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CARBON FOOTPRINT AND ECONOMIC ANALYSIS OF FUEL CELL ASSISTED ROAD TRANSPORT REFRIGERATION SYSTEM

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ABSTRACT

The present study examines the feasibility of Solid Oxide Fuel Cell (SOFC) assisted Vapor Absorption Refrigeration System (VARS) for refrigerated transport to replace the conventional TRU, where the heat generated from SOFC can be used to run the VARS. The study investigates and compares the GHG emissions from SOFC assisted VARS, diesel, and natural gas (NG) engine powered TRU, and cryogenic transport refrigeration systems. The operational and production related emissions were considered here to find out the total GHG emissions from the above-mentioned systems. Hydrogen fueled SOFC was considered in this work, and four different hydrogen (H_2) production methods (solar based electrolysis, wind-based electrolysis, biomass gasification, and NG reforming) were studied to calculate the hydrogen production related emissions. The analysis was then applied to systems for chilled and frozen products over a 10-hour vehicle operation. Finally, to select an optimum system configuration, both environmental and economic aspects were be considered. The mass intensity of the various fuels to obtain the required amount of refrigeration load in the different systems was calculated. The result showed that the considered novel SOFC-VARS emitted considerably lower amounts of GHG (50- 75 % reduction) compared to diesel and natural gas (NG) fueled TRUs, and cryogenic transport refrigeration systems.

Keywords: Sustainable Road Transport Refrigeration, Greenhouse Gas Emissions, Solid Oxide Fuel Cell (SOFC), Absorption Refrigeration.

NONMENCLATURE

Abbreviations

SOFC	Solid Oxide Fuel Cell
VARS	Vapor Absorption Refrigeration System
VCRS	Vapor Compression Refrigeration System
LN_2	Liquid Nitrogen
LCO_2	Liquid Carbon Dioxide
NG	Natural Gas
GHG	Green House Gas
TRU	Truck Refrigeration Unit
PM	Particulate Matter
WTW	Wheel to Tank
TTW	Tank to Wheel
CADC	Common Artemis Driving Cycles

1. INTRODUCTION

Total number of refrigerated vehicles around the world are more than 4 million which include trucks, vans, semi-trailers and trailers [1]. Number of refrigerated vehicles are predicted to increase by 2.5 % within 2030. In addition, there are around 80000 refrigerated railcars, 650000 refrigerated containers and 1300 refrigerated cargo ships are employed for transportation [1]. In Europe today, more than a million transport refrigeration units (TRU) and in the UK more than 180000 TRUs are in operation using vapor compression refrigeration technology powered by diesel engines. They produce significant greenhouse gas (GHG) and particulate matter (PM) emissions and at the same time not being covered by any environmental regulation [2]. VCRS employed on all refrigerated trucks use R404, R410A or R134A chemicals as refrigerants. These refrigerants have high global warming potential and annual leakage rate of the refrigerant rom the VCRS can be high as 25 % [3]. TRUs operate in abundant harsh conditions compared to stationary VCRS which causes reduced efficiency of the system. On board TRUs are responsible for 40 % of the total vehicle fuel consumption [4]. R404A is widely used refrigerant for TRU and it has 4000 times great GWP compared to CO2 thus leakage of the R404A from the TRU is one of the major issues in conventional system. During food distribution, refrigerated transport consumes 40 % of the total energy consumption [1]. Study conducted by Dearman [3] concluded that health and environmental impacts from the refrigerated trucks cost the EU € 1.9 billion and predicted to increase to € 2.5 billion by 2025. In the EU, 40000 tonnes of NOx, 5000 tonnes of PM and 13 Mt CO2 emitted by refrigerated trucks which are more than 26 million Euro VI diesel cars in 2015. Fuel consumption of TRU increase by 16 % when it operates in city/urban area compared to highway driving due to frequent engine idling scenario and frequent stops [1]. Above illustrated data proved that conventional TRUs are inefficient and harmful to environment. The primary crux of the problem lies in fact that the diesel engines depict 6 to 7 % efficiency [4] during idling mode and vapor compressor of the TRU has 65 % efficiency. With global pressures such as global warming and climate change, there is a need to design and develop alternate technology for temperature-controlled transportation and refrigerated road transportation. Many researchers are eager to develop alternate technologies for sustainable and green transport refrigeration. In recent decades, there has been keen interest from the industries and researchers to adopt fuel cell for the automobile applications. On board fuel cells are used as part of power train or auxiliary power unit (APU). Increasing power requirement especially on large refrigerated trucks obligated the implementation of APUs to reduce the load on the primary internal combustion engine. SOFC is the optimum option for large trucks as an APUs. Some the major industries involved to develop SOFC APUs for large trucks are Cummins power generation, Delphi and AVL. Their research finding can be accessed through the following references [5-7]. However, there are lack of resources available for the SOFC integrated VARS for automobile applications. Ballard power system [8] has developed SOFC assisted VCRS for refrigerated truck. In this configuration, they have used SOFC as an auxiliary power unit (APU) to run VCRS instead of auxiliary diesel engine. Although, there is ample residual heat available from SOFC to drive the heat driven VARS. If compact heat driven VARS can be developed for trucks, then novel powertrain for refrigerated trucks can be designed and developed where SOFC and batteries will act as a power unit for propulsion of refrigerated trucks. Therefore, internal combustion engines can be eliminated which will make refrigerated transport completely environment friendly with negligible carbon emissions. Therefore, sustainable and green refrigerated transport is an efficient and effective way towards making overall transportation green and sustainable.

2. SOFC-VAR SYSTEM

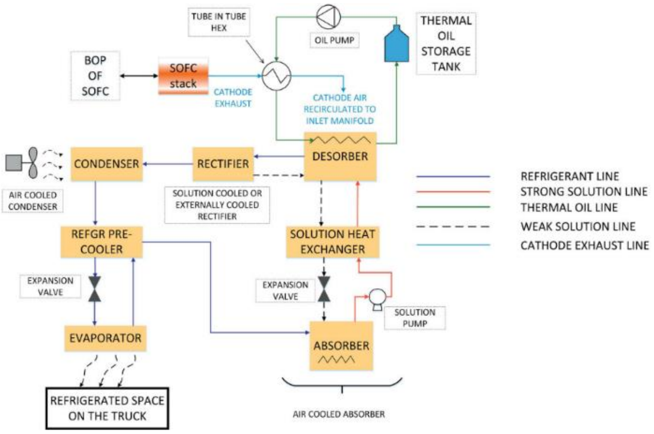

Fig.1: Schematic of SOFC-VARS

The system configuration is depicted in the Figure 1. The SOFC is coupled to the VARS via thermal. Exhaust temperature from the SOFC stack is in the range of 700-800 °C. Residual heat from the SOFC coupled to Paratherm HR^{TM} oil (heat transfer fluid) in a tube in tube heat exchanger which transfer the heat to the desorber of the VARS.

3. Methodology

Mathematical model is divided into four parts (I) Thermal load calculation of the refrigerated trailer (II) Mass required to cater the hourly refrigerated load (III) Overall well to wheel emissions (WTW) and (IV) cost analysis of the fuel. For diesel, wheel to tank (WTT) emission factor and tank to wheel (TTW) emission factor are considered as 0.926 kgCO_2/Liter and 2.9 kgCO_2/Liter respectively [9]. For LN_2 and LCO_2 wheel to tank (WTT) emission factor is considered as 0.254 kgCO_2/kgLN_2 and 0.305 kgCO_2/kgCO_2 respectively [9]. TTW emission factor is taken as 0.97

$kgCO_2/kgH_2$, 2.5 $kgCO_2/kgH_2$, 11.89 $kgCO_2/kgH_2$ and 4.5 $kgCO_2/kgH_2$ for hydrogen production from wind electrolysis, solar electrolysis, natural-gas reforming and biomass gasification respectively [10]. Production cost of diesel, LN_2, LCO_2 is taken as £0.6, £0.08 and £0.12 respectively [9]. Hydrogen production cost is estimated to be £5.44, £6.3, £1.24 and £1.4 for wind electrolysis, solar electrolysis, natural-gas reforming and biomass gasification respectively [11]. In this study, 10 hours of delivery journey of 18 tonne medium rigid refrigerated trailer is assumed for chilled milk and frozen peas distribution to find out the thermal load of refrigerated vehicle throughout the year. Driving distance is derived with the help of Common Artemis Driving Cycles (CADC) [9].

4. Result and Discussion

4.1. Average Thermal Load of the Refrigerated Vehicle

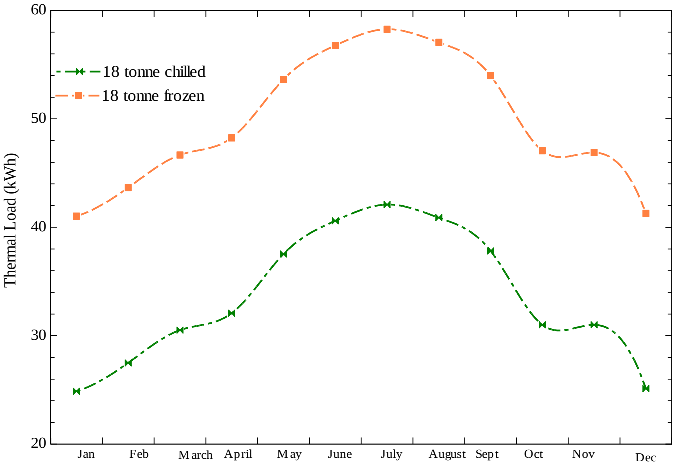

Fig 2 Average thermal load for each month of the year

Fig 2 depicts the distribution of average thermal load of refrigerated vehicle for each month of the year. Due to high temperature during summer in the UK (May-August), average thermal load is comparatively higher of the vehicle compared to winter season. Required amount of the fuel is also evaluated to cater the particular thermal load of the vehicle. It was found that SOFC-VARS required the least amount of fuel (2 to 7 kg of H_2) while the fuel mass intensity of cryogenic refrigeration systems was the highest (up to 540 kg of LN_2 and LCO_2) while the amount of diesel and natural gas required for conventional TRUs varied from 15 to 35 kg and 12 to 30 kg, respectively

4.2. Carbon Footprint of Diesel Fuel, Cryogenic Fluid and Hydrogen Fuel

Fig 3 illustrates the total GHG emissions from the different refrigerated transportation technologies for the distribution of chilled milk. It can be seen from the figure that conventional VC system emits highest amount of GHG emissions for all considered cases followed by LCO_2 and LN_2 cryogenic systems. It is found that, novel considered refrigerated transportation technology (SOFC-VARS) emits considerably lower amount of GHG emissions if it is fueled by green hydrogen. Total GHG emissions emit by SOFC-VARS is averagely 50-70 % lower compared to conventional VCRS fueled by diesel and natural gas and cryogenic systems powered by LN_2 and LCO_2. Total GHG emissions during distribution of frozen peace is depicted in Fig 4.

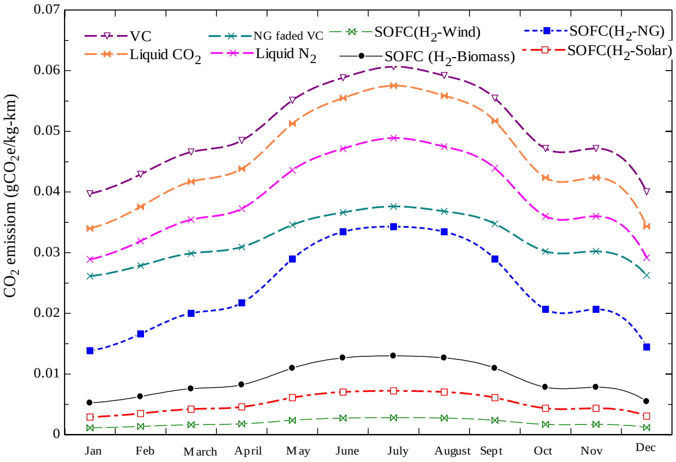

Fig 3 GHG emmisions during refrigerated distribution of milk

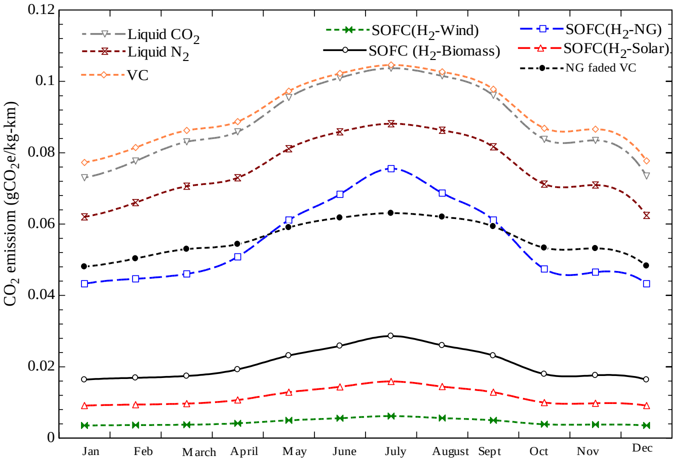

Fig 4 GHG emmisions during refrigerated distribution of peas

4.3. Cost Analysis of Diesel Fuel, Cryogenic Fluid and Hydrogen Fuel

Figures 5 and 6 present the cost associated with fuel required for different refrigerated transportation technologies for chilled and frozen distribution. It is found that, conventional VCRS powered by natural gas depictes lowest fuel cost followed by hydrogen derived from the natural gas reforming and biomass gasification.

Cost of the hydrogen production from the natural gas reforming and biomass gasification is 50 % lowere compared to VCRS powered by diesel.Therefore, it is prooved that novel confuiguration of VARS powered by SOFC has potential to replace conventional VCRS powered by diesel and natural gas and recently developed cyrogenic transportation technologies.

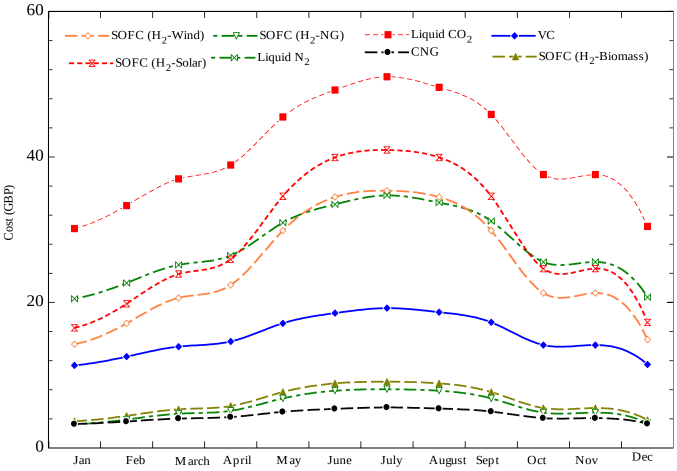

Fig 5 Fuel cost for the refrigerated distribution of milk

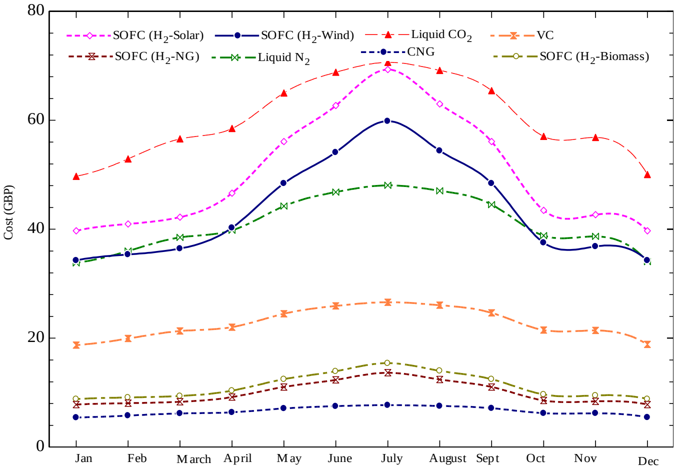

Fig 5 Fuel cost for the refrigerated distribution of peas

5. Conclusion

This study examines the energy consumption and GHG emissions of the various refrigerated road transport technologies. It is found that the, VARS assisted by SOFC emits least amount GHG emmission (50-75 % less) compared to conventional VCRS fueled by diesel and natural gas and also recently developed cryogenic food transportation technologies under identical operating conditions. It is interesting to note that the GHG emission from SOFC-VARS greatly depends upon the hydrogen production method. Wind based H_2 production emitted the least amount of GHG (0.001 to 0.006 gCO_2e/kg-km) followed by solar based production (0.002 to 0.01 gCO_2e/kg-km), biomass gasification (0.005 to 0.02 gCO_2e/kg-km), and NG reforming (0.01 to 0.07 gCO_2e/kg-km). The fuel production cost associated with the different systems is also evaluated. As Natural gas reforming is the main current H_2 production method, it depicted the lowest production cost followed by biomass gasification, wind electrolysis, and solar electrolysis.

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