Carbon footprint, helium recycling and the approach at Aarhus

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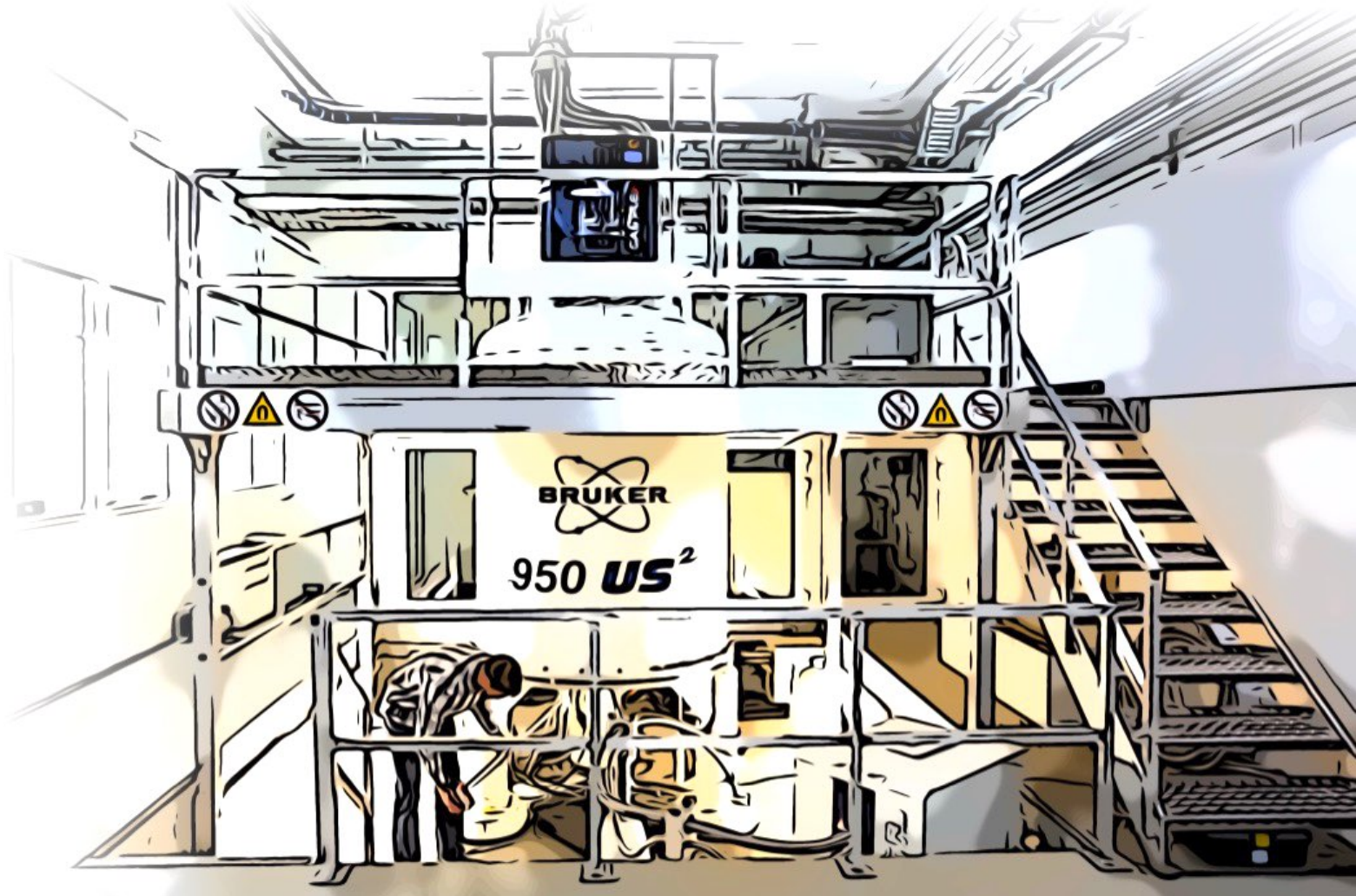

rNMR - carbon footprint of NMR facilities

CO_2 estimate includes

- Transport of personel
- Sample shipment
- Air conditioning
- Electricity
- Liquid helium
- Liquid nitrogen

} Include in a CO_2 calculator

Monitoring the carbon footprint
(R-NMR Task 2.5)

Description of work: In task 2.5, we will select a set of tools for the calculation of carbon footprint that are suitable to cover the range of impacts caused by the operation of NMR infrastructures. All partners will adopt a common approach to the calculation of the footprint of their users' travel. In addition, we will look into tools that can capture the footprint of equipment usage. The results of these analyses will be communicated to the relevant stakeholders.

Introduction

Virtually all our activities leave a carbon footprint and NMR is no different. Some activities are directly related to burning fossil fuels. These include transport (sea, air, road and, to an extent, rail) and heating (excluding heat pumps). However, most NMR related activities are dependent on electricity and here the carbon footprint is closely tied to the type of power generation plants used in a specific country. Countries with many hydro, nuclear and renewable power generating plants will generate a smaller carbon footprint per unit of electric power. On the other hand, countries with mostly coal or gas powered plants will leave a much larger carbon footprint. When considering EU member states, the difference can be on the order of a hundredfold (Figure 1). The EU-27 average of 275 g CO_2e equivalents per kWh will be used in all calculations.

Figure 1 - CO_2 equivalents per kWh of electricity produced in different member states (Source: EEA). For completeness, the value for the UK is 269 CO_2 equivalents per kWh.

1

Credits:

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Sara Whittaker
Daniel Mathieu
Christina Redfield

CO_2 equivalents per kWh

EU average: 275 gCO_2/kWh

Country	CO_2 equivalents (g/kWh)	Source
Algeria	635	Our world in data
Norway	29	Our world in data
Qatar	603	Our world in data
Russia	436	Our world in data
United Arab Emirates	561	Our world in data
United Kingdom	256	Our world in data
United States	386	Our world in data

Country	CO_2 equivalents (g/kWh)	Source
Austria	80	European Environment Agency
Belgium	154	European Environment Agency
Bulgaria	455	European Environment Agency
Croatia	170	European Environment Agency
Cyprus	591	European Environment Agency
Czechia	407	European Environment Agency
Denmark	117	European Environment Agency
Estonia	693	European Environment Agency
Finland	62	European Environment Agency
France	74	European Environment Agency
Germany	368	European Environment Agency
Greece	394	European Environment Agency
Hungary	181	European Environment Agency
Ireland	305	European Environment Agency
Italy	297	European Environment Agency
Latvia	66	European Environment Agency
Lithuania	110	European Environment Agency
Luxembourg	62	European Environment Agency
Malta	348	European Environment Agency
Netherlands	310	European Environment Agency
Poland	681	European Environment Agency
Portugal	171	European Environment Agency
Romania	250	European Environment Agency
Slovakia	95	European Environment Agency
Slovenia	202	European Environment Agency
Spain	178	European Environment Agency
Sweden	8	European Environment Agency

NMR Spectrometers

Console type	Power (kW)
Liquid state	2.1
Liquid w/cryo	13.7
Solid state	3.8
Solids & liquids	3
Solids & liquids w/cryo	8.8

^{1}H frequency (MHz)	Magnet temperature (K)	Helium boil off (L/week)	Nitrogen boil off (L/week)	Source
400	4	2.2	50	R-NMR carbon footprint report
500	4	2.2	50	R-NMR carbon footprint report
600	4	2.7	50	R-NMR carbon footprint report
700	4	4.4	80	R-NMR carbon footprint report
800	4	7.9	100	R-NMR carbon footprint report
800	2	42.0	120	R-NMR carbon footprint report
850	4	8.4	67	Jarl Underhaug estimate (*)
900	2	42.0	120	R-NMR carbon footprint report
950	2	50.0	67	Thomas Vosegaard estimate (*)
1000	4	13.4	67	Miquel Pons
1000	2	42.0	150	R-NMR carbon footprint report
1200	2	42.0	150	R-NMR carbon footprint report

He liquefaction

Type	Separation (kWh/L)	Liquefaction (kWh/L)	Loss (liq) (%)	Transport (kWh/L)	Total (kWh/L)	gCO_2e/L
Remote (USA)	7.43	5.66	10	0.38	14.10	386
Remote (Qatar/Algeria)	7.43	5.66	10	0.38	14.10	619
Local turbine	n/a	5.6	10	0	6.22	Local
Local coldhead/pulsed tube	n/a	10.55	10	0	11.72	Local

Calculation from Aarhus

Country: Denmark — Clear all

CO_2 equivalents: 117 g/kWh

Site setup			CO_2 equivalents	Boil off		Power consumption			
Magnet	Console	Helium supply		Helium	Nitrogen	Spectrometer	He liq	N liq	
400 (4K)	Solid state	Remote (Qatar/Algeria)	5042 kg/year	2.2 L/week	50 L/week	3.8 kW	0.18 kW	0.15 kW	details
500 (4K)	Liquid state	Remote (Qatar/Algeria)	3299 kg/year	2.2 L/week	50 L/week	2.1 kW	0.18 kW	0.15 kW	details
700 (4K)	Solids & liquids	Remote (Qatar/Algeria)	5310 kg/year	4.4 L/week	80 L/week	3 kW	0.37 kW	0.24 kW	details
950 (2K)	Solids & liquids w/cryo	Local coldhead/pulsed tube	13834 kg/year	50.0 L/week	67 L/week	9.3 kW	3.49 kW	0.20 kW	details
		Total	27.48 tons/year	3064 L/year	12888 L/year				

Saving through local liquefaction

CO_2 equivalents 117 g/kWh

Site setup			CO_2 equivalents	Boil off		Power consumption			
Magnet	Console	Helium supply		Helium	Nitrogen	Spectrometer	He liq	N liq	
400 (4K)	Solid state	Remote (Qatar/Algeria)	5042 kg/year	2.2 L/week	50 L/week	3.8 kW	0.18 kW	0.15 kW	details
500 (4K)	Liquid state	Remote (Qatar/Algeria)	3299 kg/year	2.2 L/week	50 L/week	2.1 kW	0.18 kW	0.15 kW	details
700 (4K)	Solids & liquids	Remote (Qatar/Algeria)	5310 kg/year	4.4 L/week	80 L/week	3 kW	0.37 kW	0.24 kW	details
950 (2K)	Solids & liquids w/cryo	Remote (Qatar/Algeria)	33010 kg/year	50.0 L/week	67 L/week	9.3 kW	4.20 kW	0.20 kW	details
		Total	46.66 tons/year	3064 L/year	12888 L/year				

Site setup			CO_2 equivalents	Boil off		Power consumption			
Magnet	Console	Helium supply		Helium	Nitrogen	Spectrometer	He liq	N liq	
400 (4K)	Solid state	Local coldhead/pulsed tube	4206 kg/year	2.2 L/week	50 L/week	3.8 kW	0.15 kW	0.15 kW	details
500 (4K)	Liquid state	Local coldhead/pulsed tube	2462 kg/year	2.2 L/week	50 L/week	2.1 kW	0.15 kW	0.15 kW	details
700 (4K)	Solids & liquids	Local coldhead/pulsed tube	3634 kg/year	4.4 L/week	80 L/week	3 kW	0.30 kW	0.24 kW	details
950 (2K)	Solids & liquids w/cryo	Local coldhead/pulsed tube	13834 kg/year	50.0 L/week	67 L/week	9.3 kW	3.49 kW	0.20 kW	details
		Total	24.14 tons/year	3064 L/year	12888 L/year				

CO_2 calculator web site

https://csdm.dk/rnmr/consumption.html

Carbon footprint of NMR instruments

Country: Denmark — Clear all

CO_2 equivalents: 117 g/kWh

Calculation details

Item	Consumption	Conversion	Energy	CO_2 equiv
He boil off (950 MHz)	50.0 L/week	11.72 kWh/L 117 gCO_2/kWh (Denmark)	30582 kWh/year	3578 kg/year
N boil off (950 MHz)	67.0 L/week	500 Wh/L 117 gCO_2/kWh (Denmark)	1748 kWh/year	205 kg/year
Console (Solids & liquids w/cryo)	8.8 kW	117 gCO_2/kWh (Denmark)	77141 kWh/year	9025 kg/year
Magnet pumping	500 W	117 gCO_2/kWh (Denmark)	4383 kWh/year	513 kg/year
Total			118237 kWh/year	13834 kg/year

Magnet: 400 (4K), 500 (4K), 700 (4K), 950 (2K)

liq: 15 kW details; 15 kW details; 24 kW details; 20 kW details

R-NMR Calculation details

https://csdm.dk/rnmr/details.html

The calculator is based on the report Monitoring the carbon footprint, which is one of the deliverables of the Remote-NMR project (Horizon Europe grant 101058595). You find the calculator here.

He liquefaction

The power consumption for liquefying helium at a helium production site (a side product in the liquid natural gas production) is given in Zaitsev *et al. Int. J. Energy Res.* **44** (2020) 6430. In this paper, Figure 11 reports the power consumption per kmole of He. The average of existing sites is ca. 235 kWh/kmole. The density of He is 125 g/L (hence the concentration is 31.25 mol/L), so the power consumption is 7.43 kWh/L (The R-NMR report says the number is 6.25 kWh/L). Jones estimate a transport contribution (to Europe) of 88 gCO_2/L He corresponding to 0.38 kWh/L He. Since the helium liquefaction plants are located in both Qatar, Algeria, and USA, we separate the remote production depending on the origin. Local liquefaction of is estimated in Jones *et al. Low Temp. Phys.* **49** (2023) 967-970 for a local turbine-driven liquefier to 1.93 kWh/L. The loss associated with this kind of liquefaction is estimated to 10% by Jones. Linde specifies a similar consumption of 2.0 kWh/L, but that assumes liquid N_2 precooling, without this, the power consumption is 5.6 kWh/L. For cold-head or pulsed-tube-based liquefiers our estimates is based on datasheets from Bruker (12.1 kWh/L) and Cryomech (9 kWh/L), so we end up with an average estimate of 10.55 kWh/L. In brief, the numbers are as follows

Type	Separation (kWh/L)	Liquefaction (kWh/L)	Loss (liq) (%)	Transport (kWh/L)	Total (kWh/L)	gCO_2e/L
Remote (USA)	7.43	5.66	10	0.38	14.10	386
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Local turbine	n/a	5.6	10	0	6.22	Local
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Aarhus He liquefaction

He liquefaction in Aarhus

Current setup

- Only He from the 950 MHz magnet is recycled
- ATL 160 from QuantumDesign
- Capacity ~25 L/day
- Balloon 28 m^3
- The balloon fills up upon filling (reduction from 4 → 3 weeks recycling period)
- In operation since 2016
- Average recovery 80% (hole in the balloon)
- Estimated total saving: 20.000-25.000 L (400-500 k€)

Installation in progress

System being/to be installed

- Capacity of 100 L/day
- 10 NMR spectrometers hooked up (33%)
- Additional collection from
  - STM (33%)
  - PPMS (33%)
- Transport up to 100 m (under municipal road)

Credits:
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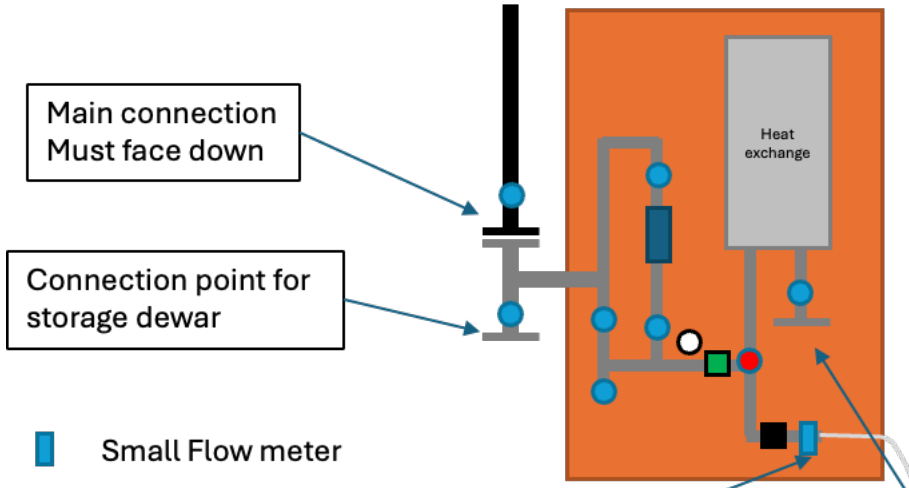
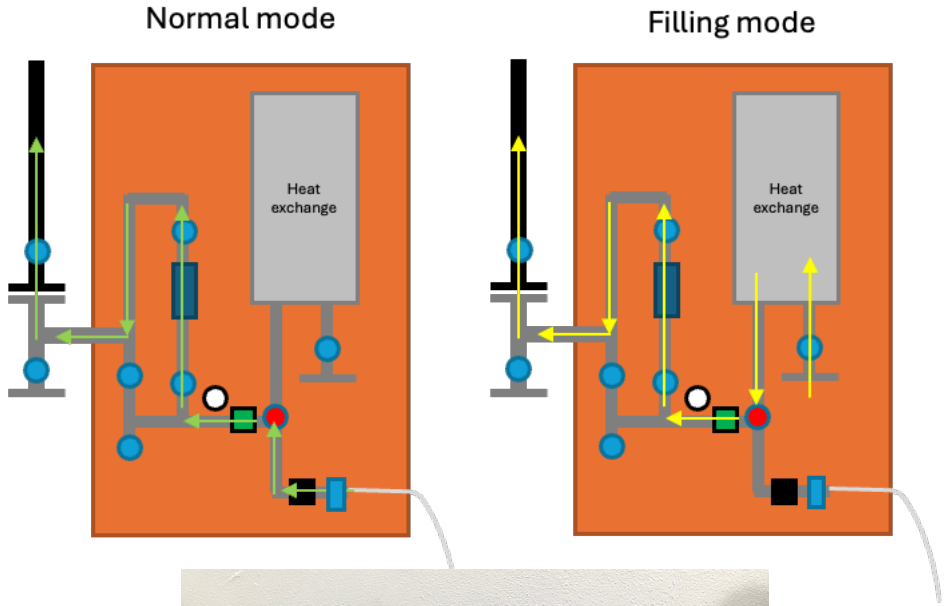
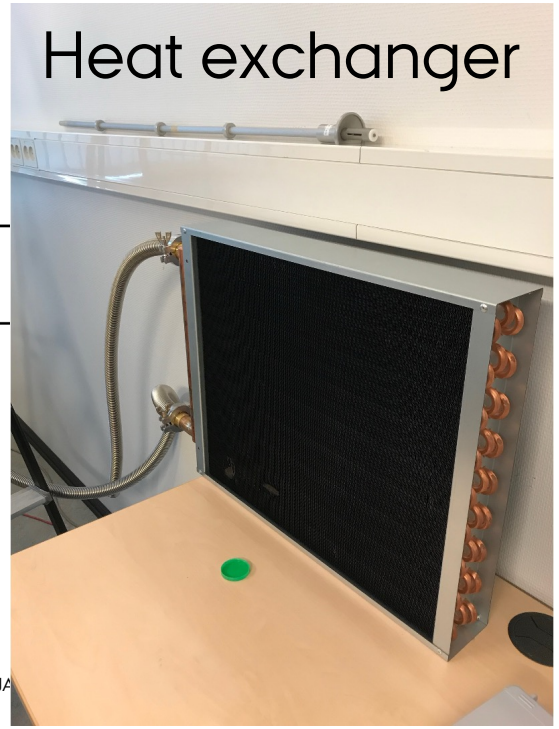
Dennis W. Juhl
Anders B. Nielsen
Niels Chr. Nielsen

Connector to magnets



- Small Flow meter
- Big Flow meter
- Ball valve
- T valve
- Back pressure regulator
- Pressure gauge and safety relief
- One-way disc valve





Conclusions - learning from the carbon footprint calculator

- He liquefaction is a good climate action
  - Reduced CO_2/reduce fossile usage
  - Reuse of a limited resource
  - Uses locally produced power rather than power in the Middle East
- Supply safety
- He liquefaction is a good business case (~half price)

https://csdm.dk/rnmr/consumption.html

Also find the link on the r-NMR web site