Universität Stuttgart
Institute of Energy Economics and Rational Energy Use

Comparison of Cooling Technologies for Transport Logistics

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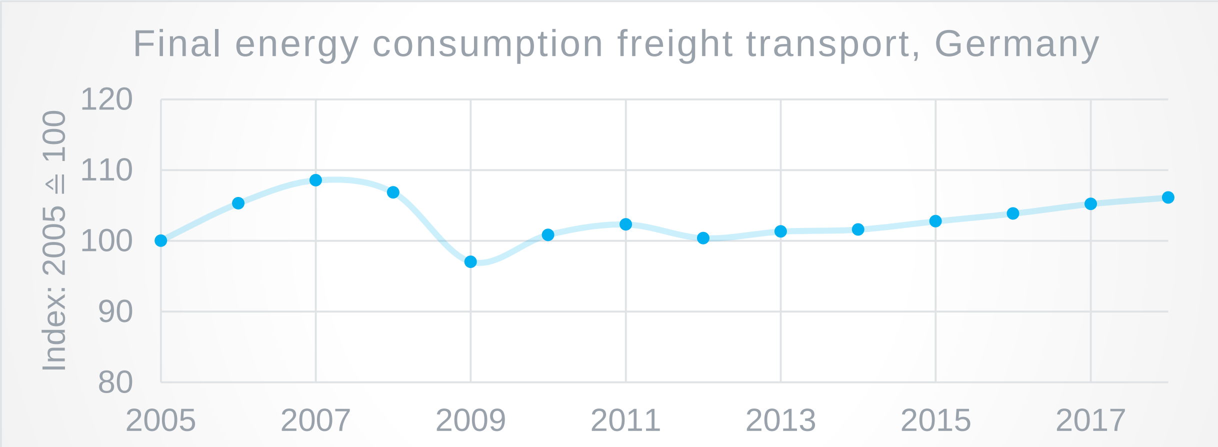
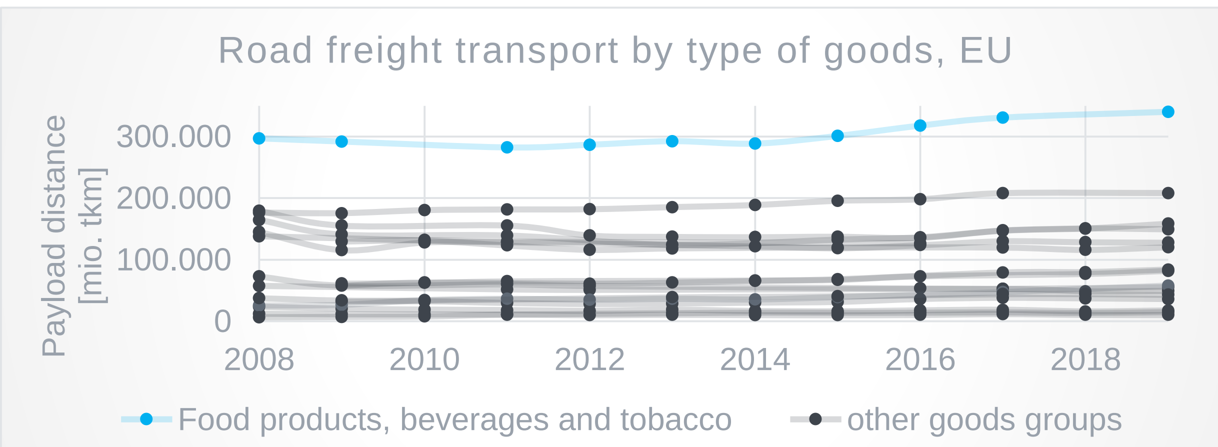
Motivation

Motivation



Source: German Environmental Agency, 2020



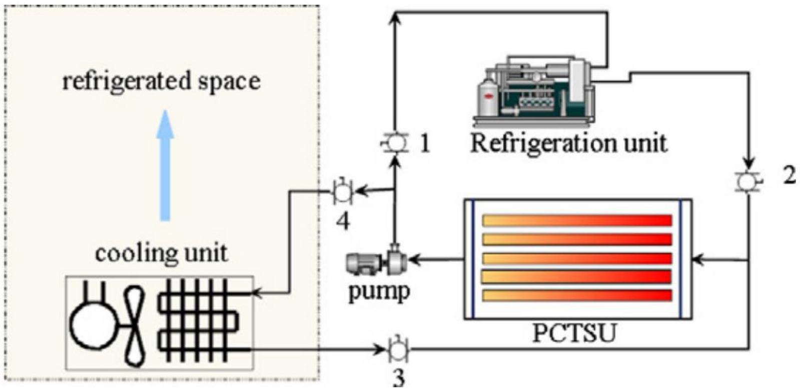
Source: Eurostat, 2021

- ~1/3 of the transported food requires cooling or refrigeration
- Standard technology: vapour-compression refrigeration (VCR)
- ~90% operated via dedicated diesel engine

Alternative refrigeration technologies

Alternative refrigeration technologies

(i)

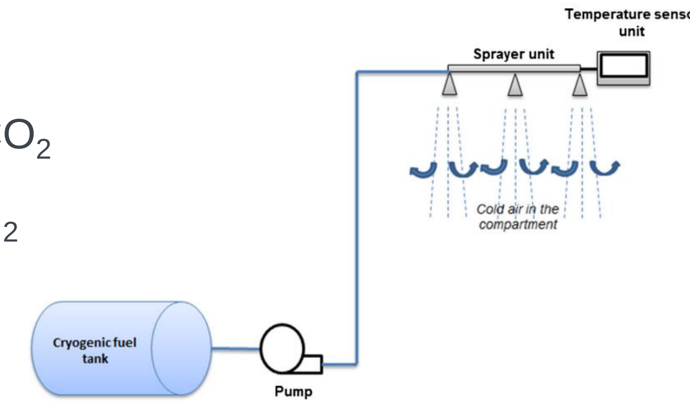


Eutectic cooling

Source: M. Liu et al., 2012

(ii)

- Liquid CO_2
- Liquid N_2

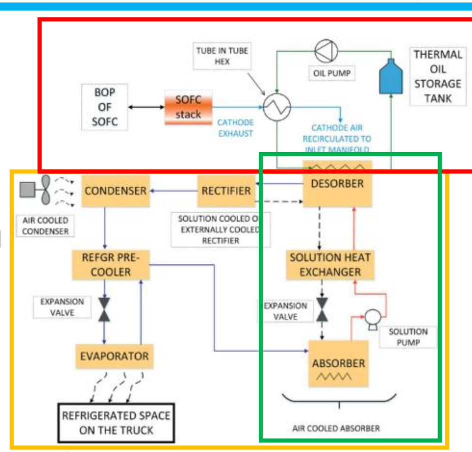


Cryogenic cooling

Source: A. Rai, S.A. Tassou, 2017

(iii)

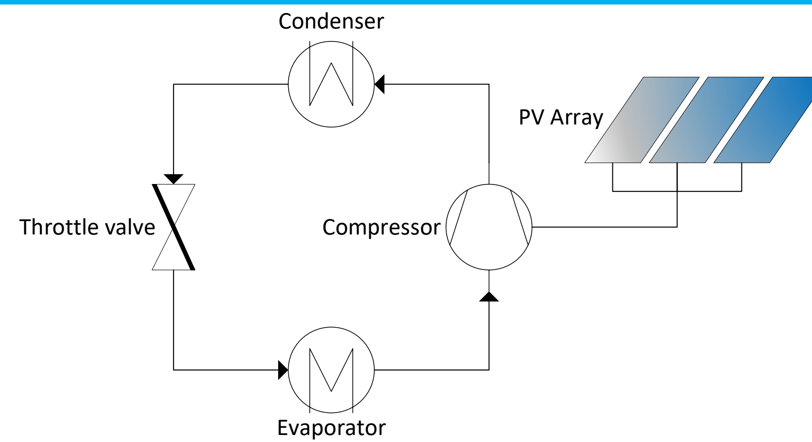
- Vapour absorption refrigeration system
  - Thermal compressor
- Solid oxide fuel cell



VARS+SOFC

Source: V. Venkataraman et al., 2016

(iv)



PV refrigeration

Source: own illustration

Calculation of the cooling load

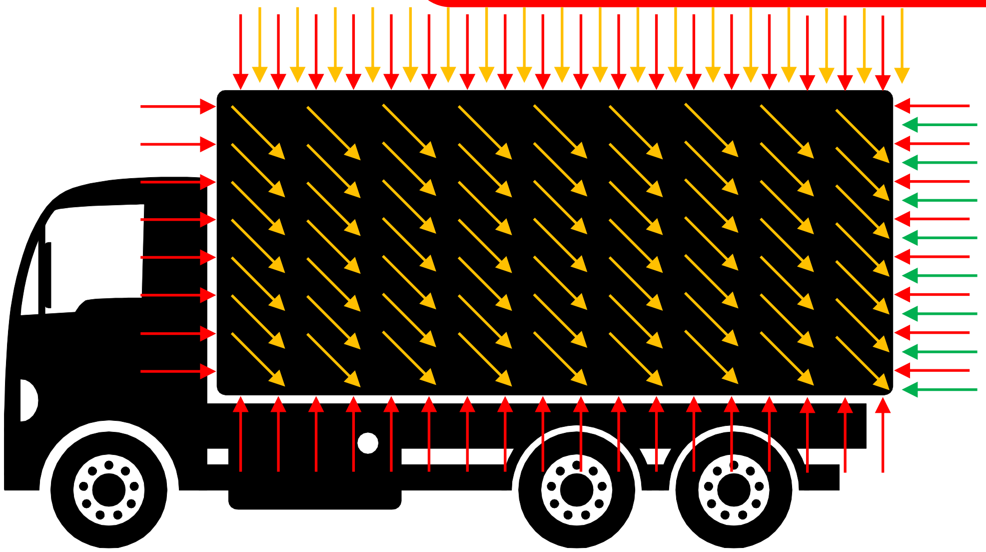
Calculation of the cooling load

$$Q_{CL} = Q_{THL} + Q_{SHL} + Q_{SL}$$

Approach based on Venkataraman et al., 2016

Transmission Heat Load

- Surface area
- Temperature difference
- Thermal transmittance



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Solar Load

- Surface area exposed to the sun
- Surface absorptivity
- Solar radiation (monthly averages depending on the latitude)

Service Heat Load

- Internal volume not occupied by cargo
- Enthalpy change
- Time between door openings

Scenario settings

Scenario settings

Parameter	Unit	Long-distance delivery		Short-distance delivery	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Vehicle size	-	Large[1]	Large[1]	Medium[2]	Medium[2]
Refrigeration temperature	°C	-20	0	-20	0
Average load	%	85	85	40	40
Time between door openings	min	270	270	30	30
Duration of door openings	min	8	8	3	3
Operating hours per day	h	9	9	7	7

[1] $lenght * width * height = 13.6\,m * 2.6\,m * 2.8\,m$

[2] $lenght * width * height = 9.4\,m * 2.5\,m * 2.4\,m$

Consideration of two different latitudes: Hamburg, Germany & Catania, Italy

→ 8 scenarios overall

Evaluation

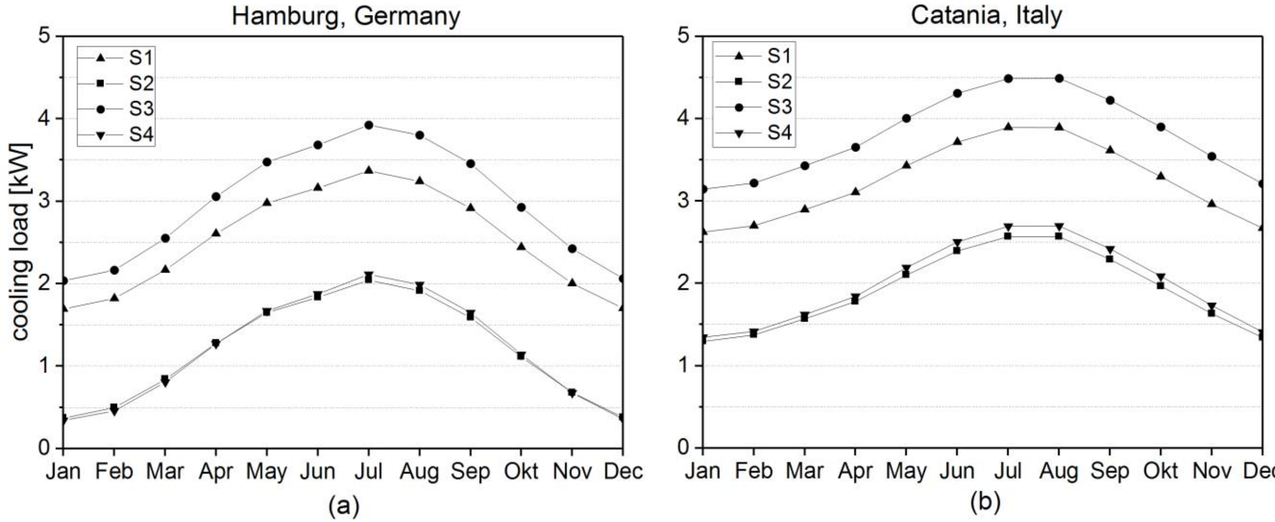
Evaluation

- Environmental comparison (greenhouse gas emissions)
  - operational emissions
  - production emissions

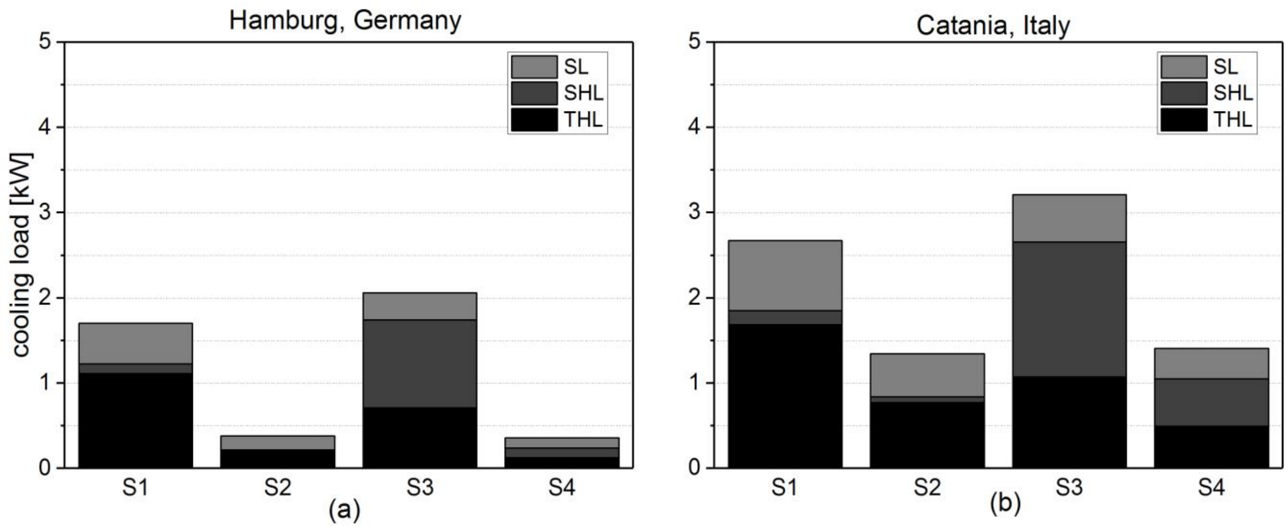
- Economical comparison
  - Net Present Value (NPV)
  - Investment costs
  - Operational costs

Results

Results: cooling load

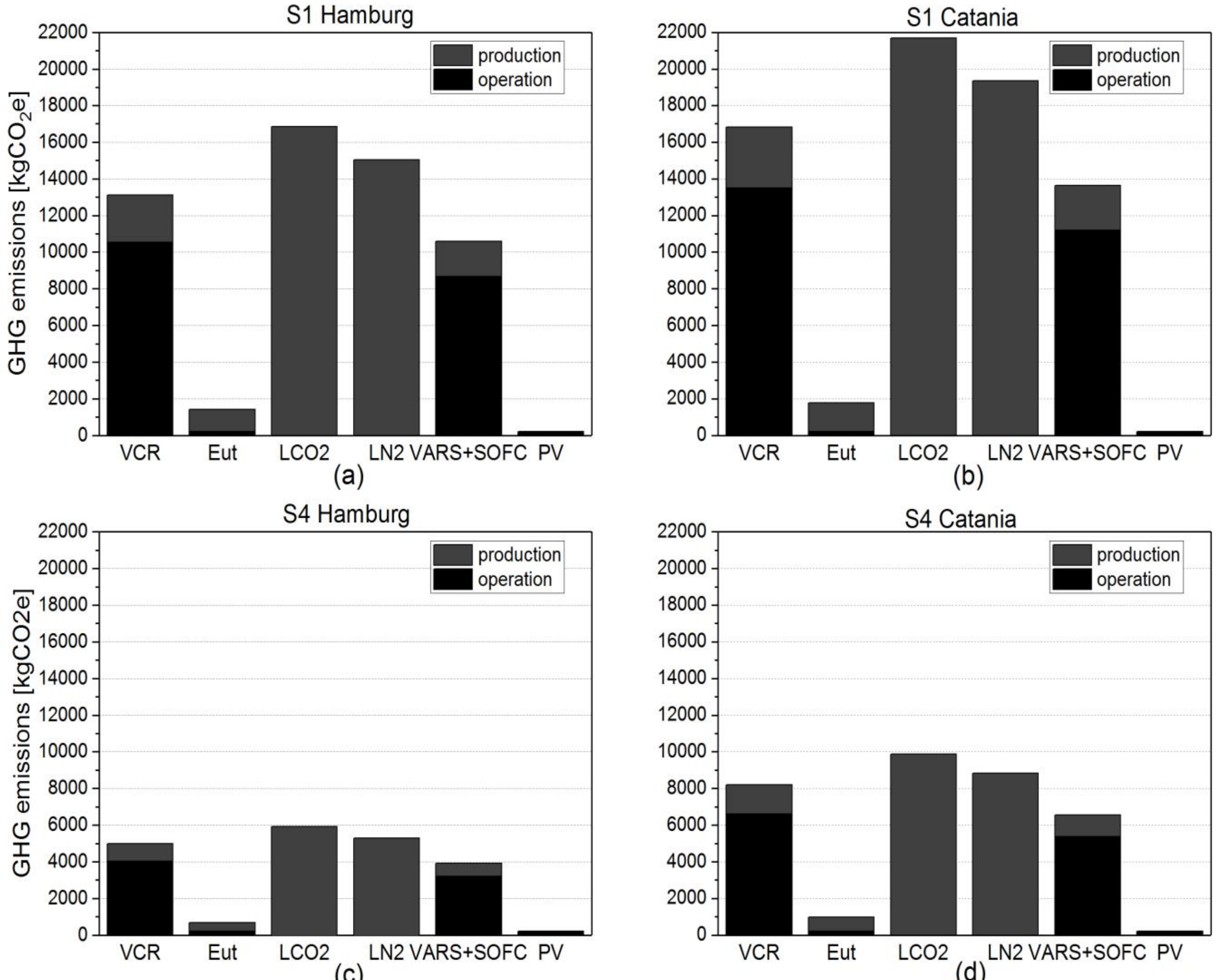


- S1 & S3 higher
- Catania generally higher
- S2 & S4 do not differ significantly



- Example month: December
- S1 & S2: mainly THL and SL
- S3 & S4: SHL significantly higher

Results: annual GHG emissions



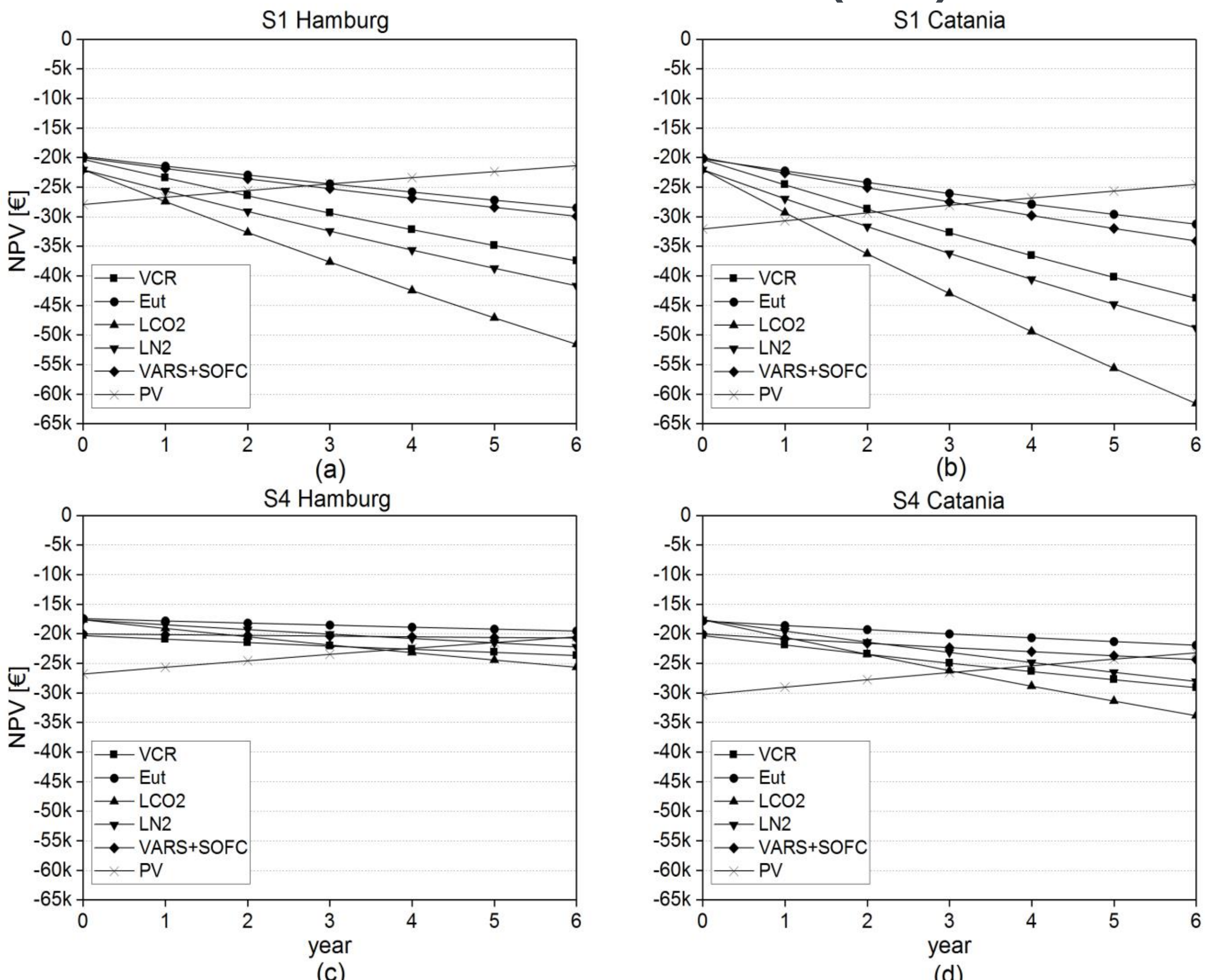
- Cryogenic fluids: no operational emissions, but high production-related emissions
- VCR and VARS+SOFC: high operational emissions
- Eutectic and PV: most promising in terms of emissions

Results: potential limits for the PV-driven VCR system

COP	Hamburg				Catania			
	S1	S2	S3	S4	S1	S2	S3	S4
Jan	2.6	0.6	3.7	0.6	0.9	0.4	1.3	0.5
Feb	1.6	0.4	2.2	0.5	1.0	0.5	1.4	0.6
Mar	0.8	0.3	1.1	0.3	0.6	0.4	0.9	0.4
Apr	0.5	0.3	0.7	0.3	0.4	0.3	0.6	0.3
May	0.6	0.3	0.8	0.4	0.4	0.3	0.6	0.3
Jun	0.5	0.3	0.7	0.4	0.4	0.3	0.6	0.3
Jul	0.6	0.4	0.8	0.4	0.4	0.3	0.6	0.3
Aug	0.6	0.4	0.9	0.5	0.5	0.3	0.7	0.4
Sep	0.9	0.5	1.2	0.6	0.6	0.4	0.9	0.5
Okt	1.3	0.6	1.8	0.7	0.8	0.5	1.1	0.6
Nov	2.4	0.8	3.5	1.0	0.9	0.5	1.3	0.6
Dec	3.0	0.7	4.3	0.7	1.0	0.5	1.4	0.6

- COP above 2 is difficult to achieve and above 2.5 cannot be achieved in mobile applications
- Better performance in summer than in winter
- Other systems like eutectic refrigeration are also limited by the size of the storage unit (potential problems in traffic jams)

Results: cumulative Net Present Value (NPV)



- PV system: largest investment, but lowest operational costs
- Cryogenic system very mass intensive → high operational costs
- Costs of alternative technologies could fall with increasing market penetration

Conclusion

Conclusion

- Cooling with **cryogenic liquids** is highly mass intensive and therefore causes **more GHG emissions than the VCR system** in the studied scenarios
- **Eutectic cooling systems** as well as the use of **PV electricity** for an electric VCR system seem to be the **most promising** solutions in terms of emissions and cost reduction
- **Challenges** are arising for the **PV system** from the **strongly fluctuating** available solar electricity

Thank you very much!

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Backup

Assumptions

- The refrigerated trucks are operated 20 days each month (the operating hours differ in the different scenarios)
- The refrigerated cabinet is a perfect cuboid of rectangular shape
- There is only one door located at the back of the truck with a height of 96% of the total external height and an effective door area of 88% of the rear face
- The wall of the truck consists of three different layers: aluminium, styrofoam and glass reinforced plastic with thicknesses of 0.005m, 0.125m and 0.005m, respectively and thermal conductivities of 205 $Wm^{-1}K^{-1}$, 0.027 $Wm^{-1}K^{-1}$ and 0.25 $Wm^{-1}K^{-1}$, respectively.
- The thermal transmittance of the refrigerated body is contant at 0.3 $Wm^{-2}K^{-1}$
- The outside heat transfer coefficient is constant at 25 $Wm^{-2}K^{-1}$
- All products are loaded at the refrigeration temperature. Heat load from products is therefore equal to zero
- Heat loads from sources inside the trailer (such as lights) are not taken into condideration
- The ratio of actual enthalpy change to maximum theoretical enthalpy change is constant at 0.6
- To present a worst-case scenario, no shading of the trailer is considered for the calculation of the solar heat load. The solar radiation hits on the roof of the truck and one of the two side walls
- For the NPV calculation, a discount rate of 4%, a taxation of 27% and a depreciation time of 6 years is assumed