“Well-to-Wheel analysis on transport refrigeration”

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MSc .Thesis Report
Part 2 of project:
“Optimization of energy/performance in the cooling chain using cold physical exergy of cryogens”

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Disclaimer

The contents of this report is based on the the information in the reference section and assumptions that made where it has been relevant. The initial title of the project "Optimization of energy/performance in the cooling chain in combination with the Dearman approach" was changed to "Optimization of energy/performance in the cooling chain using cold physical exergy of cryogens" to encompass a wider range of alternative solutions for comparison. Based on the information by Dearman co. and the preliminary study performed, it has been decided to focus on the transport application of Dearman engine considering the fact that it is the most viable application.

Part I
Well-To-Wheel analysis

Abstract

This study is dedicated to the Well-To-Wheel analysis of transport refrigeration units(TRUs) with the main focus on refrigeration using combined cooling and expansion work of cryogenic fluid. Considering the need for a shift from current diesel based refrigeration to cleaner fuels, the various means of cooling for transport refrigeration are evaluated in terms of energy density, cost of ownership, emissions, lifetime, system range/weight and overall viability of the solution. The study involves examining the stages of energy carrier production and storage(Well-to-Pump) and energy carrier to desired energy form that is in KWh cooling (Tank-To-Wheel); then it is all combined together to provide the overall effect(Well-to-Wheel). Different sources of fuel to be considered are: Diesel, Bio-gas(Bio-diesel), CNG, LNG, hydrogen(gas/liquid), electricity, heat recovery adsorption cycle, heat recovery ORC and physical exergy of cryogenic fluids such as liquid air, liquid nitrogen, liquefied natural gas and liquid hydrogen.

Nomenclature

	()
ΔT_{min}	Minimum temperature difference achieved in a heat exchanger flows
$\dot{m}$	Mass flow rate (Kg/s)
η_{Aux}	Efficiency due to auxiliary power consumption
η_{Shaft}	Efficiency of the shaft between compressor and expander
$Evap$	Evaporation enthalpy of a fluid($\frac{J}{Kg}$)
Exp	Fluid expansion work($\frac{J}{Kg}$)
HXF	Heat exchange fluid
ICE	Internal combustion engine
LiA	Liquefied air
LiH	Liquefied hydrogen
LiN	Liquefied nitrogen
LNG	Liquefied natural gas
$MJTR$	Mixed refrigerant Joule–Thomson refrigeration cycle
P	Pressure(Pa)
PM	Particulate matter
$Q_{C\ in\ Exp}$	Heat absorbed by cryogen inside the expander (W)
$Q_{Cond\ R}$	Heat absorbed by cryogen inside the expander (W)
$Q_{HX\ in\ Exp}$	Heat absorbed by HXF inside the expander (W)
R_U	Universal gas constant ($\frac{J}{K.Mol}$)
RBC	Reverse Brayton cycle
T	Temperature (K)
VCC	Vapor compression cycle
Subscripts	
amb	Ambient condition at 293.15(K) and 101325 (Pa)
C	Cryogenic fluid(cryogen)
HX	Heat exchange fluid
R	VCC refrigerant
x	This is a superscript

1 Introduction

Refrigeration and cooling is one of the challenges of the new world; As a growing sector and as an inevitable corollary of rising population and global warming. It is expected that cooling energy demand will surpass the energy needed for heating by 2060. Furthermore, it is projected a 6-fold increase in number of refrigerated vehicles. The predicted fleet size if 1.2 million TRUs in Europe in 2025 estimated to produce 39 million ton of CO_2, 120 000 ton of NO_x and 15000 ton of PM per year. The current fleet based on data from Cemafroid co. is estimated to be 1 million unit mostly ran on diesel, to make situation even worse, they are using secondary diesel engine which produces 14 times more particulate matter(PM) and 6 times more NO_x than primary diesel engine used for power-train.[3] Expansion and cold exergy extraction engine as a cutting-edge technology can redress this need in form of a sustainable low-CO2 cooling system with lower impact on Ozone layer compared to conventional technology. It is worth mentioning that cryogenic fluid used for example, liquefied nitrogen (LiN), can be easily produced by pressurizing air which only needs electricity. This electricity can be provided at off-peak hours of consumption from renewable sources which would be itself a storage method of renewable energy.[3, 2]

Current refrigerated vehicles rely heavily on fossil fuel and mainly on diesel, leading to high level of toxic pollutants specially in urban areas. This project is mainly focused on this application; evaluating the possibility of a shift from fossil fuel based diesel to a more sustainable way.

A comparison of competitive sustainable technologies for future of transportation is available in literature as Lin [24] who performed software simulation on the alternative fuels energy use and emissions. Another Well-to-Wheel analysis has been performed by US energy department[25] which takes a comprehensive look on the all possible scenarios based on fuel-cycle model. In another study by European commission, the Well-to-Wheel analysis on alternative fuel has been performed indicating the cheapest fuels in Europe in price per 100km in euros are: 4.24, 4.27 and 5.678 for electricity, fuel cells and natural gas respectively. It is worth noting that in this study the price of electricity is assumed to be the household application while for the refrigeration application it is the industrial application.[27] Regarding the transport refrigeration there are not many resources available, considering this, an overview study has been performed and the list of possible scenarios has been narrowed down to: Internal combustion engine based on CNG(or LNG), fully electric with Li-Ion batteries , fuel cell powered refrigeration and combined physical exergy and expansion work using various cryogens. In this study it is assumed that the TRU is used on average 12 hours a day; 6 hours on the road(cooling requirement of 15 kw) and 6 hours parked with cooling requirement of 5 kw. For the cases of "LNG as cryogen" and "LiH as cryogen" the price is calculated based on extra components required (ICE and PEM FC respectively) for 6 hours the truck is parked and

the container needs to be self sustained in terms of cooling as there is no possibility of getting cold exergy from truck fuel. [3]

Regarding the refrigeration for transport application there are not many resources available, considering this, it was decided to perform an overview study to examine the competitive technologies.

2 Well-to-Pump

2.1 Diesel

The state of the art system used for transport cooling is mostly based on diesel. Diesel is mainly produced by fractional distillation of fuel oil. There are other sources of diesel production, as bio-diesel with no CO2 emissions that can be produced from vegetable oil(agricultural, food and etc.) or by solar power in biomass conversion. Diesel(C12H24 average formula) is 86% Carbon(by mass) producing 43.1 kj/kg. Based on study performed by "Global CCS institute" life cycle energy efficiency for diesel is 0.83 for petroleum diesel and 4 for bio-diesel from vegetables oil. This means for every 1 Kj of energy from petroleum diesel, 1.2 kj of energy already consumed while producing it while for bio-diesel it is only 0.25Kj; this, shows how inefficient it is to use petroleum diesel as a fuel. This means an efficiency of:

$$(1kj)/(1+1.2)Kj = 0.45$$

And CO2 emission of:

$$1.2 * 2.25kgCO2/kgdiesel = 2.7kgCO2/kgdiesel$$

And this is all even before the diesel is transferred to truck.[31]

Similar study performed by NREL, suggesting 1.2007 MJ per MJ of fuel is required in the life cycle of diesel. [32]

The energy and emission life cycle of soybean is also evaluated, indicating that almost 1.2414 Mj of fuel is required to produce 1 Mj of Bio-diesel, and only 0.311 MJ needed to be provided as form of energy(used in processing) which can be from renewable sources.[32] In fig. 1 the CO_2 cycle has been shown.

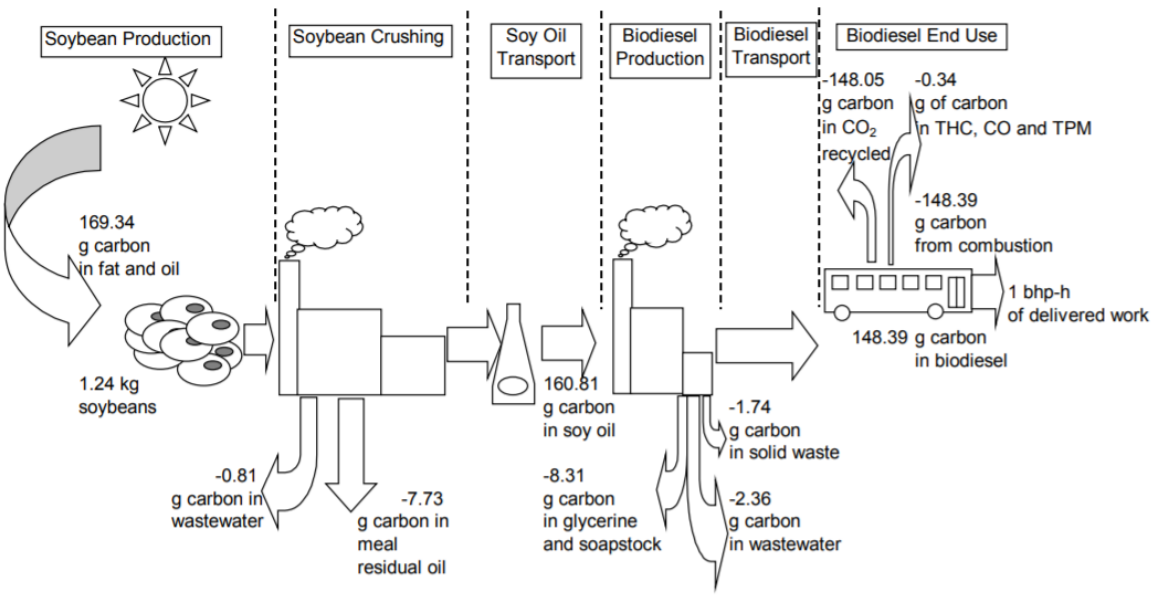


Figure 1: Biomass carbon balance for bio-diesel life cycle (g carbon/bhp-h)

2.2 Liquefied nitrogen(LiN)

2.2.1 Nitrogen thermodynamic properties and applications

Physical and Chemical properties Nitrogen is an inert, colorless, non-aromatic, nonflammable, noncorrosive gas with chemical element symbol of N. Having concentration by volume of 78.08% in air it is the most abundant component in atmosphere.[33]

Applications Nitrogen is the most sold inorganic chemical in terms of volume, used in series of industries ranging from food processing(quick freezing) and superconductors to plastic(or rubber) production and metal machining.

2.2.2 Air separation technologies

Fuel suggested as input for Dearman is LiN and not liquid air, meaning that there will be further process involved rather than just the liquefaction of air. Air separation processes can be divided into two main groups, non-cryogenic processes and cryogenic processes. Selection method of the optimum method depends on various factors, specific rate, pressure, purity. There are also integration methods and processes.[3]

Non-cryogenic processes

Adsorption There are both synthetic and natural material for adsorption process mostly absorbing N2 in air mixtures. Zeolite is one of the materials with electric fields that are not uniform causing it to absorb N2. Carbon acts as a sieves due to having pores in the order of picometers; Having molecular diameter slightly smaller than N2(3 picometers), O2 molecules leave N2 behind and get out of cavities. Pressure swing adsorption, uses similar material while introducing pressure reduction to gain more yield with the help of the vacuum obtained. PSA is a common used method due to simplicity and being relatively low energy intensive. Schematic of the process is shown in fig. 2

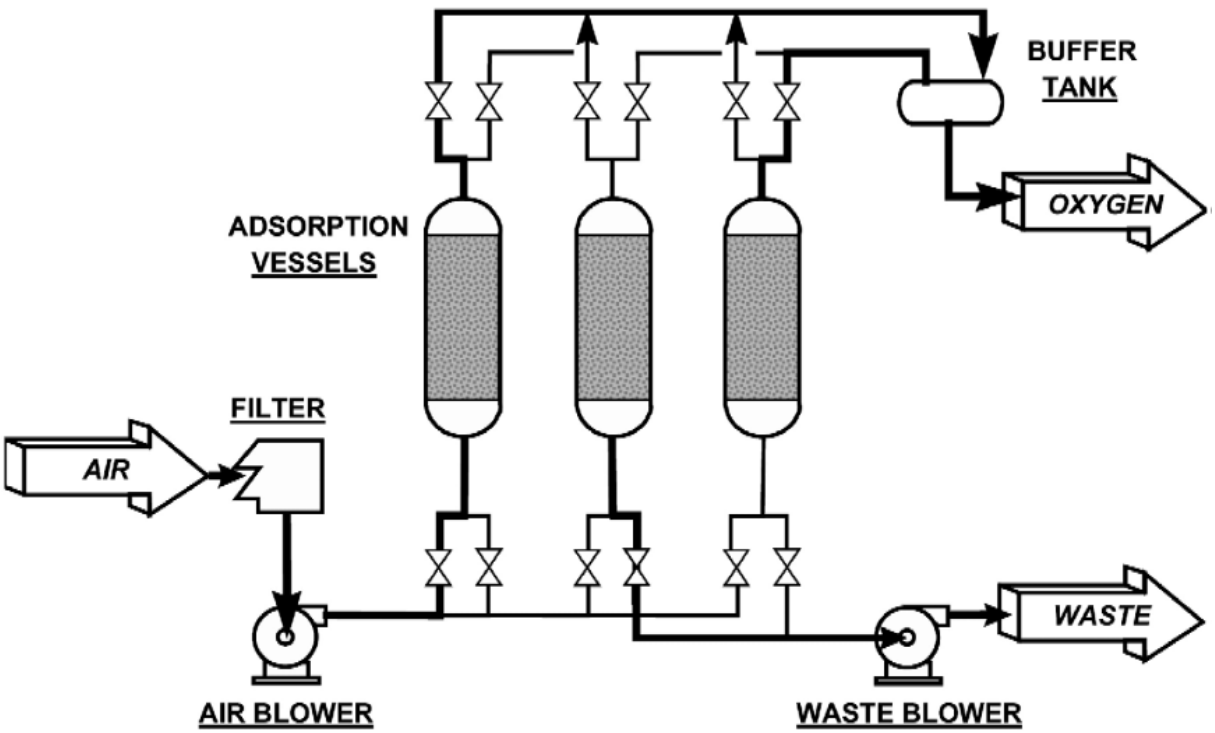


Figure 2: Air separation using adsorption method.[34]

Chemical method This method is based on capability of materials to absorb O2 at specific temperature and pressure. Though producing high purity of O2, is highly energy intensive (in the range of 750-900 k) and combination of salt/Oxygen forms corrosive environment making this method economically not viable.

Polymeric membrane Similar to the PSA, this method is based on differences in diffusion coefficient for various components in air. Membranes used can enrich Oxygen are limited to 50% purity. Fast startup and scalability of this technology are the main benefit of this method.

Ion transport membrane This type of membranes provide passage to Oxygen ion and to turn Oxygen molecules to ion it requires massive amount of energy (reaction happens at over 850 k). Similar to the chemical method, it suffers from energy efficiency. It works best for applications involving integrated gas turbine to generate power.

Cryogenic processes

Cryogenic distillation Air separation using cryogenic method is the most efficient and most economically viable option for air separation at high purity. In LiN production using this method a multi-column cryogenic distillation is performed producing high purity of valuable Argon, O2 and He(very low amount) that could be sold separately to cover some part of air separation cost. Main process for cryogenic air separation are indicated in figure 3 . Starting from air compression and then pre-treated to remove water, CO2 and other contaminants, then it exchanges heat in heat exchanger. After turning the air turned to liquid it is distillated to get separated components one by one. In order to save cooling potential the cryogenic distillation is warmed up by exchanging heat with incoming fresh air to precool it.[34]

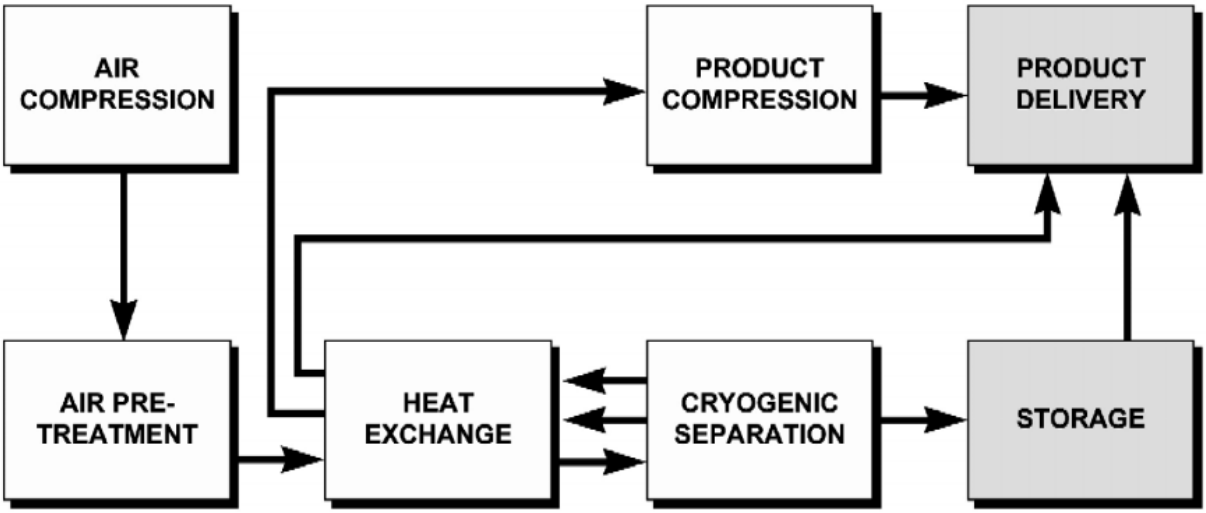


Figure 3: Air separation using cryogenic distillation technology.[34]

As depicted on fig. 4 the cryogenic air separation is the most viable method providing unrivaled purity and byproduct that can be used in many applications.

Table 1
Technology comparison table

Process	Status	Economic range (sTPD)	Byproduct capability	Purity limit (vol.%)	Start-up time
Adsorption	semi-mature	< 150	poor	95	minutes
Chemical	developing	undetermined	poor	99 +	hours
Cryogenic	mature	> 20	excellent	99 +	hours
Membrane	semi-mature	< 20	poor	~ 40	minutes
ITM	developing	undetermined	poor	99 +	hours

Figure 4: Air separation technologies comparison.[34]

2.2.3 Cryogenic technologies(Liquefaction)

Mixed-refrigerant Joule–Thomson refrigeration cycle (MJTR) and reverse Brayton cycle (RBC) are the most used cryogenic liquefaction technologies. MJTR employing a range of refrigerants with various boiling points. The aforementioned systems are believed to have unrivalled performance in temperature ranges of 80 k to 230 K, also providing high system reliability, as well as being cost effective. Pure gas RBC is mostly used in cryogenic refrigeration, with main application in air-separation. The simplified schematic of both technologies is depicted on fig. 5. The key difference between the two technologies lies in the expansion process; MJTR uses Joule-Thampson valves ,while in RBC expansion is done through turbo expanders.

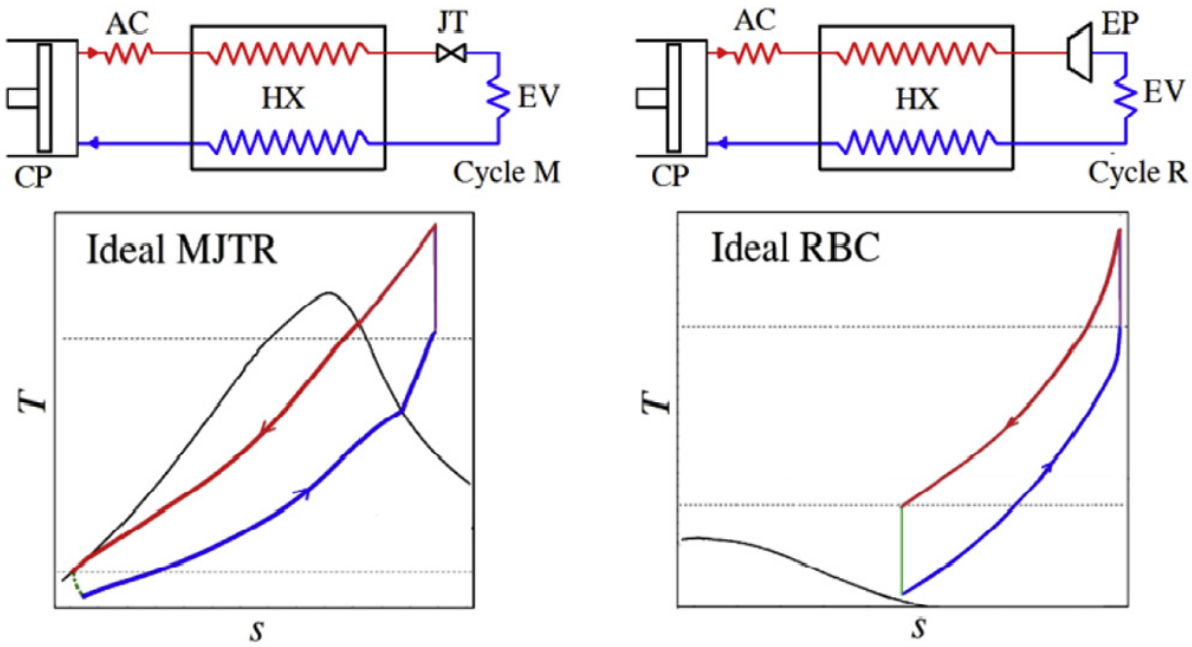


Figure 5: Cycle configurations and ideal T-s diagrams for single-stage RBC and MJTR.[35]

The exergy analysis by Wang et al. showed a direct correlation in 2nd law of thermodynamics efficiency for the case of MJTR; the higher the refrigeration temperature the higher the efficiency would be.[35] For the case of RBC a peculiar behavior is observed; as the refrigeration temperature drops from 180k to 80k the 2nd law efficiency rises steadily from 18.88 to 23.51. This indicates that for air liquefaction, the suitable process would be RBC, considering that the normal boiling temperature of nitrogen is 77.36 K. Fig. 6 and 7 represent the variations of 2nd law efficiency in different refrigeration temperatures and the volumetric cooling capacity of the two technologies respectively.

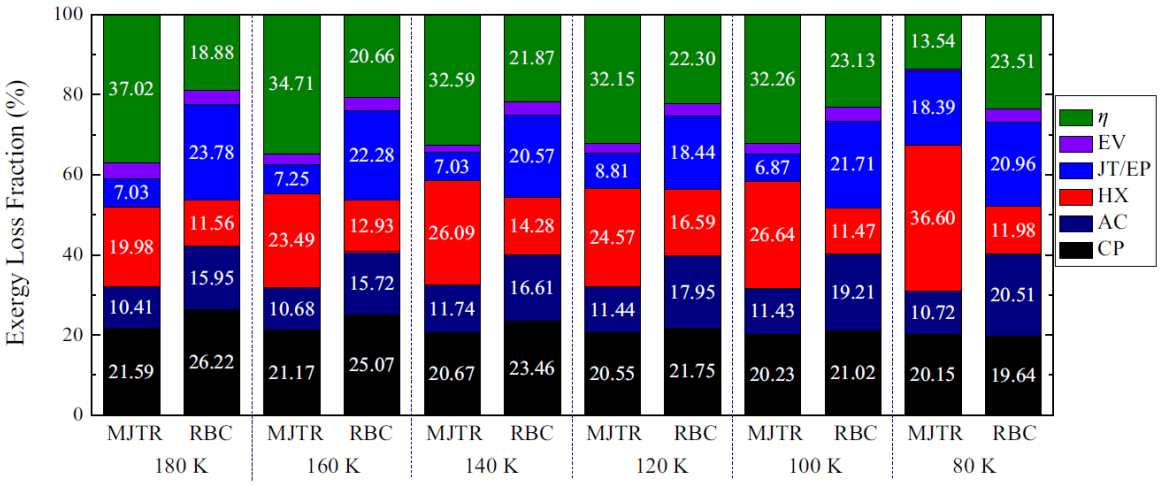


Figure 6: 2nd law analysis of MJTR and RBC from 80 to 180 K.[35]

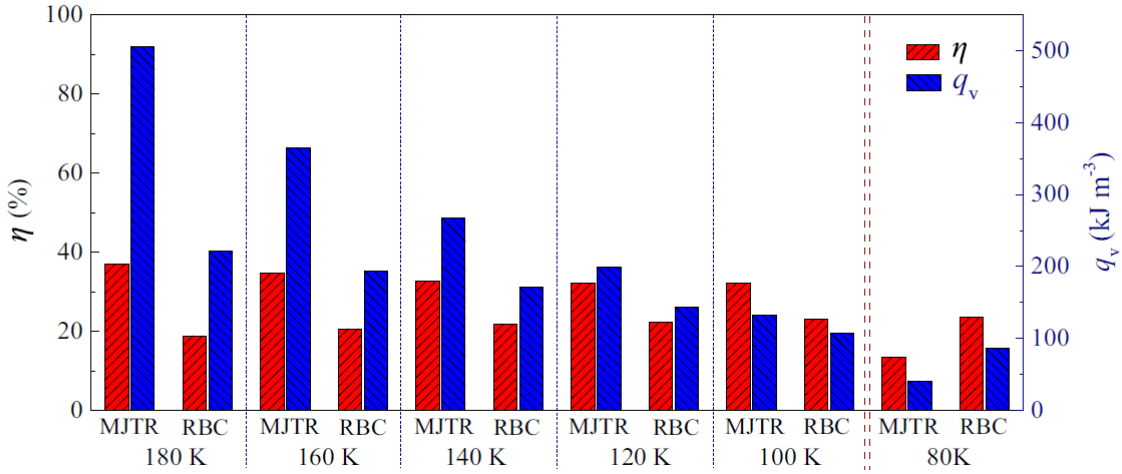


Figure 7: Exergy efficiency (η) and volumetric cooling capacity of MJTR and RBC.[35]

2.2.4 LiN Production on different scales

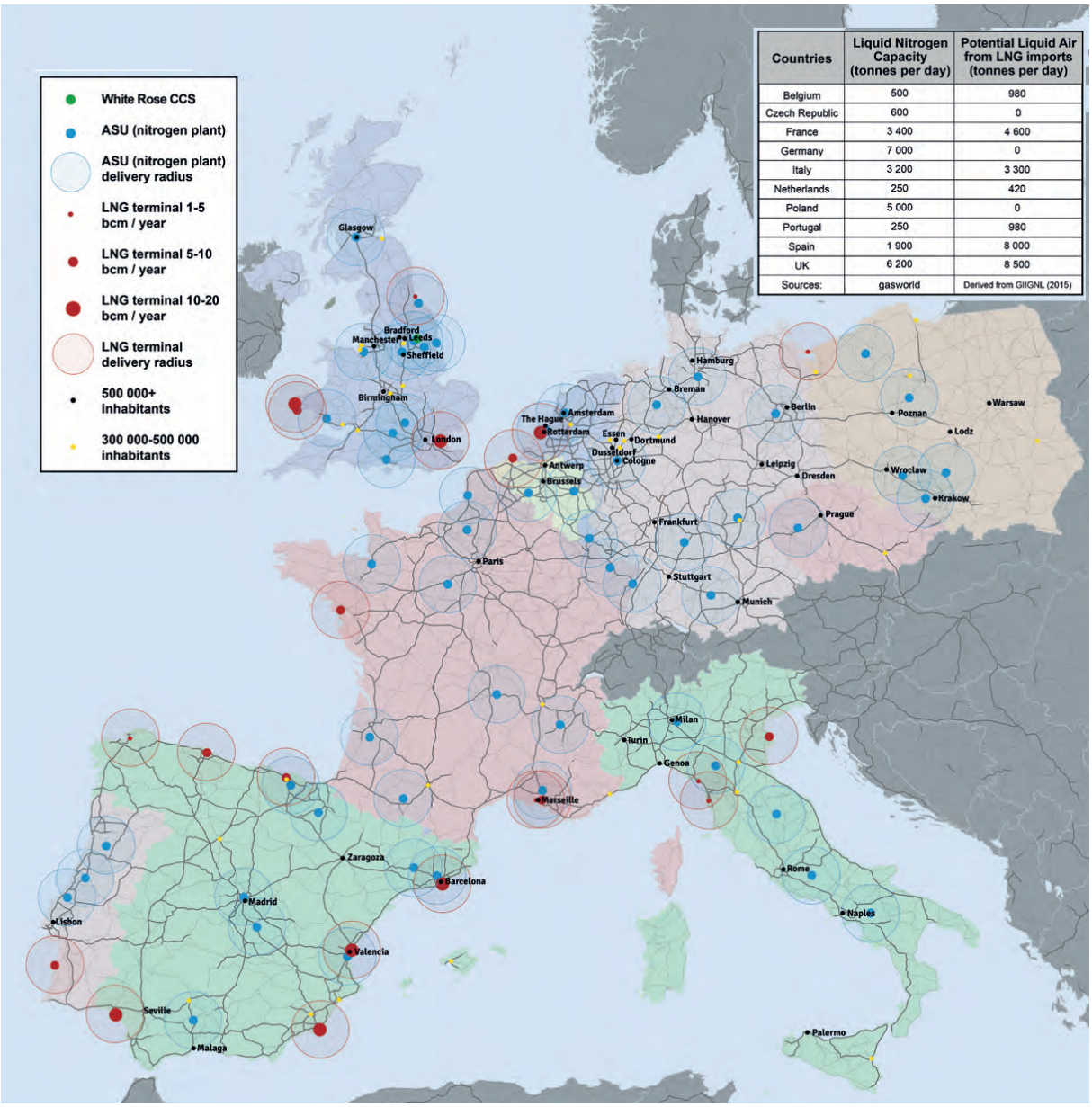
Centralized(Large scale) production As indicated on fig. 7, RBC process provides the highest efficiency in LiN and LiA production. RBC utilizes turbo expanders that have better performance when used in larger scales, this translates in higher efficiency for RBC at large scales. There can be two general scenarios for large scale LiN and LiA production:

LNG terminals high quality cold exergy LNG regasification terminals have vast cold exergy potentials that are mostly wasted due to lack of proper infrastructure. LNG at 109 k is a decent source of cold exergy that can drastically decrease the energy required for air liquefaction process by up to 70% according to Dearman co. [3, 36]. Based on the King & Spalding LNG in Europe 2018 report, by the end of 2017 total regasification capacity in Europe's 28 large-scale LNG terminals was 227 billion cubic meters. Fig. 8 presents the LNG terminals around Europe.

Figure 8: Map of LNG terminals in Europe.

Centralized with wrong time electricity for peak shaving and electricity storage Abundant and low cost electricity in peak time of production from intermittent renewable sources is an opportunity for LiN production, considering the independency and ease of LiN storage, this can be a low cost way to store excess electricity.

Local(small scale) production Considering the map of air liquefaction and LNG terminal positions shown in fig. 9 it can be noticed that there is need for small scale productions in remote areas.



Countries	Liquid Nitrogen Capacity (tonnes per day)	Potential Liquid Air from LNG imports (tonnes per day)
Belgium	500	980
Czech Republic	600	0
France	3 400	4 600
Germany	7 000	0
Italy	3 200	3 300
Netherlands	250	420
Poland	5 000	0
Portugal	250	980
Spain	1 900	8 000
UK	6 200	8 500
Sources:	gasworld	Derived from GIIGNL (2015)

Figure 9: Map of air liquefaction plants and LNG terminals in Europe.[3]

LiN(high purity) or LiA can be easily produced in small scale using MRJT, considering the simplicity of the system and ease of down-scaling. Wang, et al. performed exergy analysis on the small scale LiN production. Accordingly, for pure N_2 at 8.0 bar, the specific power consumption(SPC) would be 0.656 KWh Kg^{-1} and in case of using ambient air with use of "Pressure swing approach", SPC is 1.052 KWh Kg^{-1}.

District heating using low grade heat During the liquefaction process there is a large amount of heat produced at relatively low temperature(low grade heat) that can be used for district heating application. In Denmark 63.3% of houses use low grade heat for district heating with almost 50% coming from renewable. Utilizing the waste heat for district heating can considerably decreases the amount of losses.

2.2.5 LiN shipment and safety

Safety in storage of LiN Cryogenic storage tank is bottle which body is made of a vacuumed layer to be kept away from exchanging heat. There are also pressure and temperature control system involved. Safety relief valves placed in order to prevent high pressure build ups. According to DOT(Department of Transportation) the container should at least stand 2.7 bar pressure.

LiN tank is placed inside the cooling compartment so in case of leakage of heat the cooling potential is not lost to environment

Leiden-frost effect When LiN is boiling it creates an isolating vapor layer preventing the rest of the liquid to boil. This phenomena can be seen if you leave LiN in atmospheric condition which takes relatively long time to evaporate. This means even in case of leakage LiN will not evaporate immediately.

Health effects Although being nontoxic, nitrogen is lighter than Oxygen and considering that it has no smell, color or any other way to be sensed, In case of leakage in indoor environment can cause low oxygen concentration. This is called asphyxiation and in case of inhalation leads to dizziness and unconsciousness and in extreme conditions even death. Another hazard regarding LiN is getting in direct contact with LiN that will cause severe skin burn.

2.3 LNG

The demand for cleaner fuel is rising and role of natural gas as a clean and easy to retrofit for most polluting fuels currently in use is vital. By the end of 2017, total gas demand of Europe's 28 was 568 billion cubic metres (of gas) (bcm), while United States remain the biggest consumer with 848 bcm based on data from Global Energy Statistical yearbook.

2.3.1 LNG and CNG cost

For the case of European countries the cost per kg of CNG and LNG is almost the same, also CNG made of natural gas or Bio-gas also very close in terms of pricing. CNG and LNG prices per country is depicted on table 1. [41]

Table 1: CNG and LNG prices in Europe [41]

EU country	Stations	Average price	EU country	Stations	Average price
Austria	169	0.99 €/kg	Lithuania	4	0.94 €/m3
Belarus	44	0.32€/kg	Luxembourg	2	0.68 €/kg
Belgium	101	L-gas : 0.94 €/kg	Macedonia	5	0.62 €/kg
		H-gas : 1.07 €/kg	Moldova	18	0.40 €/kg
Bosnia and Herzegovina	2		Norway	21	1.77 €/kg
Bulgaria	114	0.75 €/kg	Netherlands	176	1.13 €/kg
Croatia	2	1.34 €/kg	Poland	23	CNG - 0.87€/m3
Czech Republic	171	0.97 €/kg			LNG- 1.08€/kg
Denmark	17	1.6 €/kg	Portugal	7	CNG - 0.92 €/ m3
Estonia	15	0.86 €/kg			LNG - 1.1€/kg
		bio-methane 0.9 €/kg	Romania	3	0.94 €/kg
Finland	39	1.34 €/kg(Bio)	Russia	235	0.27 €/m3
		1.21 €/kg(CNG)	Serbia	20	0.77 €/kg
France	77	1.24 €/kg	Slovakia	12	1.08 €/kg
Germany	868	H-1.08 €/kg	Slovenia	5	1.1 €/kg
		L-0.95€/kg	Spain	63	0.94 €/kg
Great Britain	6	0.78 €/kg	Sweden	174	1.87 €/kg
Greece	15	0.889 €/kg			(18SEK)
Hungary	18	1.30 €/kg	Switzerland	146	1.32 €/kg
Iceland	5	1.31 €/kg	Turkey	20	0.54 €/m3
Italy	1044	0.96 €/kg	Ukraine	205	0.45 €/m3
Liechtenstein	2	1.33 €/kg			

2.4 Battery(Electricity)

According to EuroStat data, in the second half of 2018 the average price of electricity in Europe (Taxes included) was 14.2 €cents / KWh that is for non-household application.This value includes all taxes and with the assuming the consumption within the range of 500-2000 MWh. Furthermore information were depicted in table 2. The CO_2 equivalent also for average European country was almost 0.3 Kg CO_2 equivalent/KWh electricity. [42]

2.4.1 Battery technologies

There are several battery technologies used today; the most used battery technology in transport application is Li-Ion batteries. High round-trip efficiency, high energy density and high lifetime are the main reasons behind this widespread application. Fig. 10 presents the pros and cons of each technology.

Strengths and weaknesses of lead-acid, Li-ion, NiMH and NiCd batteries.

Battery type	Strengths	Weaknesses
Lead-acid	+ Relatively low initial cost + Mature technology + Large number of manufacturers worldwide + Reliance on abundant cheap materials + Satisfactory round-trip efficiency + No memory effect + Low self-discharge rate + Proven efficiency of recycling schemes	- Modest specific energy and power - Short cycle life - High O&M requirements - Performance sensitive to temperature - Limited reliability - Long charging time - Safety concerns; gas release - Reliance on hazardous lead[a]
Li-ion	+ Outstanding specific energy and power + Long calendar and cycle lives + High roundtrip efficiency + Low O&M requirements + Satisfactory operating temperature ranges + High reliability + Technological diversity; several chemistries + Intensive global R&D efforts + Chemistries with eco-friendly materials available + Reasonable self-discharge rate + Relatively fast recharge	- High initial cost - Advanced BMS required - Safety concerns; thermal runaway incidents - Material bottleneck concerns; lithium and cobalt - Currently weak recovery and recycling schemes
NiMH	+ Moderate initial cost + Satisfactory specific energy and power + Satisfactory round-trip efficiency + Low O&M requirements + High reliability + Reliance on eco-friendly materials + Good safety record + Satisfactory operating temperature ranges + Relatively fast recharge	- High self-discharge rate - Slight memory effect - Relatively short cycle life - Currently weak recovery and recycling schemes
NiCd	+ Relatively low initial cost + Outstanding calendar and cycle lives + Mature technology + High reliability + Low O&M requirements + Reasonable self-discharge rate + Good safety record + Extensive operating temperature ranges + Relatively fast recharge	- Modest specific energy and power - Memory effect - Relatively low round-trip efficiency - Reliance on hazardous cadmium[a]

[a] Lead and cadmium are restricted elements under the RoHS (Restriction of Hazardous Substances) directive of the European Commission [13]. This EU legislation limits the use of hazardous substances in electrical and electronic equipment while promoting collection and recycling.

Figure 10: Strength and weaknesses of each battery technology.[37]

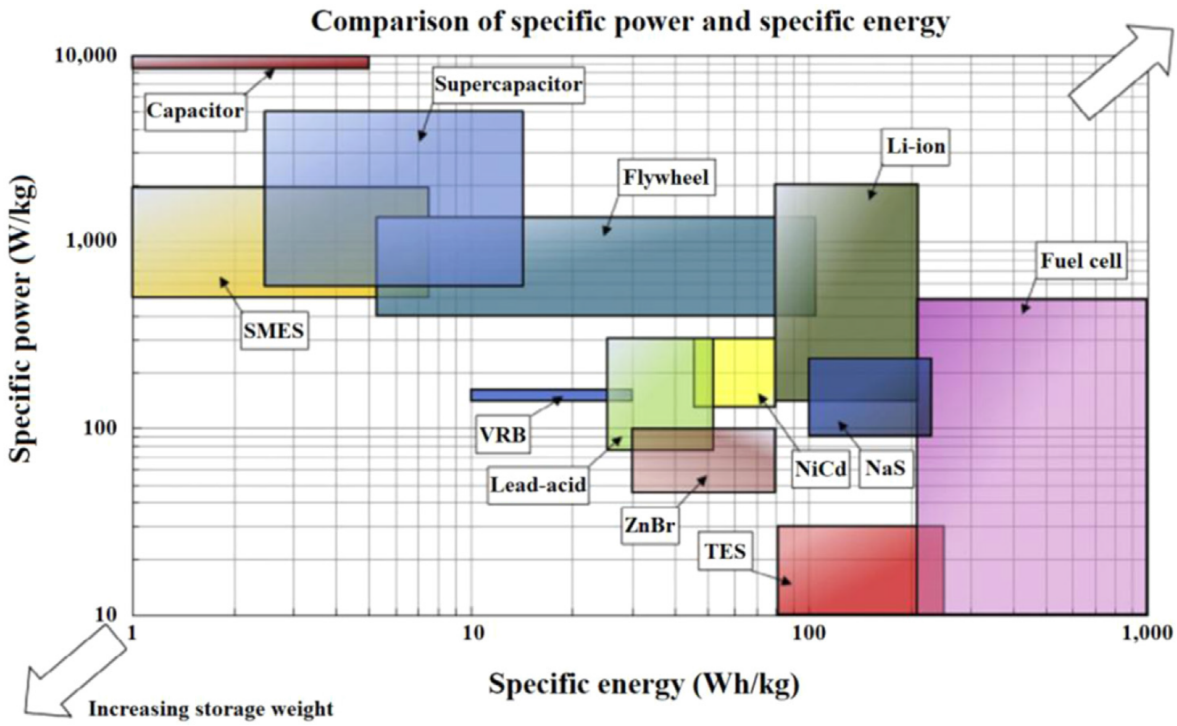


Figure 11: Specific power and specific energy comparison for various storage technologies.[37]

Table 2: Electricity price(tax included) for non-household application in EU countries for 2nd half of 2018 [40]

EU Country	[€/KWh Electricity]	EU Country	[€/KWh Electricity]
EU - 28 countries	0.1422		
Belgium	0.1381	Austria	0.1214
Bulgaria	0.1015	Poland	0.1088
Czech republic	0.0872	Portugal	0.1440
Denmark	0.2510	Romania	0.1030
Germany	0.1987	Slovenia	0.1057
Estonia	0.1109	Slovakia	0.1441
Ireland	0.1518	Finland	0.0876
Greece	0.1184	Sweden	0.0909
Spain	0.1329	United Kingdom	0.1699
France	0.1053	Norway	0.1090
Croatia	0.1144	Montenegro	0.0970
Italy	0.1662	North Macedonia	0.0796
Cyprus	0.2137	Serbia	0.0863
Latvia	0.1267	Turkey	0.0733
Lithuania	0.1089	Bosnia and Herzegovina	0.0764
Luxembourg	0.0914	Kosovo	0.0791
Hungary	0.1023	Moldova	0.0966
Malta	0.1424	Ukraine	0.0742
Netherlands	0.0978	Georgia	0.0666

2.5 Fuel cells

There are various fuel cell technologies available among which proton exchange membrane(PEM) is the most used for non-stationary application due to the relatively simple design, mild working temperature and favorable performance. PEM fuel cells are very sensitive to the purity of hydrogen used and slightest impurities can cause catalyst poisoning and electrochemical surface area(ECSA) loss.

2.5.1 Physical properties

Hydrogen has highest chemical energy density among the conventional sources of fuel, with 120 Mj/kg for LHV and 142 Mj/kg for HHV. In fig. 12 the physical properties of hydrogen is compared with other fuels.[1]

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Figure 12: Physical properties of hydrogen.[38]

2.5.2 Hydrogen production

Hydrogen is produced by chemical reactions of "Gas reforming" combined with "Water gas shift" at temperatures of 900°C and 360°C respectively. This process requires methane and CO2 is mostly released to environment at the end of process.

Hydrogen is also produced by water electrolysis in an electrolizer with state of art technologies already reached to 78% using Alkaline electrolysis. In this case we assume a value of 73 % that means 53.4 KWh of electricity required to produce 1 kg of H2.[32] The CO2 emissions for production of 1 kg of H2 then becomes:

$$53.4KWh * .299kgCO2/KWh = 15.96kgCO2$$

State-of-art electrolizer technologies and a future outlook of the technology is shown n fig. 13. It should be noted that the thermal energy put into steam generation for the case of SOEC is not included in the electrical efficiency.

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
Operating pressure (bar)	1–30			30–80			1		
Operating temperature (°C)	60–80			50–80			650 – 1 000		
Stack lifetime (operating hours)	60 000 – 90 000	90 000 – 100 000	100 000 – 150 000	30 000 – 90 000	60 000 – 90 000	100 000 – 150 000	10 000 – 30 000	40 000 – 60 000	75 000 – 100 00
Load range (%, relative to nominal load)	10–110			0–160			20–100		
Plant footprint (m^2/kW_e)	0.095			0.048					
CAPEX (USD/kW_e)	500 – 1400	400 – 850	200 – 700	1 100 – 1 800	650 – 1 500	200 – 900	2 800 – 5 600	800 – 2 800	500 – 1 000

Notes: LHV = lower heating value; m^2/kW_e = square metre per kilowatt electrical. No projections made for future operating pressure and temperature or load range characteristics. For SOEC, electrical efficiency does not include the energy for steam generation. CAPEX represents system costs, including power electronics, gas conditioning and balance of plant; CAPEX ranges reflect different system sizes and uncertainties in future estimates.

Sources: Buttler and Spliethoff (2018), "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: a review"; Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), *The Future Cost of Electricity-Based Synthetic Fuels*; NOW (2018), *Studie IndWEDe Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme*; Schmidt et al. (2017), "Future cost and performance of water electrolysis: An expert elicitation study"; FCH JU (2014), *Development of Water Electrolysis in the European Union, Final Report*; Element Energy (2018), "Hydrogen supply chain evidence base".

Figure 13: Techno-economic analysis on different electrolyser technologies.[38]

In a report published by IEA the value chain of hydrogen in 2019 is described as in fig. 14. With the production of today standing around 323 Mtoe the emissions for its production is 830 $MtCO_2/year$. The total production in terms of hydrogen mass is 115Mt H2/year among which only 0.01 Mt of it is consumed in transport sector.[38]

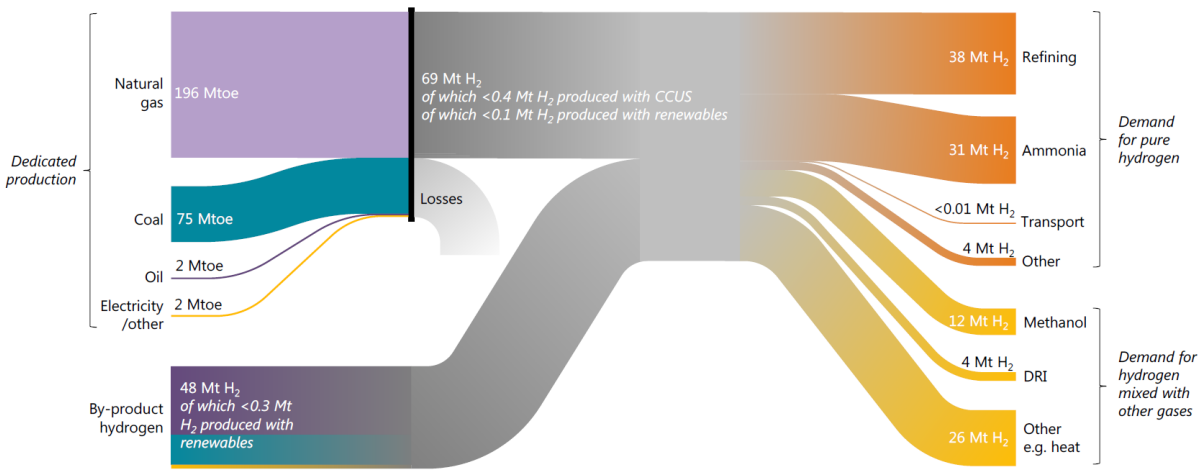
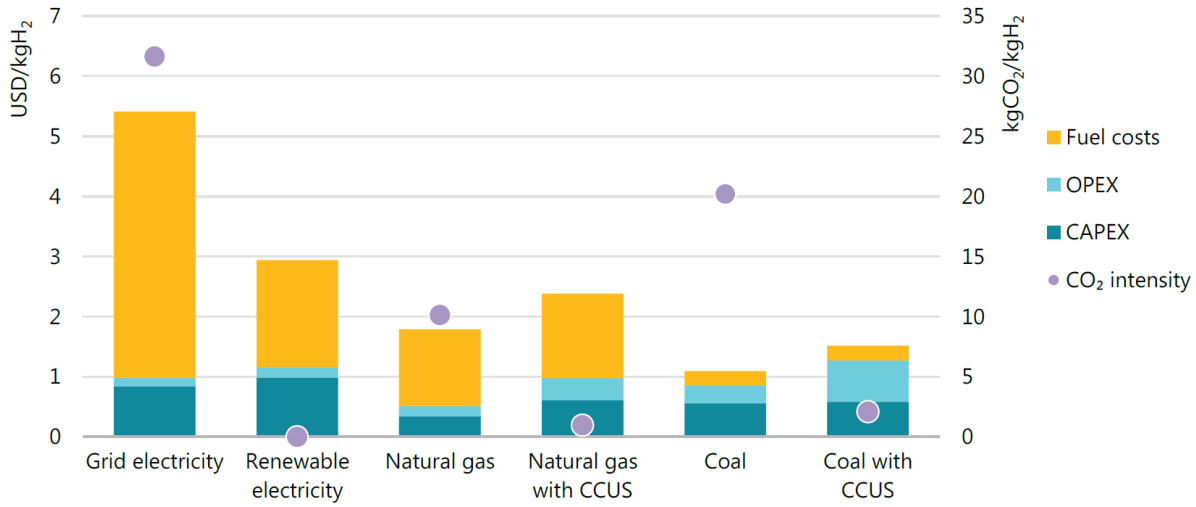


Figure 14: Value chain of hydrogen.[38]

2.5.3 Cost of production and emissions

The cost of hydrogen production can vary on the pathway and method used(Varies considerably for each method itself as already shown on fig. 13, as well as the initial energy source, this comparison can be also shown in terms of emissions of each process. On fig. 15, China's current cost of hydrogen production is examined along with the breakdown of the cost as OPEX, CAPEX, fuel cost and emissions of each process.

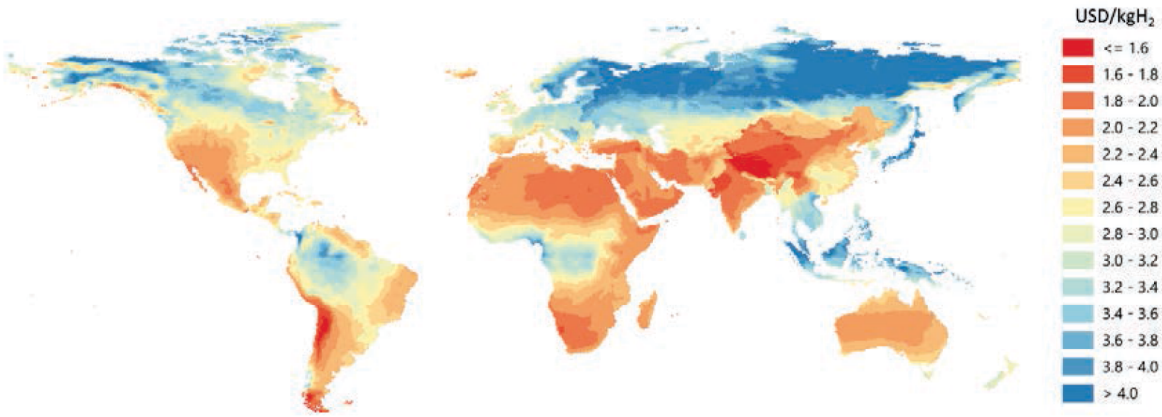


Notes: CAPEX of coal with CCUS = USD 1 475/kW_{H_2}. Renewable electricity costs = USD 30/MWh at 4 000 full load hours. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Source: IEA 2019. All rights reserved.

Figure 15: Cost and emission of hydrogen production in China.[38]

The current falling trend in renewable electricity sources price, shows a growing potential for cheap production of hydrogen using these intermittent sources in a sustainable way. According to IRENA report, Onshore wind and solar PV costs of 3-4$ cents/KWh are already possible. A record-low auction prices for solar PV in Chile, Saudi Arabia, and the United Arab Emirates have seen a levelised cost of electricity as low as 3$ cents/KWh. Based on IEA report, there is potential to produce hydrogen(Electrolysis) from these renewable sources as cheap as 1.5 €/kgH_2 for specific regions. Comparing this with current retail price of hydrogen as 9.5 €/kgH_2 it can be concluded that there is vast potentials to be exploited in that regards.16



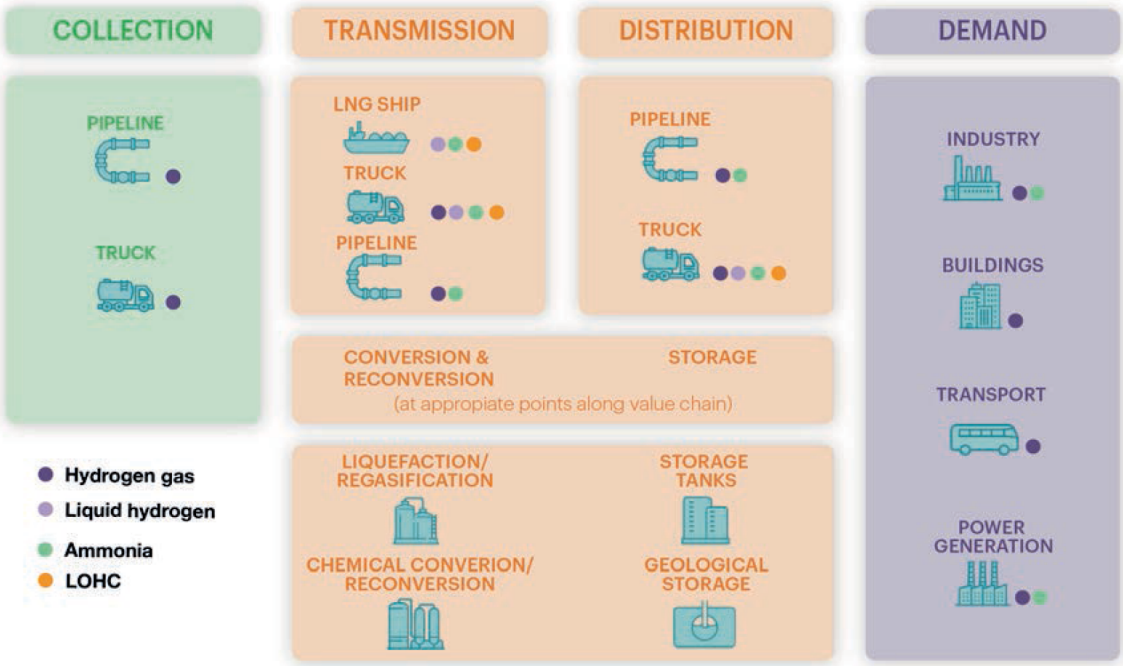
Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. Electrolyser CAPEX = USD 450/kW$_e$, efficiency (LHV) = 74%; solar PV CAPEX and onshore wind CAPEX = between USD 400–1 000/kW and USD 900–2 500/kW depending on the region; discount rate = 8%.

Source: IEA analysis based on wind data from Rife et al. (2014), *NCAR Global Climate Four-Dimensional Data Assimilation (CFDDA) Hourly 40 km Reanalysis* and solar data from renewables.ninja (2019).

The declining costs of solar PV and wind could make them a low-cost source for hydrogen production in regions with favourable resource conditions.

Figure 16: Cost of hydrogen production from hybrid of solar PV and onshore wind in USD/kgH_2.[38]

Moving to a hydrogen economy requires infrastructure for transmission, distribution and storage. A close look at the map of potential sources for hydrogen production from renewable sources indicate that there would be need for long distance transportation of hydrogen. As a rule of thumb in oil and gas industry, for distances longer than 2000Km pipes are no longer viable solution for natural gas transport and instead liquefying gas is suggested, similar approach can be expected for hydrogen transport. As for an example, transporting hydrogen from Middle east to Europe or from Australia and China to eastern Asia. Fig. 17 shows the requirements for a hydrogen value-chain. The current trend with liquefying natural gas prior to its shipping can happen to hydrogen in near future, accordingly, there would be a need for hydrogen liquefaction before transferring it from production facilities. In case of using the LiH instead of compressed hydrogen, there will be higher volumetric energy density of the fuel($\rho_{H2}^{-256^{\circ}C\ \&\ 1bar} = 70.9\ kg/m^3$ vs. $\rho_{H2}^{25^{\circ}C\ \&\ 700bar} = 39.1\ kg/m^3$) that leads to a higher cost of production, based on a study performed by Valenti et al. [6, 14, 7, 8] there is almost 20Mj/kg H_2 required in order to liquefy hydrogen. This adds up to the production cost but decreases the transport cost substantially; this physical exergy can also be recovered later in form of high quality cold exergy in the destination.



Note: LOHC = liquid organic hydrogen carrier.
Source: IEA 2019. All rights reserved.

Figure 17: Infrastructure for hydrogen value chain.[38]

3 Tank-to-Wheel

3.1 Conventional secondary diesel engine (Cooling)

The most conventional system used today is based on diesel. The efficiency of auxillary engine compared to the main engine is considerably lower while the emissions are higher in relative terms. Fig. 18 represents the schematic of such system.

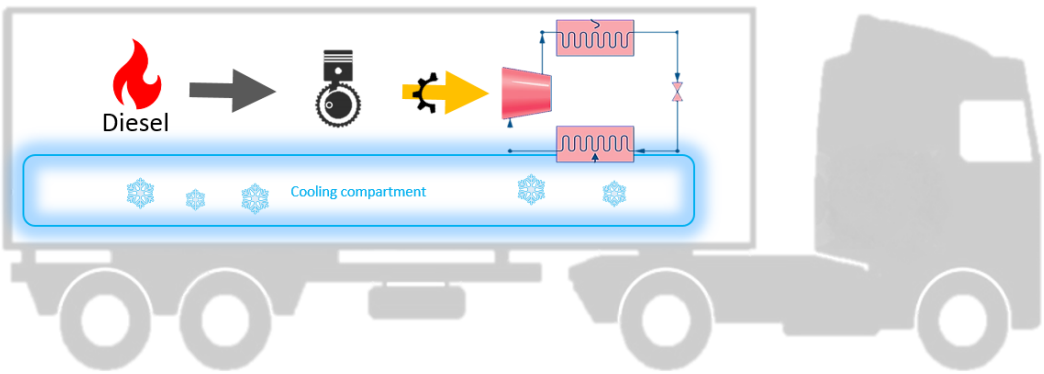


Figure 18: Schematic of the refrigeration system running on a conventional secondary diesel engine.

The other ongoing issue with diesel is the diesel bans starting to be enforced in major European cities, Under the agreed scenario, the last vehicle with an internal combustion engine will be sold in 2028 and diesel and petrol cars will be banished from the roads by the mid-2040s. Fig. 19 represents the emissions of NO_X and particulate matter from diesel compared with a zero-emission refrigeration system.

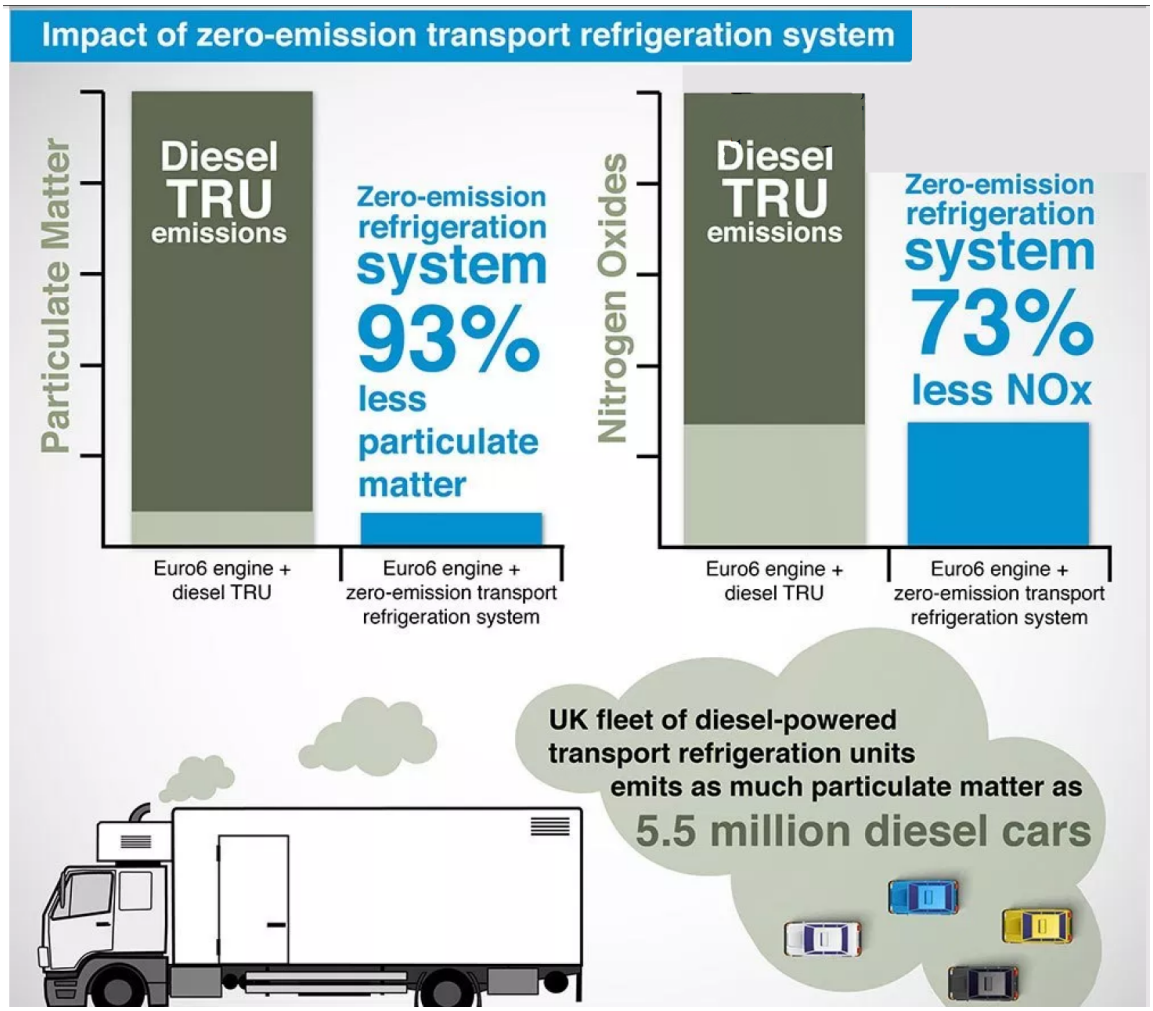


Figure 19: Emission comparison of diesel TRU compared with a zero emission technology

3.2 Dearman engine

Dearman Engine Company Ltd has launched prototype of a truck running on liquefied nitrogen as cryogen, indicated in 20; The system starts with flow of LiN form cryogenic vessel(at $P = 2$ bar)in the cylinder of the engine; coming into contact with heat removed from inside refrigerated container causes vaporization and expansion of the LiN lead to work extraction from the piston as shown in fig.21. Finally, this expansion work powers a refrigeration cycle and auxiliaries (fans, pumps and etc.). Cooling from refrigeration cycle accounts for nearly half of total heat absorbed from container.[26]

According to figures and texts published by Dearman, the heat exchanging fluid(from Water-cooled condenser) is mixed with nitrogen in every cycle. This water and nitrogen(in gas phase) mixture is separated in every cycle with 98% efficiency of separator; this means there is loss of heat exchanging liquid which consist of 50% Ethylene Glycol and 50% water. The simplified schematic of system is shown in fig. 20

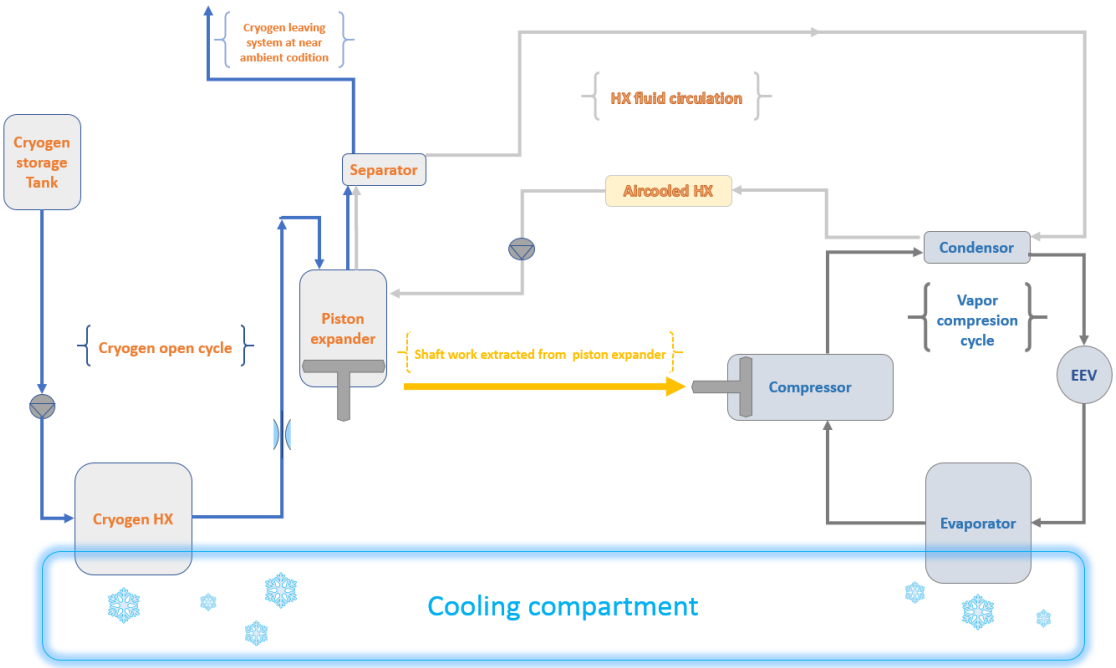


Figure 20: Combined refrigeration system using cryogenic expander engine

3.2.1 Piston expander engine(Dearman approach)

Dearman system is using a single piston expander that has 3 strokes; at intake stroke's initial degrees, the HXF(Ethylene Glycol 50%) that absorbed heat from condenser, is pumped into the chamber. At top dead center this valve is closed and the cryogn valve opens allowing high pressure cryogen to enter the piston expander. As soon as the cryogen valve closes, the near isothermal expansion occurs(power stroke). When reaching bottom dead center, the exhaust valve is switched open that lets the nitrogen and HXF move to the separator. Fig. 21, shows 4 main stages a piston expander is going through. The piston expander consist of a cylinder with 3 valves(cryogen, HXF and exhaust), piston sliding in the cylinder which is connected with connecting rod to crank that transfers power to crankshaft. As indicated in fig. 21. [3, 9, 10, 11].

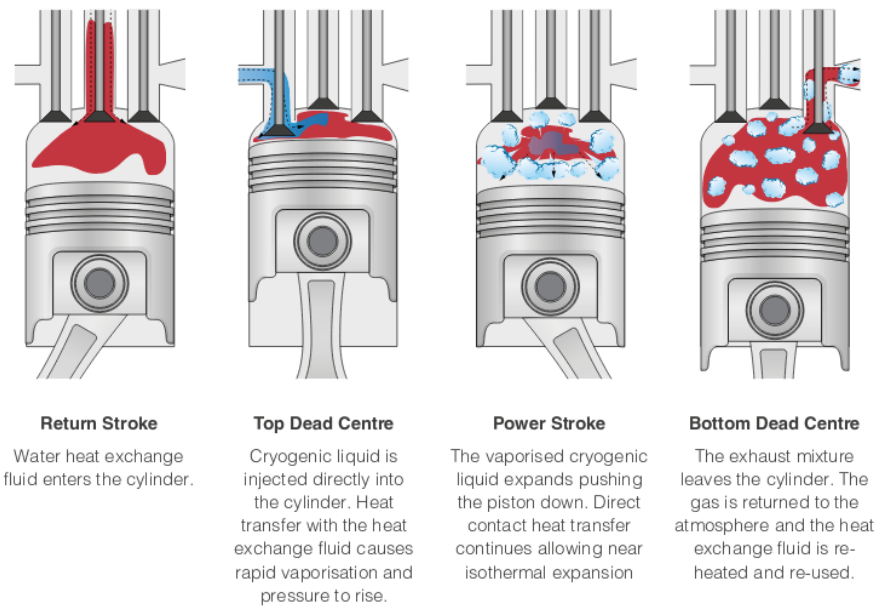


Figure 21: Dearman piston expander various states

3.2.2 Rotary expansion engine(Epicam approach)

Epicam Ltd, proposed a friction-free rotary displacement design called EpiQair, with application in air compression and liquefaction as well as using as expander for automotive and power generation purposes. This type of expander design can be an alternative to Dearman piston expander, but it should be noted that it is in very early stages of development.[46]

3.3 LNG and hydrogen physical exergy

LNG is mostly composed of methane, kept at atmospheric pressure and $-162^{\circ C}$, this means the cold exergy potential of almost 1052 Kj/kg in form of both thermal and expansion exergy. In a conventional LNG truck this potential is just wasted by warming it up with exhaust gas to vaporize it and send it to the truck internal combustion engine. There are several work of research regarding LNG cold potential usage among which fig.24 is well describing the benefits of such systems. [20, 28, 29, 30].

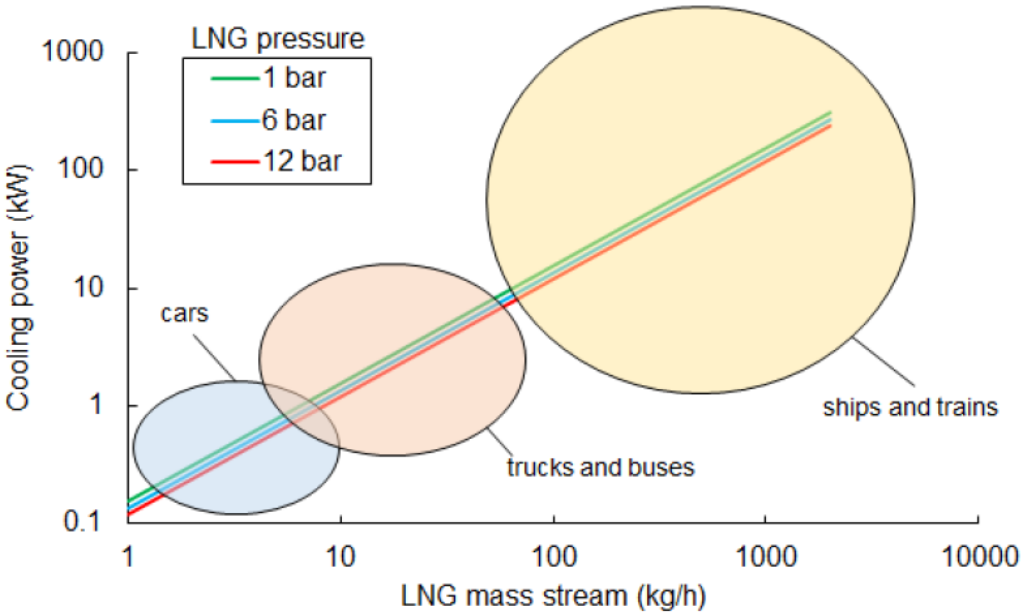


Figure 22: Potential physical exergy for LNG depending on application.[20]

Hydrogen as fuel can be stored in both compressed and liquid form; although storing as liquid is energy intensive, it can provide benefits in terms of energy density.[7, 8] For hydrogen at 700 bar there is 8456 Kj/kg exergy available in the form of pressure exergy. This exergy is also wasted as hydrogen is throttled down to 1.5 bar for using in a fuel cell. Using pressure and thermal exergy in VCC is an energy efficient, environmentally friendly and low cost mean for producing cooling effect. Utilizing LNG and hydrogen cold physical exergy for cooling means the refrigeration would depend on the same fuel as the power train; schematic of the system and the P-H diagram of exergy extractions is shown on fig. 24 . 23 respectively.[17, 18, 19, 21]

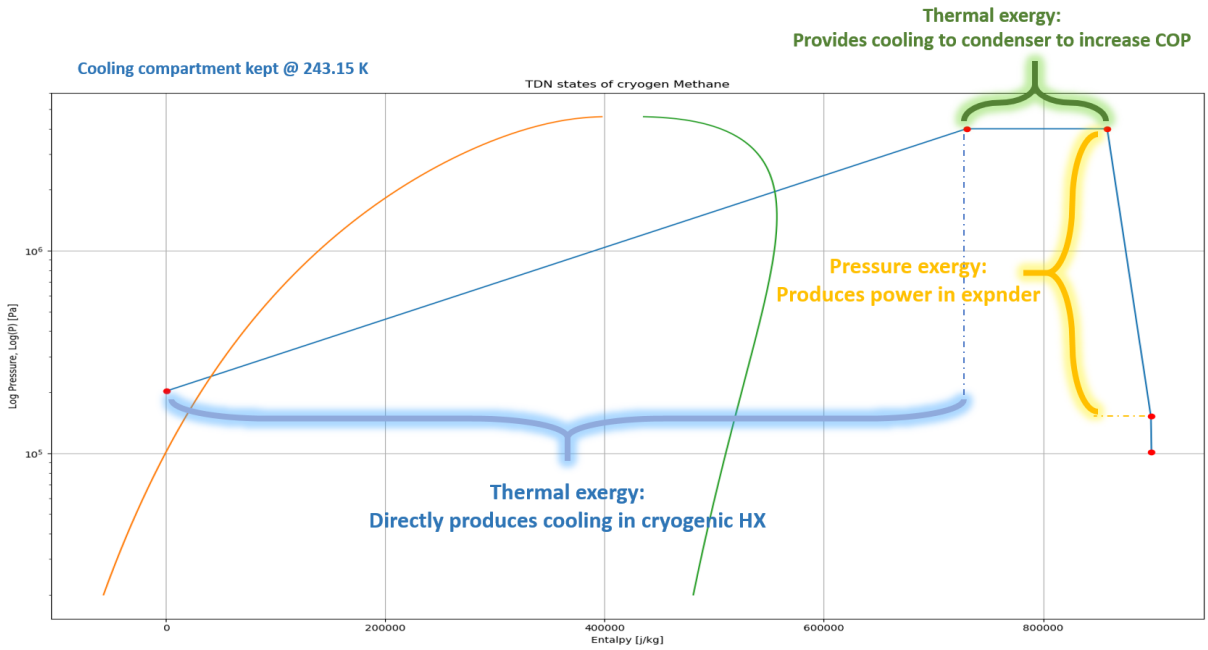


Figure 23: P-H diagram of LNG and exergies that can be exploited.[5, 16]

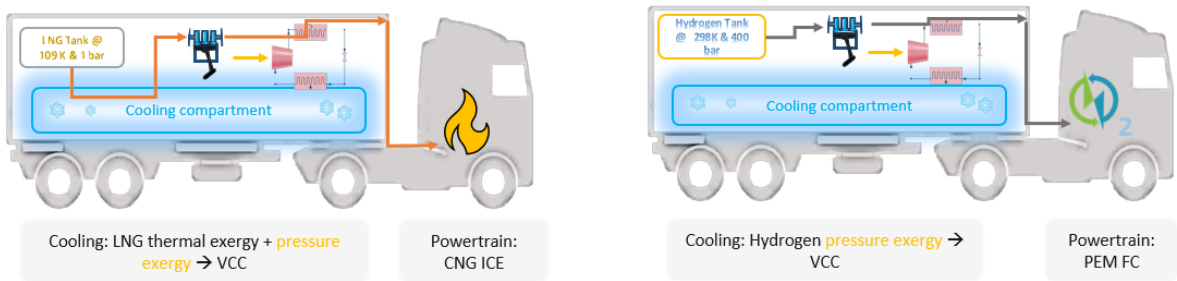


Figure 24: Combined refrigeration and power-train system using cryogenic expander engine, Liquid fuel system(on the left) and compressed gas system(on the right)

3.4 Electric batteries (Cooling)

In this approach the batteries are charged overnight or within each TRU stop, and they will provide electricity to an electrical motor to run the vapor compression cycle. Schematic diagram showed in fig. 25. The main challenge with Li-Ion batteries is the limited range, this can be partially solved by adoption of regenerative systems from axle of truck or with heat recovery using organic Rankine cycles. Considering the weight of a refrigeration system and the high capital costs, it is best to adopt hybrid solutions with batteries to gain the benefits of its high round-trip efficiency, while striking a balance between cost of system and range.

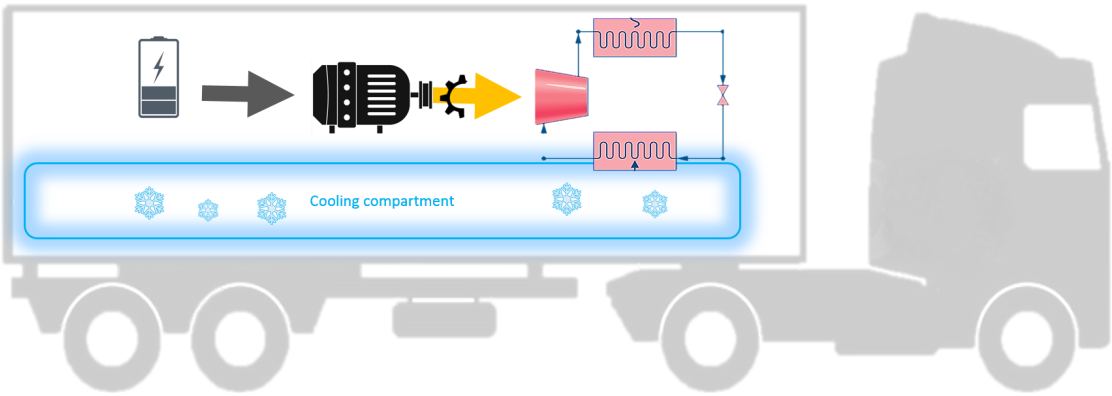


Figure 25: Schematic of the refrigeration system running on batteries.

3.5 Fuel cell (Cooling)

Most battery critics point at battery range as its biggest pitfall but this can be solved when a hybrid system of battery and fuel cell is used. PEM FCs have high energy intensity, high range, no pollution and no far less life-cycle issues as in the case of Li-Ion batteries, these characteristics make them suitable for future fuel of long haul transport. High cost(mainly hydrogen fuel) and lifetime is the main factor keeping it behind competitive technologies. [22, 23] The schematic of the fuel cell based refrigeration is depicted on fig. 26.

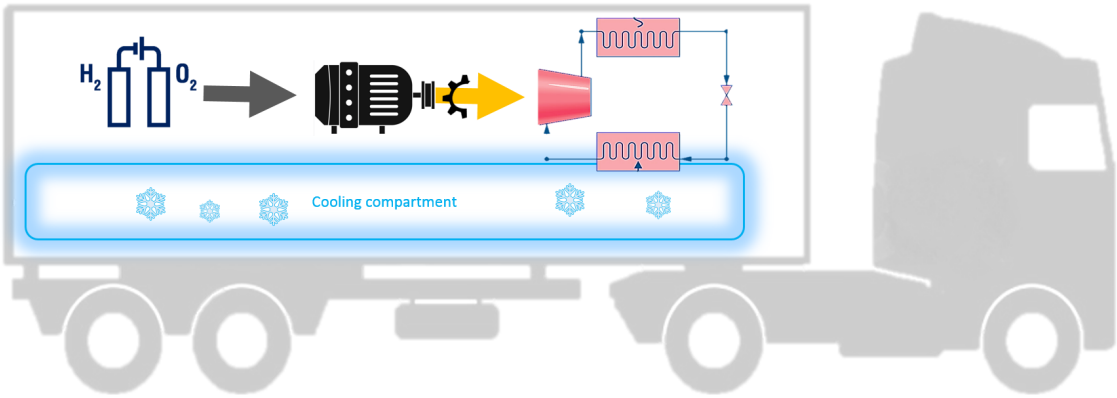


Figure 26: Schematic of the refrigeration system running on PEM FC.

3.6 LNG(or CNG) auxiliary internal combustion engine (Cooling)

This approach uses similar secondary engine as in the first, case with only difference of substituting diesel for natural gas. Emissions of this system is 20% lower while providing 20% more power per kg of fuel. Fig.27.

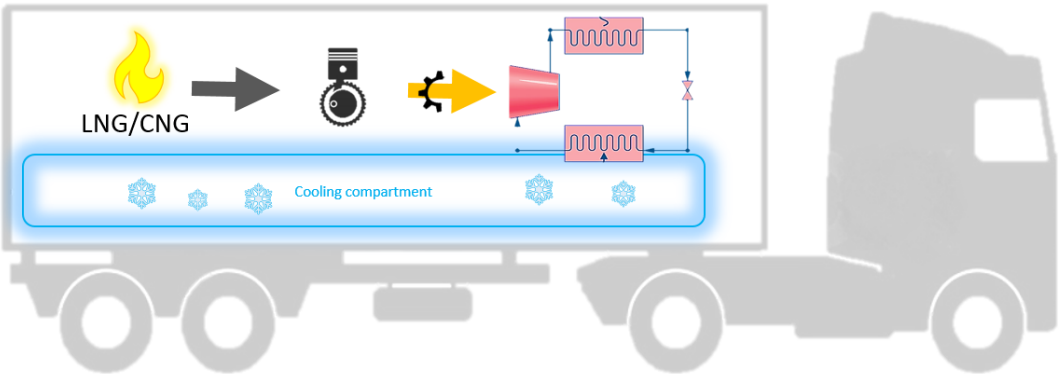


Figure 27: Schematic of the refrigeration system relying on auxiliary ICE with CNG as fuel.

3.7 Alternative-driven primary engine(Cooling and transportation)

3.7.1 Direct approach

The main engine here is responsible for both cooling and power-train. The truck axle is providing power through a gearbox to the VCC compressor. This system is usually more efficient than using secondary diesel engine but can only keep the VCC running as long as the main engine is running.

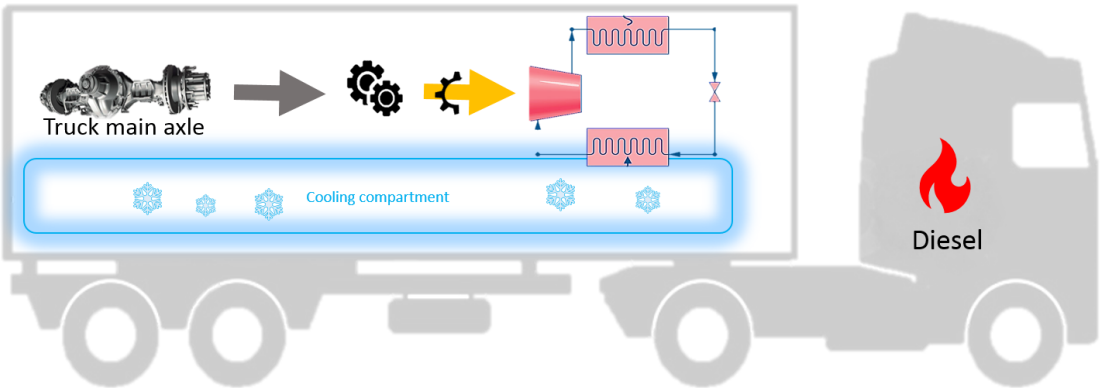


Figure 28: Schematic of alternative-driven using power of primary engine

This solution is best to apply as hybrid system with batteries to cover the gaps that the truck engine is not running.

3.7.2 Regenerative system

Motion is inextricably linked to energy, no matter a river flowing down the mountains or a truck on the road. For a moving vehicle,when brake applied, there is a huge amount of energy going somewhere (friction mainly). Back in old days, not many cared about where these energy goes, but now thanks to becoming more environmentally aware, every bit of it counts.

Recent technological advances has brought a series of revolutionary energy saving solutions; regenerative braking transfers kinetic energy of a vehicle with a generator to convert most of the energy lost when not accelerating back into stored energy in the vehicle's battery. Then, the next time the vehicle accelerates, it uses the energy previously stored from regenerative braking instead of tapping in further to its own energy fuel tank. [47] Schematic of the proposed system depicted on fig. 29. It is worth mentioning that this system needs to be combined with batteries solution but provides much more flexibility considering the fact that the batteries will be charged as the truck is on the road and when the trailer is detached it can use its own battery to run VCC.

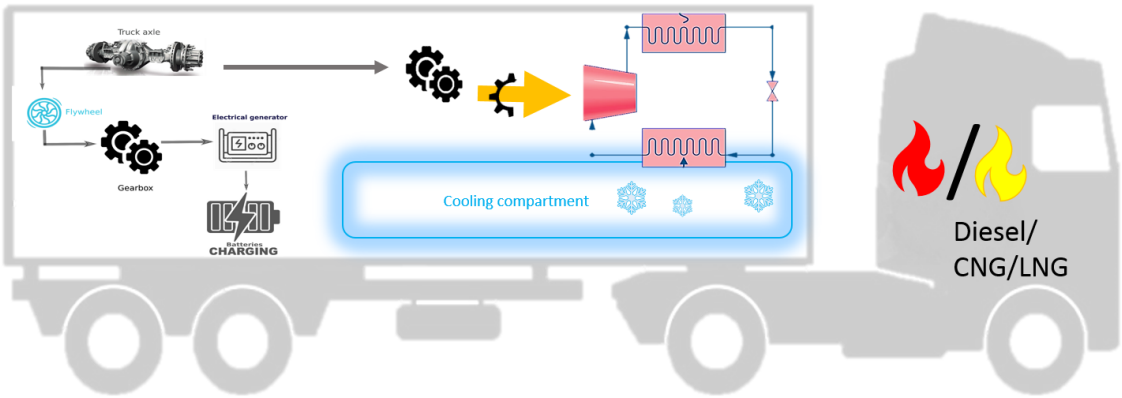


Figure 29: Schematic of the refrigeration system relying on regenerated power from primary ICE.

3.8 Heat recovery from main internal combustion engine

As indicated on fig. 33, on average 36% of the fuel is wasted in exhaust; although this energy is a low quality source of heat, it can still be used for running ORC or adsorption cooling.[43]

3.8.1 Adsorption refrigeration

Sorption technology includes absorption and adsorption technology. The key difference is the sorbents, The absorbents are generally liquid such as LiBr and NH_3, and the adsorbents compact solids; silica gel, zeolite and chlorides are the most common ones.[49]

Studies been performed on evaluation of absorption systems from various heat sources ; in a study by Karakas, the solar refrigeration performance has been evaluated.[4] There are advantages associated with adsorption technology, such as wide range of working condition(50-400$°C$) and feasibility to apply them in conditions with high vibrations, unlike absorbents that need rectifiers and may be at risk of crystallization. Considering the working condition of a transport refrigeration that involves a harsh environment with constant vibration the selected sorption technology would be adsorption. Nishiyodo Kuchouki Co. invented the Silica gel- water adsorption chiller in 1986; the schematic diagram of system was shown in fig. 30.

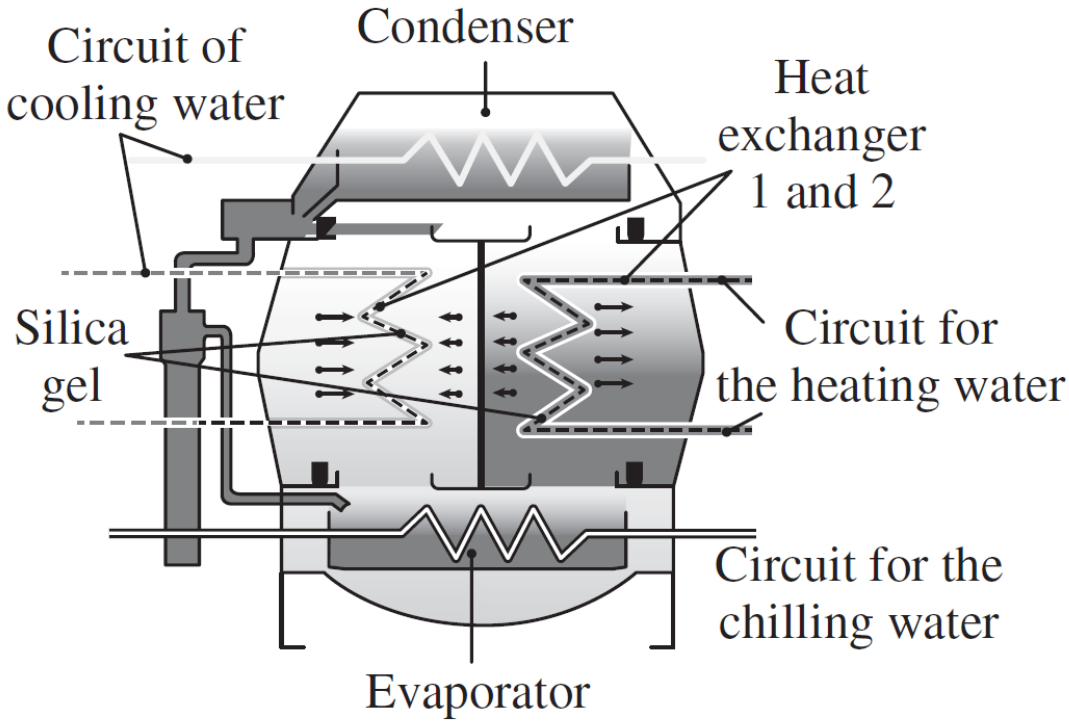


Figure 30: Schematic diagram of Silica gel- water adsorption chiller

Silica gel- water is the most preferred pair for adsorption refrigeration for low temperature heat sources due to decent performance but there is no possibility of reaching sub-zero temperatures. Performance comparison of different adsorption working pairs is shown in fig. 2.

Considering the required working temperature of $-25°C$, Lai [48] suggested a system running on pairs of $CaCl_2$-activated Carbon-Amonnia with experimentally measured COP of 0.36 and specific cooling power(SCP) of 627 W/kg.

Regarding the cost calculation of a system it is possible to use data from cost estimation done on absorption system that is closely similar to adsorption system. [49]

Evaporation temperature (°C)	Adsorption working pair	*COP*	*SCP* (W/kg)	Characteristics	Data source
8	Activated carbon-NH_3	–	1000	Convective thermal wave cycle	Calculation[a] [54]
1	Activated carbon fiber/$CaCl_2$-NH_3	0.6	330	Composite adsorbent, heat pipe heating	Experiment[b] [6]
3	Activated carbon-NH_3	0.67	557	Convective thermal wave cycle	Calculation [55]
−10	$SrCl_2$-NH_3	0.32	230	Single effect system	Experiment [56]
−25	$(MnCl_2 + NiCl_2)$-NH_3	0.4	70×2[c]	Double effect system	Calculation [56]
−10	Metal hydride-hydrogen	0.43	25×2	Thermal wave cycle	Experiment [29]
3	Graphite/silica gel-water	–	35×2	Composite adsorbent	Experment [57]
10	Silica gel-water	0.4	85	Split heat pipe type evaporator	Experiment [24, 25]
5	Zeolite-water	0.9	125×2	Intermittent convective thermal wave cycle	Calculation [58]
−15	$CaCl_2$/activated carbon −ammonia	0.41	731	Composite adsorbent, heat pipe type heating and cooling	Experiment [59]
−25	$CaCl_2$/activated carbon −ammonia	0.36	627.7	Composite adsorbent, heat pipe type heating and cooling	Experiment [59]

[a]Calculation: data calculated from the adsorption performances of working pairs or from the simulation of an adsorption refrigeration cycle.
[b]Experiment: data obtained experimentally.
[c]The *SCP* in the original literature was calculated based on the total cycle time, with same adsorption and desorption time. To allow a fair comparison, the original value was multiplied by two.

Figure 31: Comparison of adsorption technologies based on working pair, COP,SCP and minimum achievable evaporation temperature.[49]

3.8.2 Organic Rankine cycle powering vapor compression cycle

Organic Rankine Cycles(ORC) are mostly used for work extraction from a low quality heat source. This technology does not suffer from the pitfalls of a steam Rankine cycle. to mention a few, upon right selection of working fluid, expansion occurs only in dry region, that provides the possibility of using various type of expanders(Scroll for example), the working fluid is a design parameter this means for each application there is an optimum fluid and the flexibility in evaporation temperature means theoretically there is potential to extract power from a wide range of heat source temperatures.

Exoes is a company providing solutions for energy savings in trucks, by utilizing the waste heat. Two of the expanders they offer are: Exoes EVE-T2 , that is a piston expander and Exoes EVE-T3 that is a scroll expander. Fig. 32 depicts the schematic of exhaust gas used for running ORC and fig. 33 shows the benefits of using such system.[44]

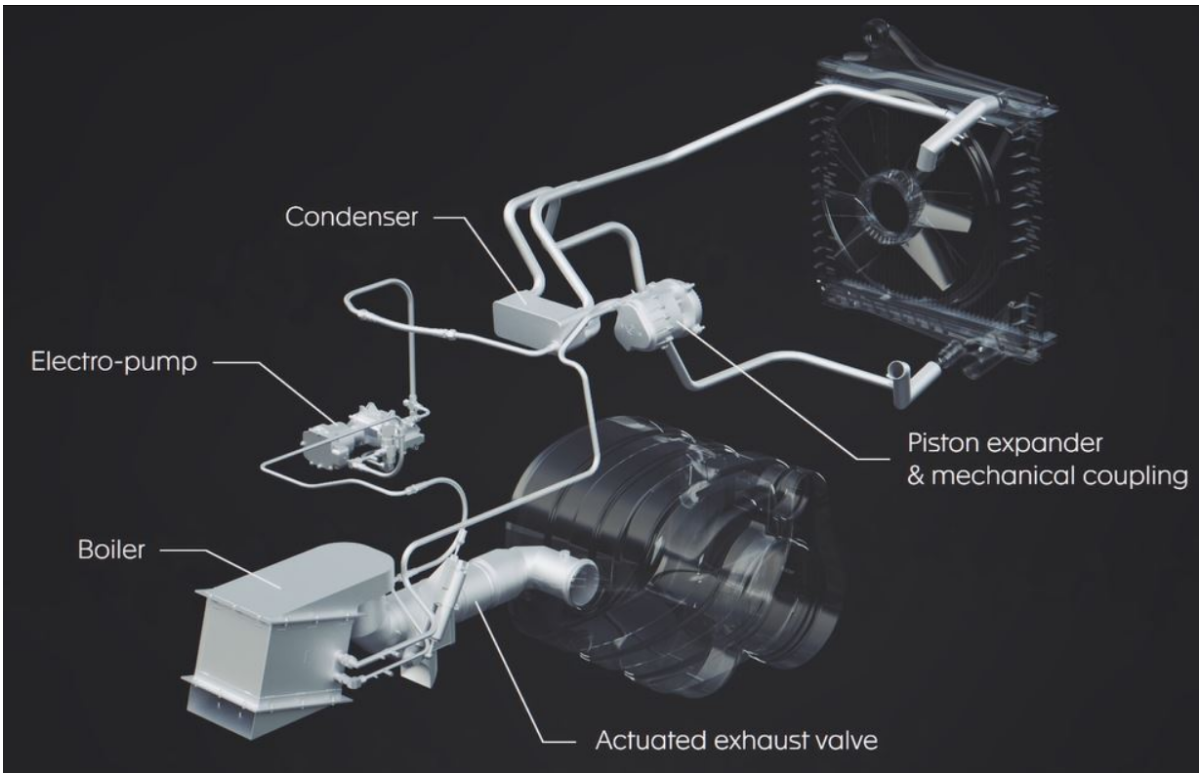


Figure 32: ORC system utilizing Exoes expander

According to Exoes, the fuel saving for a truck is up to 5% of the fuel. [43, 44] For the case of a refrigerated truck, this shaft power can be directly use for powering refrigeration cycle, eliminating the need for auxiliary diesel engine.

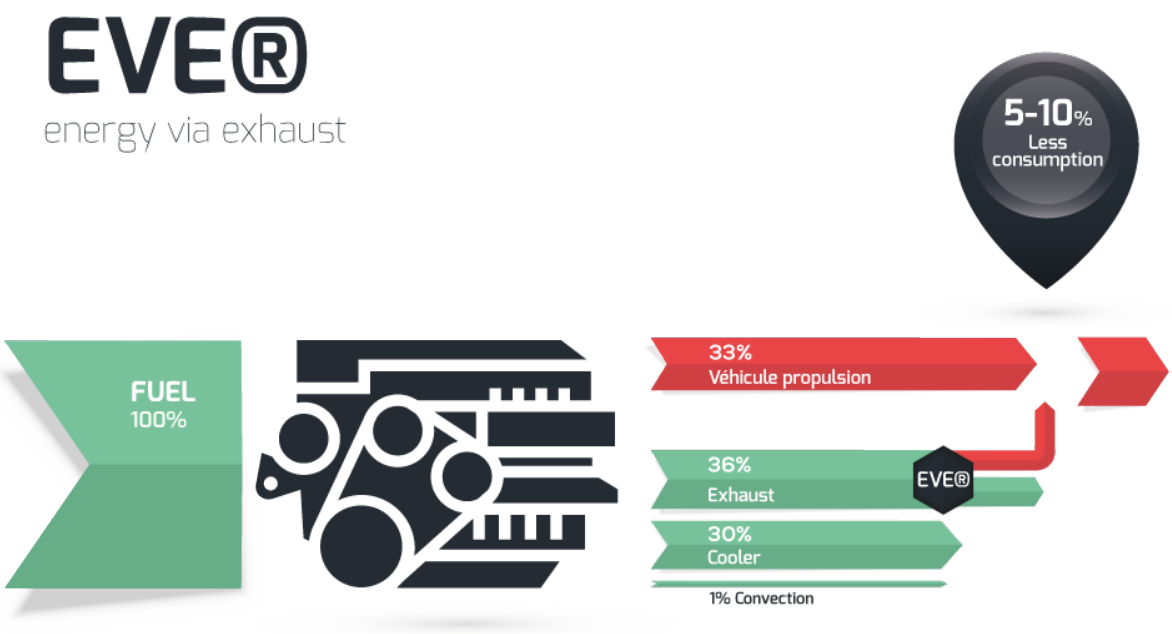


Figure 33: Energy savings using ORC to recover ICE waste heat

Daccord made a cost-benefit analysis on exhaust heat recovery systems with the cost breakdown shown in fig. 34. Accordingly, the expanders developed by Exoes have an effective isentropic efficiency of 65-70%. leading to a 2 year payback time for a long haul truck application. [44]

Component	Weight [kg]	Main material (if applicable)	Purchase parts and services	Total Toolings	Total Assembly investments	Assembly labor	SG&A & profit	Total
Exhaust bypass valve	4.2	Stainless steel	56.83 €	600,000 €	500,000 €	4 €	19.57 €	**84.80 €**
Exhaust evaporator	46.6	Stainless steel	321.78 €	600,000 €	1,000,000 €	8 €	99.65 €	**431.84 €**
Expander, coupling & vapor bypass valve	15.3	Cast iron / Steel	315.00 €	1,800,000 €	2,000,000 €	16 €	100.26 €	**434.46 €**
Condenser	13.8	Stainless steel	69.52 €	600,000 €	1,000,000 €	8 €	23.98 €	**103.90 €**
Cooling pump	0.4	Cast iron / Steel	19.00 €	600,000 €	300,000 €	4 €	7.98 €	**34.58 €**
Piping	15.4	-	52.82 €	250,000 €	0 €	4 €	17.35 €	**75.17 €**
Tank system	2.6	Plastic	56.00 €	300,000 €	300,000 €	8 €	18.72 €	**81.12 €**
Fluids	8.6	-	20.00 €	0 €	0 €	0 €	7.20 €	**31.20 €**
Feed pump	0.4	Plastic / Steel	41.00 €	300,000 €	500,000 €	4 €	14.46 €	**62.66 €**
Control valve	0.2	Plastic / Steel / Copper	22.00 €	600,000 €	500,000 €	4 €	9.12 €	**39.52 €**
ECU, harness & sensors	2.5	-	58.00 €	0 €	0 €	0 €	18.60 €	**80.60 €**
Total	**110 kg**	-	1,032 €	5,650,000 €	6,100,000 €	60 €	342 €	**1,481€**

Figure 34: ORC cost breakdown.

4 Well-to-Wheel(Overall effect)

4.1 Assumptions & Calculation

4.1.1 System cooling output, emission and cost

- **Auxiliary Deisel ICE** : Efficiency of auxiliary diesel engine is mostly lower than a power-train engine, also there are losses in the shaft work that should also be included. The COP of VCC is assumed 1.1 that is fair value considering the operating temperatures and the air-cooled compressor used.

Table 3: Assumptions & Calculations [51]

Parameter	Value	Unit(description)
Efficiency(ICE)	0.25	All losses included
Energy density	42.9	MJ/kg
Energy recovered	10.73	MJ/kg
COP(Air-cooled)	1.1	
Auxiliary consumption	0.2	Engine fan, shaft
Cooling per kg diesel	9.438	MJ/kg
Cooling per kg diesel	2.621	KWh/kg
Diesel density	0.832	kg/L
Diesel price (Ave EU)	€1.32	€/L
Diesel price (Ave EU)	€1.58	€/kg

- **Auxiliary LNG(CNG) ICE** :

  Natural gas is considered a cleaner substitute for diesel and petrol; higher energy density, lower cost and lower emissions that can even be reduced to almost zero in case of Bio-gas make it a sustainable fuel for the future. ICE efficiency and COP is assumed to be almost the same as Diesel case.

Table 4: Assumptions & Calculations

Parameter	Value	Unit(description)
Efficiency(ICE)	0.28	All losses included
Energy density	53.60	MJ/kg
Energy recovered	15.01	MJ/kg
COP(Air-cooled)	1.1	(-)
Auxiliary consumption	0.2	Engine fan, shaft
Cooling per kg LNG	13.20	MJ/kg
Cooling per kg LNG	3.668	KWh/kg
LNG price (Ave EU)	€1.13	€/kg

- **Alternative main engine based on diesel** : Here the power is taken from the truck axle to power the VCC, this means extra power required and extra fuel consumed. On the plus side, the system cost and emissions are lower compared to auxillary engine and one the down side there is dependency of VCC to the main engine

Table 5: Assumptions & Calculations [51]

Parameter	Value	Unit(description)
Efficiency(ICE)	0.40	All losses included
Energy density	42.9	MJ/kg
Energy recovered	17.16	MJ/kg
COP(Air-cooled)	1.1	
Auxiliary consumption	0.35	Engine fan, shaft
Cooling per kg diesel	12.2694	MJ/kg
Cooling per kg diesel	3.408166667	KWh/kg
Diesel density	0.832	kg/L
Diesel price (Ave EU)	€1.32	€/L
Diesel price (Ave EU)	€1.58	€/kg

- **LiN/LiA evaporation only** : This system is based only on evaporation of LiN/LiA, that means there is no VCC required for cooling. The round trip efficiency is so poor for the system that makes it the most expensive system to run,

Table 6: Assumptions & Calculations [3]

Parameter	Value	Unit(description)
Efficiency	0.950	Evap, HX
Energy density	0.413	MJ/kg
Energy recovered	0.392	MJ/kg
LiN liquefaction efficiency	0.250	
Auxiliary consumption	0.200	Engine fan, shaft
Cooling per kg	0.314	MJ/kg
Cooling per kg	0.087	KWh/kg
Density	0.800	kg/L
Price (Ave EU)	€0.08	€/kg

- **PEM hydrogen FC**: Hydrogen is has the highest power density of conventional transportation fluids with possibility of using it in electro-chemical reaction to directly produce electricity at very low temperatures and pressures. Not being bound to Carnot efficiency, PEM FC can reach relatively high round-trip efficiency's of around 50%. Here the TTW efficiency of fuel cell is assumed to be 65% based on Hydrogen low heating value. [55]

Table 7: Assumptions & Calculations [53]

Parameter	Value	Unit(description)
Efficiency(PEM-FC)	0.65	All losses included
Energy density	140.00	MJ/kg
Energy recovered	91.00	MJ/kg
COP(Air-cooled)	1.1	
Auxiliary consumption	0.25	Engine fan, shaft
Cooling per kg H2	75.075	MJ/kg
Cooling per kg H2	20.854	KWh/kg
H2 price (Ave EU)	€9.50	€/kg

- **LNG evaporation only** : The lost cold exergy of LNG evaporation only, is 4-7 KW of cooling in a LNG truck. This means with miminum initial cost of system(heat exchangers only) there is potential to get that amount of cooling without spending anything on fuel.

Table 8: Assumptions & Calculations [3]

Parameter	Value	Unit(description)
Efficiency	0.950	Evap, HX
Energy density	0.812	MJ/kg
Energy recovered	0.771	MJ/kg
Auxiliary consumption	0.200	Engine fan, shaft
Cooling per kg	0.617	MJ/kg
Cooling per kg	0.171	KWh/kg
Density	0.460	kg/L
Price (Ave EU)	€1.08	€/kg
LNG as fuel	47.8	MJ/kg
Efficiency	0.35	
Transport	4.647222222	KWh/kg
Ratio Cold/Power	0.035574781	
Price for Cooling	€0.22	

- **Dearman Engine**: Dearman engine, is capable of producing 175 Kj/Kg of LiN in work that is supplied to a VCC with COP of 2, Also 360 Kj/Kg of LiN in cooling from thermal exergy. It should be noted that the COP of VCC is higher in this case due to the potential of cooling the condenser to lower than ambient temperature from the expander outlet HX fluid.

Table 9: Assumptions & Calculations [3]

Parameter	Value	Unit(description)
Efficiency Evaporator	0.950	Evap, HX
Expansion work	0.040	KWh/kg
Energy density	0.413	MJ/kg
Energy recovered(Evap only)	0.392	MJ/kg
Auxiliary consumption	0.100	Engine fan, shaft
COP(Water cooled)	2.000	Hot sink at lower Temp
Evaporation Cooling per kg	0.353	MJ/kg
Evaporation Cooling per kg	0.098	KWh/kg
Total cooling(Evap+VCC)	0.178	KWh/kg
Density	0.813	kg/L
Cooling delivered power	12.00	kW
Price (Ave EU)	€0.08	€/kg

- **LNG or LiH evaporation and expansion** :

  Similar to the case of Dearman technology, this system is based on physical exergy extraction of a cryogenic fluid. The power-train and cooling is correlated that means the same fuel is providing both effects. The pitfall in this approach is that the amount cooling depends on the fuel consumption in ICE and the fact that it can not exceed 12 KW of cooling. This system is best to be used in hybrid configuration with batteries to cover for the cases that the truck engine is not running at required fuel rate or not running at all. The same process can be applied for LiH, that provides up to 22KW for a truck running on PEM FC as the power-train.[56] There is also the possibility of getting 11KW of cooling based from compressed hydrogen at 700 bar(only pressure exergy available.)

Table 10: Assumptions & Calculations [28]

Parameter	Value	Unit(description)
Efficiency	0.950	Evap, HX
Energy density from evap	0.812	MJ/kg
Energy density from expansion	0.3654	
Energy recovered	1.502	MJ/kg
Auxiliary consumption	0.200	Engine fan, shaft
Cooling per kg	1.202	MJ/kg
Cooling per kg	0.334	KWh/kg
Density	0.460	kg/L
Price(Ave EU)	€1.08	€/kg
LNG as fuel	47.8	MJ/kg
Efficiency	0.45	
Transport	5.975	KWh/kg
Ratio Cold / Power	0.0264	
Price for Cooling	€0.09	

- **Electric battery(Li-Ion)**: This is on of the easiest approaches with unrivalled round-trip efficiency and low emissions. There are though some challenges regarding the maximum range, recharge time and system weight. The round trip efficiency is chosen as 82% with the electrical motor efficiency of 90%. [52]

Table 11: Assumptions & Calculations

Parameter	Value	Unit(description)
Efficiency(WTW)	0.82	WTP and PTW(Round-trip)
Efficiency(Elec Motor)	0.90	All losses included
Specific energy	0.20	KWh/kg
COP(Air-cooled)	1	
Auxiliary consumption	0.25	Fan, pump ...
Cooling per kg Li-Ion bat'	0.15	MJ/kg
Cooling per KWh grid	0.5535	KWh cooling/KWh grid
EU 28 KWh grid price	€0.142	€/KWh(tax included)

4.1.2 Basis for system weight

There are assumptions made for getting a decent estimation of system weight, For VCC it is assumed a single stage refrigeration without receiver.

Table 12: Assumptions & Calculations

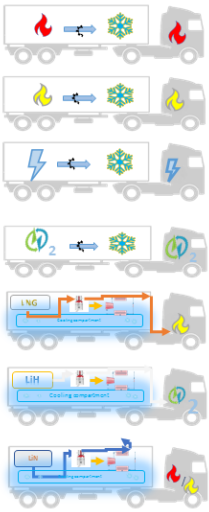
System or fuel	Value [Kg]	Description
VCC	200	All the components used in VCC
Diesel engine	100	Auxiliary engine
Gas engine	100	Auxiliary engine
PEM FC system	300	PEM FC modules + Batteries + Electrical motor
Cryogen system	70	Similar to Dearman [3]
Li-Ion for 24 h	1700	Based on Tesla batteries [50]
LiN tank for 24 hour	1400	
Diesel 24 hour	137	
H2 for 24 hour	17	
ORC system weight	110	[44]
Axle regenerative	150	

	Possible Senarios for Future TRUs													
										Hybrid solutions		Heat recovery		Power recovery
	Auxilary diesel engine	Auxilary LNG engine	Alternative driven main engine	Electric (Li-Ion)	PEM-FC	LiN Evap	LiN Dearman	LNG Evap	LNG Evap+Exp	LNG Evap+Exp Dearman Hybrid 50%	LNG Evap+Exp Li-Ion Hybrid 50%	Adsorption refrigeration	ORC	Regenerative axle driven
Cooling specific energy (KWh cooling/kg)	2.622	3.669	3.408	0.554	20.8541667	0.08718889	0.178	0.171	0.334	0.256	0.362	-		-
Cost per unit of Cooling (€/KWh)	€ 0.604	€ 0.308	€ 0.465	€ 0.257	€ 0.456	€ 0.918	€ 0.449	€ 0.224	€ 0.086	0.267	0.240	-		-
Annual operational cost (€/year/TRU)	€ 19,857	€ 10,118	€ 15,275	€ 8,428	€ 14,965	€ 30,141	€ 14,757	€ 7,363	€ 2,812	€ 8,784	€ 7,895	€ 3,000	€ 3,000	€ 3,000
Annaul maintanance cost(€/year/TRU)	€ 2,000	€ 2,000	€ 1,000	€ 500	€ 1,000	€ 500	€ 1,500	€ 500	€ 1,500	€ 1,500	€ 1,500	€ 1,000	€ 1,000	€ 1,000
Capital cost (€/TRU)	€ 20,000	€ 20,000	€ 20,000	€ 45,000	€ 35,000	€ 25,000	€ 25,000	€ 15,000	€ 25,000	€ 30,000	€ 65,000	€ 35,000	€ 30,000	€ 60,000
Infrastracture cost (€/Lifetime/TRU)	€ 0	€ 0	€ 0	€ 2,500	€ 5,000	€ 2,500	€ 2,500	€ 1,000	€ 1,000	€ 1,000	€ 1,000	€ 2,000	€ 500	€ 1,000
Cost of ownership in 5 years(€/Lifetime/TRU)	€ 129,285	€ 80,592	€ 101,373	€ 92,138	€ 119,823	€ 180,707	€ 108,784	€ 55,313	€ 47,559	€ 82,421	€ 112,976	€ 57,000	€ 50,500	€ 81,000
Cost of ownership in 10 years(€/Lifetime/TRU)	€ 238,570	€ 141,184	€ 182,747	€ 136,776	€ 199,646	€ 333,915	€ 190,068	€ 94,627	€ 69,118	€ 133,843	€ 159,951	€ 77,000	€ 70,500	€ 101,000
Greenhouse gas emissions(T CO2 Equivalent/5 years/TRU))	141	81	108	89	101	207	112	19	10	61	49	2	2	2
Lifetime(years)	20	20	20	10	6	20	20	20	20	20	15	10	15	10
Refill time(min)	minutes	minutes	minutes	10s of mintutes to an hour	minutes	minutes	minutes	minutes	minutes	minutes	minutes	-	-	-
Possibility of Powertrain+Cooling from single fuel	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	✓	✓	✓
System weight(kg)	392	340	292	1333	512	2137	1203	270	270	503	553	400	310	350
Cooling limitation	-	-	-	-	-	-	-	5KW	11KW	11KW	11KW	15Kw	15 KW	10 KW

Figure 35: Well-to-Wheel analysis on possible scenarios of transport refrigeration units

5 Conclusion

A summary of non-recovery solutions for refrigerated vehicle is shown on fig. 36.



Fuel type	10 year cost of ownership (Cooling only) [€/TRU]	10 year Ton CO2 equivalent [TCO2/ 10 year/TRU]	Range (Hours without refuel)[hour / tank]	Refuel time	Lifetime [years]	System weight [kg]
Diesel	240k	141	48	minutes	20	480
CNG	140k	80	48	minutes	20	380
Electricity	130k	90	6	10s of minutes	10	600
Hydrogen	200k	100	48	minutes	10	380
LNG	70k	10	Same as truck	minutes	15	380
Hydrogen	70k	10	Same as truck	minutes	10	410
Liquid Nitrogen	190k	112	6	minutes	15	500

Figure 36: Summary of WTW analysis on non-recovery solutions

Transition from diesel to CNG is cheapest to implement due to ease of retrofitting the current fleet of TRUs. CNG is 50 % cheaper compared to diesel and causes 30% less emission while providing higher energy density.

Batteries(Li-Ion) are the simplest system requiring least maintenance, also cheap to run; on the other hand, limited range, high system weight and high initial cost are the biggest challenge.

Fuel cell (PEM FC) is expensive to run(assuming hydrogen price of 9.5 €/kg) but with the current trend it can be considered as viable option in near future. Considering the renewable intermittent sources, high energy density of hydrogen and ease of storage at high pressure with relatively low cost, it can be considered as a highly potential energy carrier for the future of transportation.

The LNG "Evaporative + Expander "solution provides on of the lowest 10 year cost of ownership. The limiting factors are, low number of refueling stations and system complexity. The benefit on the other hand is using same fuel for both cooling and transportation and cooling that coms at zero cost for fuel.

Hydrogen "Expander " emits the lowest and one of the cheapest to run, the only limitation is requirement of having the power-train from hydrogen, that we are a decade or less away from fuel cell trucks becoming widespread.

Dearman approach based on liquefied nitrogen is lagging behind the other alternatives; considering the poor round-trip efficiency(35%), low energy density and lack of proper infrastructure.

Heat recovery can provide huge amount of saving to the system considering that only the waste heat is used. Adsorption technology(direct) is cheap to run with few moving components that provide very competitive cost and very low emission. ORC technology(indirect) is capable of producing power for VCC utilizing the waste heat of diesel ICE. This system requires scroll expanders that send the power trough shaft to VCC compressor. This system provides the cheapest solution in terms of 10 year cost of ownership with 70 k €for a TRU. Both of the heat recovery solutions are available only in case of a ICE system running.

Regenerative axle driven relies on wasted power of a truck axle, the power absorbed during the non-accelerating phase of power-train. Compared to alternative driven case this method can reduce fuel consumption but there is a challenge that it is not always enough to support the high cooling loads so this would be viale solution only in case it is used in hybrid configuration.

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