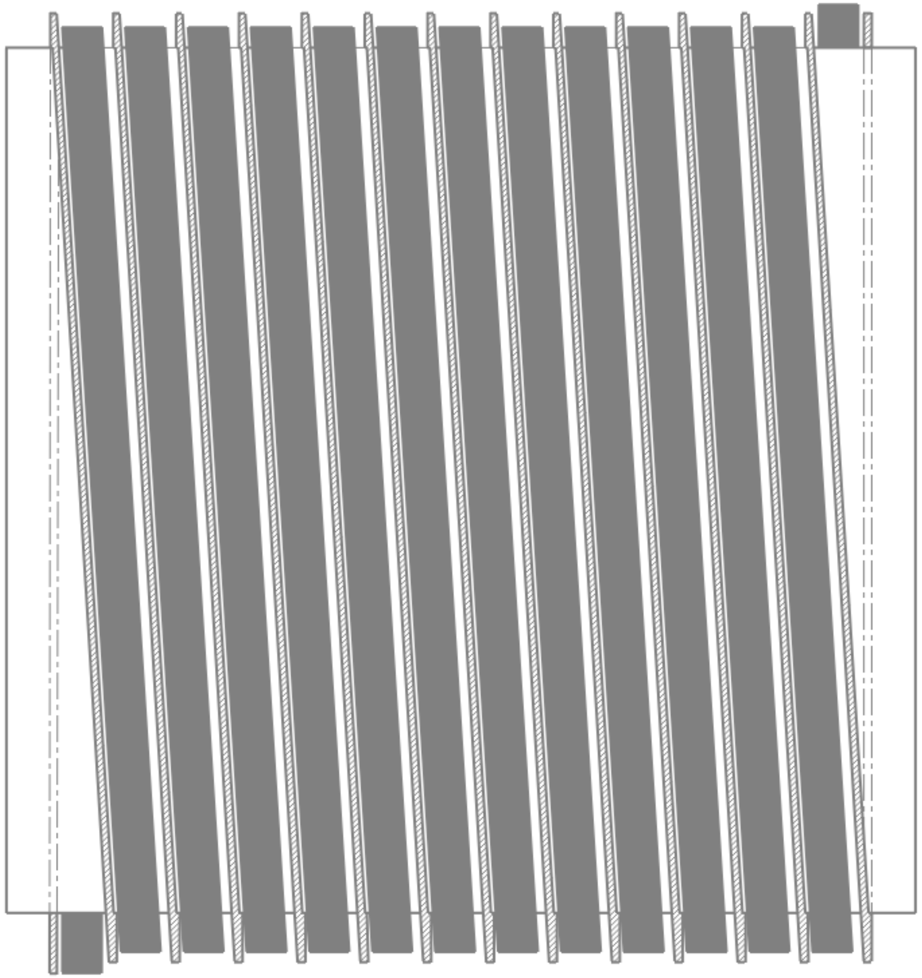
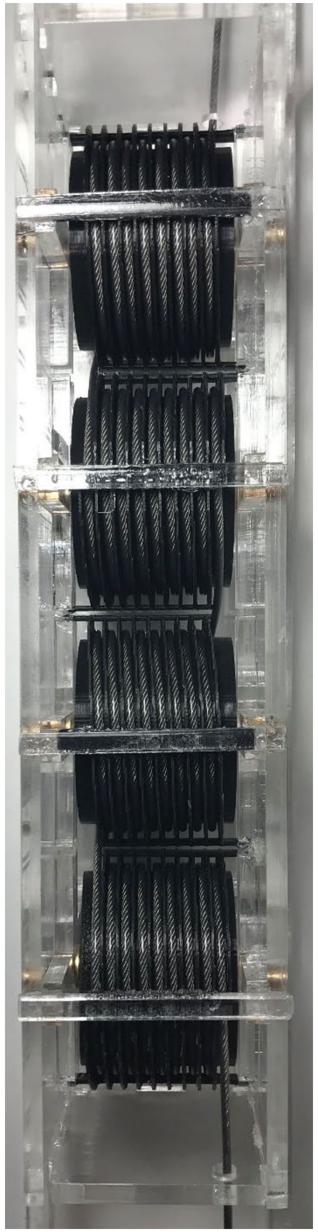
“Cable Combs”





Available →

Cable Data and Parameter Input		Copper Stress Calculations		XLPE Insulation Stress Calculations	
Drum/Cable Diameter Factor	22	Yield Strength (Pa)	3.33E+08	Yield Strength (Pa)	2.00E+08
Cable Insulation OD (m)	0.125	Shear Modulus (Pa)	4.60E+10	Shear Modulus (Pa)	4.83E+09
Conductor OD (m)	0.06	E (Pa)	1.10E+11	E (Pa)	1.30E+09
Diameter of Drums (m) for Degas	2.75	EI (Pa*m^4)	0.437	EI (Pa*m^4)	1.48E+04
Diameter of Nuetral Axis of Cable (m)	2.88	Radius of Curvature (m)	1.41	Radius of Curvature (m)	1.44
Area of Conductor (m^2)	2.83E-03	Curvature (/m)	0.710	Curvature (/m)	0.696
Packing Fraction Circles (Milliken)	0.9069	I (m^4)	3.98E-12	I (m^4)	1.13E-05
Single Conductor Strand Diameter (m)	0.003	Internal Moment (Pa*m^3)	0.311	Internal Moment (Pa*m^3)	1.03E+04
Number of Layers in Conductor	10	Max Bending Stress (Pa)	1.17E+08	Max Bending Stress (Pa)	5.65E+07
Total Number of Strands (Concentric Stranded)	331	Density (kg/m^3)	7.76E+03	Density (kg/m^3)	1.27E+03
Lay Angle (Degrees)	45	Max weight of suspended cable (N)	2.91E+03	Max weight of suspended cable (N)	2.91E+03
Max Tensile Traction Force on Cable (N)	1.70E+05	Loading	84%	Loading	16%
Clearance Between Cable on Neighboring Drums (m)	0.1	Tensile Stress from dead weight (Pa)	8.65E+05	Tensile Stress from dead weight (Pa)	4.93E+04
Distance Between Drum Centers (m)	3.1	Total Max Axial Stress (Pa)	1.18E+08	Total Max Axial Stress (Pa)	5.66E+07
Clearance to Bottom of the railcar (m)	0	Normal Force Drum to Cable (N/m)	3.49E+03	Normal Force Drum to Cable (N/m)	3.49E+03
Max Length of Suspended Cable (m)	8.74	Delta Deformation of Insulation (m)	1.64E-06	Delta Deformation of Insulation (m)	2.48E-05
Weight Per Meter of Cable (N/m)	333	Strain	5.05E-05	Strain	7.63E-04
Poisson's Ratio Copper	0.364	Contact Patch Area (m^2) per unit length	6.28E-04	Contact Patch Area (m^2) per unit length	3.52E-03
		Force Constraint	3.49E+03	Force Constraint	3.49E+03
Calculation of Optimum # of Reels per Railcar	*CSX Boxcar*	Side Wall Pressure from Drum (Pa)	5.56E+06	Side Wall Pressure from Drum (Pa)	9.91E+05
Inner Height (m)	3.327	Coefficient of Friction XLPE to Steel	0.2	Coefficient of Friction XLPE to Steel	0.2
Inner Width (m)	2.896	Normal Force from Comb (N/m)	698	Normal Force from Comb (N/m)	698
Inner Length (m)	15.418	Delta Deformation of Insulation (m)	5.34E-07	Delta Deformation of Insulation (m)	8.49E-06
Drum Diameter (m)	2.75	Strain	1.78E-05	Strain	2.61E-04
Clearance Between Cable on Neighboring Drums (m)	0.1	Contact Patch Area (m^2) unit length	3.58E-04	Contact Patch Area (m^2) unit length	2.06E-03
Drums Per Car/Container Vertical (#)	1	Force Constraint	700	Force Constraint	700
Drums Per Car/Container Horizontal (#)	4	Side Wall Pressure from Comb (Pa)	1.95E+06	Side Wall Pressure from Comb (Pa)	3.39E+05
Total Drums Per Car/Container (#)	4	Torque on Cable @ Cable Center (N*m)	34.9	Torque on Cable @ Cable Center (N*m)	34.9
Clearance Between Drum and Walls (m)	0.4	Internal Torque Constraint (N*m)	34.89	Internal Torque Constraint (N*m)	34.89
Cable Length per Car/Container (m)	625.7	Max dPhi / dx (Degrees/m) from Rolling	1.41E-05	dPhi / dx (Degrees/m) from Rolling	1.41E-05
Degassing Time (hrs)	168	Max Stress from Twist (Pa)	1.95E+04	Max Stress from Twist (Pa)	4.26E+03
Cable Production Speed Goal (m/hour)	80				
Number of Cars/Containers (#)	22	Max Axial Stress Total (Pa)	1.18E+08	Max Axial Stress Total (Pa)	5.66E+07
Length of Degassing Section of the Train (m)	339.2	Max Radial Stress Total (Pa)	5.56E+06	Max Radial Stress Total (Pa)	9.91E+05
		Max Circumferential Stress Total (Pa)	1.95E+04	Max Circumferential Stress Total (Pa)	4.26E+03
		Safety Factor	2	Safety Factor	2
		Von Mises at Danger Point (Pa)	1.63E+08	Von Mises at Danger Point (Pa)	7.93E+07
		Good for Static Case?	YES	Good for Static Case?	YES
		Von Mises at Comb/Cable Contact (Pa)	1.66E+08	Von Mises at Comb/Cable Contact (Pa)	7.98E+07
		Good for Static Case?	YES	Good for Static Case?	YES

Continuous Comb		Discrete Comb		Discrete Rollers	
Thickness (m)	0.0127	Thickness (m)	0.0127	Radius of the Rollers (m)	0.0141
Largest Expected Cable OD (Gap) (m)	0.125	Largest Expected Cable OD (m)	0.125	Approximate Largest Expected Cable OD (m)	0.125
Length of Drum (m)	2.286	Angle (Degrees)	0.874	Length of Drums Flange-to-Flange (m)	2.286
Revolutions	16.51	Number of Comb Rows	4	Number of Roller Rows	4
Angle (Degrees)	0.874	Circumferential Sep. (m)	2.16	Number of Revolutions	14
Normal Force on Comb (N/m)	698	Length of Flat Section (m)	0.05	Angle (degrees)	0.971
Delta Deformation of Insulation (m)	4.28E-07	Normal Force on Comb (N/m)	3.15E+04	Force Acting on Each Roller (N)	1.58E+03
Strain	1.37E-05	Delta Deformation of Insulation (m)	7.94E-04	Delta Deformation @ Contact (m)	4.62E-04
Contact Patch Area (m^2) per unit length	4.63E-04	Strain	0.0244	Strain	0.0142
Force Constraint	698	Contact Patch Area (m^2) unit length	9.93E-04	Elliptical Contact Patch Area (m)	8.52E-05
Side Wall Pressure from Drum (Pa)	1.51E+06	Force Constraint	3.15E+04	Force Constraint (N)	1.58E+03
FEA Result?	Good!	Side Wall Pressure from Comb (Pa)	3.17E+07	Pressure on Insulation (Pa)	1.85E+07
		Fin Attachment Good? (FEA)	YES	Roller Attachment Good? (FEA)	Good!
		Von Mises at Fin-Cable Cont. (Pa)	6.95E+07	Von Mises at Roller-Cable Cont. (Pa)	7.07E+07
		Safety Factor	2.88	Safety Factor	2.83
		Flat Section of Fin Sufficiently Long?	YES	Roller Radius Sufficiently Large?	YES
		Worst Case Precaution - Fin Terminal Radius		Pitch (m)	0.153
		Radius at the End of Fin (m)	5.00E-03	Shift Between Bars (m)	0.0383
		Force from Friction in Jamming (N)	698	Drum Length (m)	2.286
		Delta Deformation of Insulation (m)	4.01E-04	Drum Length Constraint	2.286
		Strain	0.0123		
		Contact Patch Area (m^2) unit length	4.35E-05		
		Force Constraint	698		
		Side Wall Pressure from Comb End (Pa)	1.60E+07		
		Von Mises at Fin-Cable Cont. (Pa)	7.14E+07		
		Safety Factor	2.80		
		Terminal Radius of Fin Sufficiently Large?	YES		

Lifetime Costing of a System Produced by the Cable Train

HVDC Trackside UGC Characteristics	
Transmission line route length, *L* (km)	350
Transmission line voltage rating, *V* (kV)	660
Transmission line power capacity, *P* (GW)	4
Trench width, *w* (m)	2.0
Trench depth, *d* (m)	1.5
Concrete slipform and precast thickness, *t* (m)	0.1
Cable outer diameter, *OD* (m)	0.2
Number of cable splices, *N*	-
System Lifetime, *lifetime* (years)	40
Discount Rate, *rr*	5%
HVDC Trackside UGC Produced by Cable Train - Capital Costs, (I)	
Capital cost of the full Cable Train, *CT_Capex* ($)	61,150,000
Lifetime of the Cable Train in number of projects completed, CT_*lifetime_projects*	20
Preparatory work cost, cost_*prep_work* ($)	-
Termination and converter station cost, *cost_converter* ($) [17], [28]	700,000,000
Contingency added to historical submarine cable manufacturing cost [17]	10%
Cable raw material and production cost for bipole, *kilocost_cable* ($/km) [17]	2,970,000
Total cable cost for entire route, *cost_cable* ($)	1,039,500,000
Equipment cost, *cost_equipment* ($)	1,739,500,000
Cable Train raw material inventory in equivalent cable distance, *CT _inventory* (km)	12
Total raw material shipping distance during project, mat_*transport_dist* (km)	4,900
External, unpriced cost to ship cable raw materials by rail, *cost_railroad_ship* ($/ton-km) [29]	0.005
Cable weight per meter, *cable_weight* (kg/m)	50
Total cost of cable raw material delivery during project build, *cost_mat_shipping* ($)	16,172
Number of skilled workers required for cable installation, *workers_req*	20
Cable Train rate of cable production, *CT_rate* (m/hr)	180
Labor cost for skilled workers performing cable installation, *hourly_wage* ($/hr)	40
Cable installation cost, kilo*cost_installation* ($/km)	1,555,556
Trenching cost, kilo*cost_trenching* ($/km) [25]	23,000
Slip-forming cost for duct-structure, kilo*cost_slipform* ($/km) [25]	74,000
Precast cover cost, kilo*cost_precast* ($/km) [25]	187,000
Fuel costs for all machines, kilo*cost_fuel* ($/km)	30,000
Construction contingency as a percentage of base construction cost, *build_contingency [17]*	15%
Construction cost, kilo*cost_construction* ($/km)	2,150,035.09
Total Construction Cost, *construction_cost_total* ($)	752,512,283
Total Build Cost, *total_build_cost* ($)	2,495,069,782.73
Planning and engineering cost as a percentage of total construction cost, *percent_planning* [17]	20%
Planning and engineering cost, cost_planning ($)	499,013,957
I ($)	2,994,083,739

Lifetime Operation and Maintenance Costs of Trackside UGC (OM)	
Annual cost of preventative maintenance as a percentage of system equipment cost, *percent_lmp* [26]	0.1%
Lifetime preventative maintenance, *lmp* ($)	29,848,231
OM ($)	29,848,231
Lifetime Energy Loss Costs of Trackside UGC (E)	
Circuit loading factor (CLF) of transmission system, *clf* [26], [30]	35%
Short run marginal cost (SRMC) of generation, *srmc* ($/MWh) [17]	45
Resistive energy losses over lifetime of trackside UGC system, *kilocost_resistance* ($/km)	41,831
Converter energy losses as a percentage of power [17]	2%
Converter energy losses over lifetime of trackside UGC system, *cost_convert_losses* ($)	183,983,842
Total lifetime energy losses of trackside UGC system, *total__energy_losses* ($)	198,624,811.03
Long run marginal cost (LRMC) of generation, *lrmc* ($/MWh) [17]	50
Loss load factor (LLF), *llf [17]*	39%
Peak power losses (PPL), cost of power required to replace losses, *ppl* (MWh)	271,057
Lifetime power losses, *cost_power_losses* ($)	232,554,515
E ($)	431,179,326
Decomissioning and End-of-Life Costs of Trackside UGC (D)	
Decomissioning costs as a percentage of total build cost, *percent_decomissioning* [26]	5%
D ($)	17,720,694
Territorial Cost of Trackside UGC (T)	
Trench width, *w* (m)	2.0
Land cost for "noncore, non-metro, non-micro, land without a town of 2,500," *cost_land* ($/acre) [31]	1,655
Kilometric territorial cost, *kilocost_territory* ($/km)	817.92
T ($)	286,271
Lifetime Cost of Random Repairs for Trackside UGC, (R)	
Historical failure rate, *hfr* (/100 km-year) [32]	0.3
Percent of historical failures attributable to joints, *failures_joints* [8]	37.1%
New failure rate for Trackside UGC system without joints, *nfr* (/100 km-year)	0.19
Cable repair cost, *cost_random_repair* ($/event)	2,970,000
R ($)	33,658,174.19
Total Lifetime Cost of Trackside UGC System Produced by the Cable Train (LCTS)	3,506,776,436

Available

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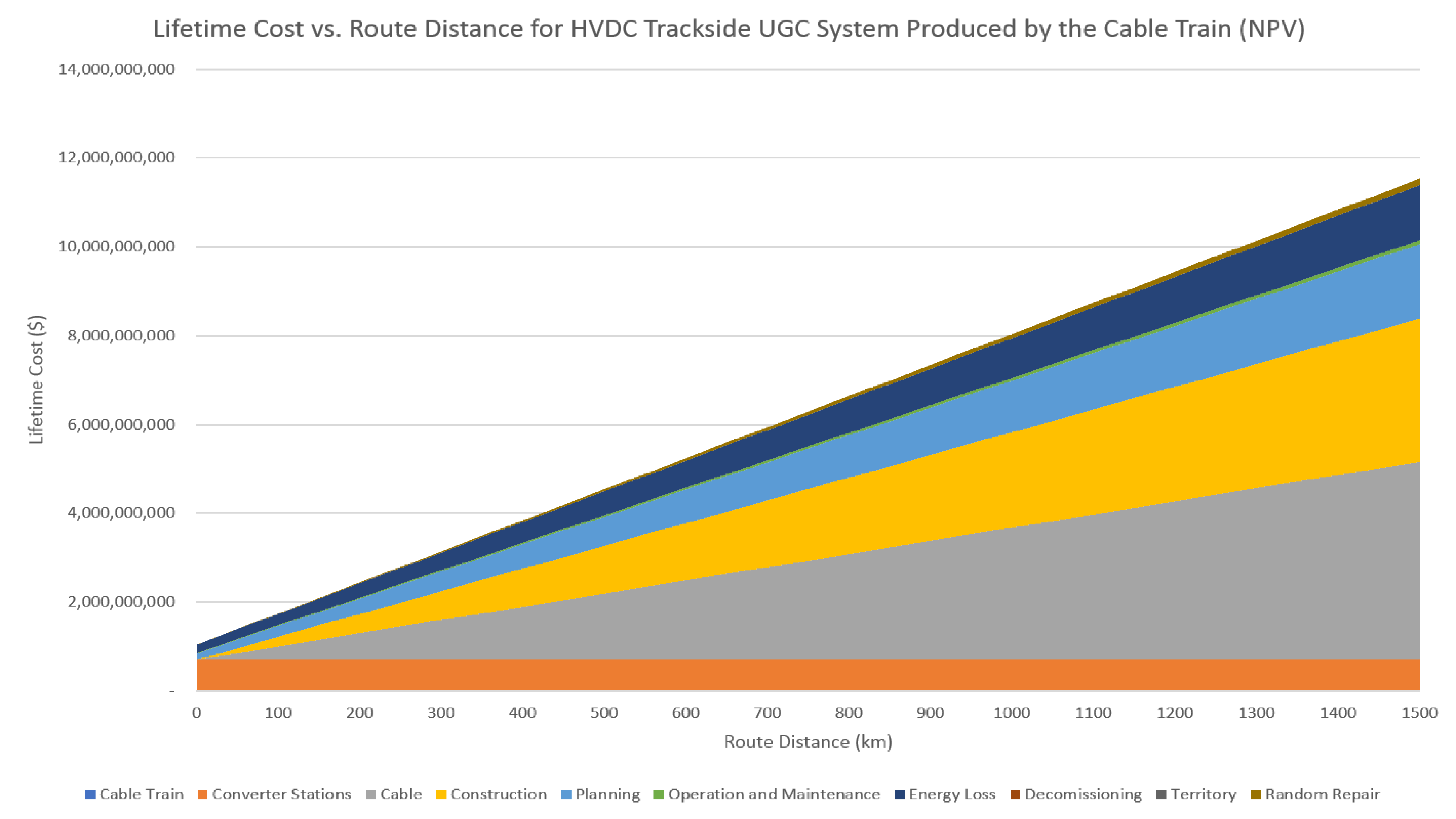
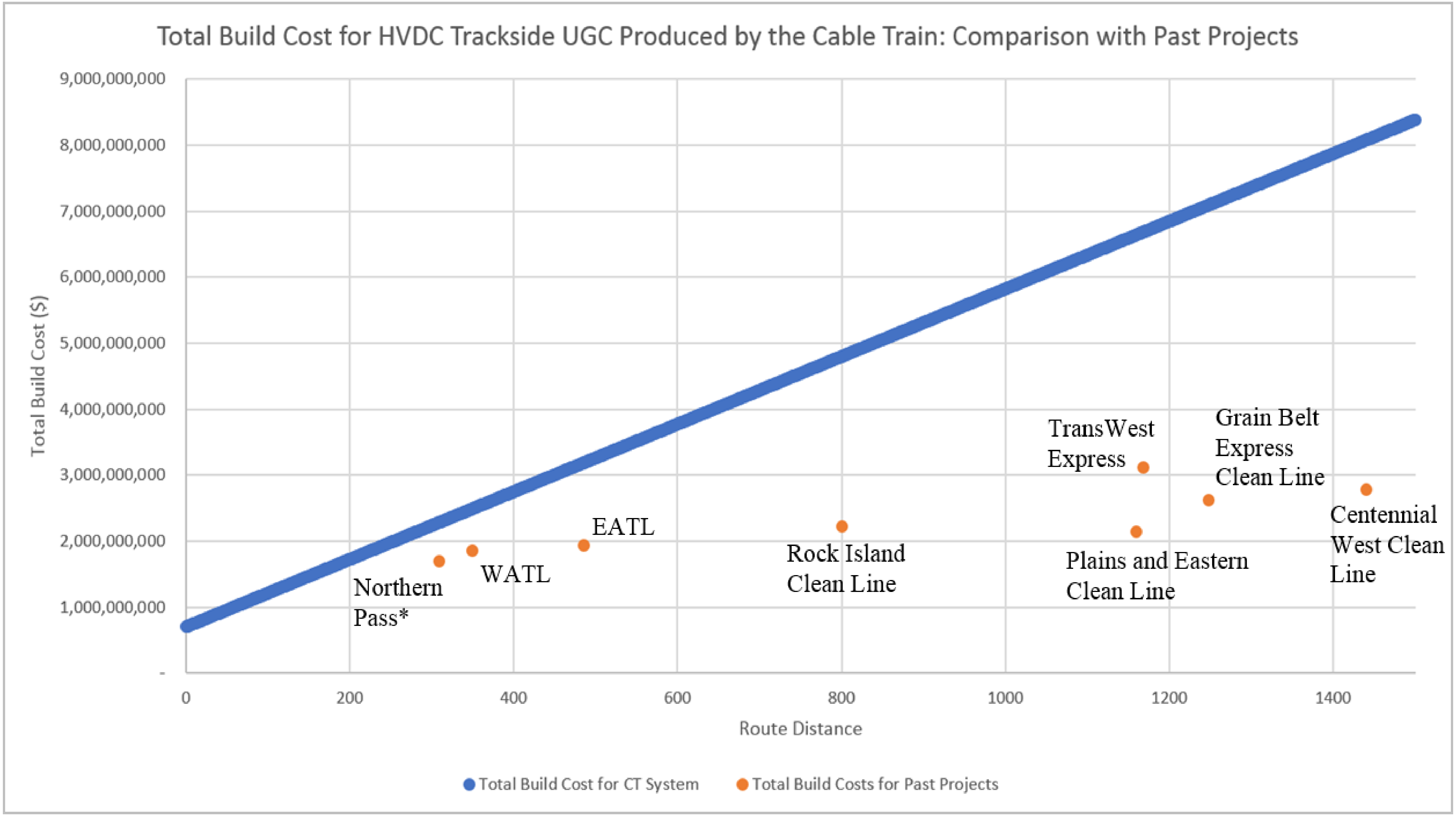

Lifetime Cost vs. Route Distance for HVDC Trackside UGC System Produced by the Cable Train (NPV)
Lifetime Cost ($)
14,000,000,000
12,000,000,000
10,000,000,000
8,000,000,000
6,000,000,000
4,000,000,000
2,000,000,000
-
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
Route Distance (km)
Cable Train
Converter Stations
Cable
Construction
Planning
Operation and Maintenance
Energy Loss
Decomissioning
Territory
Random Repair



Total Build Cost for HVDC Trackside UGC Produced by the Cable Train: Comparison with Past Projects
9,000,000,000
8,000,000,000
7,000,000,000
6,000,000,000
5,000,000,000
4,000,000,000
3,000,000,000
2,000,000,000
1,000,000,000
-
Total Build Cost ($)
0
200
400
600
800
1000
1200
1400
Route Distance
Northern Pass*
WATL
EATL
Rock Island Clean Line
TransWest Express
Plains and Eastern Clean Line
Grain Belt Express Clean Line
Centennial West Clean Line
Total Build Cost for CT System
Total Build Costs for Past Projects

All aboard the Cable Train!

- A pre-competitive consortium?
- More detailed case studies?
- Does the degassing car have other applications?
- What do you want to see from us?
- Anything we’ve overlooked?

MIT undergraduate thesis available.

Please play with our spreadsheets! → lagray@mit.edu