"Solar photo-voltaic application in transport refrigeration(PV-TRU)"

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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
Solar photo-voltaic application in transport refrigeration

Abstract

Rising demand for refrigerated vehicles, specially in developing countries, requires innovative solutions other than the current business as usual scenario to strike a balance between demand and available resources. Abundance of solar radiation most populated areas and developing countries bring up the possibility of tapping this potential and put it into useful work. An integrated system consists of solar panels on top of the refrigerated trailer can deliver power to make saving on the ordinary fuel used. The main benefit of this method would be lowering the need of fuel storage tank unlike the application in electric cars, accordingly, as the sun comes up and starts heating the vehicle that is when the solar PV kicks in to compensate for the warmer weather, so this would be harnessing the sun energy in our favor. A back-of-envelope initial calculations provided promising outcomes. For solar cell (efficiency=20%) covering 90% of a 53 ft long container in Copenhagen will produce on average 0.84 KW power output all year round, this value reaches to 1.82 KW for Mexico City. The payback time of the system depends heavily on the location and the technology providing the main cooling power, ranging from 3 years in Oslo to 1.36 in Mexico City for a refrigerated truck running on diesel.

Nomenclature

ESH	Equivalent sun hours ($\frac{h}{day}$)
GHI	Global horizontal irradiation ($\frac{KWh}{m^2 * year}$)
KW_P	Peak electricity production in STC condition (KW)
COP	Coefficient of performance (($-$))
ICE	Internal combustion engine
$LCOE$	Levelized cost of electricity (e/MWh)
LiA	Liquefied air
LiH	Liquefied Hydrogen
LiN	Liquefied Nitrogen
LNG	Liquefied natural gas
P	Pressure(Pa)
PM	Paarticulate matter
PV	Photo-voltaic cell
R_U	Universal gas constant ($\frac{J}{K.Mol}$)
STC	Standard test condition
T	Temperature (K)
TRU	Transport refrigeration unit
VCC	Vapor compression cycle
W_{Comp}	Work supplied to the compressor (W)
W_{Exp}	Work produced in the expander (W)
WTW	Well to wheel process
Subscripts	
x	This is a superscript

1 Introduction

Refrigeration is one of the challenges of the new world; As a growing sector and as an inevitable corollary of rising population and global warming. Current refrigeration transport relies mainly on fossil fuel(diesel) leading to high level of toxic pollutants. Solar PV as a renewable, sustainable and low emitting(not zero considering the whole life cycle) technology have vital role in providing the rising energy demand. To clarify the potentials of solar power NASA made a schematic of earth energy budget as shown in figure 1.

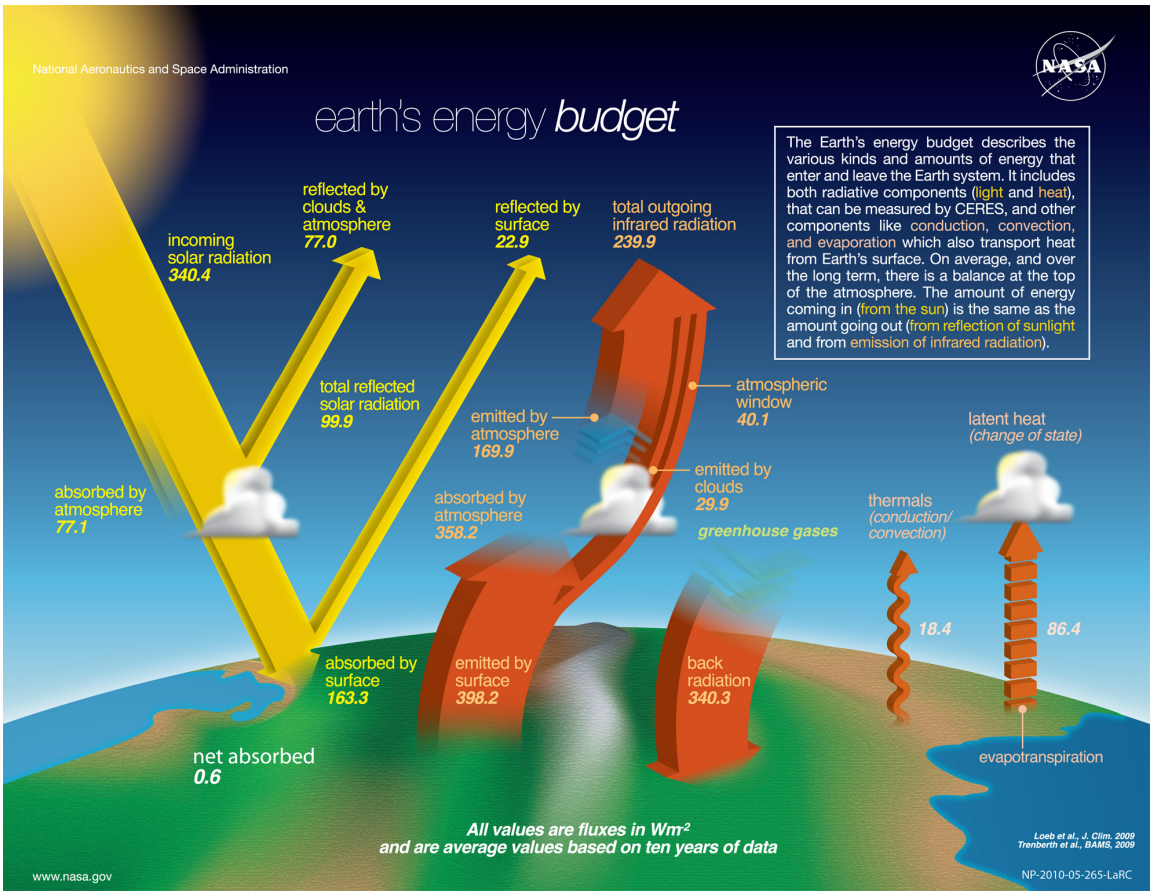

Figure 1: Schematic of earth energy budget.

The yearly flux of solar energy to the earth is 3,850,000 Exajoulee($10^{18}J$) that is almost 7000 times more than total primary energy supply of the whole planet. In other words, every 75 minutes, sun is giving us energy equal to all our yearly consumption.[1, 3, 5]

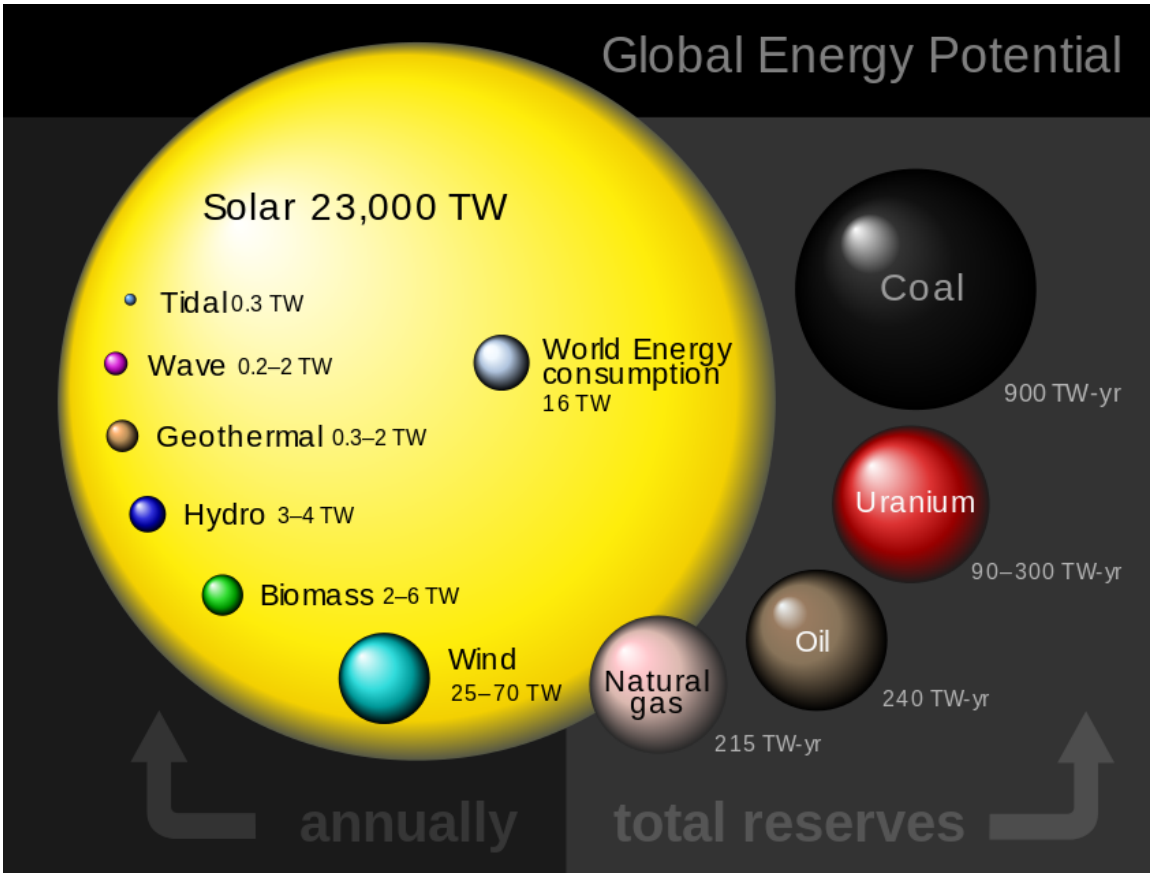

Figure 2: Global energy potential sources compared with current consumption.

2 State-of-art solar PV

2.1 Cost of PV electricity

According to Wood Mackenzie article published August 2019, the levelized cost of electricity(LCOE) from PV has just hit a new low; in Portugal's Direcção-Geral de Energia e Geologia auction a new world record for PV was set by 14.76 €/MWh beating the former record in an auction in Brazil with 15.12 €/MWh.[2]

This indicates a new era in energy production, fossil fuel is no longer the cheapest energy solution. Based on a 2018 report from IRENA and PPA database, 83% of the PV projects to be commissioned in 2020, have electricity prices that are lower than the cheapest fossil fuel based power production sources. In 2018 cost of electricity from solar PV dropped by 13% meaning PV projects undercut the fossil fuel for electricity generation even without financial assistance.[4]

	GLOBAL WEIGHTED-AVERAGE COST OF ELECTRICITY (USD/KWH) 2018	COST OF ELECTRICITY: 5TH AND 95TH PERCENTILES (USD/KWH) 2018	CHANGE IN THE COST OF ELECTRICITY 2017-2018
Bioenergy	0.062	0.048–0.243	−14%
Geothermal	0.072	0.060–0.143	−1%
Hydro	0.047	0.030–0.136	−11%
Solar photovoltaics	0.085	0.058–0.219	−13%
Concentrating solar power	0.185	0.109–0.272	−26%
Offshore wind	0.127	0.102–0.198	−1%
Onshore wind	0.056	0.044–0.100	−13%

Figure 3: Cost of electricity for various renewable sources.

2.2 Experiments and studies on PV refrigeration

Several studies has been performed on analysis and evaluation of integrated PV refrigeration systems. In a project known as “Cold storage driven by solar and wind energy” financed by the "Danish Energy Authority", development and demonstration of a grid-independent cold storage system for perishable food, medicine or other goods, for places with unreliable supply of electricity has been explored. It was based on international “SolarChill” project where a unique battery-less solar driven vaccine refrigerator was developed by Vestfrost in cooperation with Danfoss,DTI, Grundfos, Fresvik and Karise Klejnsmedie.
The core technology is a DC driven soft-start compressor, developed by Danfoss, allowing direct PV array electricity output to be used in refrigeration. Batteries in this system can be avoided by storing energy in form of latent heat in ice-packs; leading to higher efficiency and lower cost.[6]

2.2.1 Solar cooling: PV or thermal

In a techno-economic analysis by Renato, solar PV and solar thermal based refrigeration system has been compared. The goal of study was to evaluate combined effect energy extraction from sun irradiation to cooling effect in the chiller. For PV combined with VVC, the overall efficiency is calculated to be 36% ($\eta_{TotalPV} = 12\%$ and COP $= 3$) and for collector combined by adsorption chiller the overall 28% ($\eta_{heat\ recovered} = 35\%$ COP=0.8).
The comparison of capital cost shows for getting 10 KWh cooling/day, a PV driven system costs 2656€while for thermal solar system it requires 3300€. [7]

2.2.2 Solar cooling: PV or wind power

Similar comparison in Denmark between PV and onshore wind power showed that on average the electricity produced from 1 sq. meter of PV is almost the same as 1 sq. meter of wind turbine swept area but in terms of LCOE PV system is cheaper.[6]

2.2.3 Transportation using solar PV

Toyota motor corp is testing triple-junction compound solar cell module designed by Sharp Corp to the hood, roof, rear window and spoiler harness the sun energy for powertrain. On an average sunny day in Tokyo a charge can be sufficient for up to 56 kilometers of travel. The solar cells are super-slim - just 0.03 millimeters, making them easy to fit to the body of a car. It is claimed that the solar battery cells give a conversion efficiency of 34 percent.[20]

3 Techno-economical analysis

3.1 Working principles and assumptions

The idea is to install thin PV module on roof of a refrigerated truck to provide part of power required for running a VCC. This system is similar to the one used by Toyota[20] with the

difference that there is no need to store energy in batteries. This is due to the fact that when the sun is shinning the container requires more cooling power and this extra requirement is partially fulfilled by PV cells electricity. The calculations are based on a 53ft long haul truck Cerasis truck dimensions.[8]. The PV cell used is Multi-crystalline-Silicon that is the most used technology of PV(70% of all installations) due to having relatively high efficiencies and low cost of production. PV cells are usually priced and sold based on the KW_P that is calculated in STC condition. Required conditions is depicted in table 1.

Table 1: Standard test condition(STC) [3]

Parameter	Value	Unit(description)
Irradiance ($I_{e\ STC}$)	1000	W/m^2
Cell temperature	298.15	K
Air mass(in the irradiation path way)	1.5 times of air mass in 48.2° vertical (AM 1.5)	(-)

Further assumptions include: The radiation is coming from a black-body at 6000k and the mass of air is assumed to be consisting of only N_2, $,O_2$ CO_2 *and* H_2O.

3.2 Performance and cost evaluation

Global horizontal irradiation(GHI) is extracted from GSA database as shown in fig. 4 (Red color shows the highest and blue the lowest GHI) [9], based on which the equivalent sun hours(ESH) can be calculated:

$$ESH = GHI \frac{1000\ w/kW}{1000\ W/m^2 * 365\ days/year}\ , \quad [\frac{h}{year}] \tag{1}$$

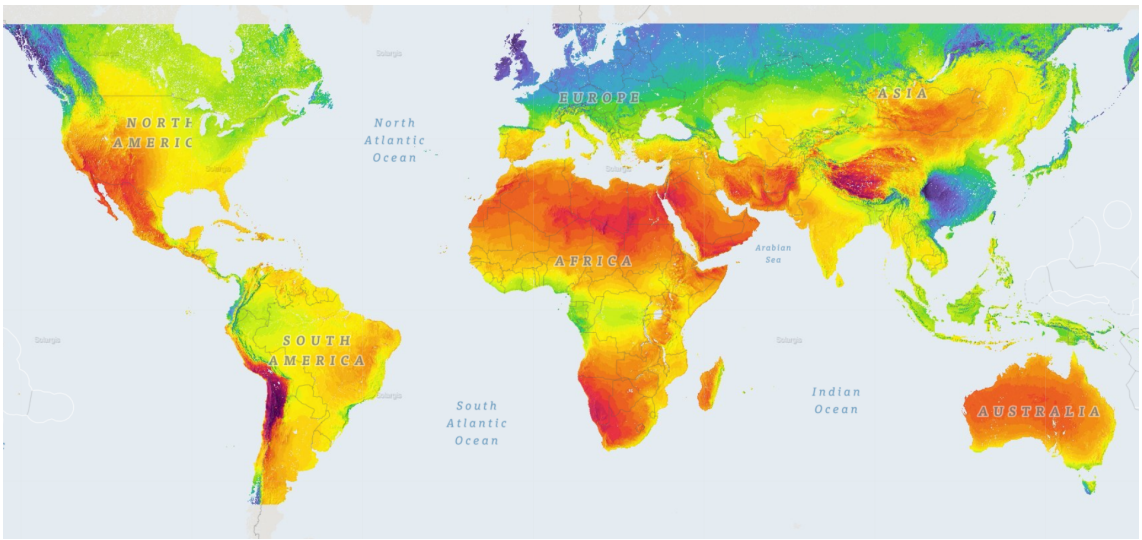

Figure 4: Global horizontal irradiation world map.

And total efficiency of a PV system can be calculated by:

$$\eta_{Total} = \eta_{\ Module} * \eta_{Area} * \eta_{Electrical} * (1 - (T_{air} - 25) * C_{t-\ d}) \tag{2}$$

Using eq. **??** average electricity produced in a day per sq. meter of PV surface is then :

$$Electricity\ Production = \eta_{Total} * ESH * 1000[W/m^2]\ , \quad [\frac{KWh}{day * m^2}] \tag{3}$$

The electricity production of a PV system using its KW_P value is:

$$Electricity \quad Production = KW_P * ESH \ , \quad [\frac{KWh}{day}] \tag{4}$$

Here it is required to calculate how many KW_P solar cells can we fit on the roof of the truck:

$$Area\ equivalent\ to\ 1\ KW_P = \frac{1000\ W/m^2}{\eta_{Total} * 1000\ w/kW} \tag{5}$$

Considering the number of KW_P and the cost data in table 2 it is possible to calculate the total cost of system.

Table 2: Cost breakdown of a PV system [10, 3]

Component	cost	Unit
PV module cost	€400	€/kWp
Inverter, scaffold and profit of installer	€350	€/kWp
Mounting stands, cables, installation cost	€500	€/kWp
Total cost per KWp	€1,250	€/kWp

Table 3: Assumptions & Calculations: PV and VCC[11, 15, 14]

Parameter	Value	Unit
PV module efficiency ($\eta_{\ Module}$)	0.2	(-)
Area efficiency (η_{Area})	0.92	(-)
Electrical efficiency ($\eta_{Electrical}$)	0.95	(-)
Auxilary consumption of total production	0.2	(-)
COP(@ $T_{evap} = 248.15K$)	1.1	(-)
Temperature linear dependence constant ($C_{t-\ d}$)	0.005	(-)
Total roof area of truck	41.82	(m^2) [8]
Area of PV that gives 1 KW_P	5.721	(m^2)

The price of electricity produced on-board differs depending on the main cooling system(mostly diesel ICE) . Here there is an example of a refrigeration system that originally runs on Li-Ion battery:

$$Price\ of\ electricity\ produced = \frac{KWh_{produced}}{year * KW_P} * \frac{Euro}{KWh_{Grid} * \eta_{WTW}} \tag{6}$$

Where, $\frac{Euro}{KWh_{Grid}}$ has been taken from data published by Eurostat [18] and η_{WTW} is the round-trip efficiency for the battery.[17]

The payback time and emissions are calculated based on the saving of cost with installation of the PV and the amount of CO_2 avoided. That is all calculated with regards to data in table 4.[15, 17, 18, 19]

Table 4: Assumptions: Electricity [15, 17, 18, 19]

Parameter	Value	Unit(description)
Average price of electricity EU28	€0.110	€/kWh
Average value of electricity delivered on-board	€0.178	€/kWh
CO2 equivalent per KWh	0.340	Kg CO2/kWh
WTW Battery efficiency	0.82	(-)

Cost per unit cooling depends on the cost of fuel and efficiency of the system that is calculated for each technology. Then based on this value and the cooling produced by PV using eq.7, the PV payback time for each technology can be found.

$$Cooling\ effect = Electricity\ Production\ *\ COP \tag{7}$$

3.3 Results and outcomes

Fig. 5 shows the cost of cooling for each technology at a location with average irradiation(Hong Kong) for various fuel sources used in TRUs. The prevented CO_2 is also calculated for case of auxiliary diesel ICE it is almost 35 ton CO_2 equivalent.

	Technology evluation based on different scenarios for Hong King(Average irridiation range)							
	Auxilary diesel	Alternative driven	Electric (Li-Ion)	PEM-FC	LiN Evaporation	LiN Dearman	LNG Evaporation	LNG Evaporation + Expansion
Cost per unit of Cooling (€/KWh)	0.6045	0.4650	0.2565	0.4555	0.9175	0.4492	0.2241	0.0856
Equivalent price of KWh produced onboard over ayear(TRUs roof)(€/KWp)	5577.40	4290.31	2367.13	4203.23	8466.06	4144.85	2068.00	789.76
Payback time of PV system for each TRU technology (years)	2.08	2.71	4.91	2.77	1.37	2.80	5.62	14.72
CO2 emission reduced in 5 year(ton CO2)	34.5	26.6	21.7	24.7	50.7	27.4	4.6	2.4

Figure 5: Payback time and emissions based on the WTW analysis on each technology [16, 15, 14, 13]

Based on data from GSA, it is possible to repeat the same analysis for various locations to check the payback time of the system; fig. 6 shows this comparison for a number of cites.

	Location															
	Oslo	Nordborg	Delft	Paris	Milan	New Dehli	Hong Kong	Ames	George Town	Canbera	Madrid	Cape town	Doha	Amman	Mexico City	Atacama
Global Horizontal Irridiation (KWh/m2/year)	934.0	1019.0	1065.0	1148.0	1391.0	1427.0	1435.0	1483.0	1569.0	1734.0	1748.0	1893.0	2123.0	2136.0	2166.0	2657.0
Equivalent sun hours(h/day)	2.559	2.792	2.918	3.145	3.811	3.910	3.932	4.063	4.299	4.751	4.789	5.186	5.816	5.852	5.934	7.279
Average Air Temperature(°C)(Near surface)	5.8	9.0	10.8	11.3	12.8	13.7	20.5	9.9	26.3	12.3	13.9	16.0	27.4	17.2	14.6	2.0
Average high Temp in year(°C)(Near surface)	9.0	14.0	16.0	18.0	19.0	27.0	25.0	12.0	30.0	17.0	19.0	21.0	33.0	20.0	22.0	10.0
Average efficiency temperature corrected(-)	0.189	0.184	0.183	0.181	0.180	0.173	0.175	0.186	0.170	0.182	0.180	0.178	0.168	0.179	0.177	0.188
Average Electricity Production(KWh/day/m2)	0.483	0.515	0.533	0.569	0.686	0.677	0.687	0.756	0.733	0.864	0.862	0.925	0.976	1.049	1.053	1.368
Average Electricity Production(KWh/year/m2)	176.3	187.9	194.5	207.7	250.4	246.9	250.8	276.1	267.4	315.2	314.7	337.5	356.3	382.7	384.3	499.3
Production per TRU in 1 year(KWh/TRU/year)	7370.4	7855.0	8131.7	8681.6	10468.4	10322.3	10485.0	11540.1	11177.5	13176.5	13155.2	14108.1	14891.5	15997.2	16063.6	20869.8
Value of electricity produced onboard(TRUs roof)(€/1 year/TRU unit)	1308.24	1394.26	1443.38	1540.98	1858.15	1832.21	1861.09	2048.36	1984.01	2338.83	2335.04	2504.19	2643.24	2839.50	2851.28	3704.38
CO2 emission reduced in 5 year(ton CO2)	15.3	16.3	16.9	18.0	21.7	21.4	21.7	23.9	23.2	27.3	27.3	29.2	30.9	33.2	33.3	43.3
Total cooling for PV-TRU in 5 years(KWh cooling/TRU/5 year)	32429.6	34561.9	35779.7	38199.1	46061.1	45418.2	46134.1	50776.3	49181.1	57976.6	57882.7	62075.6	65522.7	70387.5	70679.7	91827.0
Payback time of PV system for Li-Ion TRUs (years)	6.99	6.56	6.33	5.93	4.92	4.99	4.91	4.46	4.61	3.91	3.91	3.65	3.46	3.22	3.21	2.47
Payback time of PV system diesel TRUs (years)	2.965	2.782	2.687	2.517	2.088	2.117	2.084	1.894	1.955	1.659	1.661	1.549	1.467	1.366	1.360	1.047
Payback time of PV system LiN TRUs (years)	3.990	3.744	3.616	3.387	2.809	2.849	2.805	2.548	2.631	2.232	2.235	2.084	1.975	1.838	1.831	1.409
Payback time of PV system LNG TRUs (years)	7.997	7.503	7.248	6.789	5.630	5.710	5.621	5.107	5.273	4.473	4.480	4.178	3.958	3.684	3.669	2.824

Figure 6: Location-based payback time for various technology

Similar data as in table. 5 is shown in fig 7.

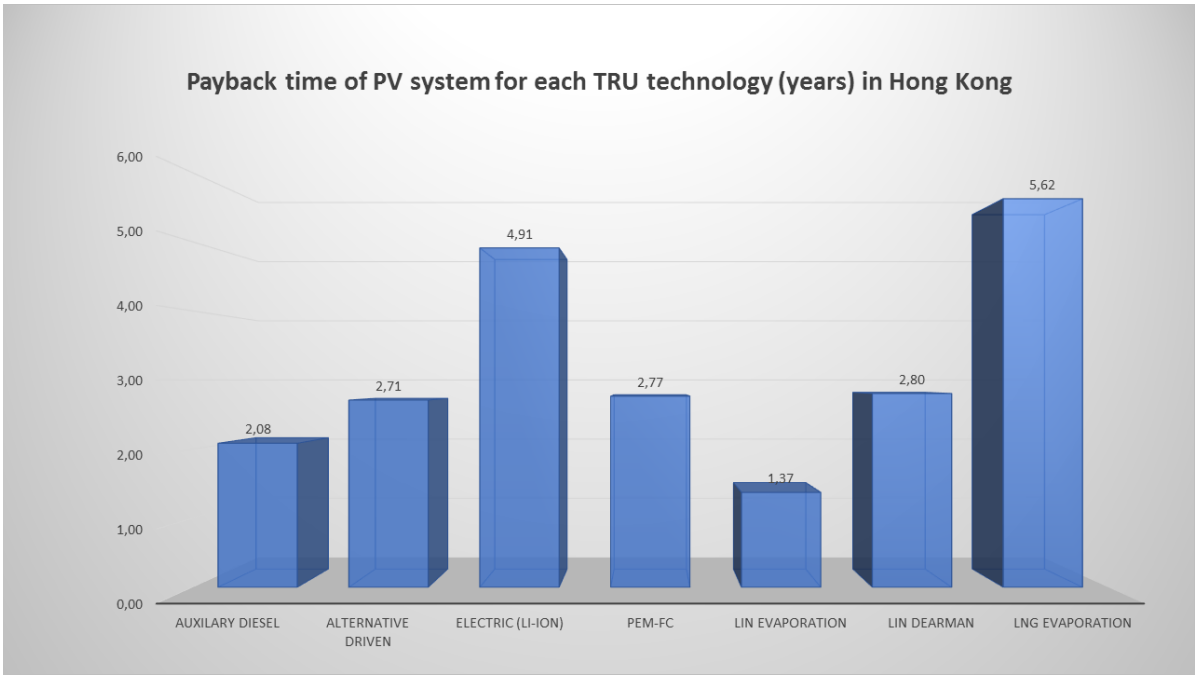

Figure 7: Each technology payback time for Hong Kong

As it is compared in fig. 8 and 9, depending on the technology currently in use, it is possible to check if PV can be considered as a viable option. For most of the conventional diesel systems currently in use, PV refrigeration have payback time less than 3 years.
When comparing this value with the case of a truck with refrigeration system running on Li-ion batteries, then PV system will have payback time less than 5 years only for regions with GHI more than 1390 $[\frac{KWh}{m^2 * year}]$.

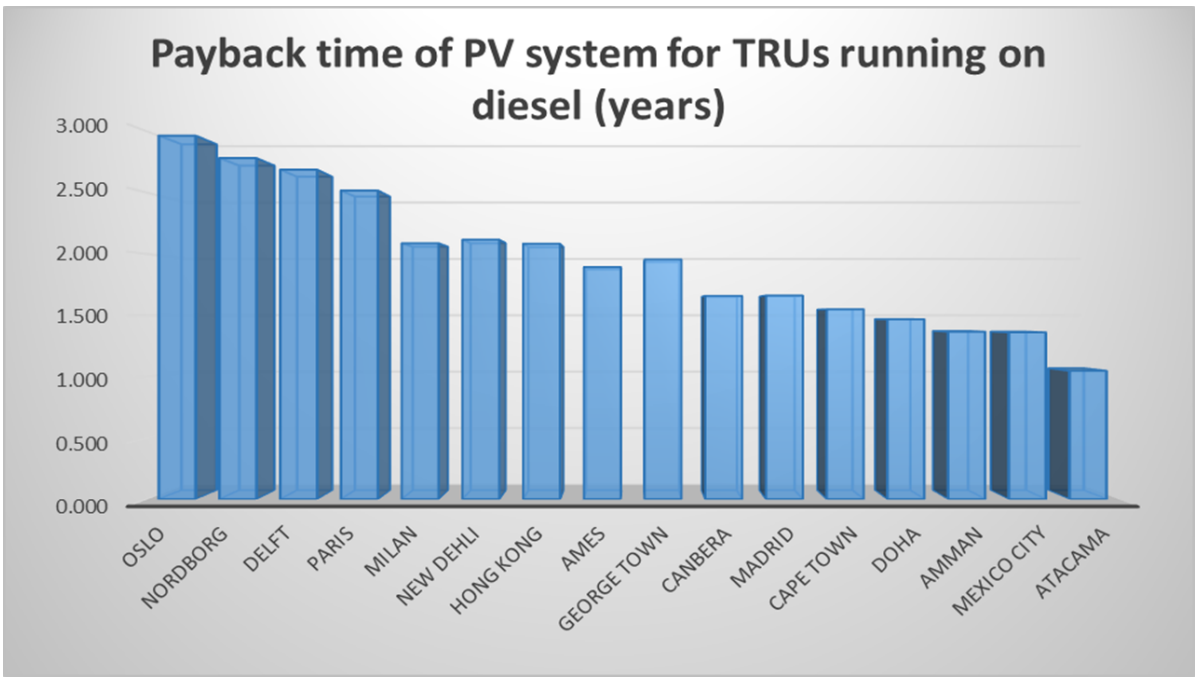

Figure 8: Diesel TRU PV system payback time

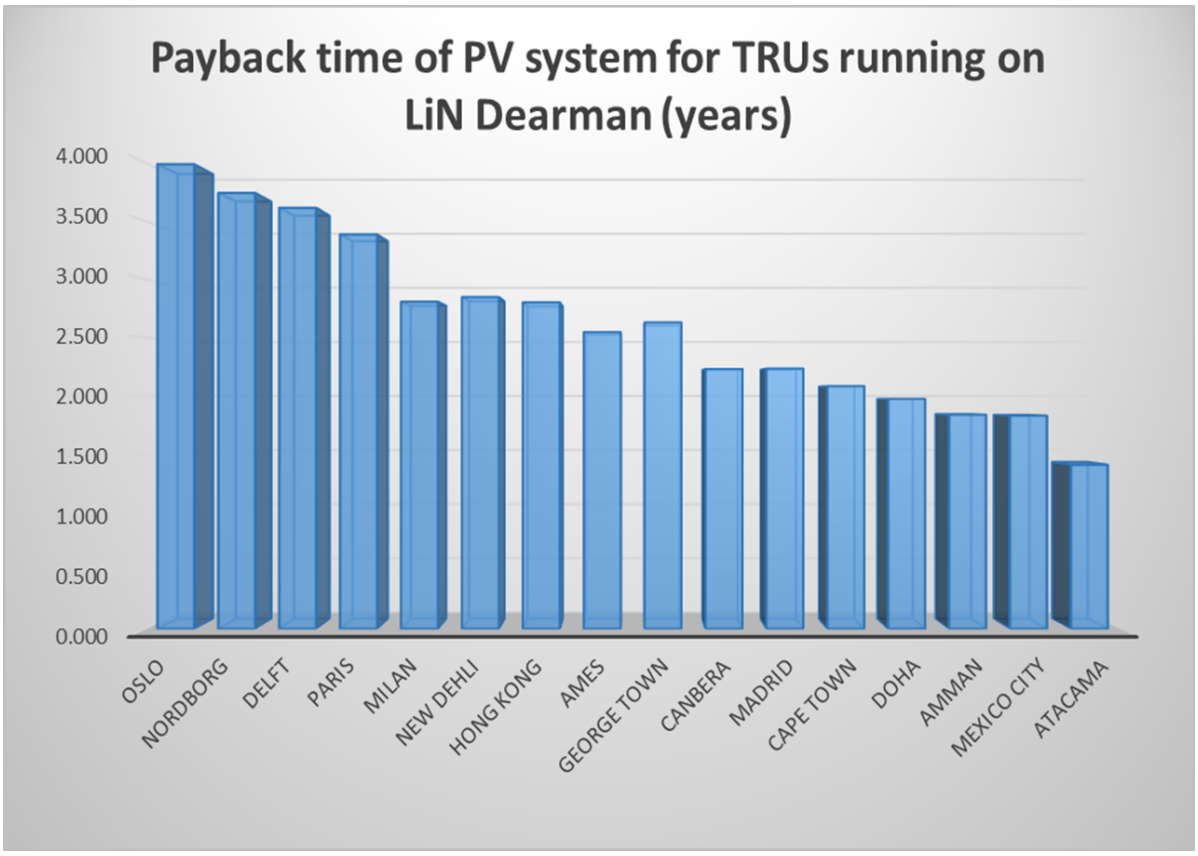

Figure 9: TRU using Dearman engine PV system payback time

As indicated in fig. 10 for Dearman and conventional desel, payback time is less than 4 years for all the cities in the sample and even in the case of Li-ion, only 4 cities of 16 have payback time more than 4 years.

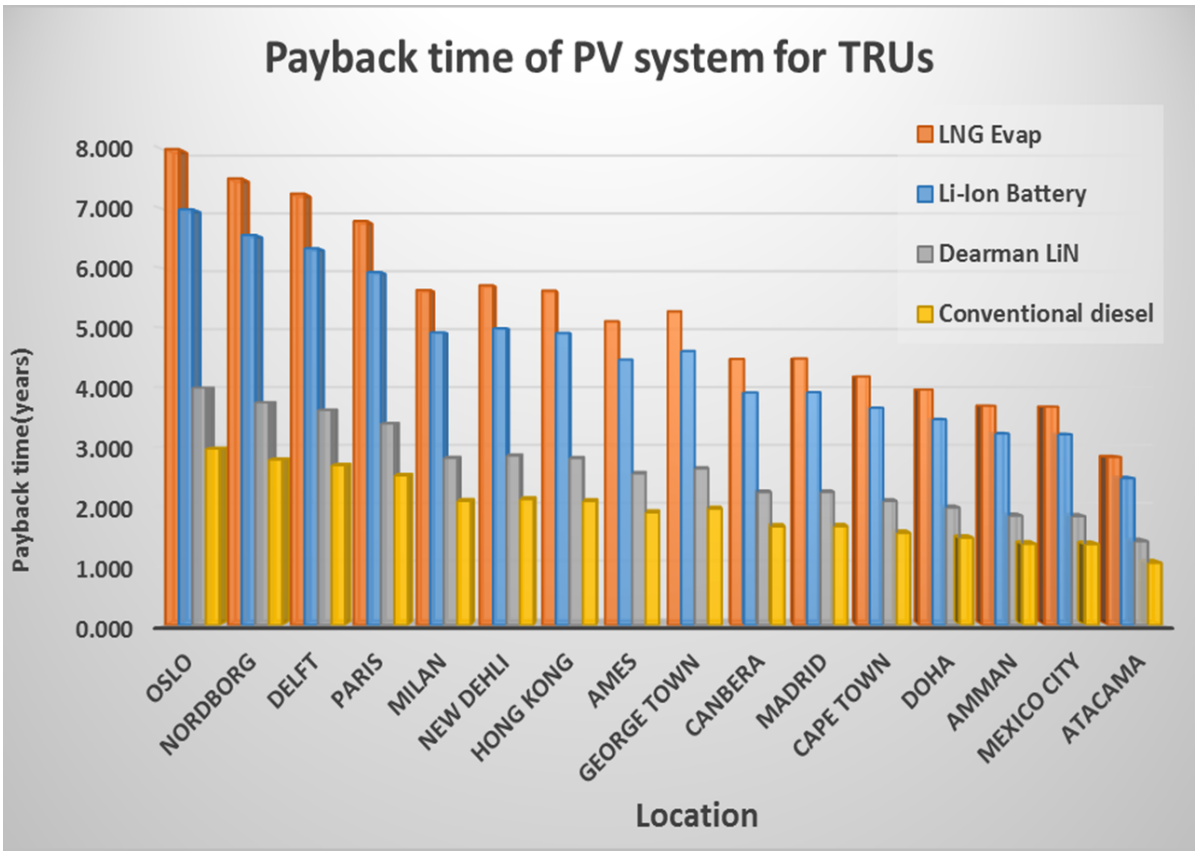

Figure 10: 4 main technologies payback time comparison for all the cities(varying GHI)

4 Conclusion

Nearly all the refrigerated trucks today are using either alternative primary or external auxiliary(secondary) diesel ICE. This means by adding PV on roof of refrigerated vehicle on average 3780 liters of diesel is saved per year. In terms of cost of fuel this means 5000 €saving on diesel cost per year, this result in payback of the whole PV system cost(10,000 €) for a TRU in only 2 years. This saving on diesel fuel translates into reduction of CO_2 emission by 7 ton each year.

PV is mostly believed to be the future of energy industry and utilizing PV on roof of trucks means there is no loss due to transportation, storage or conversion(into other forms of energy). Direct use of the electricity produced makes this application a decent solution with unrivalled efficiency with minimal cost.

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