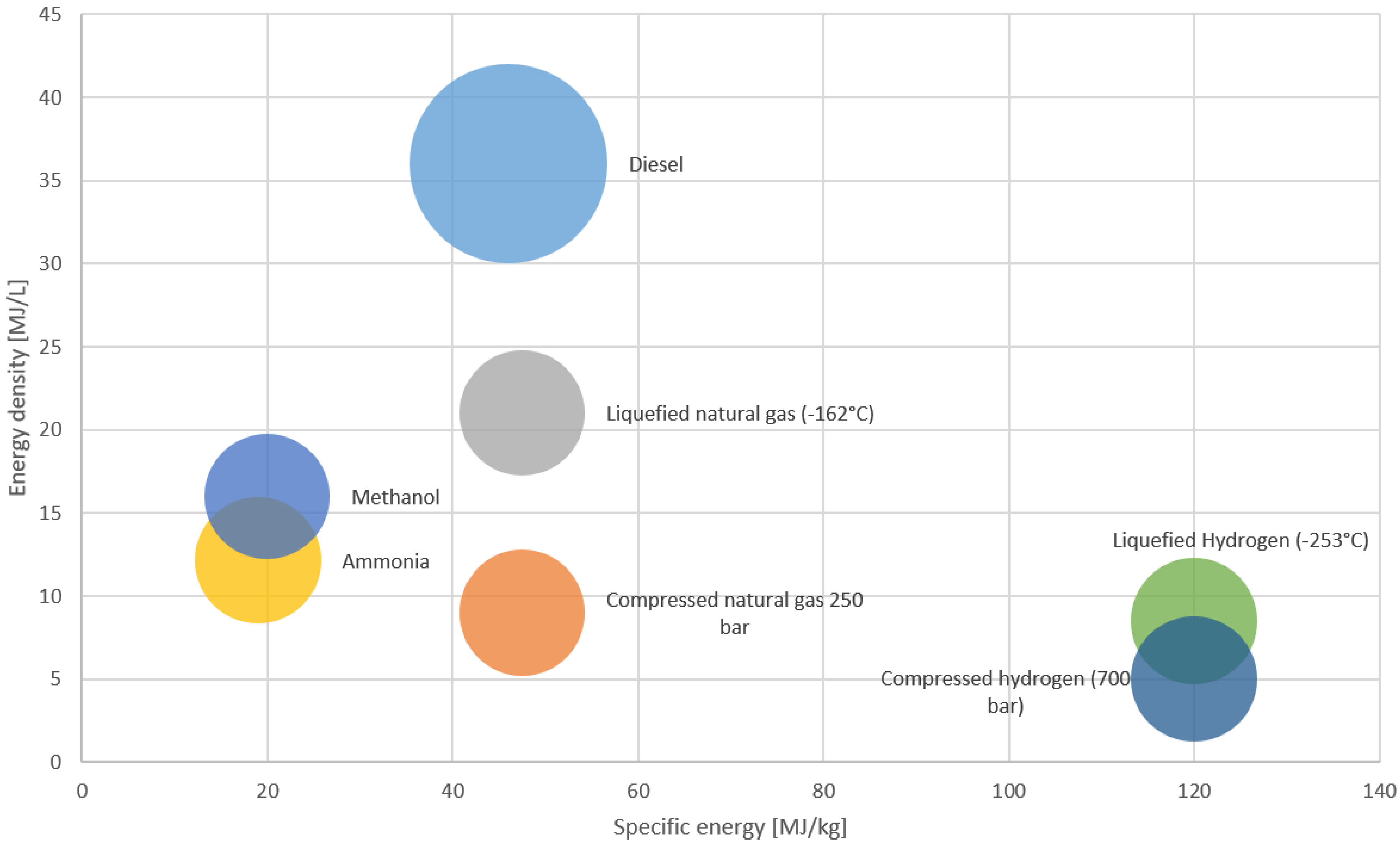
INDUSTRIAL ENERGY MANAGEMENT

ALTERNATIVE FUELS – NATURAL GAS

Dr. Davide Pivetta

AY 2024 – 2025

Fuel characteristics



Natural gas composition

General indications					
	Chemical formula	Italian gas	Russian gas	Dutch gas	Algerian gas
Methane	$\boldsymbol{CH_4}$	**99,2%**	**92,0%**	**88,85%**	**83,0%**
Ethane	C_2H_6	0,4%	3,2%	4,3%	7,5%
Prophane	C_3H_8	0,14%	0,85%	0,9%	2,0%
Butane	C_4H_{10}	---	0,2%	0,3%	0,8%
Pentane	C_5H_{12}	---	0,1%	0,1%	0,3%
Hexane	C_6H_{14}	---	0,05%	0,05%	0,3%
Carbon dioxide	CO_2	0,11%	0,3%	1,3%	0,2%
Nitrogen	N_2	0,25%	3,3%	4,2%	6,0%

Wobbe index

Wobbe index: is the main index of the interchangeability of natural gas at the same pressure. It is defined as the ratio of a gas gross calorific value (GCV) to the square root of its relative density with respect to the density of air under standard conditions (ρ).

$$I_W = \frac{\mathrm{GCV}}{\sqrt{\rho}}$$

Methane

GAS	Density (kg/Nm³)	Relative Density
Ammonia	0.771	0.597
Carbon Dioxide	1.997	1.529
Air	1.293	1.000
Nitrogen (pure)	1.251	0.967
Butane	2.703	2.091
Hydrogen	0.0899	0.0695
Oxygen	1.429	1.105
Propane	2.019	1.562
Methane (pure)	**0.71**	**0.551 = (0.713/1.293)**

Reference density is defined per Normal cubic meter (Nm^3), that is, evaluated at an absolute pressure of 1 bar and a temperature of 0°C.

Relative density is the ratio of gas density to air density (under Normal conditions).

Methane

Methane is a hydrocarbon that is part of the paraffins. It is colorless, odorless, nontoxic and non-corrosive.

Oxidation reaction:

$$CH_4 + 2(O_2) \rightarrow 2(H_2O) + CO_2 + EN$$

Calorific value: amount of heat developed by the complete combustion of a normal cubic meter of a gas.

HHV = 9.530 kcal/Nm^3 = 13.284 kcal/kg

LHV = 8.570 kcal/Nm^3 = 11.946 kcal/kg

15.44 kWh/kg

Methane

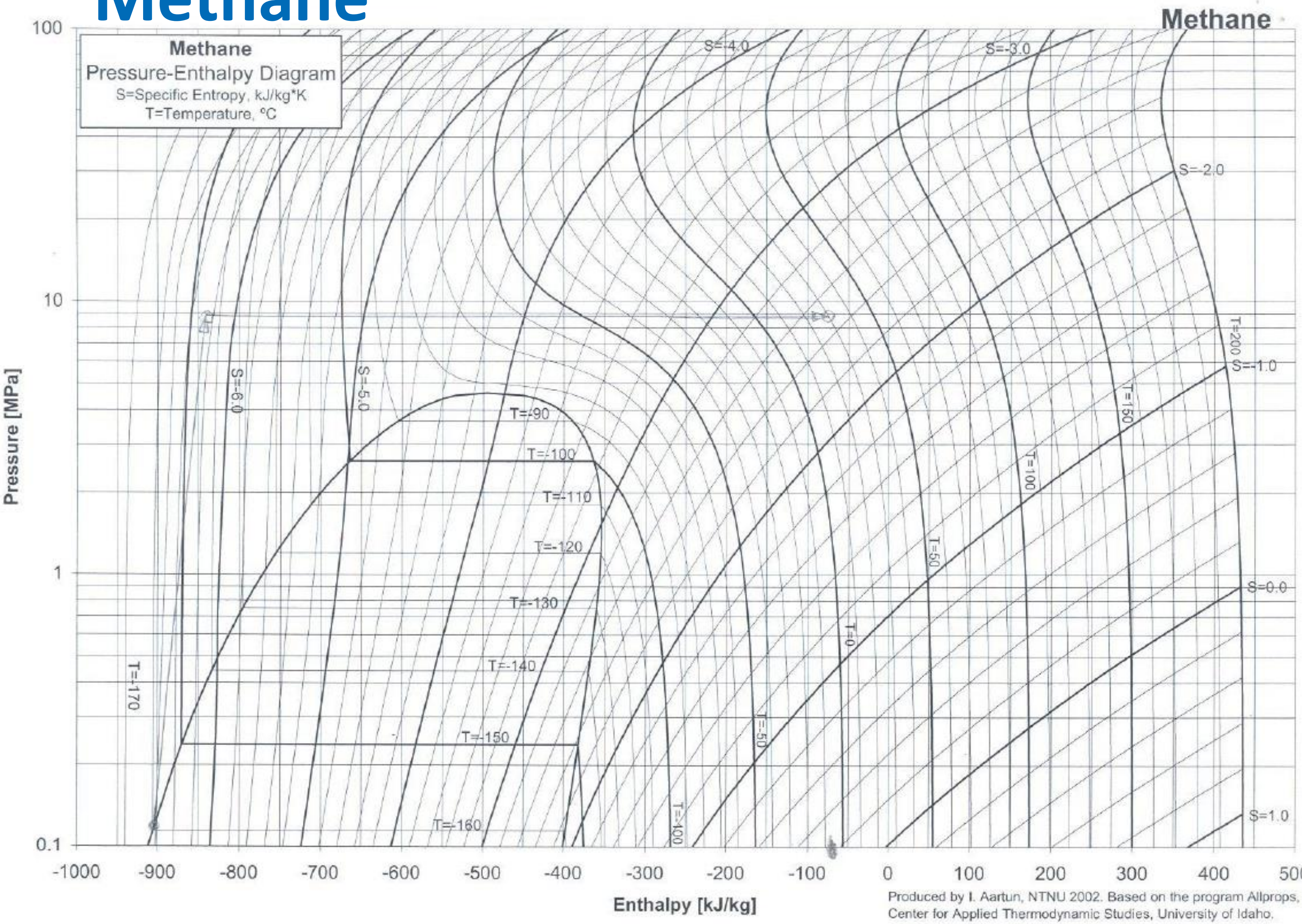
Stoichiometric air volume: volume of air technically required for complete combustion of 1 Nm^3 of gas;

For methane → 10 Nm^3 of air

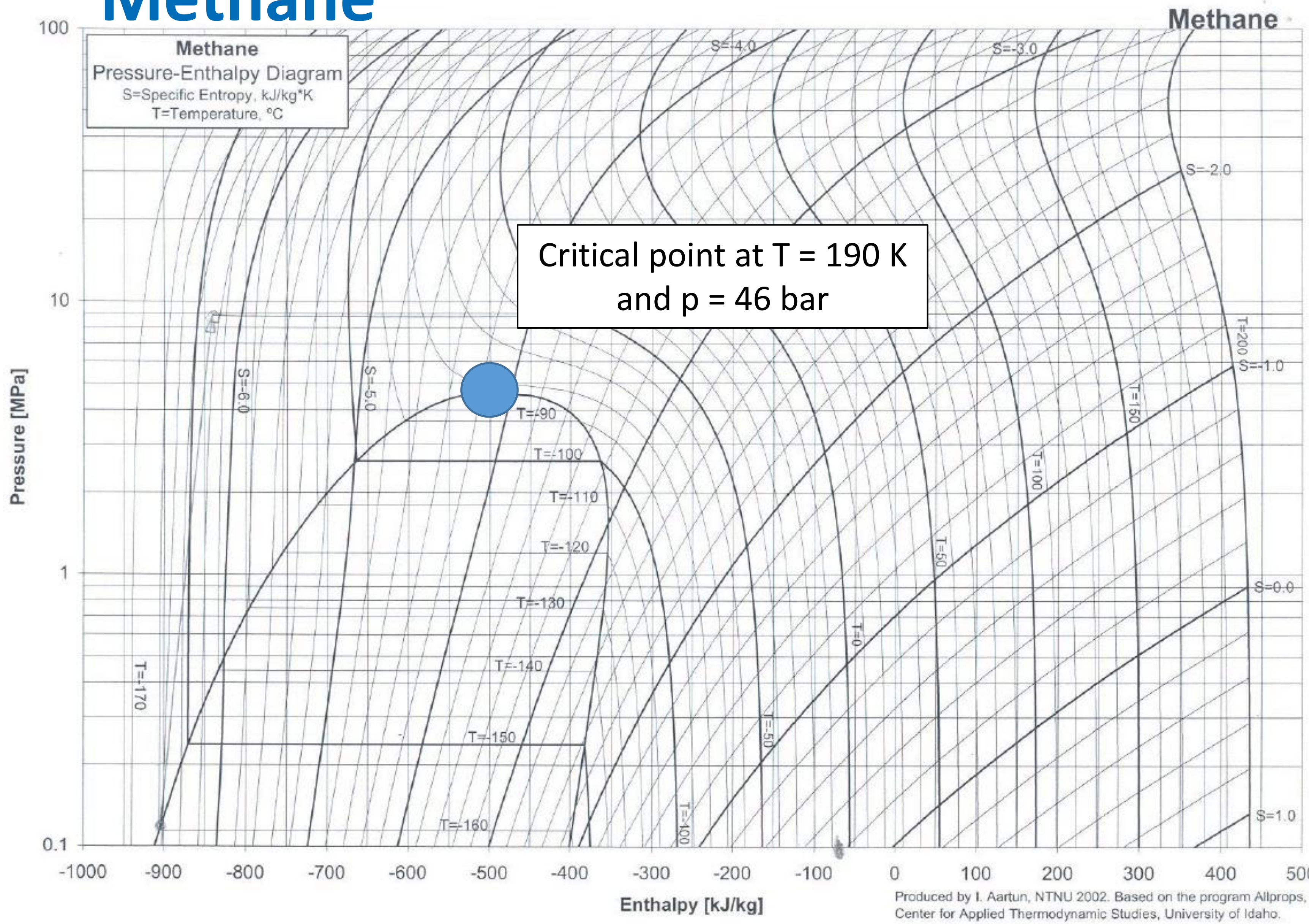
Flammability limit: defined as the ratio, by volume, of a gaseous fuel in a mixture of gas and air, below or above which the mixture will not ignite or continue to burn.

For methane → 4.5 - 15%

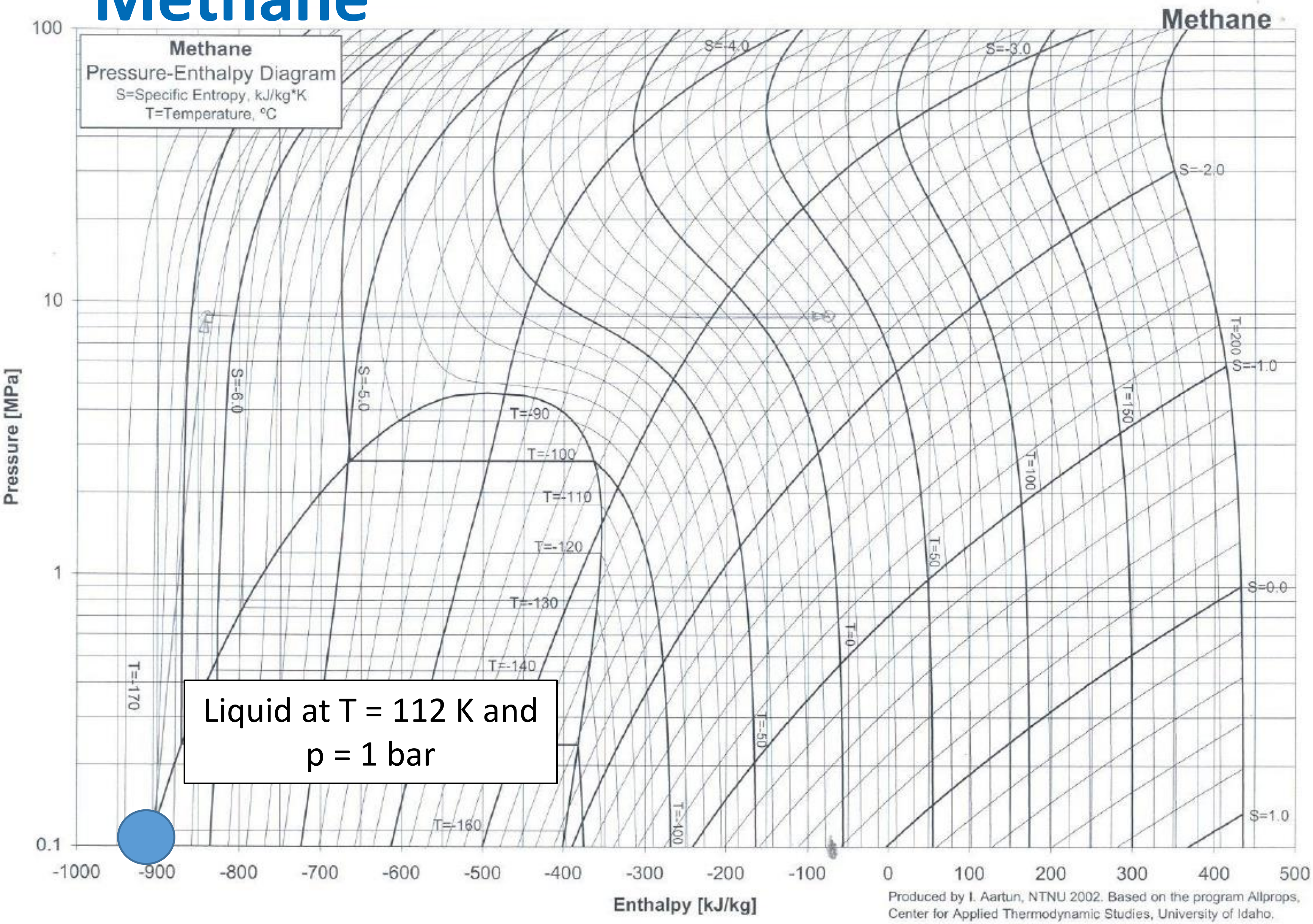
Methane


Methane
Methane
Pressure-Enthalpy Diagram
S=Specific Entropy, kJ/kg*K
T=Temperature, °C
Pressure [MPa]
Enthalpy [kJ/kg]
100
10
1
0.1
-1000
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
300
400
500
S=-6.0
S=-5.0
S=-4.0
S=-3.0
S=-2.0
S=-1.0
S=0.0
S=1.0
T=-90
T=-100
T=-110
T=-120
T=-130
T=-140
T=-150
T=-160
T=-170
T=-100
T=-50
T=0
T=50
T=100
T=150
T=200
Produced by I. Aartun, NTNU 2002. Based on the program Allprops, Center for Applied Thermodynamic Studies, University of Idaho.

Methane


Methane
Methane
Pressure-Enthalpy Diagram
S=Specific Entropy, kJ/kg*K
T=Temperature, °C
Critical point at T = 190 K and p = 46 bar
Pressure [MPa]
Enthalpy [kJ/kg]
100
10
1
0.1
-1000
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
300
400
500
S=-6.0
S=-5.0
S=-4.0
S=-3.0
S=-2.0
S=-1.0
S=0.0
S=1.0
T=-90
T=-100
T=-110
T=-120
T=-130
T=-140
T=-150
T=-160
T=-170
T=-100
T=-50
T=0
T=50
T=100
T=150
T=200
Produced by I. Aartun, NTNU 2002. Based on the program Allprops, Center for Applied Thermodynamic Studies, University of Idaho.

Methane



Methane
Methane
Pressure-Enthalpy Diagram
S=Specific Entropy, kJ/kg*K
T=Temperature, °C
Pressure [MPa]
100
10
1
0.1
Enthalpy [kJ/kg]
-1000
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
300
400
500
S=-6.0
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S=-2.0
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T=-90
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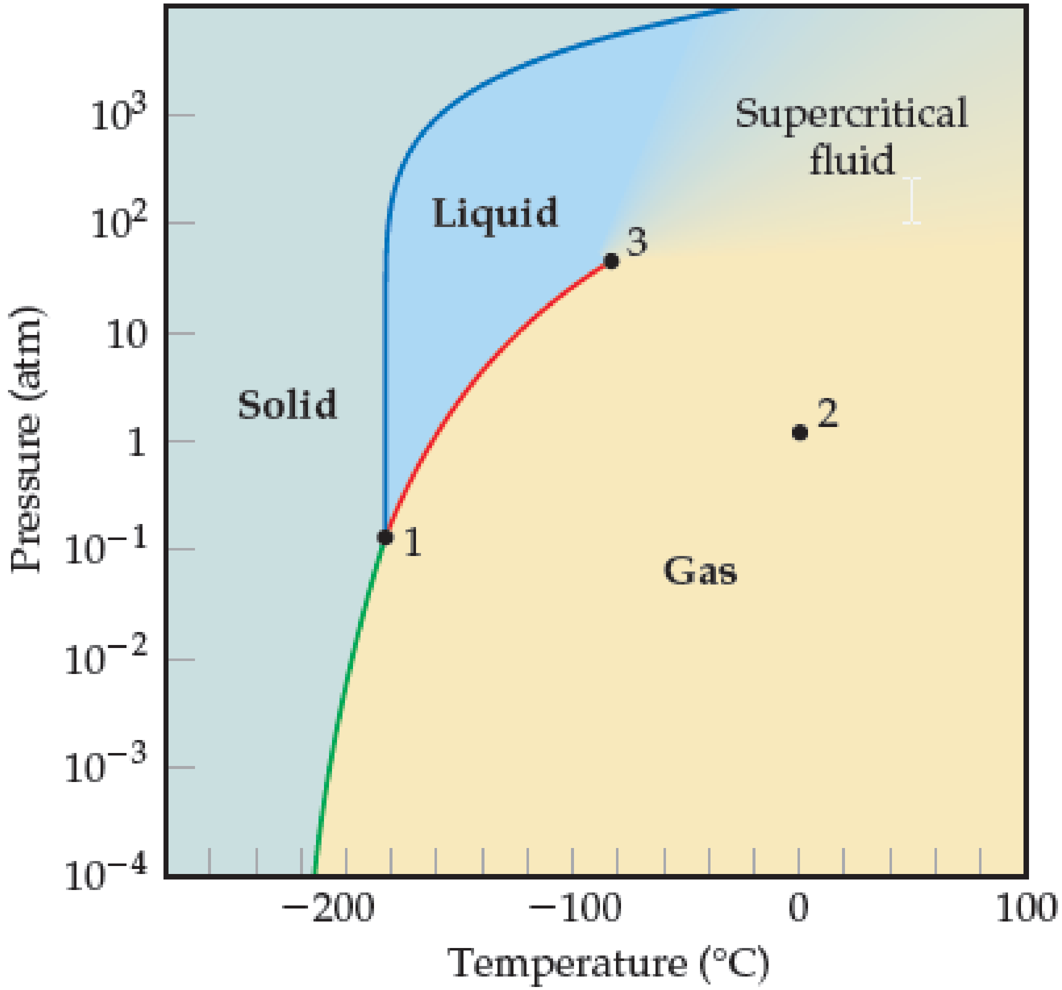
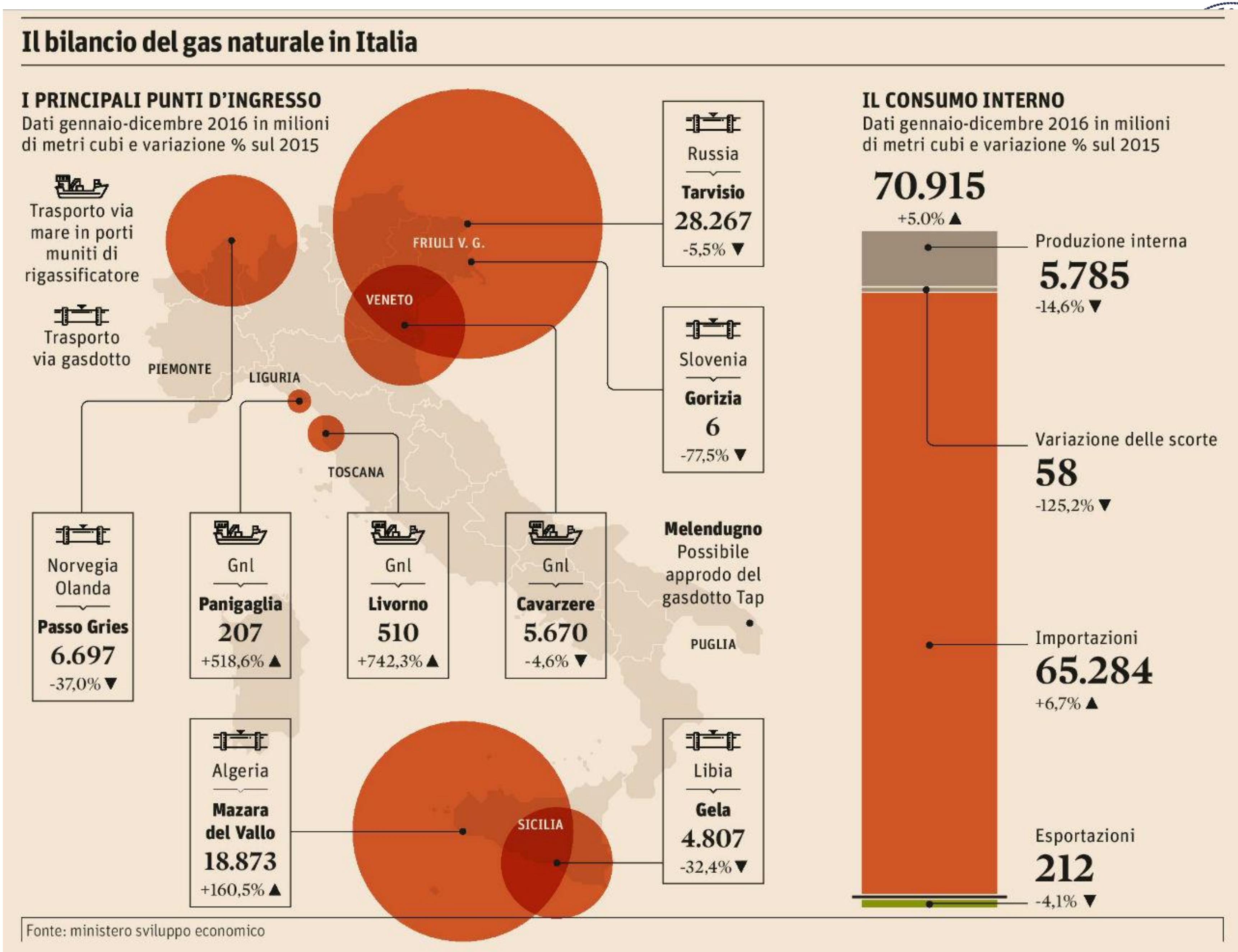
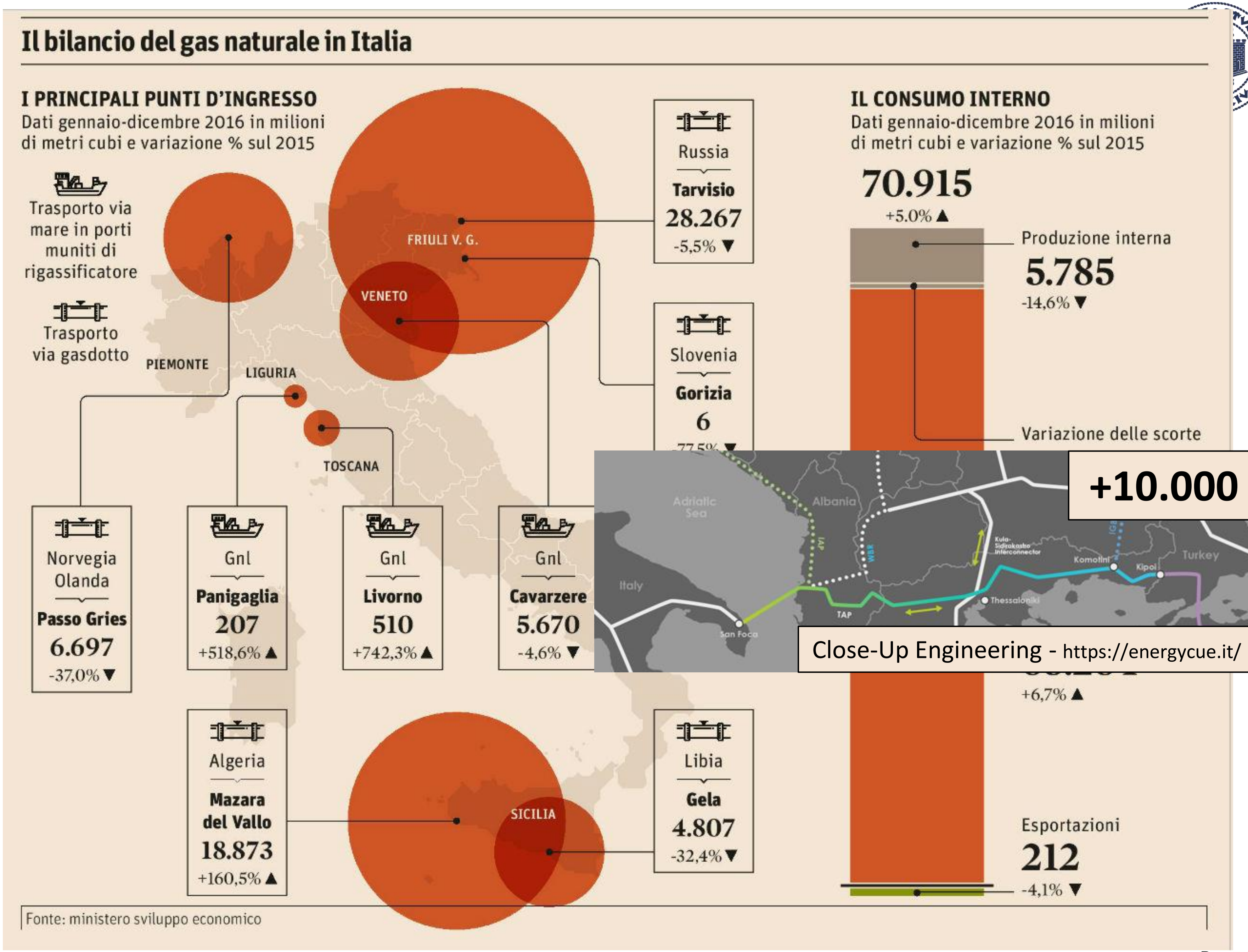
T=-110
T=-120
T=-130
T=-140
T=-160
T=-170
T=-100
T=-50
T=0
T=50
T=100
T=150
T=200
Liquid at T = 112 K and p = 1 bar
Produced by I. Aartun, NTNU 2002. Based on the program Allprops, Center for Applied Thermodynamic Studies, University of Idaho.

Methane phase diagram





Il bilancio del gas naturale in Italia
I PRINCIPALI PUNTI D'INGRESSO
Dati gennaio-dicembre 2016 in milioni di metri cubi e variazione % sul 2015
Trasporto via mare in porti muniti di rigassificatore
Trasporto via gasdotto
PIEMONTE
LIGURIA
FRIULI V. G.
VENETO
TOSCANA
PUGLIA
SICILIA
Russia
Tarvisio
28.267
-5,5% ▼
Slovenia
Gorizia
6
-77,5% ▼
Norvegia Olanda
Passo Gries
6.697
-37,0% ▼
Gnl
Panigaglia
207
+518,6% ▲
Gnl
Livorno
510
+742,3% ▲
Gnl
Cavarzere
5.670
-4,6% ▼
Melendugno
Possibile approdo del gasdotto Tap
Algeria
Mazara del Vallo
18.873
+160,5% ▲
Libia
Gela
4.807
-32,4% ▼
IL CONSUMO INTERNO
Dati gennaio-dicembre 2016 in milioni di metri cubi e variazione % sul 2015
70.915
+5.0% ▲
Produzione interna
5.785
-14,6% ▼
Variazione delle scorte
58
-125,2% ▼
Importazioni
65.284
+6,7% ▲
Esportazioni
212
-4,1% ▼
Fonte: ministero sviluppo economico



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+5.0% ▲
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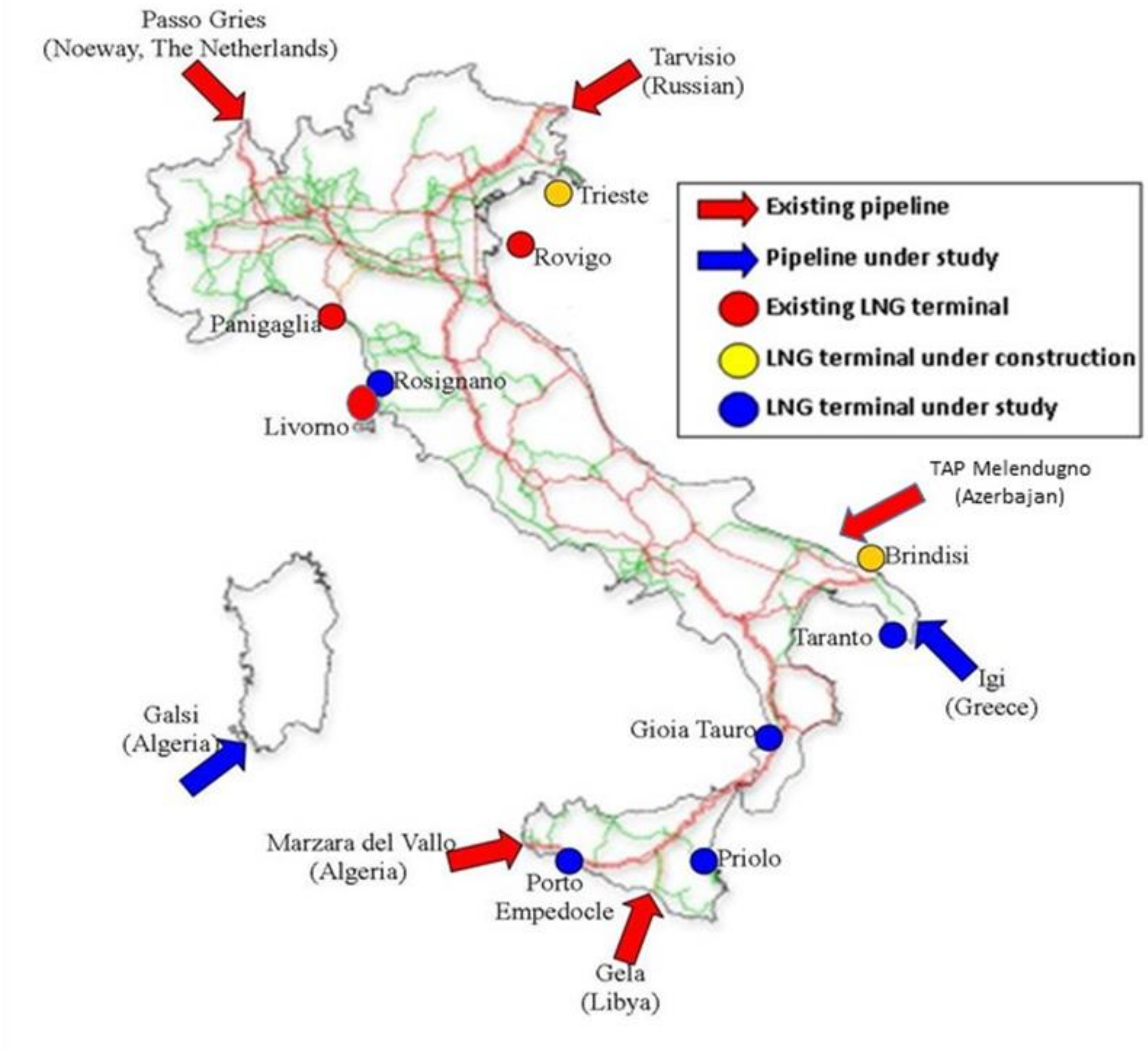
5.785
-14,6% ▼
Variazione delle scorte
+6,7% ▲
Esportazioni
212
-4,1% ▼
Fonte: ministero sviluppo economico
+10.000
Adriatic Sea
Albania
Italy
San Foca
TAP
IAP
WBR
Thessaloniki
Komotini
Kipoi
Turkey
Close-Up Engineering - https://energycue.it/

Natural gas transport in italy



https://sisen.mase.gov.it/dgsaie/bilancio-gas-naturale

BILANCIO MENSILE DEL GAS NATURALE
ITALIA (1)
(Milioni di Standard metri cubi a 38,1 MJ/m3)

			Dicembre			Gennaio-Dicembre		
			2024	2023	Variaz. %	2024	2023	Variaz. %
a)	PRODUZIONE NAZIONALE (2)		322	240	34.3%	2,940	2,988	-1.6%
b)	IMPORTAZIONI		5,421	4,836	12.1%	59,163	61,604	-4.0%
	per punto di ingresso	MAZARA DEL VALLO	1,758	1,782	-1.4%	21,068	23,040	-8.6%
		GELA	88	167	-47.2%	1,406	2,522	-44.2%
		TARVISIO	556	223	149.2%	5,607	2,844	97.1%
		PASSO GRIES	564	322	75.2%	6,005	6,567	-8.5%
		MELENDUGNO	932	804	16.0%	10,315	9,988	3.3%
		PIOMBINO (2)	392	359	9.4%	3,612	1,238	191.7%
		PANIGAGLIA (2)	-	60	-100.0%	962	2,603	-63.0%
		CAVARZERE (2)	754	727	3.7%	9,058	8,873	2.1%
		LIVORNO (2)	375	386	-2.8%	1,084	3,860	-71.9%
		GORIZIA	0	5	-96.5%	25	41	-39.6%
		ALTRI	1	2	-55.0%	21	29	-28.1%
c)	Esportazioni		74	117	-36.5%	619	2,620	-76.4%
d)	Variazione delle scorte (2)		- 2,246	- 2,276	-1.3%	- 381	457	-183.5%
e) = a)+b)-c)-d)	Consumo Interno Lordo		7,915	7,235	9.4%	61,864	61,516	0.6%

Fonte: Ministero dell'ambiente e della sicurezza energetica - Dipartimento Energia - DGIS

(1) Preconsuntivi al netto dei transiti
(2) comprende consumi e perdite

https://sisen.mase.gov.it/dgsaie/bilancio-gas-naturale

GAS NATURALE TOTALE DISTRIBUITO PER REGIONE				
ANNO 2023				
Volumi espressi in M Sm3; gas da 10,57275 25-15 kWh/Sm3 (*)				
REGIONI	**INDUSTRIALE**	**TERMOELETTRICO**	**RETI DI DISTRIBUZIONE**	**T O T A L E**
PIEMONTE	1,006.4	2,784.2	2,946.1	**6,736.7**
VALLE D'AOSTA	56.2	0.0	36.1	**92.3**
LOMBARDIA	2,218.8	5,152.3	7,059.2	**14,430.3**
TRENTINO ALTO ADIGE	272.0	17.4	627.0	**916.4**
VENETO	1,198.8	514.8	3,357.9	**5,071.5**
FRIULI VENEZIA GIULIA	526.3	691.8	727.7	**1,945.8**
LIGURIA	206.2	184.7	701.6	**1,092.5**
EMILIA ROMAGNA	2,343.5	2,800.5	3,359.6	**8,503.6**
TOSCANA	775.5	1,488.4	1,841.6	**4,105.5**
UMBRIA	232.5	141.7	419.3	**793.5**
MARCHE	282.1	2.9	679.5	**964.5**
LAZIO	474.0	459.1	1,753.6	**2,686.7**
ABRUZZO	371.5	292.1	597.8	**1,261.4**
MOLISE	16.3	91.4	121.9	**229.6**
CAMPANIA	413.4	691.6	1,029.8	**2,134.8**
PUGLIA	610.7	2,405.6	964.7	**3,981.0**
BASILICATA	95.8	23.6	217.3	**336.7**
CALABRIA	34.1	1,740.4	272.5	**2,047.0**
SICILIA	655.1	1,777.3	595.5	**3,027.9**
SARDEGNA	0.0	0.0	0.0	**0.0**
				0.0
T O T A L E	***11,789.2***	***21,259.8***	***27,308.7***	***60,357.7***

Ministero dell'ambiente e della sicurezza energetica

Statistiche energetiche e minerarie

HOME PUBBLICAZIONI OPEN DATA RILEVAZIONI

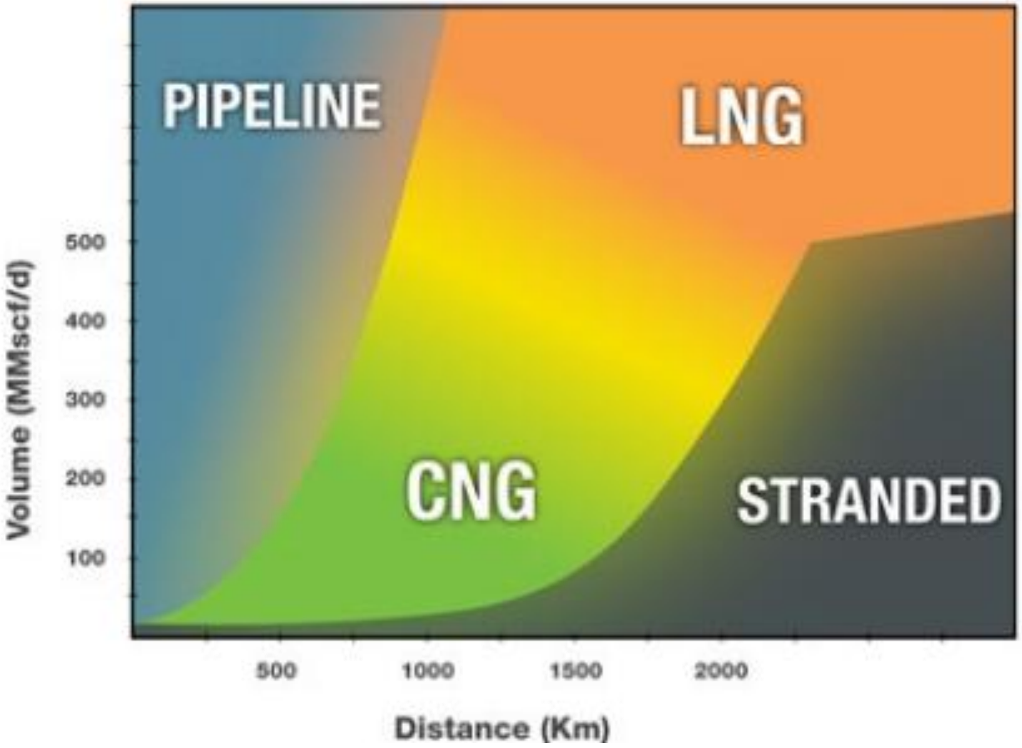
https://dgsaie.mise.gov.it/bilancio-gas-naturale

IMPORTAZIONI DI GAS NATURALE PER PUNTO DI INGRESSO - ANNO 2022- Volumi espressi in M Sm3; gas da 10,57275 $_{25-15}$ kWh/Sm$^{3\ (*)}$

	MESE													
	Gennaio	Febbraio	Marzo	Aprile	Maggio	Giugno	Luglio	Agosto	Settembre	Ottobre	Novembre	Dicembre	Totale 2022	Peso %
MAZARA DEL VALLO	2,113	1,977	2,129	2,093	2,247	2,145	1,901	2,148	2,343	2,202	2,120	2,566	**25,982**	**35.8%**
TARVISIO	1,699	1,429	2,381	1,446	1,299	1,015	1,243	1,103	801	317	467	788	**13,988**	**19.3%**
MELEDUGNO	698	674	821	852	847	854	865	750	818	869	816	1,460	**10,325**	**14.2%**
ROVIGO - CAVARZERE	437	406	551	562	694	638	666	566	669	688	731	763	**7,372**	**10.2%**
PASSO GRIES - MASARA	746	495	180	641	805	341	1,250	585	360	432	301	451	**6,588**	**9.1%**
OLT LIVORNO	292	291	414	140	34	334	409	437	355	180	174	582	**3,642**	**5.0%**
GELA	227	111	162	254	239	198	199	194	185	284	272	295	**2,619**	**3.6%**
PANIGAGLIA	26	46	5	96	253	296	207	183	0	267	286	337	**2,003**	**2.8%**
VENTIMIGLIA	2	2	3	2	2	2	2	2	2	2	1	2	**25**	**0.0%**
FALCONARA	0	1	1	1	1	3	3	3	3	3	3	3	**24**	**0.0%**
GORIZIA	10	0	0	0	0	2	1	0	0	1	1	8	**23**	**0.0%**
CAGLIARI	0	0	0	0	0	0	0	0	0	0	0	0	**0.2**	**0.0%**
CASALBORSETTI	0	0	0	0	0	0	0	0	0	0	0	0	**0.0**	**0.0%**
Totale complessivo	**6,249**	**5,431**	**6,647**	**6,087**	**6,422**	**5,826**	**6,746**	**5,972**	**5,537**	**5,245**	**5,172**	**7,256**	72,591	**100.0%**

Natural gas transport

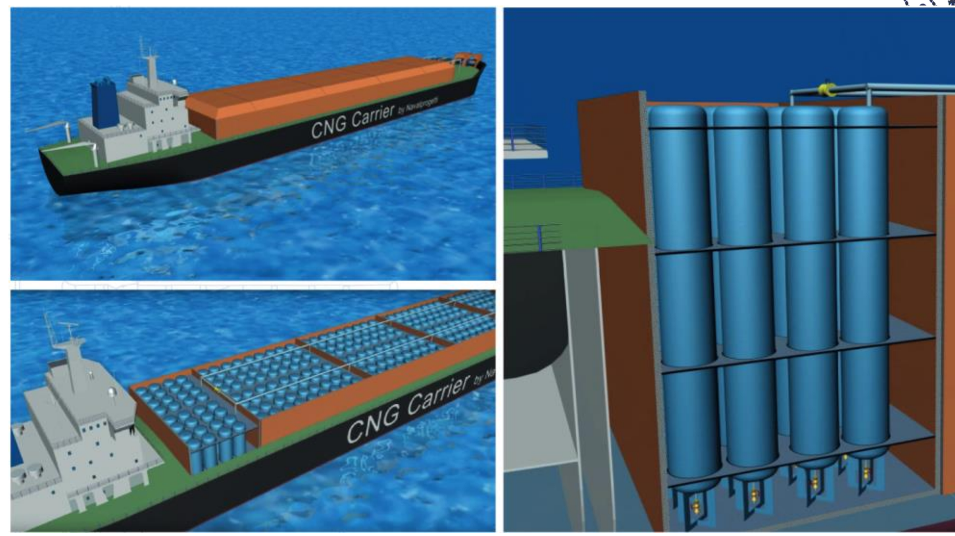
Natural gas transport



GASVESSEL Project - https://www.gasvessel.eu/wp-content/uploads/2018/06/D2.1-Scenario-Description-and-Characterization.pdf

CNG

(Compressed Natural Gas)



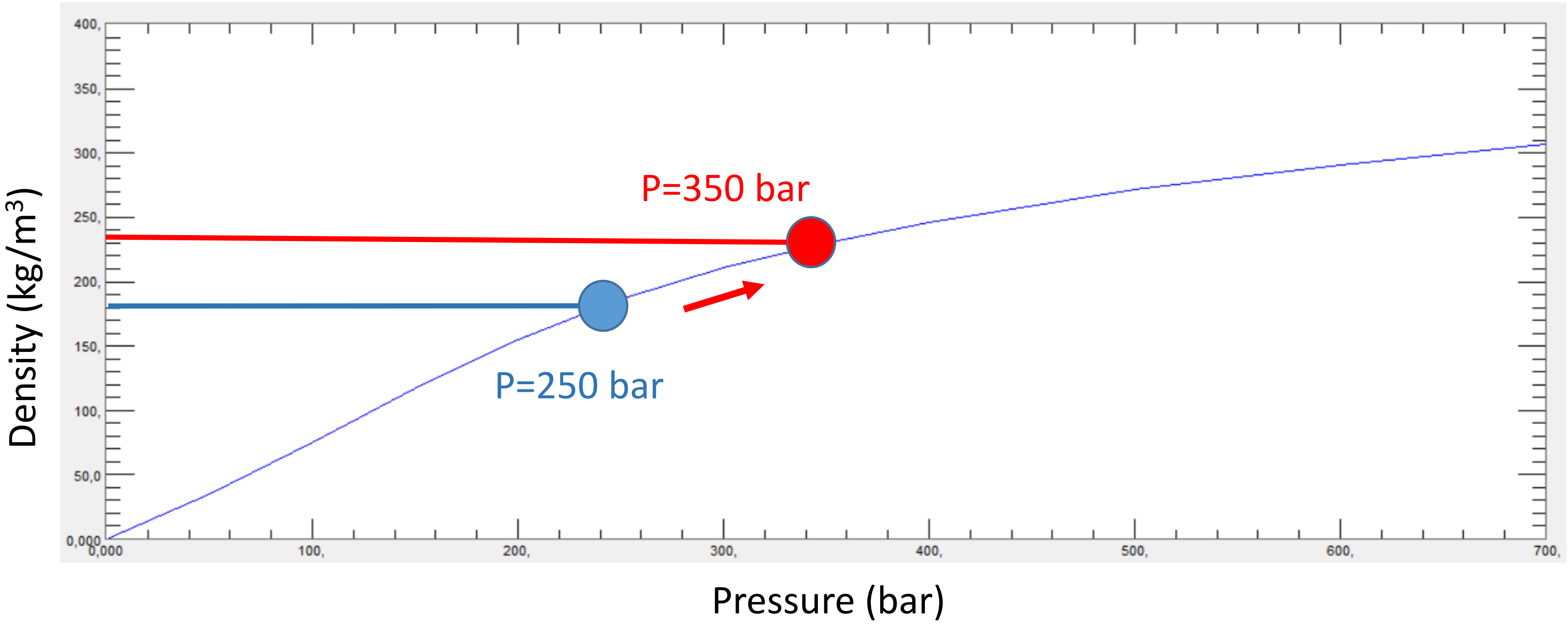
GASVESSEL Project - https://www.gasvessel.eu/

LNG

(Liquified Natural Gas)

Compressed natural gas (CNG)

Density as a function of pressure for methane at T = 300 K



Tanks for CNG

Type 1 CNG Tank

- Made entirely of steel;
- Very heavy.

Type 2 CNG Tank

- Steel construction;
- Rolled composite material;
- 25 % lighter than Type 1.

Type 3 CNG Tank

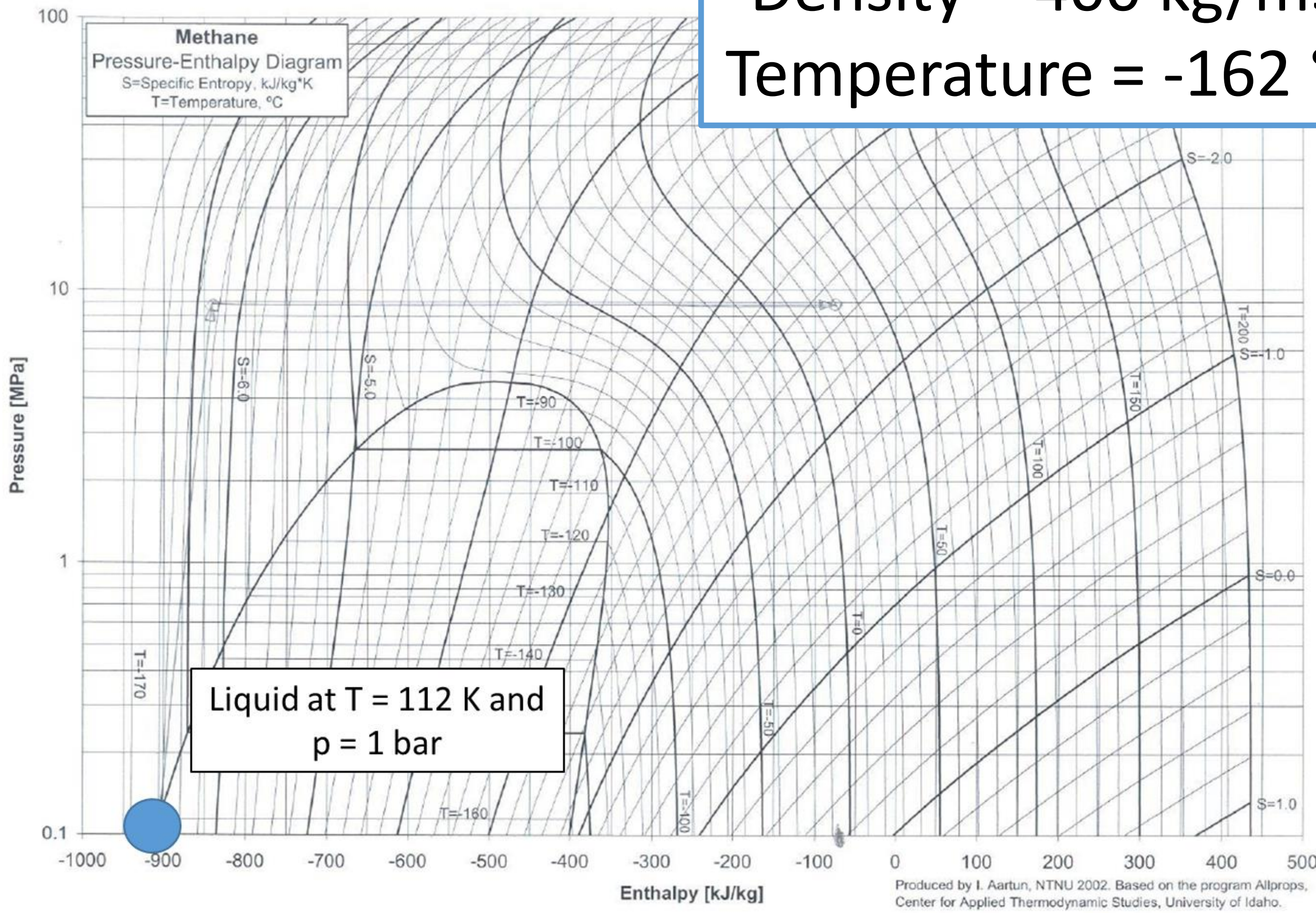
- Aluminium liner and composite shell;
- Significant weight savings.

Type 4 CNG Tank

- Polyethylene liner and composite shell;
- Significant weight savings.

Liquefied natural gas (LNG)

Density = 400 kg/m3
Temperature = -162 °C



Liquid at T = 112 K and p = 1 bar

LNG composition

Terminal	Methane	Ethane	Propane	Butane	Nitrogen
Abu Dhabi	87.07	11.41	1.27	0.14	0.11
Alaska	99.80	0.10	N.A.	N.A.	N.A.
Algeria	91.40	7.87	0.44	0.00	0.28
Australia	87.82	8.30	2.98	0.88	0.01
Brunei	89.40	6.30	2.80	1.30	0.00
Indonesia	90.60	6.00	2.48	0.82	0.09
Malaysia	91.15	4.28	2.87	1.36	0.32
Oman	87.66	9.72	2.04	0.69	0.00
Qatar	89.87	6.65	2.30	0.98	0.19
Trinidad	92.26	6.39	0.91	0.43	0.00
Nigeria	91.60	4.60	2.40	1.30	0.10

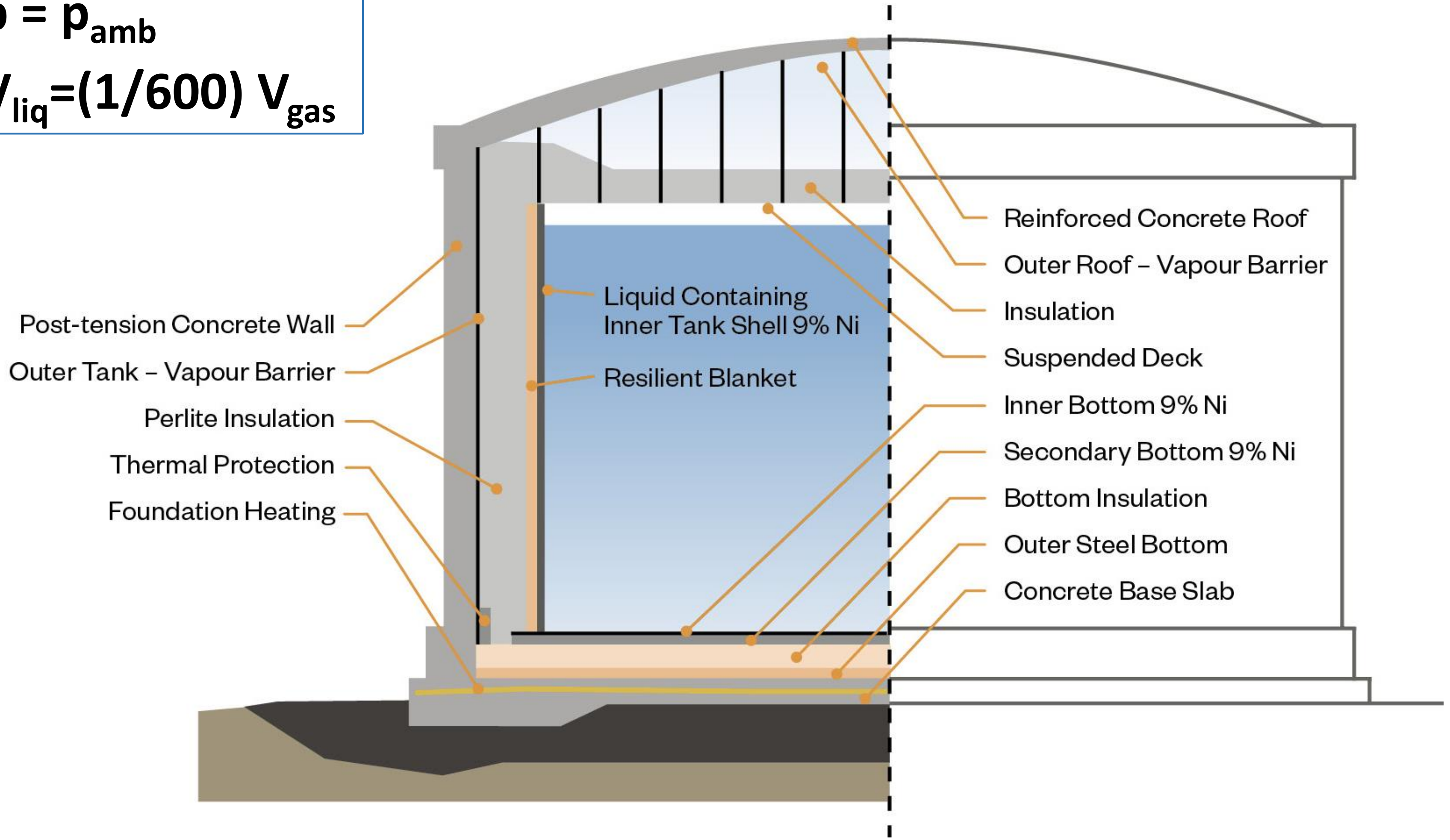
Kanbur BB, Xiang L, Dubey S, Choo FH, Duan F. Cold utilization systems of LNG: a review. Renew Sustain Energy Rev 2017;79:1171–88. https://doi.org/10.1016/J. RSER.2017.05.161.

LNG tank

$T = 112\ K$

$p = p_{amb}$

$V_{liq}=(1/600)\ V_{gas}$



LNG tank

Primary barrier:

Self supporting IMO independent tank type A.

Material Stainless steel of 9% nickel steel.

Secondary barrier:

Liquid tight thermal insulation.

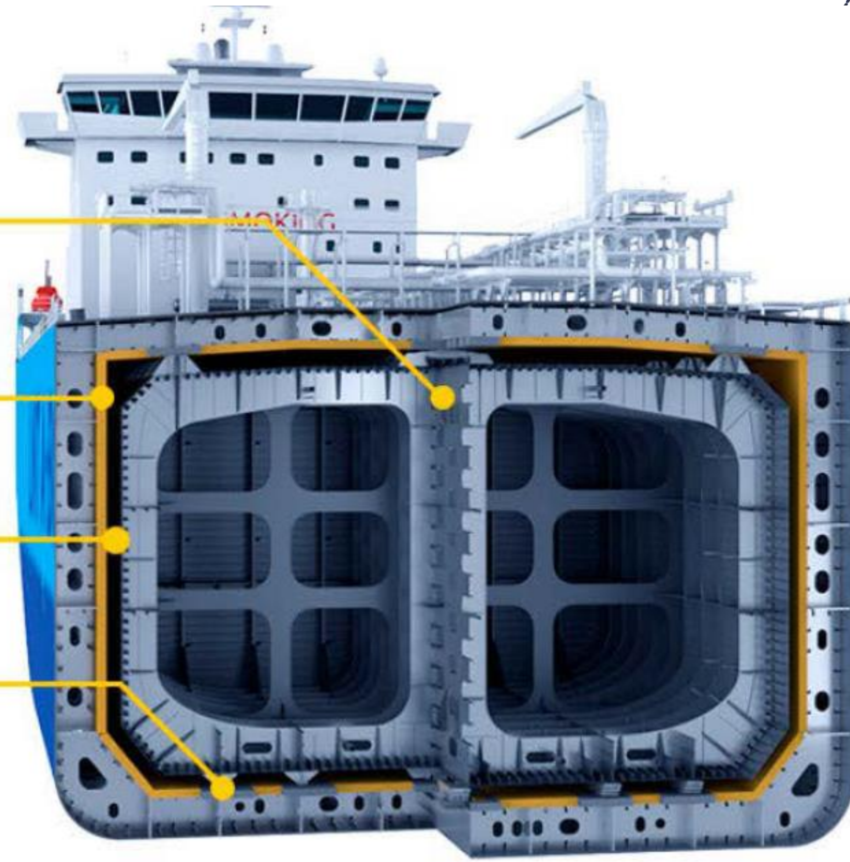
Based on polyurethane foam panels.

Interbarrier space:

Accessible space between tank and insulation.

Cargo tank support:

conventional cargo tank support system.



Phenomena to be controlled:

- **Boil-off gas:** gas produced by evaporation of the cryogenic liquid.
- **Stratification:** natural arrangement of LNG components according to specific density.
- **Roll-over:** phenomenon of abrupt mixing of layers with different densities. It causes an increase in the evaporation rate and consequent increase in pressure.

LNT-Marine – https://lntmarine.com/

LNG boil-off

Techniques to reduce boil-off::

1. Mechanical mixing of LNG to avoid stratification phenomena.
2. Adequate tank insulation to minimise heat exchange with the outside.
3. Use of nozzles that atomise part of the LNG in the upper part of the tank in order to cool its contents.
4. Removal of part of the boil-off gas in order to avoid the pressure increase that would further promote the evaporation phenomenon.

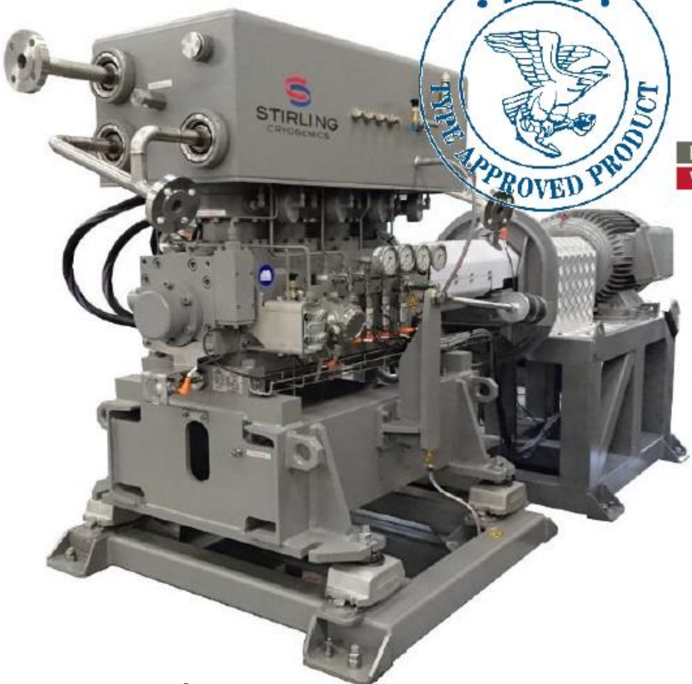
Boil-off rate = 0.1 % vol/day

Boil-off gas can be:

- **Used directly** to feed energy conversion units (e.g. engines, boilers, etc.);
- **Re-liquefied.**

The plant configuration depends on the amount of boil-off gas produced during transport

LNG boil-off re-liquefication



Stirling cryogenics

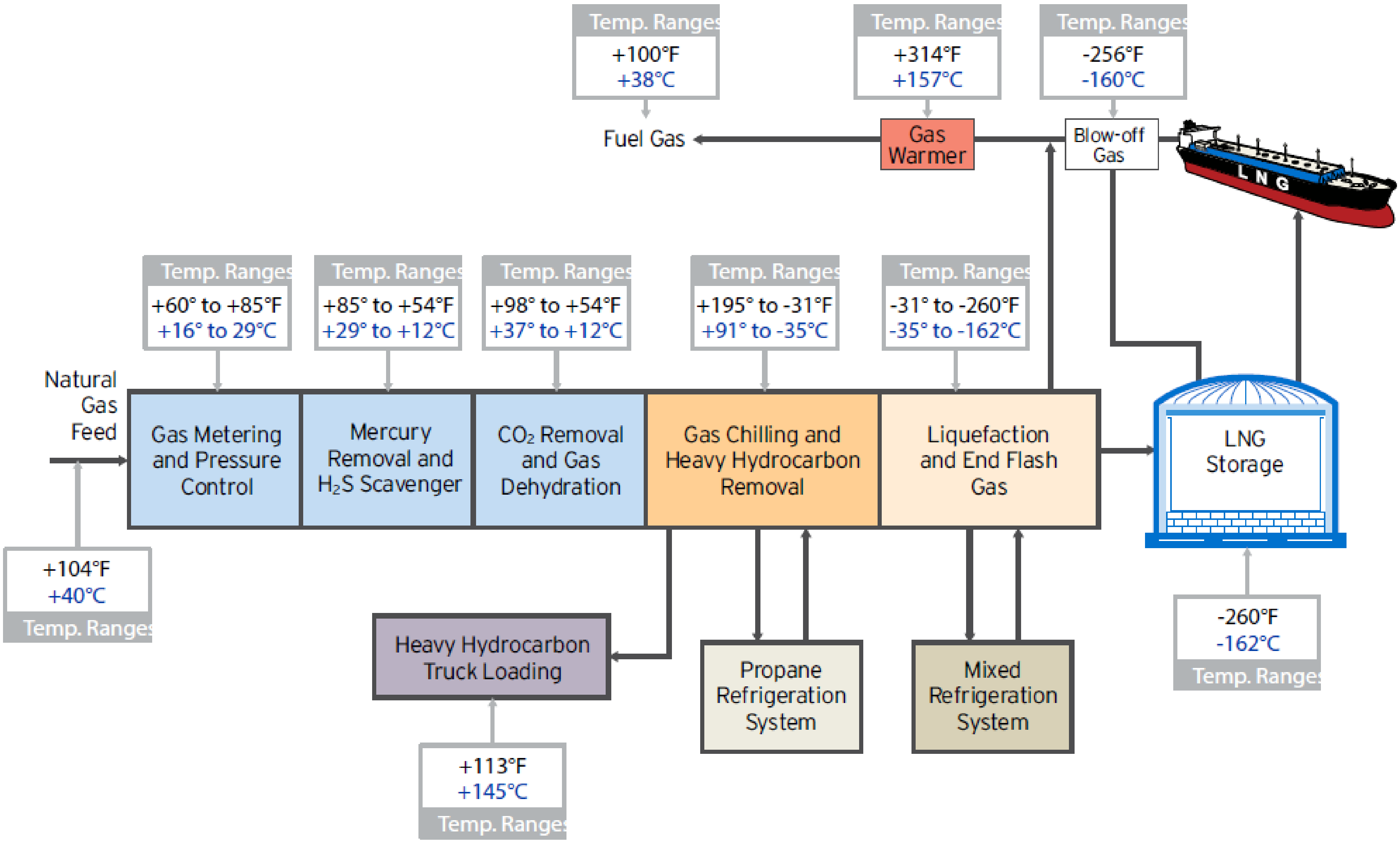
https://www.stirlingcryogenics.eu/

Cryostar

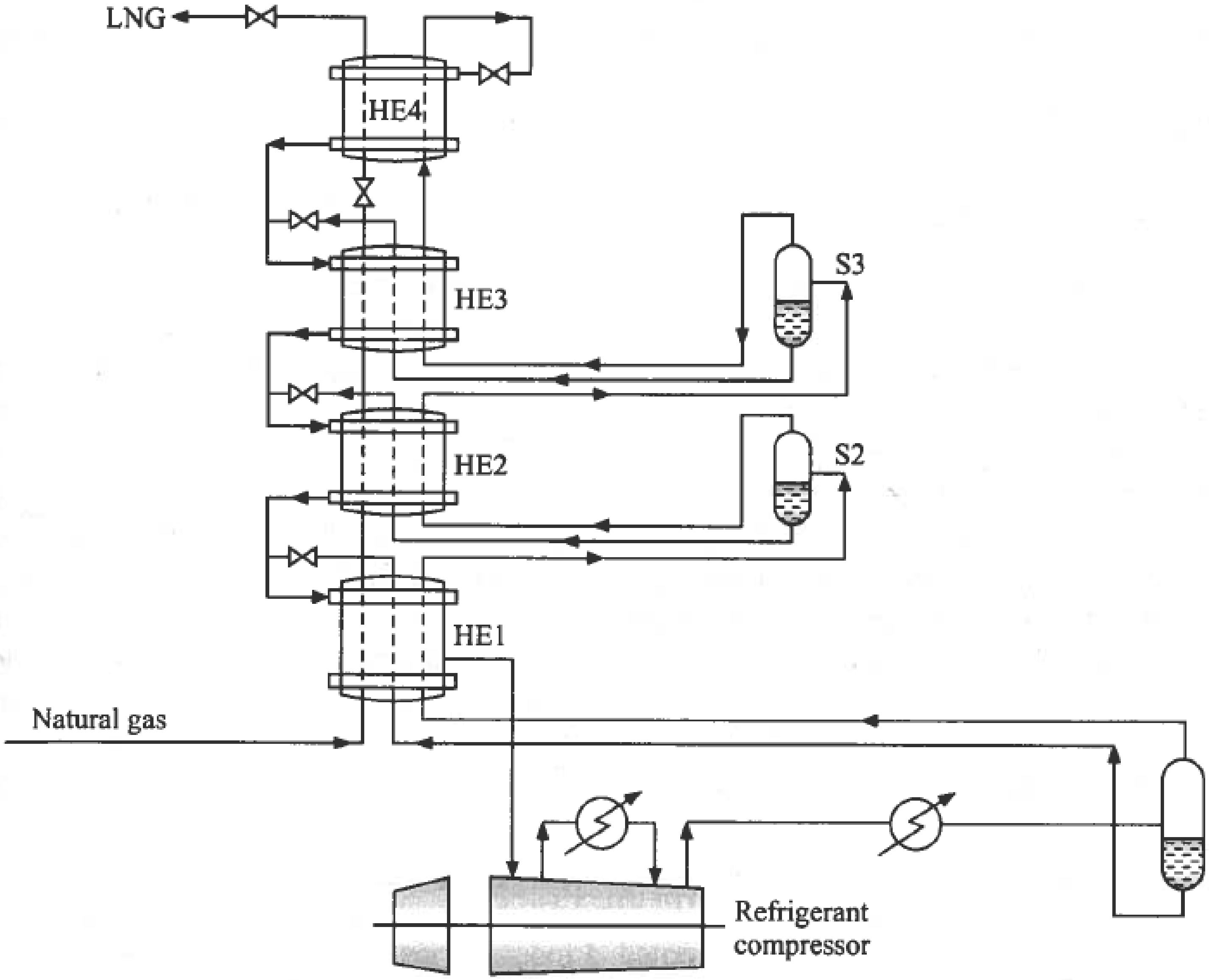
https://cryostar.com/

Liquefaction process

LNG liquefication process



MULTICOMPONENT REFRIGERANT (MCR)



Energy demand < 250 kWh/t_{LNG}

3,5 mtpa < Cap. liq. < 8 mtpa

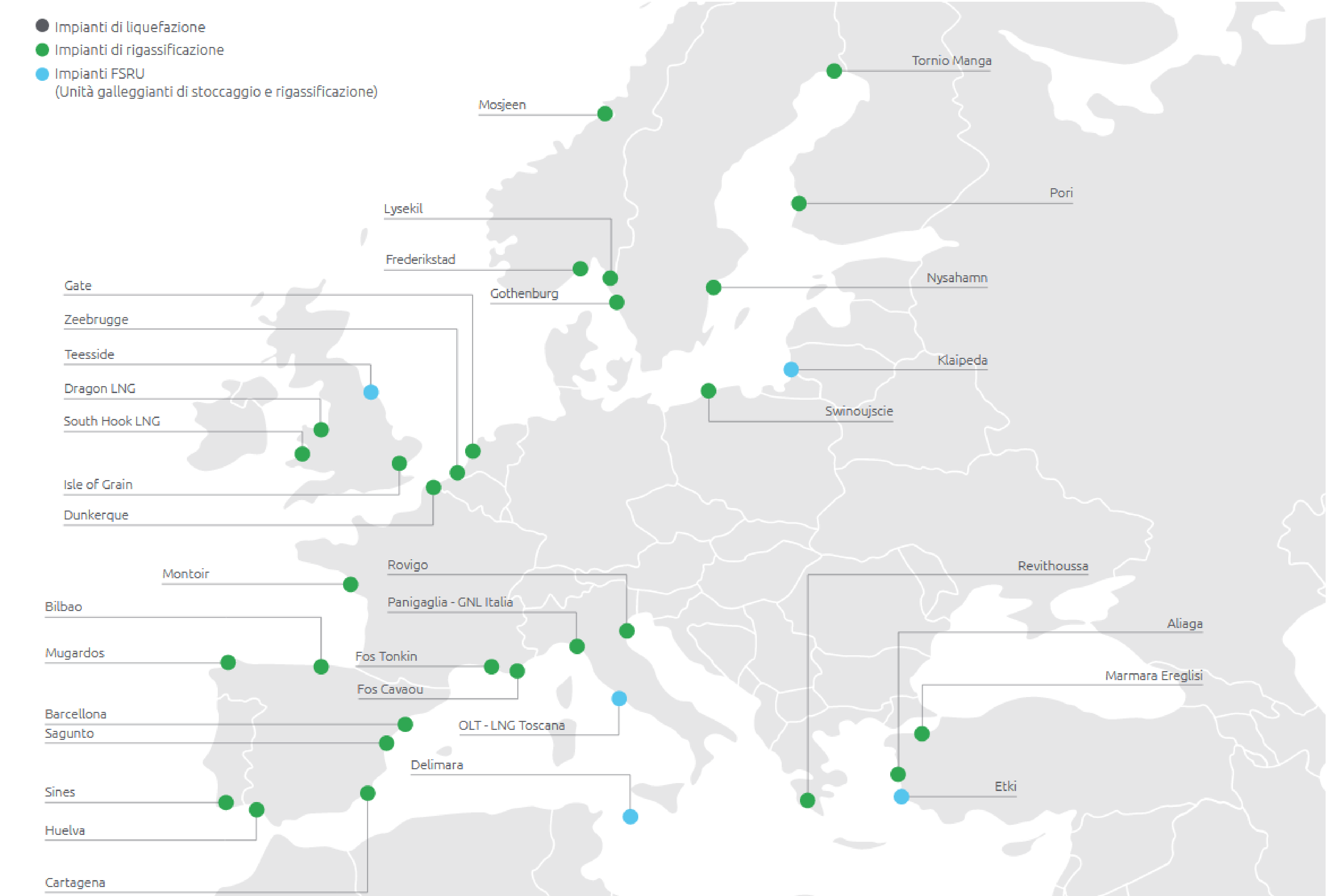
Cameron LNG - https://cameronlng.com/

LNG liquefication process

Processes with a mixed refrigerant cycle and propane pre-cooling account for more than 90 % of natural gas liquefaction plants.

Losses in the LNG value chain	
Process phases	**Percentage loss compared to natural gas input**
Liquefaction	8 - 10 %
Shipping	0.15 – 0.3 %
Regassification	2 – 2.5 %

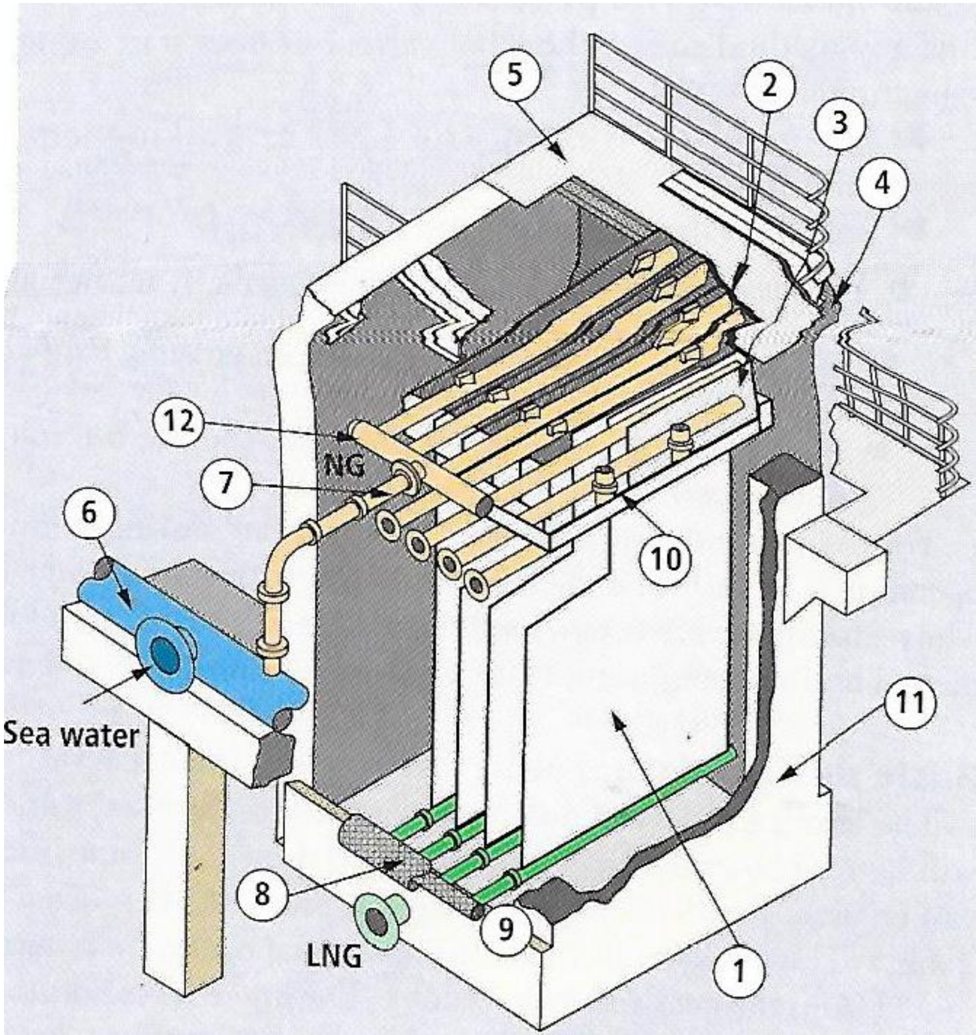
Regassification process



Note: FSRU – Floating Storage Regasification Units

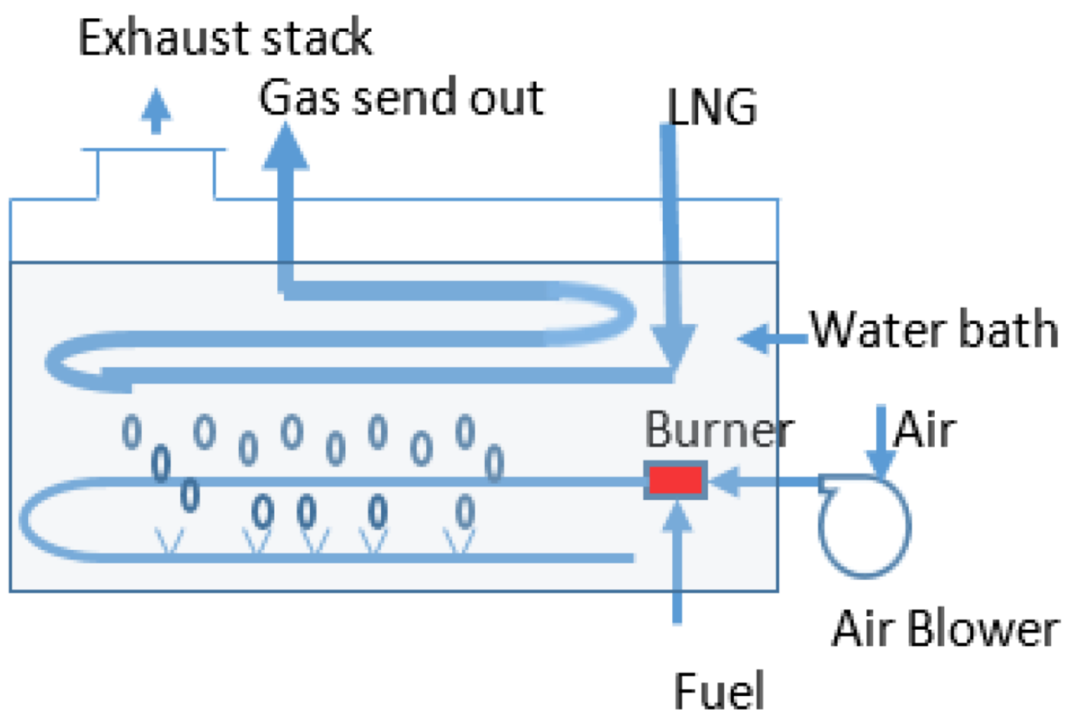
Air vaporizer

Open-rack vaporizer



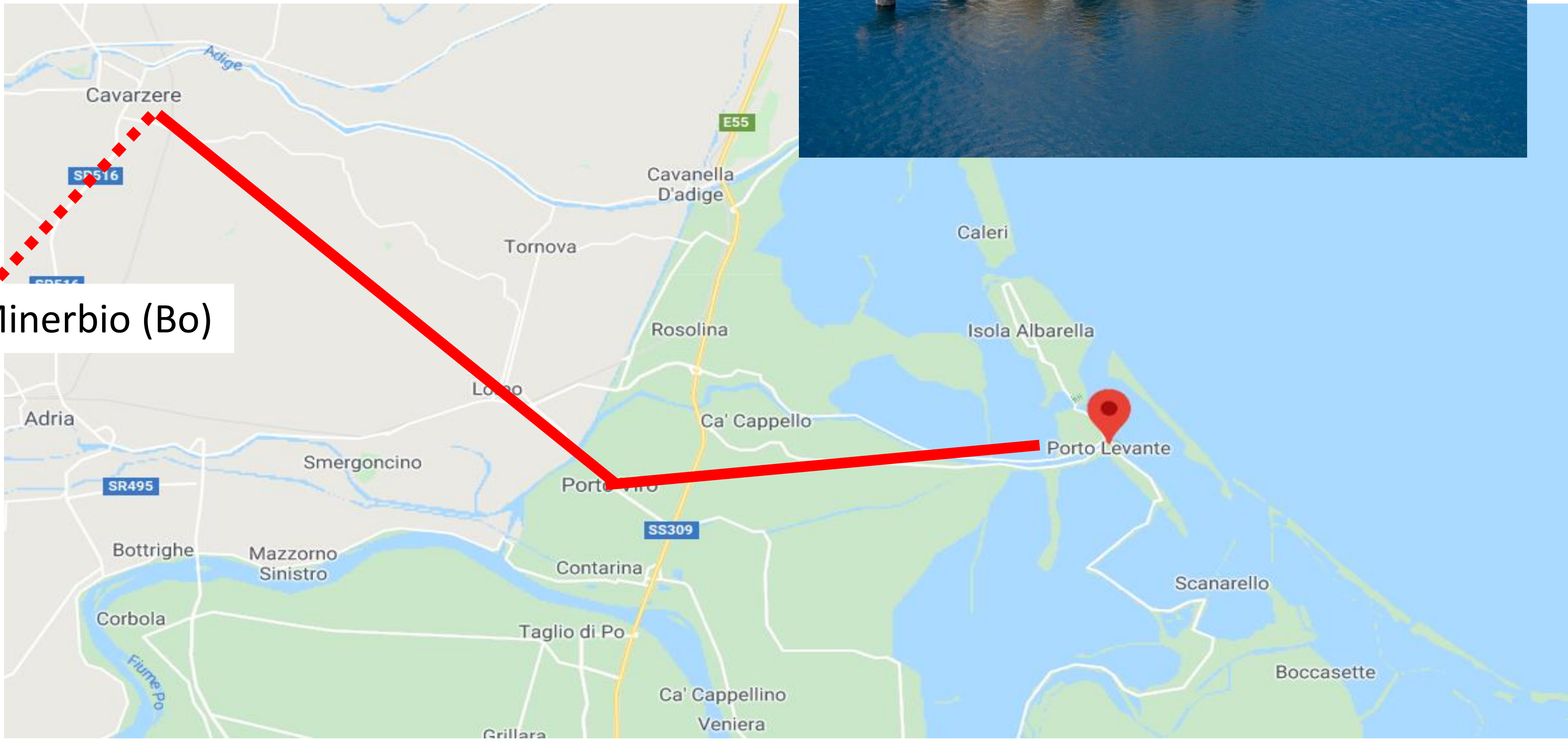
1. Heat transfer tubes;
2. Double-face trickling through;
3. Single-face trickling through;
4. Wind shield;
5. Support structure;
6. Sea water inlet manifold;
7. Sea water header;
8. Insulation;
9. LNG inlet manifold;
10. Sea water header;
11. Concrete foundation;
12. LNG outlet manifold;

Submerged combustion vaporizer



Adriatic Sea LNG terminal

C_{max}= 8 billion Nm^3/anno



Minerbio (Bo)

LNG regassification unit Panigaglia (La Spezia)

C_{max}= 4 billion Nm^3/anno

OLT Offshore in Tuscany

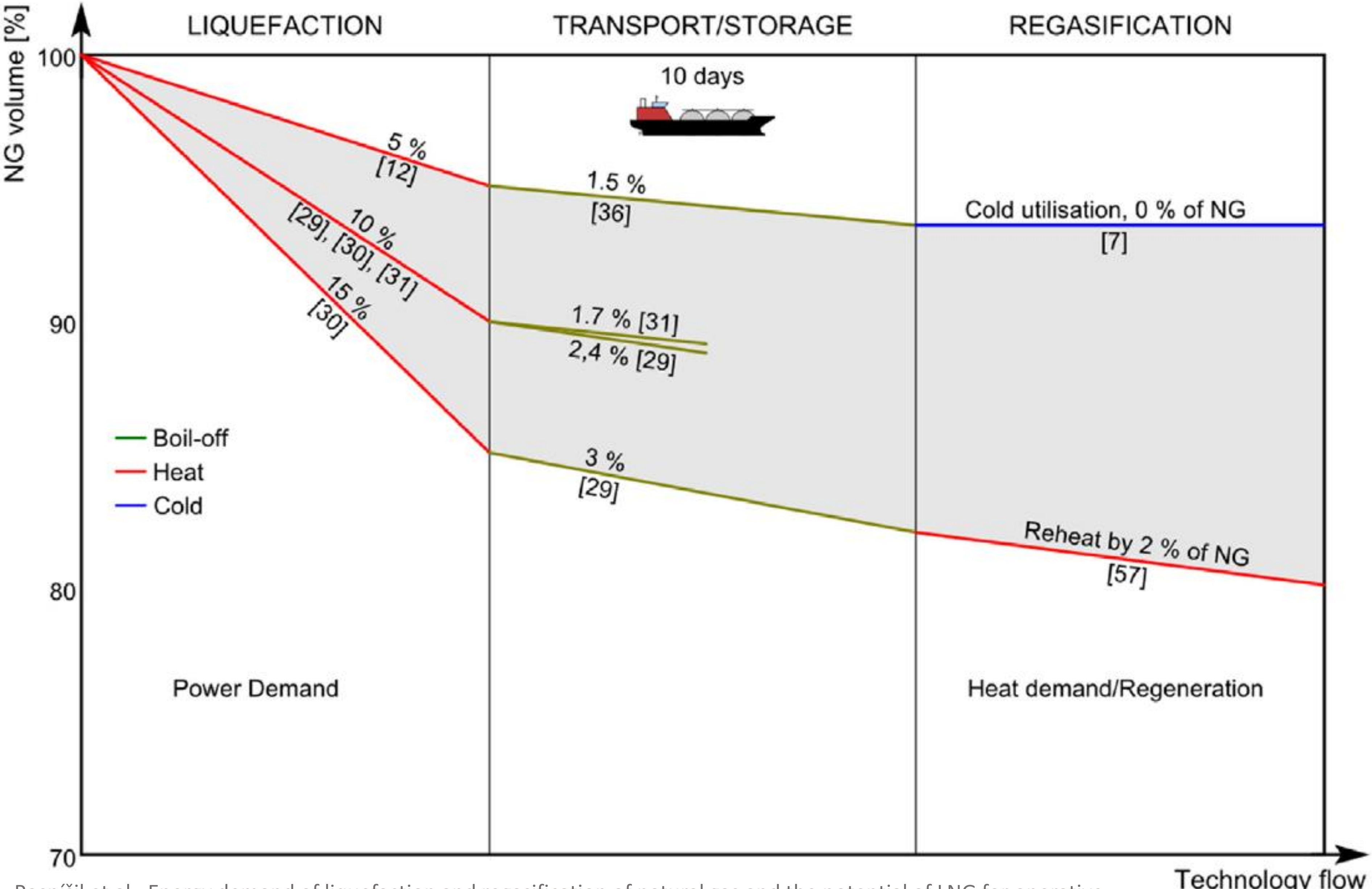
C_{max}= 3.75 billion Nm^3/anno

FSRU – Ravenna (BW Singapore)

C_{max}= 5 billion Nm^3/anno
(C_{sto} = 170,000 Nm^3)

FSRU – Piombino (Italis LNG – ex Golar Tundra)

C_{max}= 5 billion Nm^3/anno
(C_{sto} = 170,000 Nm^3)



Pospíšil et al., Energy demand of liquefaction and regasification of natural gas and the potential of LNG for operative thermal energy storage, Renewable and Sustainable Energy Reviews, 2019

Additional material

LNG value chain:

https://www.youtube.com/watch?v=uztD_gAfNzA&ab_channel=altabnetvideo

LNG regasification via FSRU:

https://www.youtube.com/watch?v=xnCIpULVlqw&ab_channel=H%C3%B6eghLNG

Thank you for your attention!

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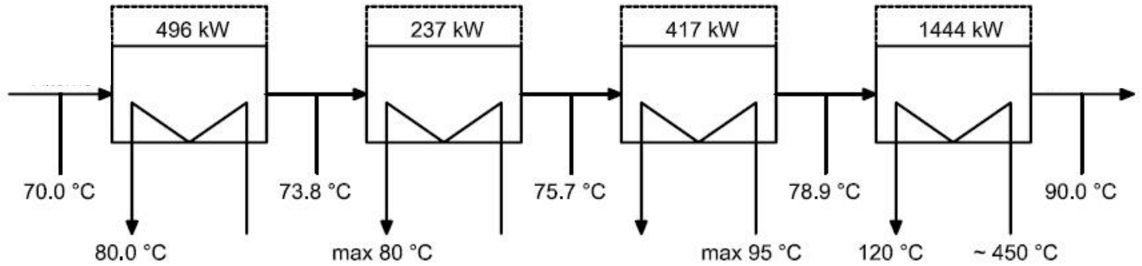
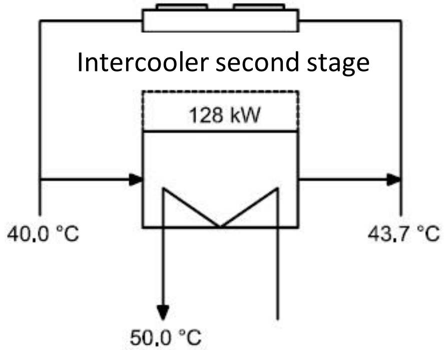
Exercise on Internal combustion engine in cogeneration mode

Example of engines in cogeneration mode

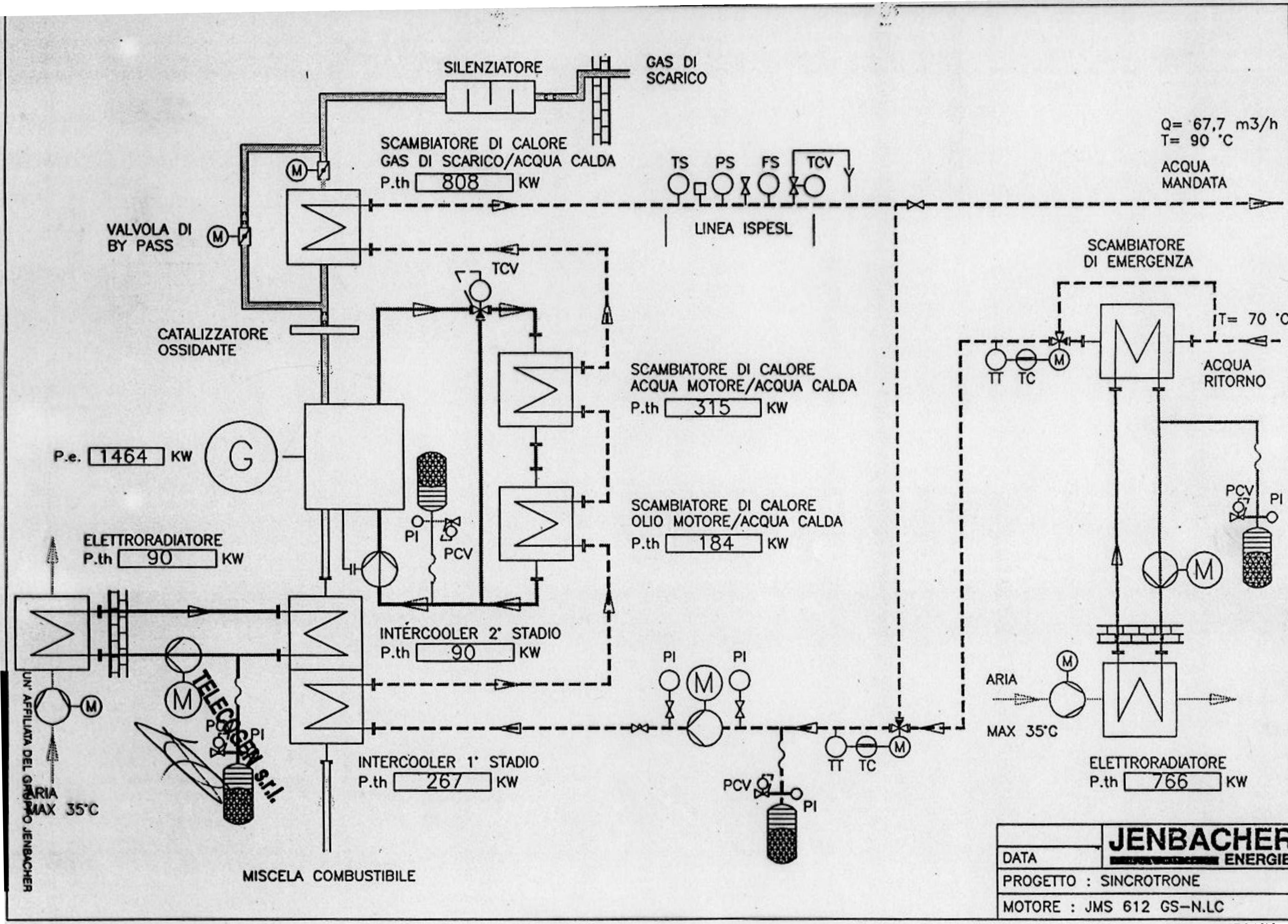
Hot water circuit
Heat recoverable = 2594 kW (±8%)
Mass flow rate = 111.5 m3/h



Low temperature circuit
Heat recoverable = 128 kW (±8%)
Cooling water mass flow rate = 30.0 m3/h



GE Jenbacher J616 GS-E12 (4 strokes)	
Cylinders	16 (V 60°)
Bore (mm)	190
Stroke (mm)	220
Engine displacement (l)	99.8
Power (kWel)	2,433
Nominal speed (rpm)	1,500
Weight (kg)	10,000
Length (mm)	4,894
Width (mm)	1,886
Height (mm)	2,503



SILENZIATORE
GAS DI SCARICO
SCAMBIATORE DI CALORE GAS DI SCARICO/ACQUA CALDA
P.th 808 KW
TS PS FS TCV
Q= 67,7 m3/h
T= 90 °C
ACQUA MANDATA
LINEA ISPESL
VALVOLA DI BY PASS
TCV
SCAMBIATORE DI EMERGENZA
CATALIZZATORE OSSIDANTE
T= 70 °C
ACQUA RITORNO
TT TC
SCAMBIATORE DI CALORE ACQUA MOTORE/ACQUA CALDA
P.th 315 KW
P.e. 1464 KW
G
PI PCV
SCAMBIATORE DI CALORE OLIO MOTORE/ACQUA CALDA
P.th 184 KW
ELETTRORADIATORE
P.th 90 KW
INTERCOOLER 2° STADIO
P.th 90 KW
PI PI
ARIA
MAX 35°C
INTERCOOLER 1° STADIO
P.th 267 KW
ELETTRORADIATORE
P.th 766 KW
ARIA MAX 35°C
MISCELA COMBUSTIBILE
TELECOGEN S.r.l.
UN' AFFILIATA DEL GRUPPO JENBACHER
JENBACHER ENERGIE
DATA
PROGETTO : SINCROTRONE
MOTORE : JMS 612 GS-N.LC

Exercise

Jenbacher JMS 612 GS-N.LC

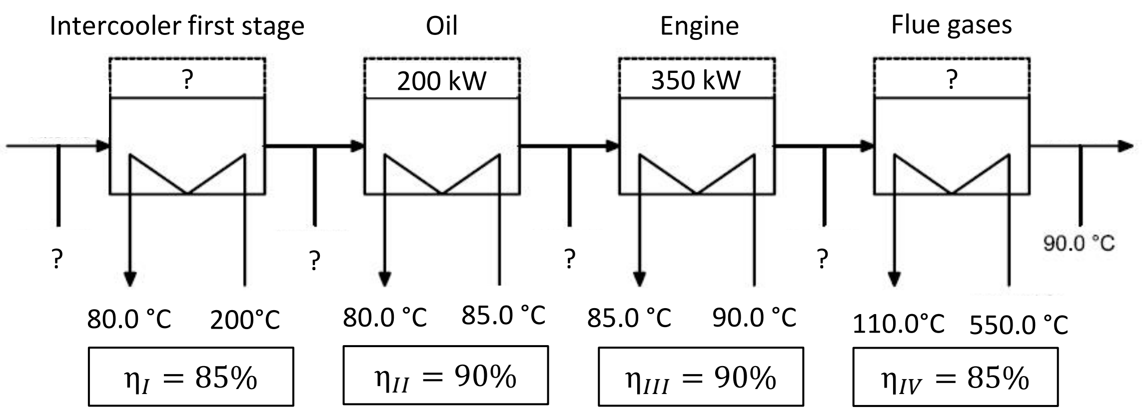
Assumptions

Water circuit:

- Mass flow rate → $\dot{m}_w = 67.7\,\frac{m^3}{h}$
- Water is heated to $T_{w_{out}} = 90°C$
- Pressure = 4 bar (pressure losses are considered negligible)
- The intermediate temperatures are assumed to be the same as those of J616 GS-E12

Other circuits:

Heat generated by engine operation is recovered based on actual data from the plant schematic shown on the previous slide. Temperatures, heat exchanger efficiencies and fluid characteristics are assumed.



Exercise

Water circuit

Mean values of water density (970 $\frac{kg}{m^3}$) and of specific heat capacity (4.19 $\frac{kJ}{kgK}$) are considered.

$$\dot{m}_w = 67.7\frac{m^3}{h} * 970\frac{kg}{m^3} * \frac{1}{3600}\frac{h}{s} = 18.24\frac{kg}{s}$$

Heat exchange for the j-th stage (I, II, III and IV).

$$\dot{Q}_j = \dot{m}_w * c_{P_w} * \left(T_{in_j} - T_{out_j}\right)$$

$$\rightarrow T_{in_j} = T_{out_j} - \frac{\dot{Q}_j}{\dot{m}_w * c_{P_w}}$$

- $T_{in_I} = 74.4\,°C$
- $T_{in_{II}} = 76.0\,°C$
- $T_{in_{III}} = 78.6\,°C$
- $T_{in_{IV}} = 83.2\,°C$

Exercise

Assuming ICE electric efficiency at nominal power equal to 45% and methane lower heating value (LHV) equal to 15.4 kWh/kg, methane mass flow rate is calculated as follow:

$$P_{ICE} = \dot{m}_{CH_4} * LHV_{CH_4} * \eta_{ICE}$$

$$\rightarrow \dot{m}_{CH_4} = \frac{P_{ICE}}{LHV_{CH_4} * \eta_{ICE}} = \frac{1464}{15.4 * 0.42} \frac{1h}{3600s} = 0.059\ kg/s$$

1) Heat recovery from intercooler first stage

It is assumed that the specific heat capacity of air is equal to 1.006 kJ/kgK. Following it is calculated the air mass flow rate and the input temperature.

$$\dot{m}_{air} = \dot{m}_{CH_4} * AF = 0.011 * 19.47 = 1.143\ kg/s$$

$$\rightarrow \dot{Q}_I = \eta_{air} * \dot{m}_{CH_4} * c_{P_{air}} * \left(T_{in_{air}} - T_{out_{air}}\right) = 59.3\ kW$$

Exercise

2) Heat recovery from oil

It is assumed that the specific heat capacity of oil is equal to 2.0 kJ/kgK. Following it is calculated the air mass flow rate and the input temperature.

$$\rightarrow \dot{m}_{oil} = \frac{\dot{Q}_{II}}{\eta_{II} * c_{P_{oil}} * \left(T_{in_{oil}} - T_{out_{oil}}\right)} = 19.3\ kg/s$$

3) Heat recovery from engine

It is assumed that water is assumed to cooling the engine with a specific heat capacity assumed equal to 4.19 kJ/kgK.

$$\rightarrow \dot{m}_{water} = \frac{\dot{Q}_{III}}{\eta_{III} * c_w * \left(T_{in_{cw}} - T_{out_{cw}}\right)} = 18.6\ kg/s$$

Exercise

4) Heat recovery from exhaust gases

It is assumed to have an engine fuelled by methane (T=20 °C; p=1 atm; $c_p = 38 \frac{kj}{kmol*k}$) and atmospheric air (T=20°C; p=1 atm). Combustion products have the following composition in molar fractions on a dry basis:

$$CO_2 = 9.7\%; \quad CO = 0.5\%; \quad O_2 = 2.95\%; \quad N_2 = 86.85\%;$$

Combustion equation:

$$aCH_4 + b(O_2 + 3.76N_2) \rightarrow 9.7CO_2 + 0.5CO + 2.95O_2 + 86.85N_2 + cH_2O$$

Balance of C → $a = 9.7 + 0.5 = 10.2$

Balance of H → $2c = 4a \rightarrow c = 20.4$

Balance of O → $9.7 * 2 + 0.5 + 2.95 * 2 + c = 2b \rightarrow b = 23.1$

$$\overline{AF} = \frac{23.1 * (1 + 3.76)}{10.2} = 10.78 \rightarrow AF = \overline{AF}\left(\frac{MM_{aria}}{MM_{fuel}}\right) = 19.47$$

Chemical reaction of combustion is:

$$10.2CH_4 + 23.1(O_2 + 3.76N_2) \rightarrow 9.7CO_2 + 0.5CO + 2.95O_2 + 86.85N_2 + 20.4H_2O$$

$$\downarrow$$

$$CH_4 + 2.265(O_2 + 3.76N_2) \rightarrow 0.951CO_2 + 0.049CO + 0.289O_2 + 8.515N_2 + 2H_2O$$

Exercise

4) Heat recovery from exhaust gases

Chemical reaction of combustion is:

$$CH_4 + 2.265(O_2 + 3.76N_2) \rightarrow 0.951CO_2 + 0.049CO + 0.289O_2 + 8.515N_2 + 2H_2O$$

$$c_{P_{eg}} = \frac{\sum c_{P_j} * n_j * MM_j}{\sum n_j * MM_j} = 1.16\ kJ/kgK$$

$$\dot{m}_{eg} = \dot{m}_{CH_4} + \dot{m}_{air} = 1.20\ kg/s$$

$$\rightarrow Q_{IV} = \eta_{IV} * \dot{m}_{eg} * c_{P_{eg}} * \left(T_{in_{eg}} - T_{out_{eg}}\right) = 522.7\ kW$$

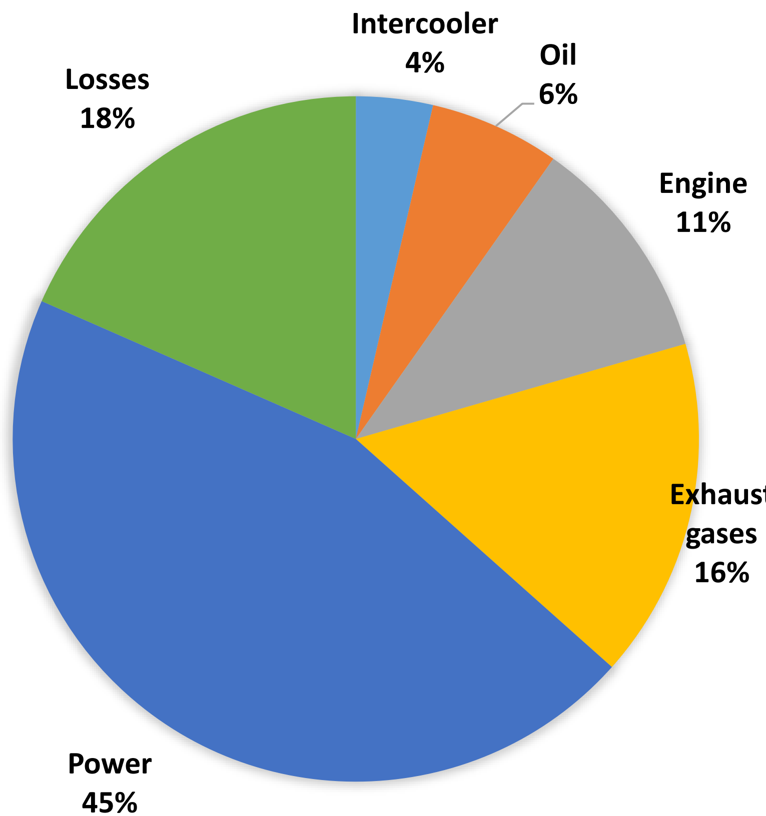
Exercise: Main results

HEAT (Intercooler, Oil, Engine, Exhaust gases)

	Power and heat (kW)
Intercooler	118
Oil	200
Engine	350
Exhaust gases	523
Power	1464
Losses	599

Electric efficiency = 45%

Thermal efficiency = 82%



Thank you for your attention!

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