INDUSTRIAL APPLICATIONS OF CLATHRATE HYDRATES

A BRIDGE TO COMMERCIAL GAS HYDRATE PRODUCTION

CLATHRATE HYDRATES . . .
FARADAY'S OTHER CAGE

First named and characterized by Michael Faraday in 1823. He first encountered clathrates during his fundamental work on chlorine. It remained a laboratory curiosity for more than 100 years

Gas field operators in the 1930's experienced hydrate blockages in pipelines during winter. Additives like methanol were developed to solve the problem making it a gas field and laboratory curiosity.

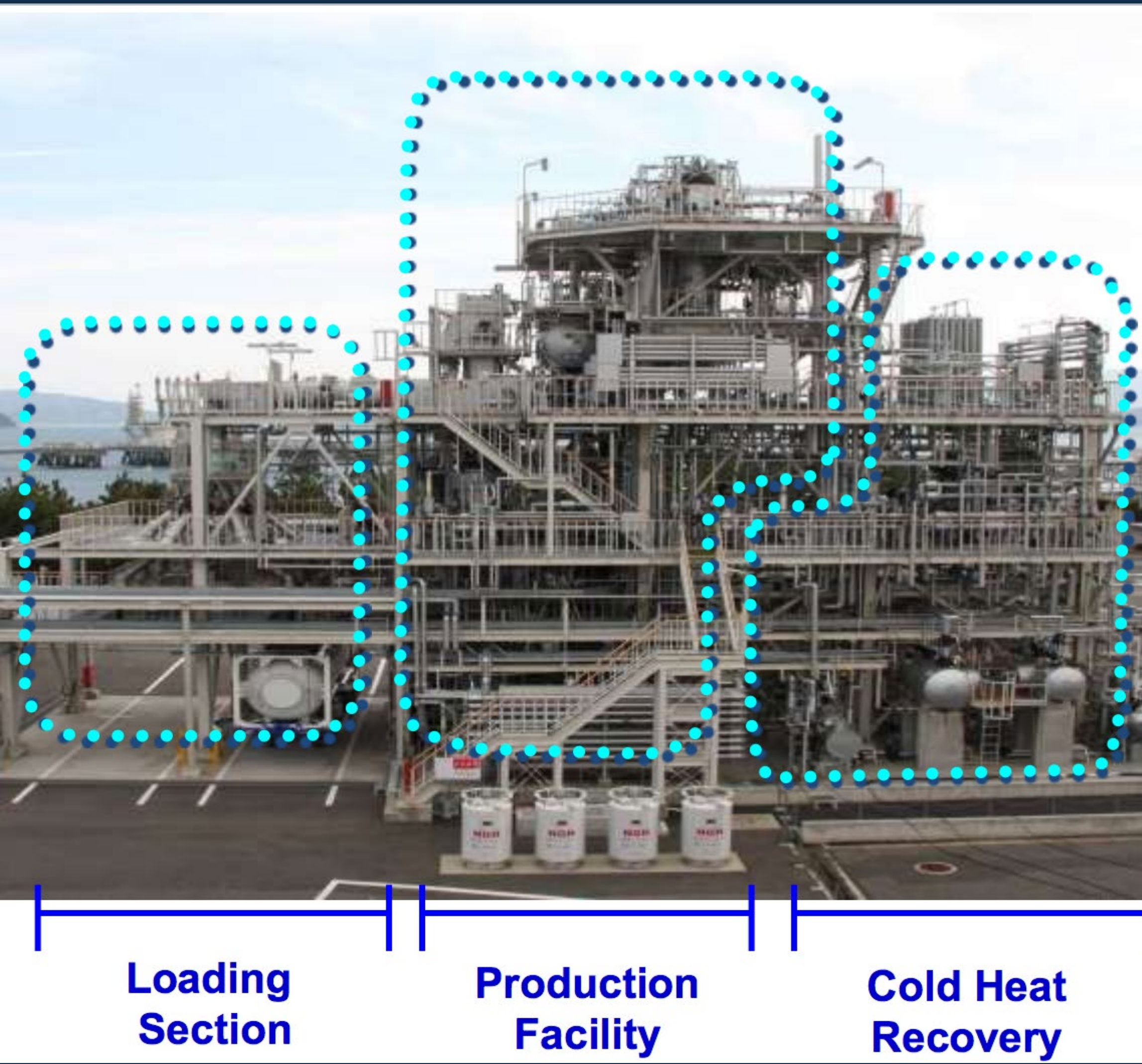
Natural methane hydrates were first observed by Soviet geologists in Siberian permafrost during exploratory drilling in 1960's. Geologists have since shown that natural hydrates dwarf traditional fossil fuel reserves.

STILL MYSTERIOUS
= OPPORTUNITY

WHAT MAKES CLATHRATE HYDRATES SPECIAL?

Thermodynamic Reversibility	Isothermal Compression
Phase Change Can Be Controlled By Both Temperature and Pressure	Both are Moderate
High Latent Heat and Higher Formation Temperature than Ice	Thermal Energy Storage
Ability to Separate Gases and Purify Water	What Else Can Do All of This?

WHY HASN'T THIS BEEN DONE BEFORE?



Wrong Model Applied to the Right Technology

LNG Worked for Largest Gas Fields

Classic Valley of Death Scenario

THE BEGINNING OF MY HYDRATE JOURNEY

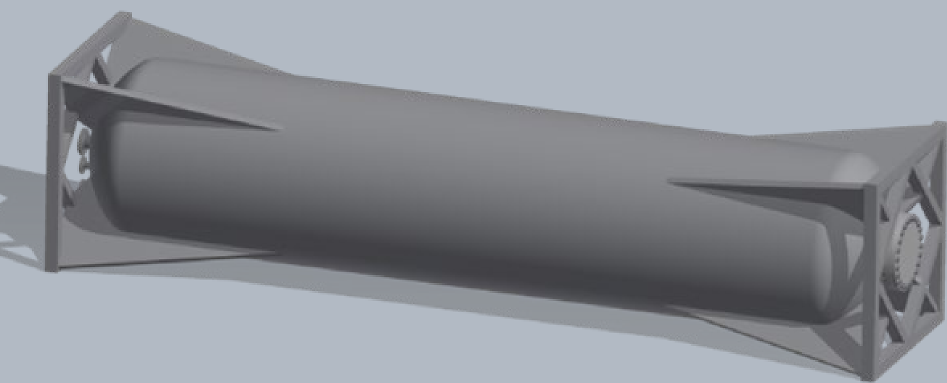
Discovery by Rudy Rogers research group at MSU that surfactants enable rapid hydrate formation in an unstirred reactor in 1997

NETL funded 1000 liter demonstration reactor that was run only 6 times.

Shortcuts were made and poor heat transfer prevented demonstration living up to its potential

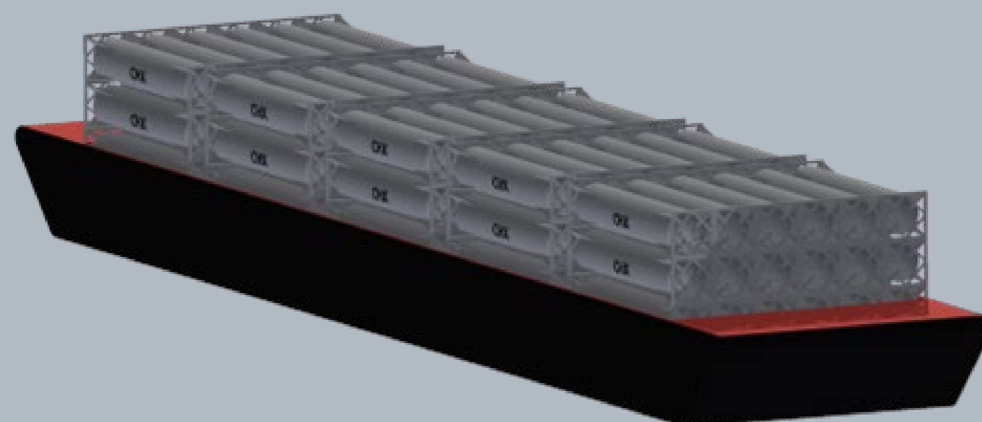
HEAT TRANSFER IS THE CRITICAL FACTOR

OUR SOLUTION



Tank Volume	50,000 liters
Storage Capacity	250 MMBtu
Formation Energy	~1800kWh
Potential Power	~30MWh

Displacement	10,000 Tons
Number of Tanks	124
Gas Storage	31,000 MMbtu
Potential Power	~3700 MWh



INCREASE FLEXIBILITY & REDUCE FIXED CAPEX

THE GAS SUPPLY CHAIN REPRESENTS THE LARGEST AND MOST EXPENSIVE ENGINEERING PROJECTS ON EARTH

HOW DOES GAS GET TO MARKET TODAY?

COMPRESS	Pipelines	Geographically and politically constrained.
LIQUIFY	Land Based	Expense limits applications to only the largest gas fields.
	Floating	Cost of $5.00-7.00/Mmbtu and $7-15 Billion CAPEX

HOW WILL HYDRATES GET TO MARKET?

THE ENERGY SUPPLY CHAIN EXPLAINS WHY OIL IS WORTH MORE THAN GAS

Oil is the Benchmark Because It Is a Liquid

Low CAPEX Storage & High Energy Density Make It Worth $20/mmbtu

Energy Resource

Transport

Unload/ Store

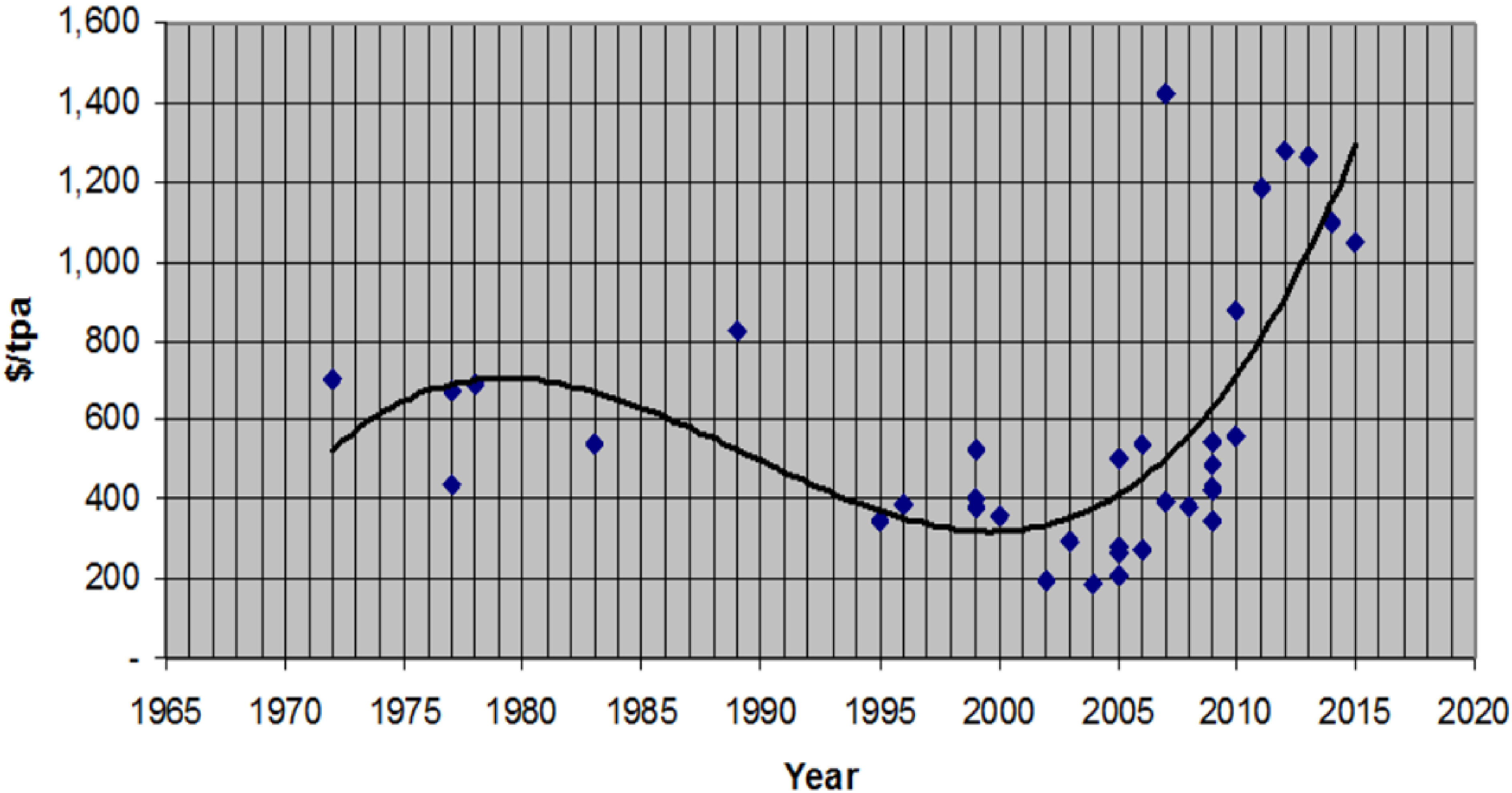
Distribute & Store

Customer

Gases are Much More Challenging

High CAPEX Storage and Volatility Make It Feasible For Only the Largest Fields and Customers

DEMAND FOR LNG HAS TRIPLED CAPEX OVER THE LAST DECADE

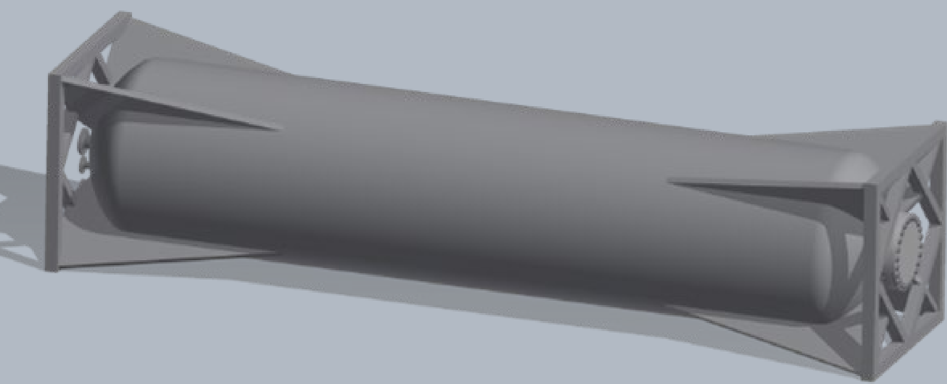


LOW HANGING FRUIT HAS BEEN PICKED

HYDRATES OFFER AN UNCONVENTIONAL ALTERNATIVE

Simple	Hydrates store simple gases in a three dimensional water crystal cage network similar to ice. Upon crystallization 150 cubic feet of gas can be stored in 1 cubic foot of water.
Safe	Hydrates are inherently safe. Like ice, hydrates require significant amounts of energy to dissociate and will not release gas fast enough to trigger an explosion
Scalable	Hydrate formation requires only pressure and chilling. Standardized modules can be scaled to applications ranging from thousands to billions of cubic feet. Modules can be reallocated
Efficient	Hydrates represent natures way of storing gases. The hydrate formation process isothermally compresses natural gas to the equivalent of 150 bar using only water at near ambient conditions.
Selective	As the hydrate crystal grows it excludes virtually everything from the lattice, including dissolved salts. Process parameters can be further tuned to selectively separate hydrate forming gases.

HYDRASTOR
MODULAR PLATFORM



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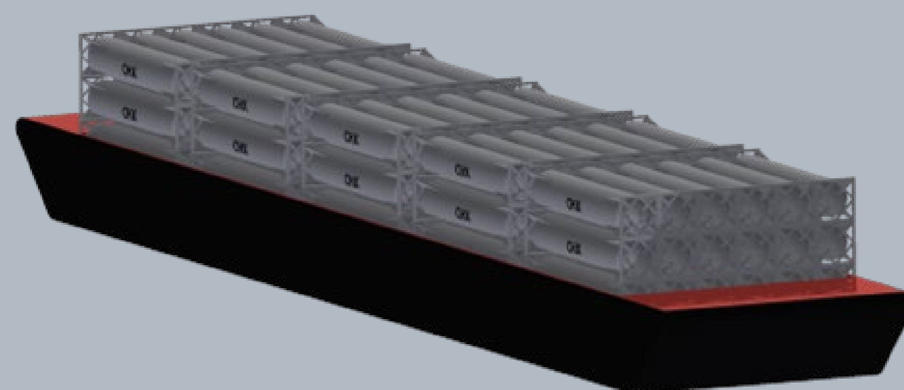
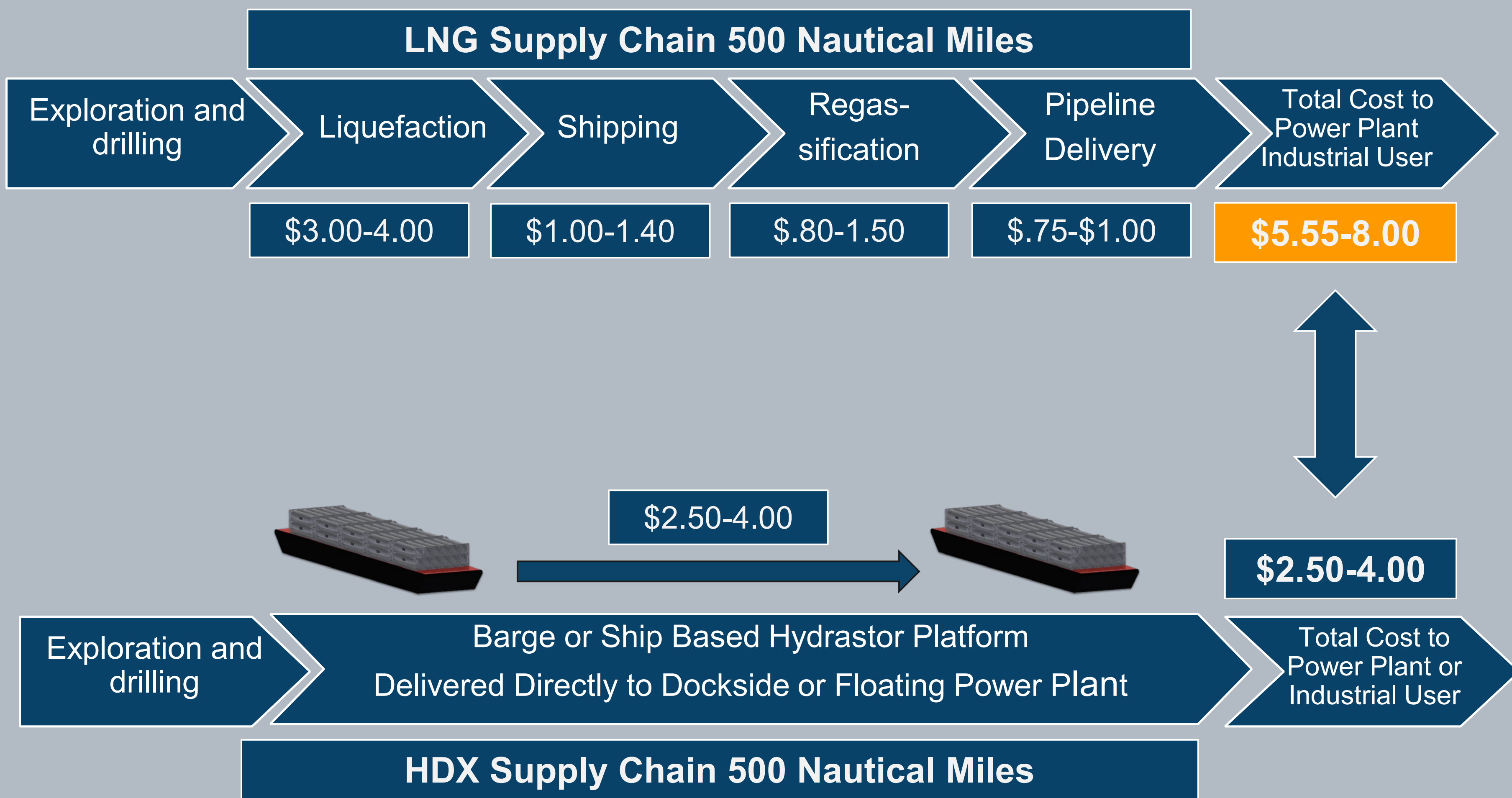
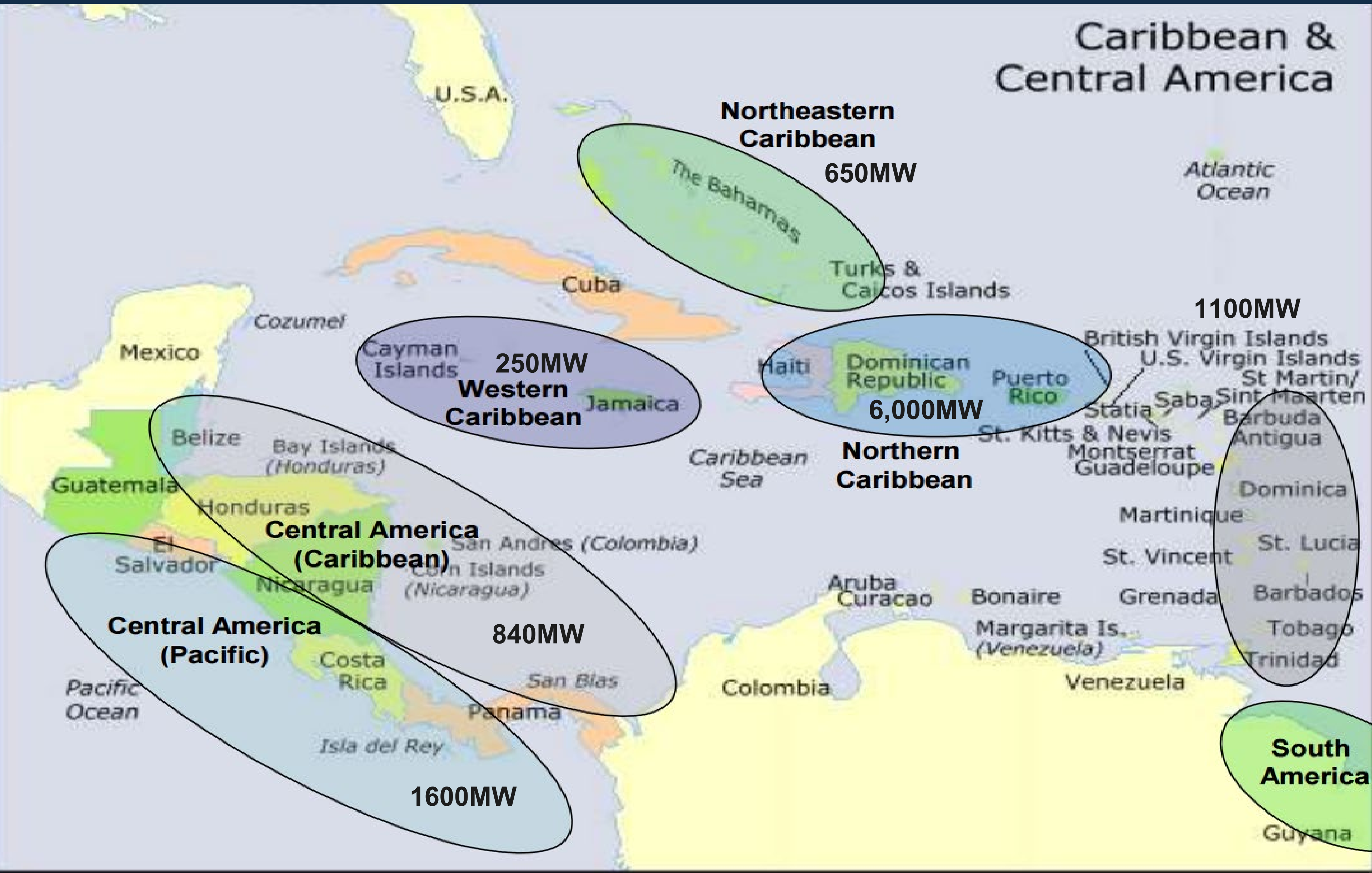


SIMPLICITY OF HYDRATES TRANSFORMS SHIPPING COSTS

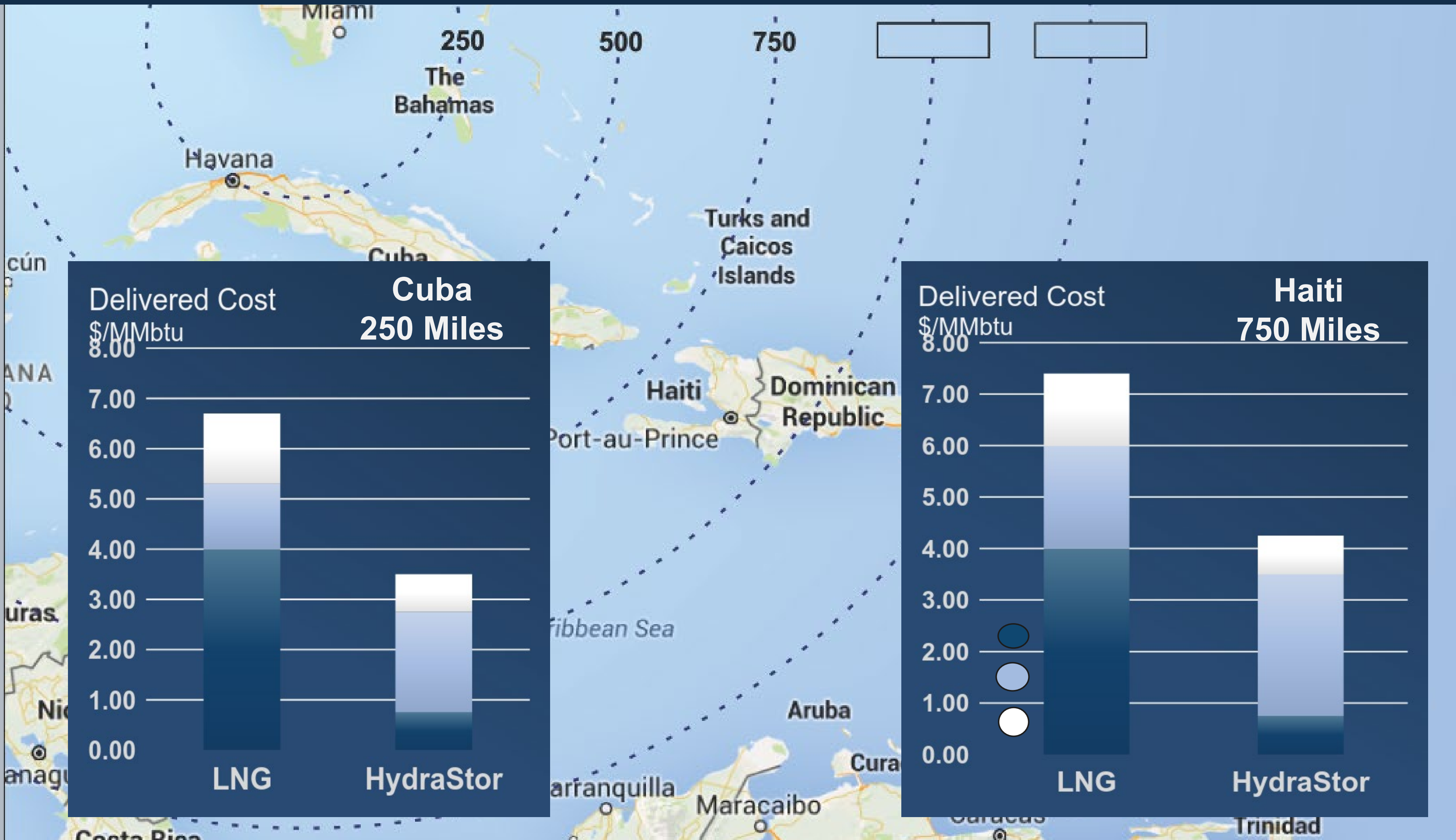


SIMPLICITY OF HYDRATES TRANSFORMS SHIPPING COSTS

10,000MW OF FUEL OIL READY FOR LOW COST US GAS



DELIVERED COST COMPARISON OF HYDRATES VS LNG

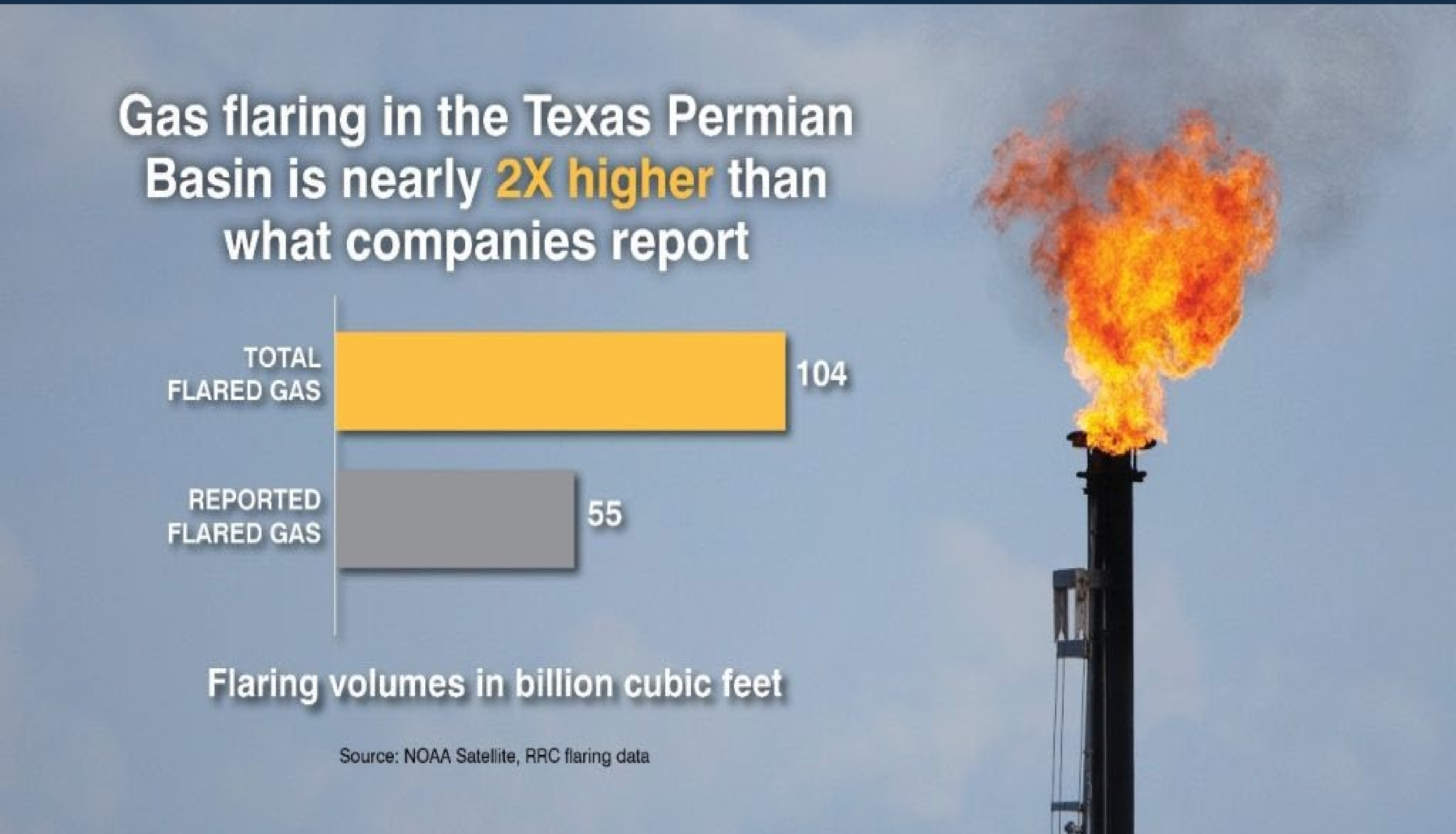


ALASKA?

ALASKA NATURAL GAS?

WHAT WILL SEA ROUTES LOOK LIKE IN 2035?

GAS FLARING

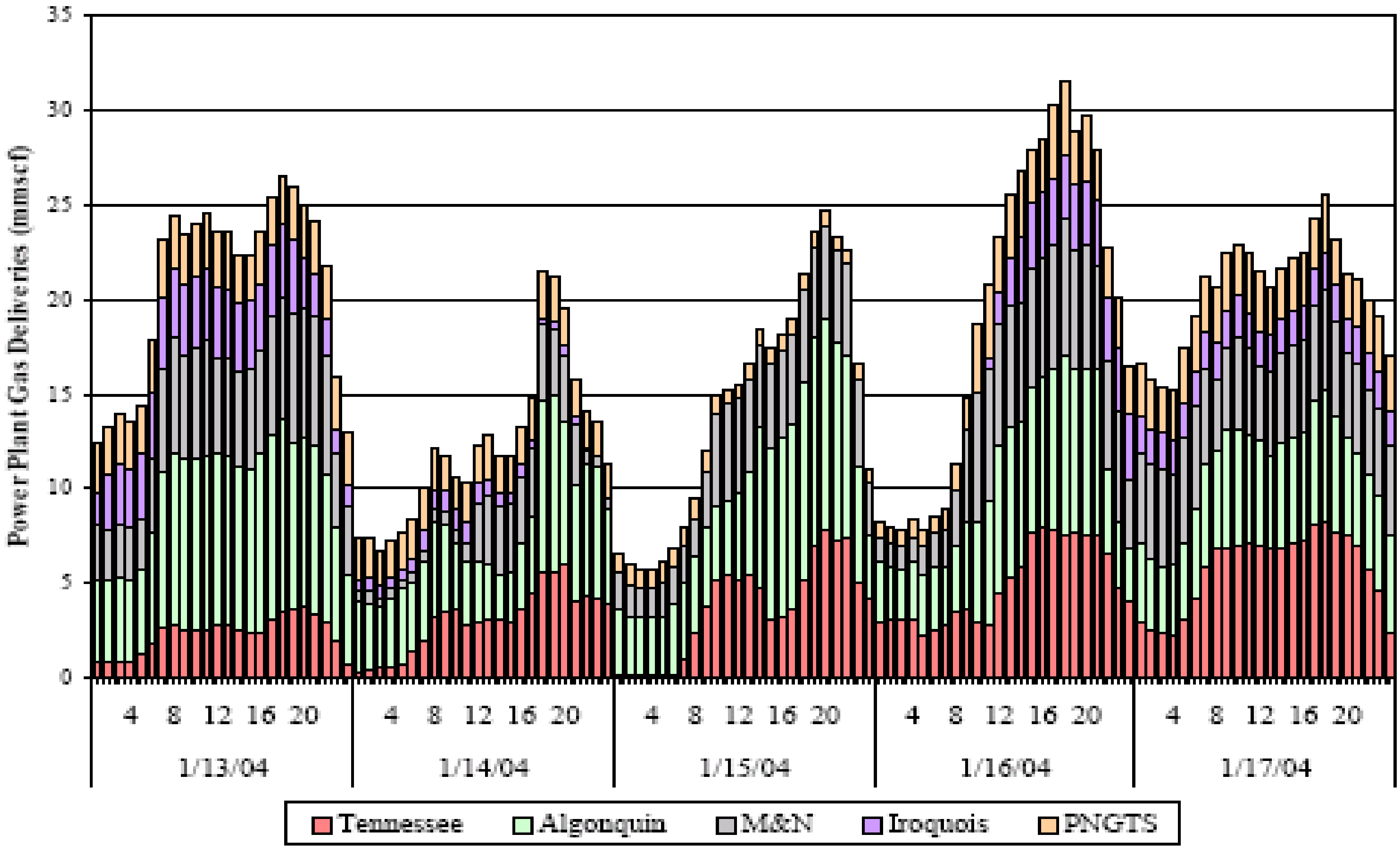


THIS IS FOR 2017 . . .SITUATION IS CLEARLY GETTING WORSE

US JUST PASSED NIGERIA IN TERMS OF GAS FLARING

RAIL ACCESSIBLE

GAS STORAGE IS CHANGING



HOURLY DEMAND VS SEASONAL

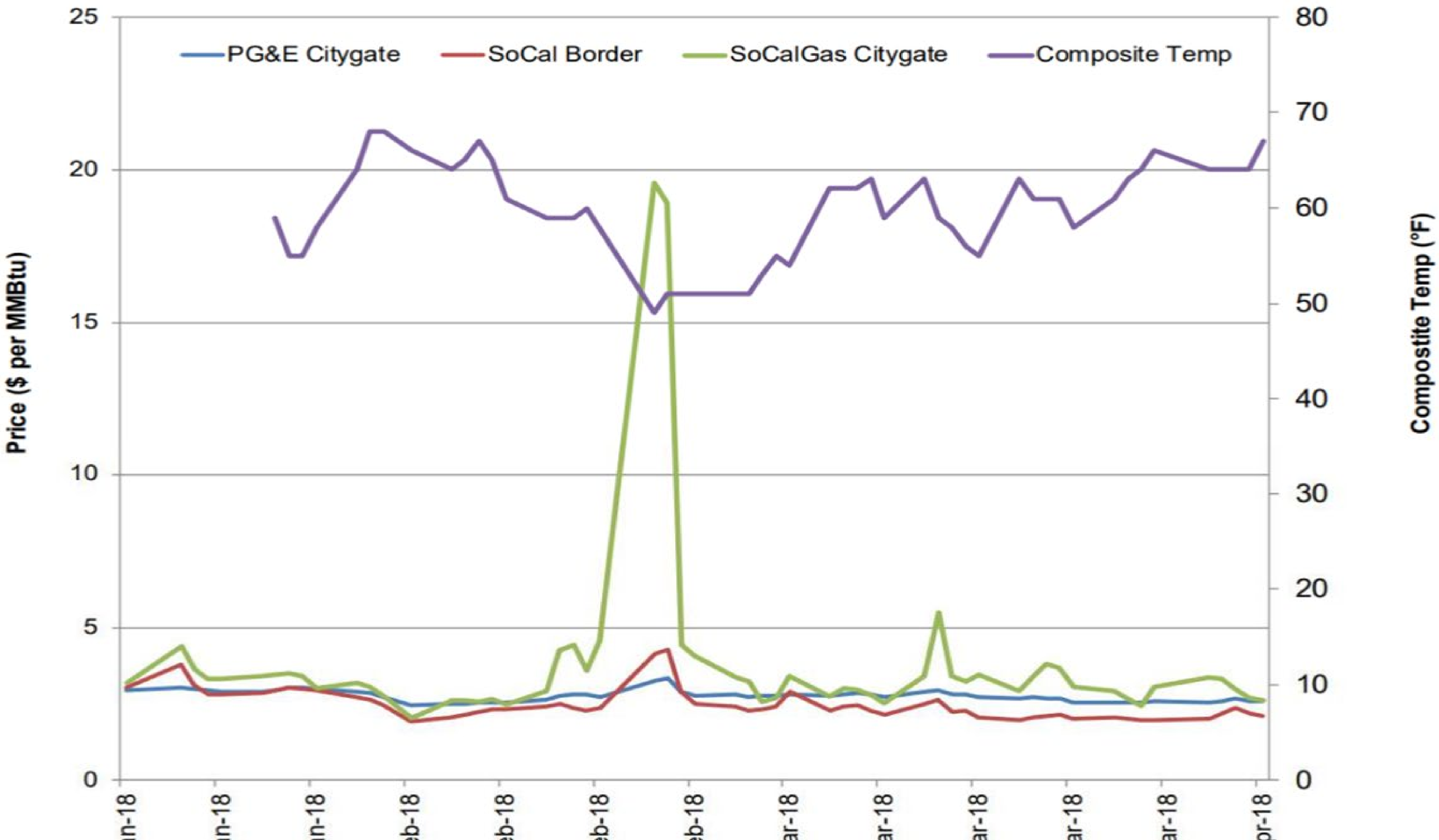
THE NATURAL GAS UNDERBELLY

GAS PIPELINES ARE AMERICA'S ACHILLES HEEL

ALISO CANYON

THE HEART OF SOUTHERN CALIFORNIA'S GAS SYSTEM

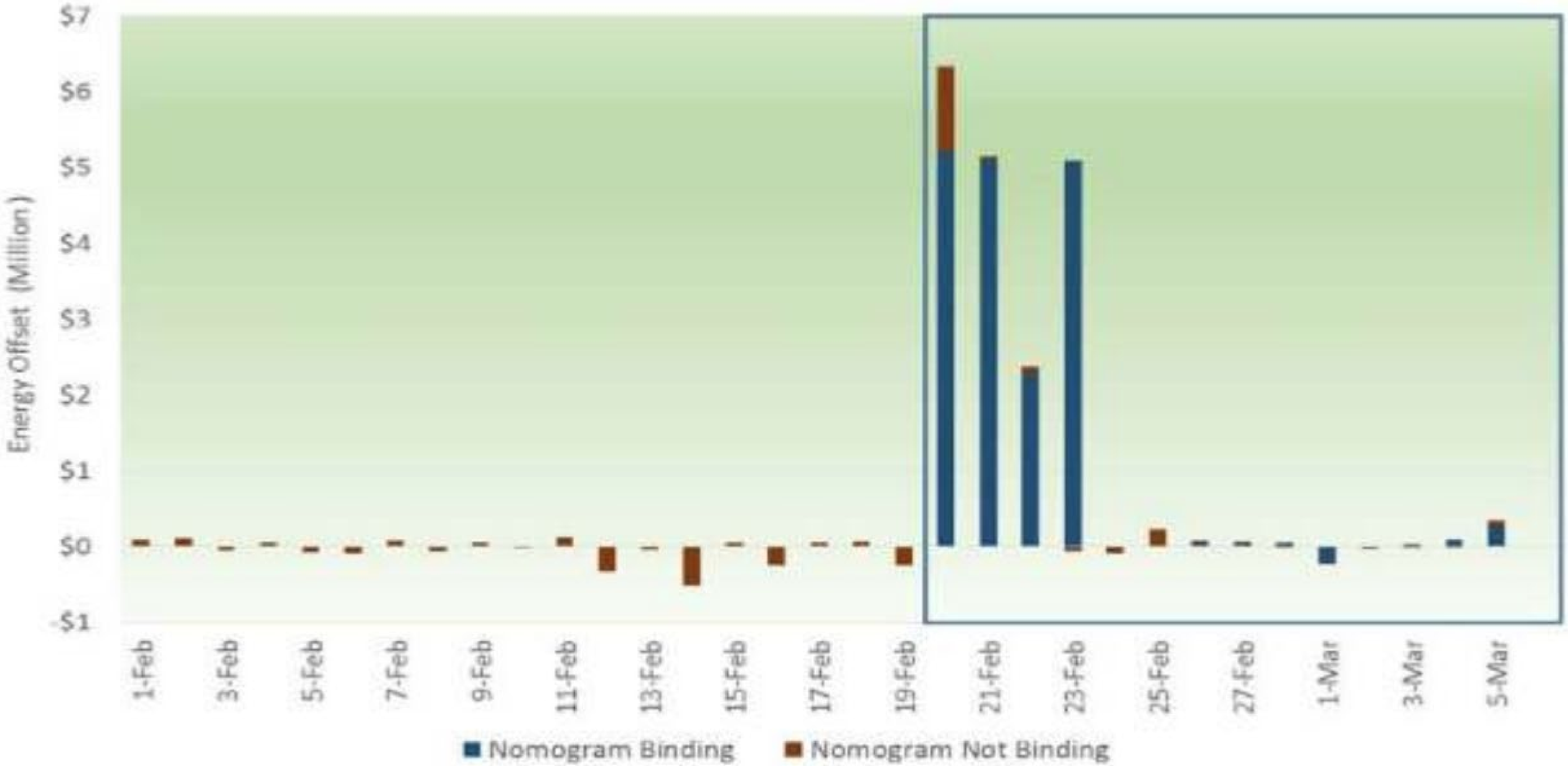
REAL CONSEQUENCES



AND NO READILY AVAILABLE SOLUTION

REAL CONSEQUENCES

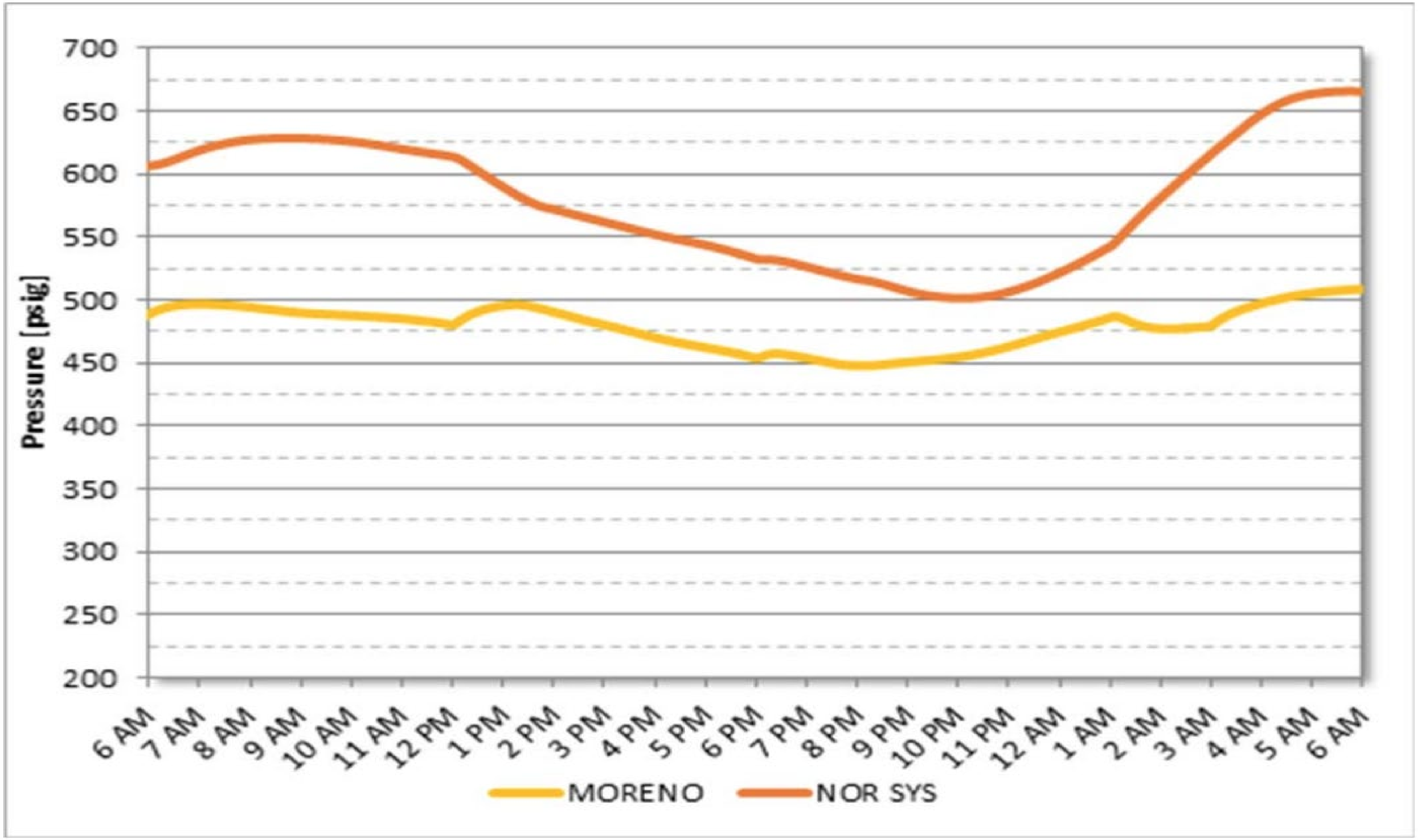
Figure 10: Daily Cost of Real-time Imbalance Energy Offset



Source: CAISO

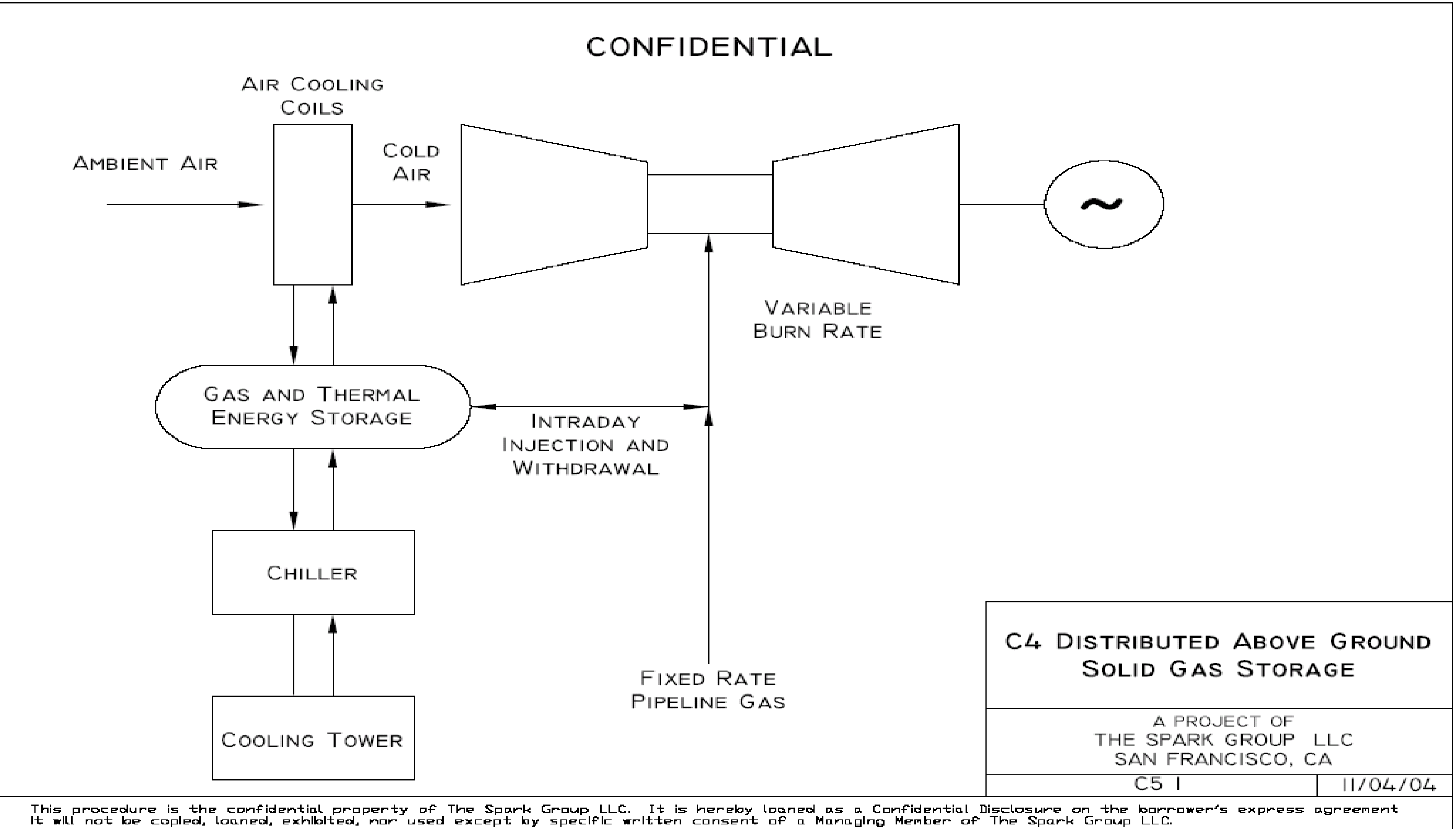
TOTAL COST >$45 MILLION IN 4 DAYS

HYDRATE LINEPACK?



HYDRATES CAN BALANCE PRESSURE WITH MINIMAL INTERVENTION

HOW TO USE MULTIPLE ATTRIBUTES OF GAS HYDRATES

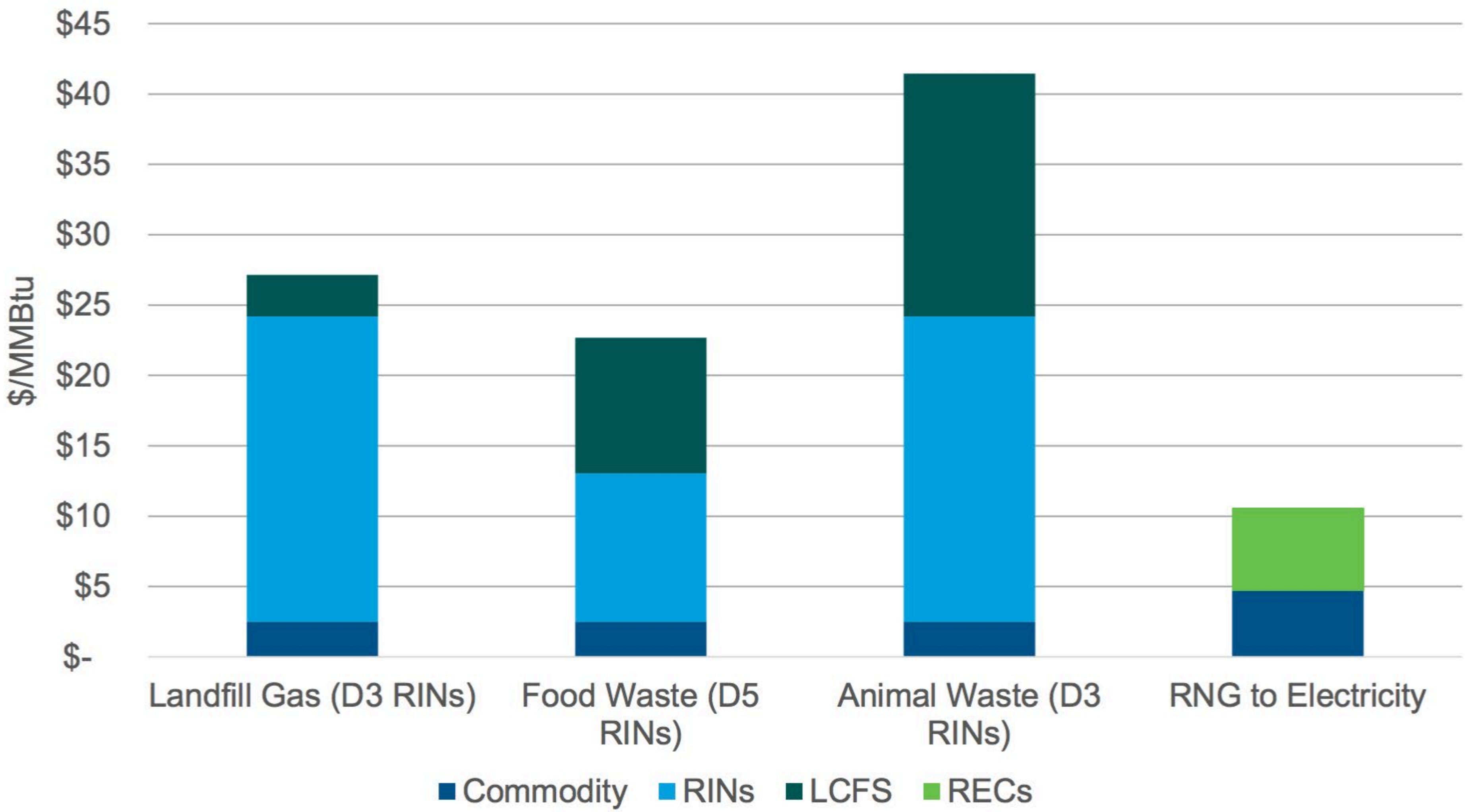


GAS + THERMAL ENERGY STORAGE

THE PROBLEM WITH BIOGAS

BASELOAD AND ONLY HALF THE ENERGY CONTENT OF NG

THE VALUE OF RENEWABLE NATURAL GAS



Assumptions: Commodity- $2.50/MMBtu; $0.04/kWh; RINs: D3 - $1.85/RIN; D5 - $0.90/RIN; LCFS: $100/credit; Carbon Intensities: LCFS Standard - 90g/MJ; Landfill Gas - 50g/MJ; Food Waste -20g/MJ; Animal Waste -100 g/MJ; RECs: $50/MWh RNG to Electricity efficiency: 40%

LCFS VALUES RNG @ >$30/MMBTU

GAS SEPARATION

- H_2S/CO_2
- CH_4/CO_2
- Ethane/Ethylene
- H_2/CO_2
- CO_2/N_2

LCFS VALUES RNG @ >$30/MMBTU

DESALINATION

- PRODUCED WATER
- BORON
- SEAWATER
- BACTERIA
- VIRUSES?

CAN BE COMBINED WITH GAS AND THERMAL ENERGY STORAGE

THERMAL ENERGY STORAGE

Cheapest form of energy storage

Formation Temperatures Higher than Ice is a Big Deal

Higher Latent Heat than Ice and Faster Formation

Can Be Combined with Desalination or Storage

THE ORIGINAL VISION

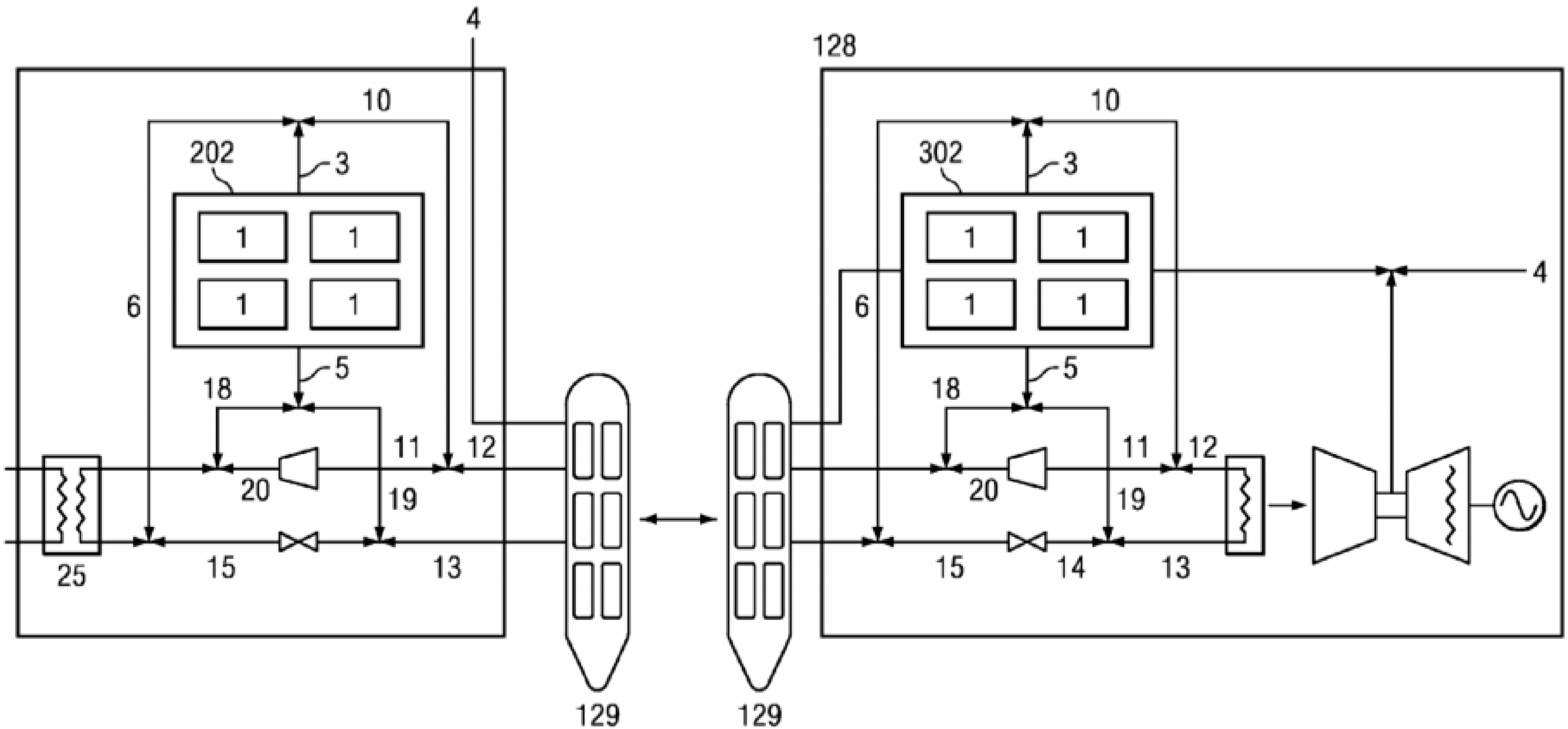


FIG. 9

OFFSHORE STRANDED GAS TO FLOATING OXYFUEL PLANT WITH INTEGRATED GAS SEPARATION AND TRANSPORT