13 CLIMATE ACTION

7 HÅLLBAR ENERGI FÖR ALLA

GLOBALA MÅLEN
för hållbar utveckling

Heat-Transfer Intensification for Heat-Harvesting,

some examples of research done at KTH

Christophe Duwig
Dept. Chemical Engineering, KTH Energy Platform & KTH Climate Action Centre
KTH Royal Institute of Technology

Short Presentation

13 CLIMATE ACTION

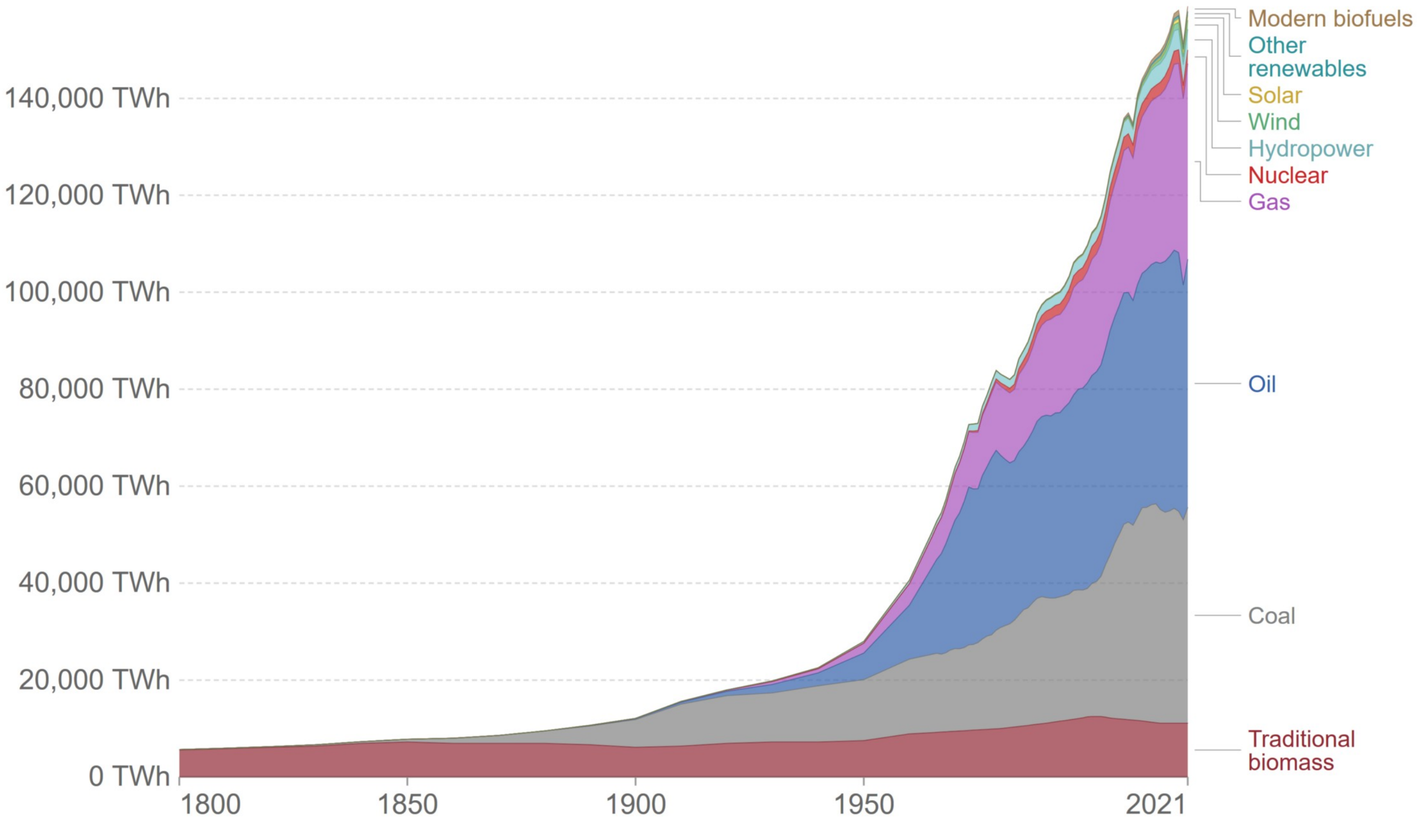
7 HÅLLBAR ENERGI FÖR ALLA

GLOBALA MÅLEN
för hållbar utveckling

- My day jobs
  - Professor at the division of Process Technology, KTH Chemical Engineering
  - Visiting Prof. at the Division of Building Technologies and Design, KTH ABE
  - Vice-Director of the KTH Energy Platform … mostly covering at ”heat”
  - Lead faculty at the KTH Climate Action Centre, topics of Energy & Negative Emissions
- Research
  - High-fidelity simulations of turbulent heat-transfer, phase-change & chemical reactions
  - Data analysis using unsupervised learning alg. (t-sne, UMAP, KMEAN, …)
  - Heat-Harvesting /Heat-Exchanger technology (additive manufacturing)
  - Negative Emissions, BeCCS, CO_2 Capture
  - Cooling of electric/ electronic systems/ Decarbonization
  - Collaborations: Hitachi Energy, ABB, Stockholm Exergy, TetraPak, AMEXCI, 3Nine, Paebbl, ...

Global direct primary energy consumption

Direct primary energy consumption does not take account of inefficiencies in fossil fuel production.



Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy

OurWorldInData.org/energy • CC BY

Kaya Identity

- Introduced by the Japanese energy economist Yoichi Kaya in 1997 to understand the factors controlling CO_2 emissions

$$CO_2 = \frac{CO_2}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P$$

CO_2 emissions by unit energy

energy per income

GDP per capita

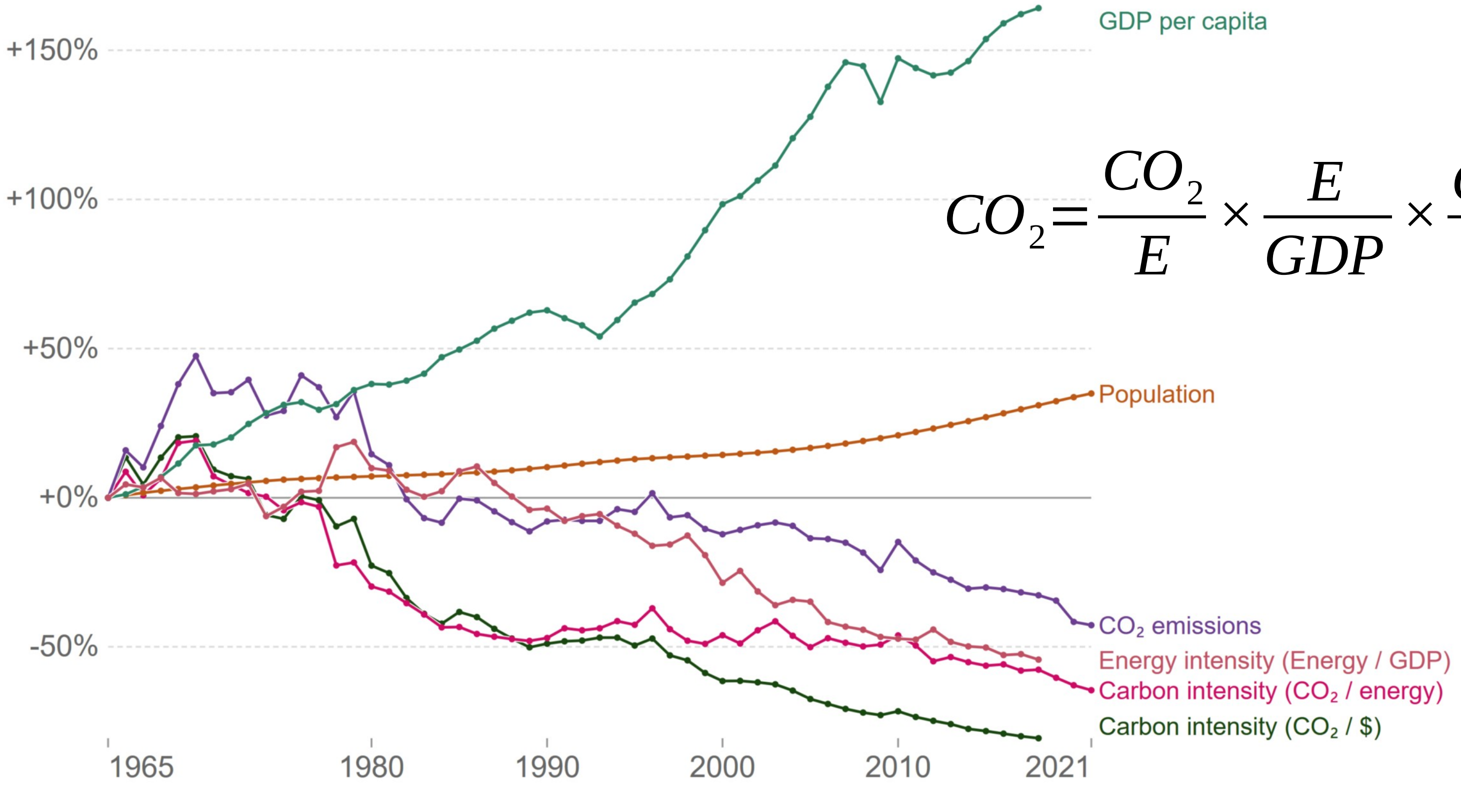
- E is energy used, GDP is a measure of income, P is the population

- Note that $\frac{1}{4} = \frac{CO_2}{E} \times \frac{1}{2} \times 2.2 \times 1.3 \Rightarrow \frac{CO_2}{E} = \frac{1}{5.7}$

Kaya, Yoichi; Yokoburi, Keiichi (1997). Environment, energy, and economy : strategies for sustainability.

Kaya identity: drivers of CO_2 emissions, Sweden

Percentage change in the four parameters of the Kaya Identity, which determine total CO_2 emissions. Emissions include fossil fuel and industry emissions[1] . Land use change is not included.

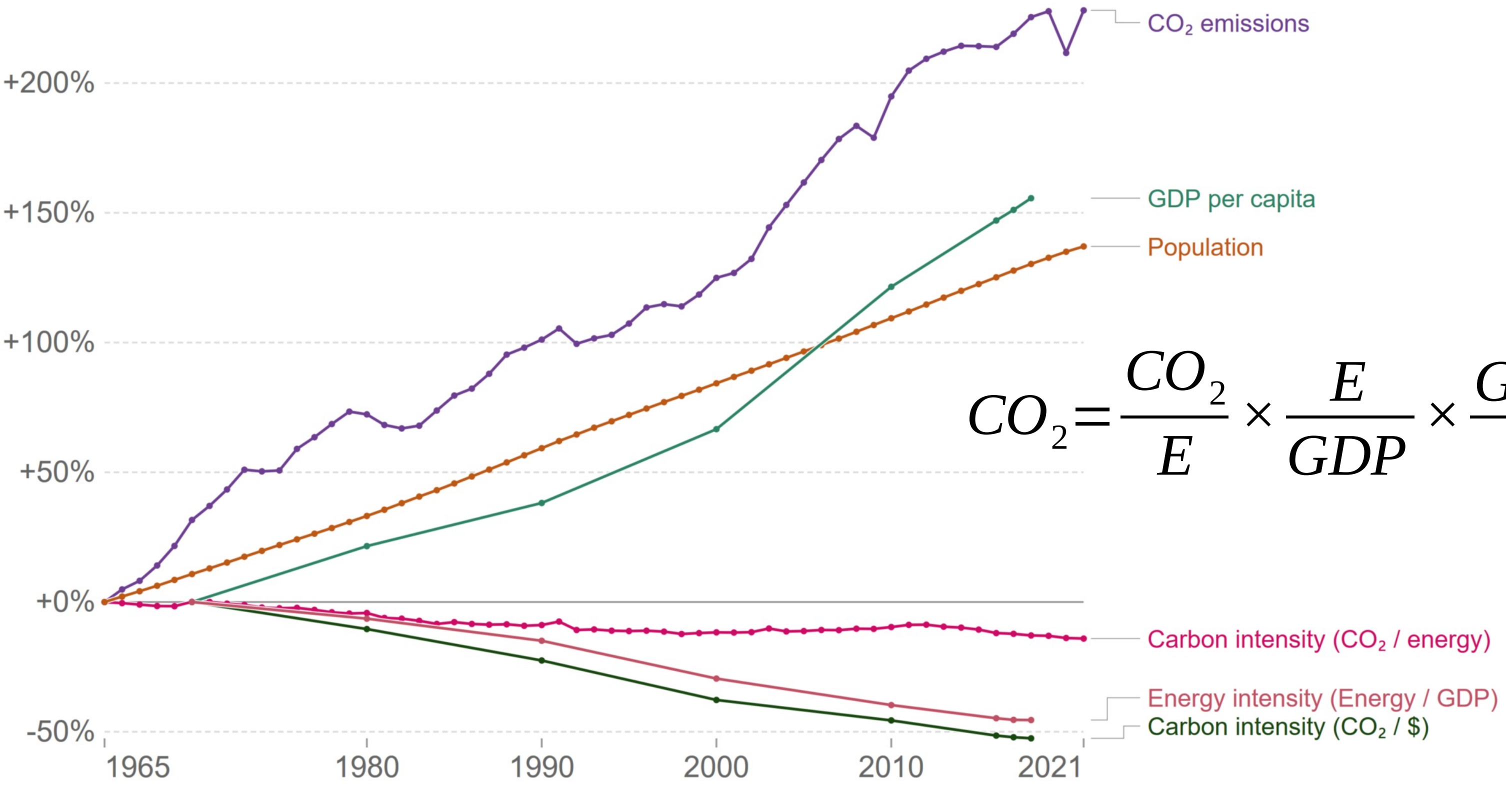


$$CO_2 = \frac{CO_2}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P$$

Source: Our World in Data based on Global Carbon Project; UN; BP; World Bank; Maddison Project Database
Note: GDP per capita is measured in 2011 international-$ (PPP). This adjusts for inflation and cross-country price differences.
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

Kaya identity: drivers of CO2 emissions, World

Percentage change in the four parameters of the Kaya Identity, which determine total CO_2 emissions. Emissions include fossil fuel and industry emissions[1] . Land use change is not included.



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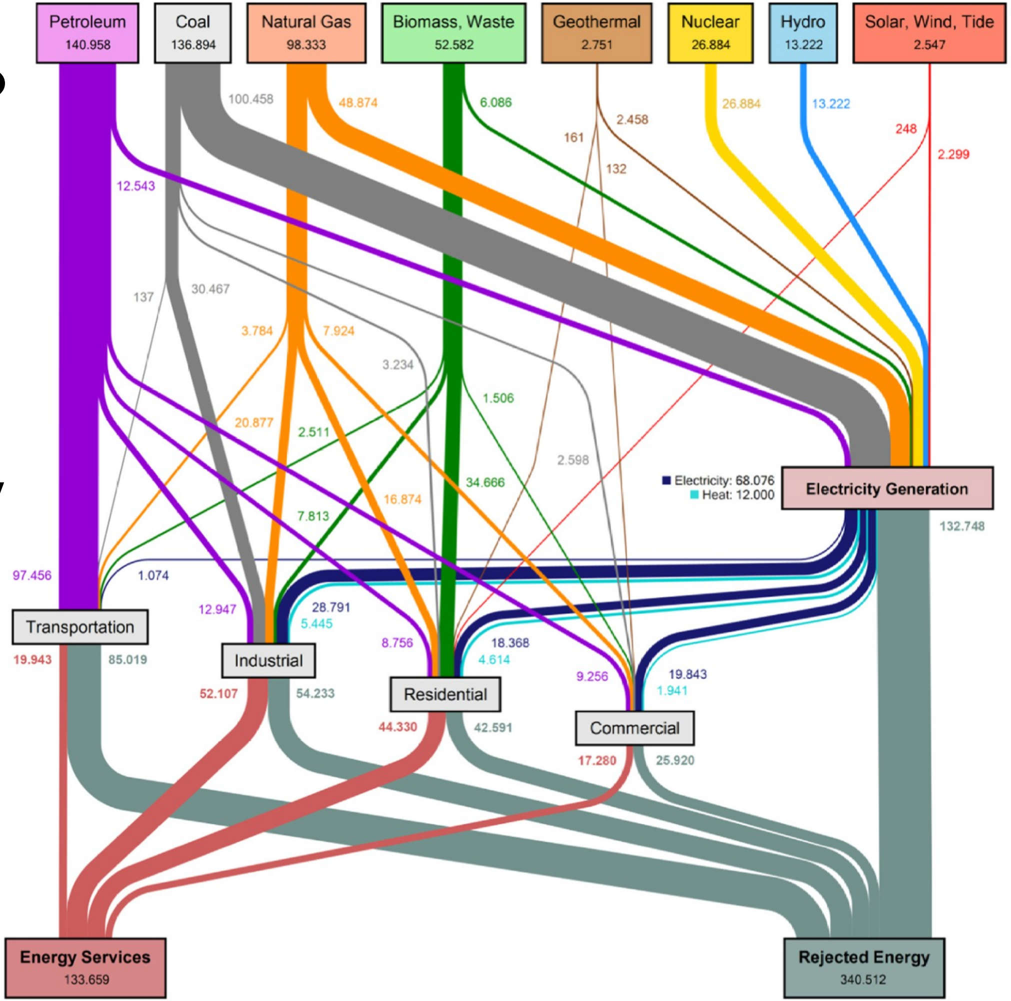
Source: Our World in Data based on Global Carbon Project; UN; BP; World Bank; Maddison Project Database
Note: GDP per capita is measured in 2011 international-$ (PPP). This adjusts for inflation and cross-country price differences.
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

$\frac{E}{GDP}$? Service or not?

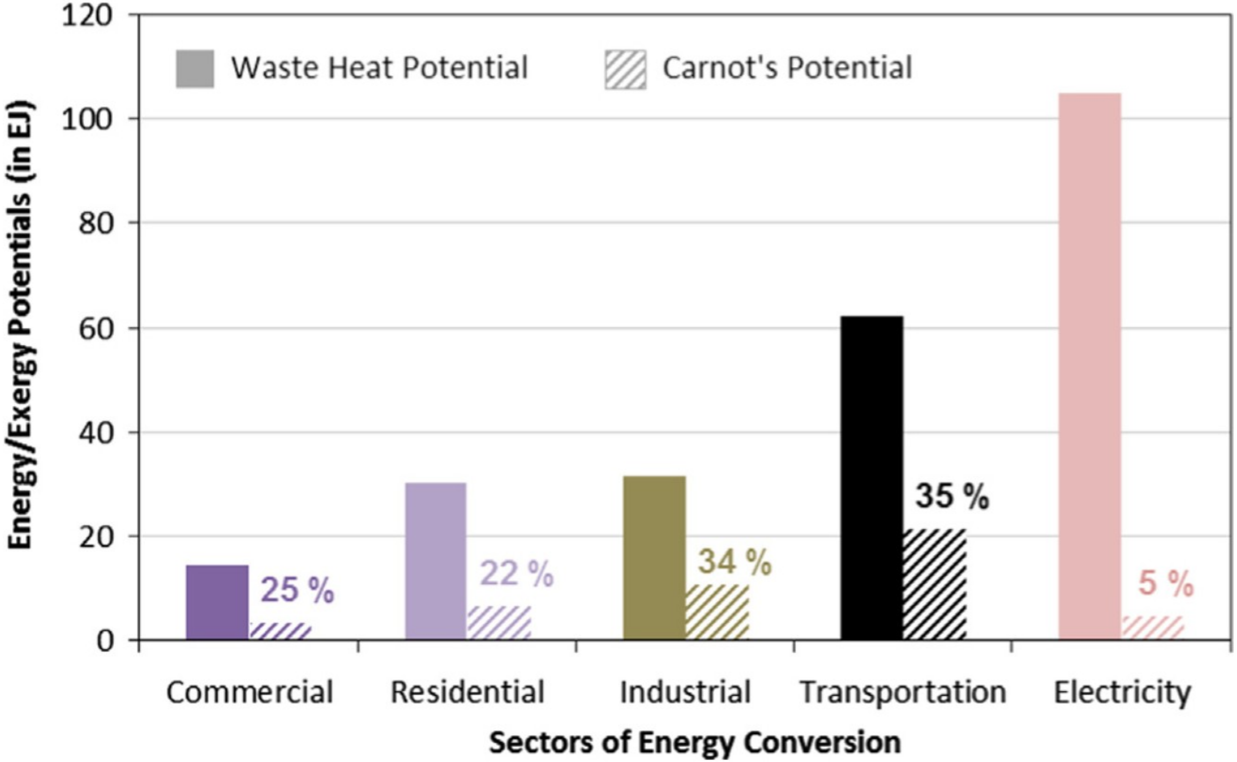
- In 2012, the world used 474 PJ
- ~70% did not offer any service
- Be careful that it is NOT Exergy
- Of course, we need to understand the second principle of thermodynamics



C. Forman et al. / Renewable and Sustainable Energy Reviews 57 (2016) 1568–1579

Energy is not the same than Exergy

- Effluents’ temp. matters
- Transportation has the highest potential, industry also!!
- Electrification will help but is not enough



- C. Forman et al. / Renewable and Sustainable Energy Reviews 57 (2016) 1568–1579

What about electrification?

- Electrified processes or vehicles have lower losses
- Sweden uses about 135 TWh of electricity today
- Electrification will require more electricity, about 200 TWh in 2045
- Complete decarbonization of the mining sector might increase the demand to 240-250 TWh in 2045
- What about residual heat?
  - **40 TWh of electric power to produce H2 by electrolysis gives about 16 TWh of unused heat < 100°C**
  - **2%-6% transmission losses gives 5-15 TWh of cooling/ losses < 100°C**
  - **Still there but at lower temperatures**

Transformers at substation near Denver International Airport, Colorado – Wikimedia commons

https://www.svensktnaringsliv.se/english/future-electricity-supply-in-sweden_1171800.html

Learning from Kaya Identity

$$CO_2 = \frac{CO_2}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P$$

Decarbonation
Electrification
Hydrogen
Biofuels
Nuclear
Renewables

Efficiency, Use Heat-Pumps, Stop waste, Smart Systems, Energy Storage, Integration,...

Policies, habits, values and democratic decisions

Over-consumption
Sufficiency

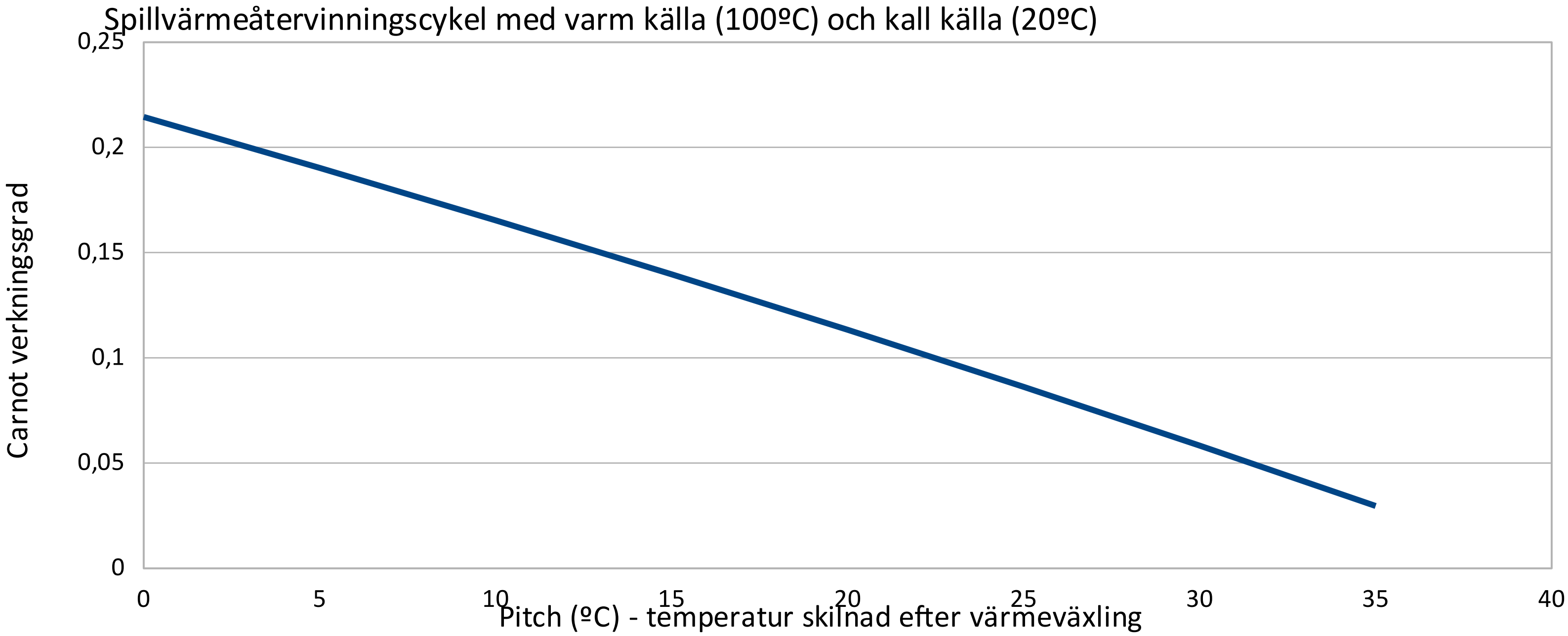
Carnot's take on efficiency

- Given a hot source at T_H and a cold source at T_C
- In general high efficiency is expected for high temperature source, e.g. combustion
- In a perfect world, the maximum efficiency is

$$\eta = 1 - T_C/T_H$$

In a real(er) world

- ΔT is a temperature difference across the Heat-Exchanger
- It gives: $\eta = 1 - (T_C + \Delta T)/(T_H - \Delta T)$

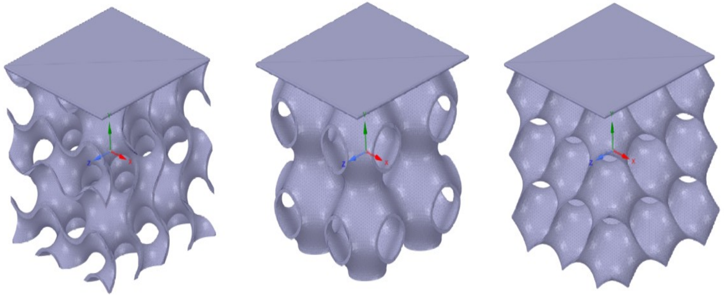


Heat-Transfer intensification

- $Q = A \cdot h \cdot \Delta T$
- with $h = f(Re, Pr, ...)$
- Increasing heat-transfer can be done by
  - Increasing A (but not making the device too big)
  - Increasing h (but there a limits in Re)
- Same Q with lower ΔT → increase A and/or h

Increasing A in a compact manner

- Additive manufacturing opens new avenues for designing energy and material efficient heat-exchangers
- Triple Periodic Minimum Surfaces are one strong candidate family



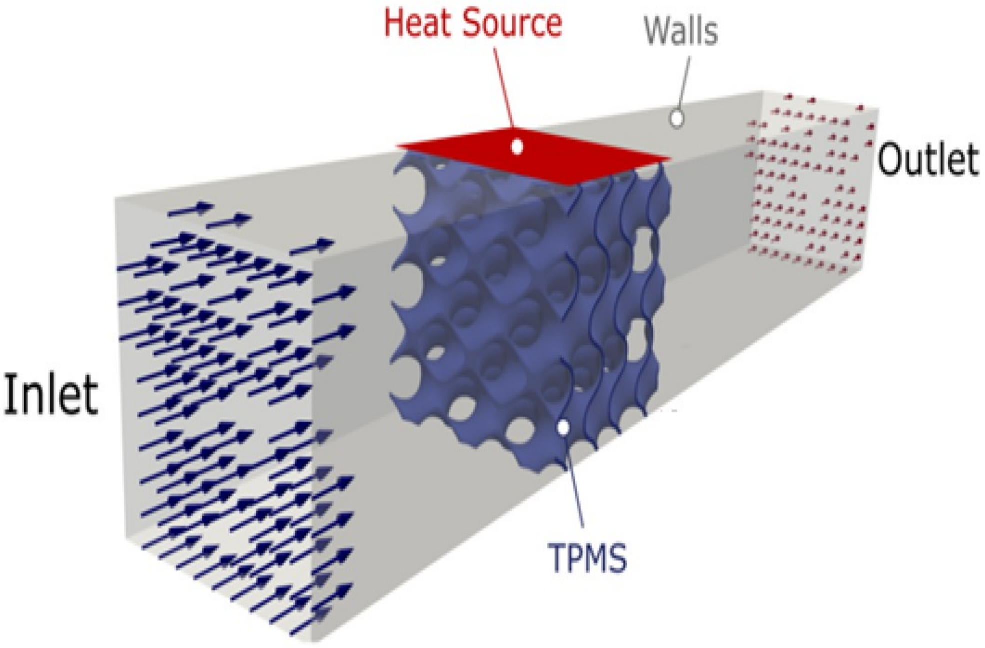
- The optimal heat transfer performance of the heat exchanger may vary depending on,

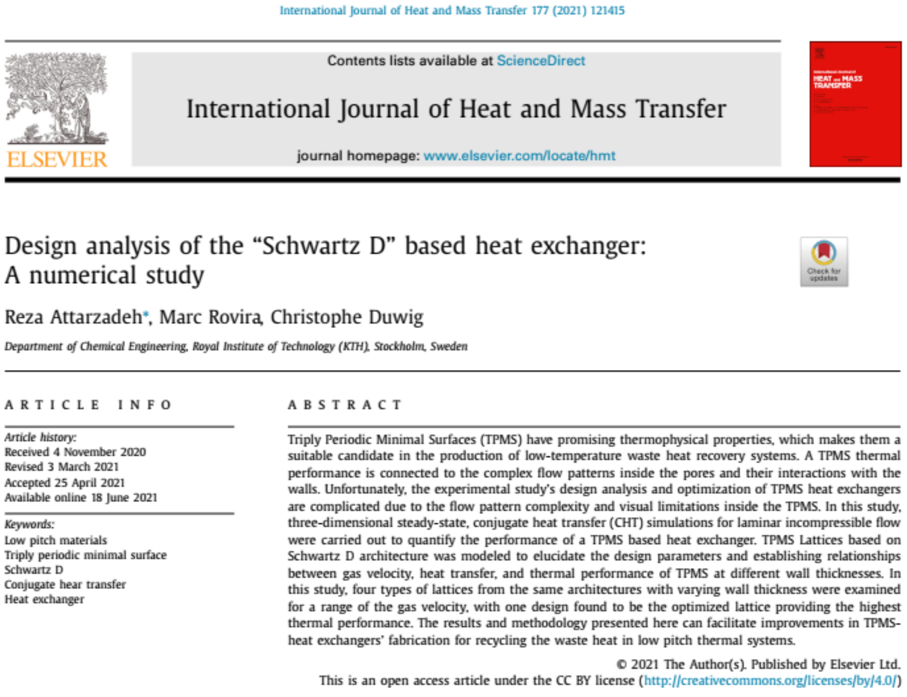
1. TPMS cell architecture,
2. Wall thickness,
3. Offset parameter,
4. Fabrication limitations,

Periodic length,
Orientation angle,
Set-up configuration,
Selection of the best TPMS material and thermal properties,

5. Selection of the best working fluid, hazardness and thermal properties.

Case Study #1 (Effect of TPMS wall thickness)





International Journal of Heat and Mass Transfer 177 (2021) 121415

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International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/hmt

ELSEVIER

Design analysis of the “Schwartz D” based heat exchanger: A numerical study

Reza Attarzadeh*, Marc Rovira, Christophe Duwig

Department of Chemical Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden

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Schwartz D
Conjugate hear transfer
Heat exchanger

ABSTRACT

Triply Periodic Minimal Surfaces (TPMS) have promising thermophysical properties, which makes them a suitable candidate in the production of low-temperature waste heat recovery systems. A TPMS thermal performance is connected to the complex flow patterns inside the pores and their interactions with the walls. Unfortunately, the experimental study's design analysis and optimization of TPMS heat exchangers are complicated due to the flow pattern complexity and visual limitations inside the TPMS. In this study, three-dimensional steady-state, conjugate heat transfer (CHT) simulations for laminar incompressible flow were carried out to quantify the performance of a TPMS based heat exchanger. TPMS Lattices based on Schwartz D architecture was modeled to elucidate the design parameters and establishing relationships between gas velocity, heat transfer, and thermal performance of TPMS at different wall thicknesses. In this study, four types of lattices from the same architectures with varying wall thickness were examined for a range of the gas velocity, with one design found to be the optimized lattice providing the highest thermal performance. The results and methodology presented here can facilitate improvements in TPMS-heat exchangers' fabrication for recycling the waste heat in low pitch thermal systems.

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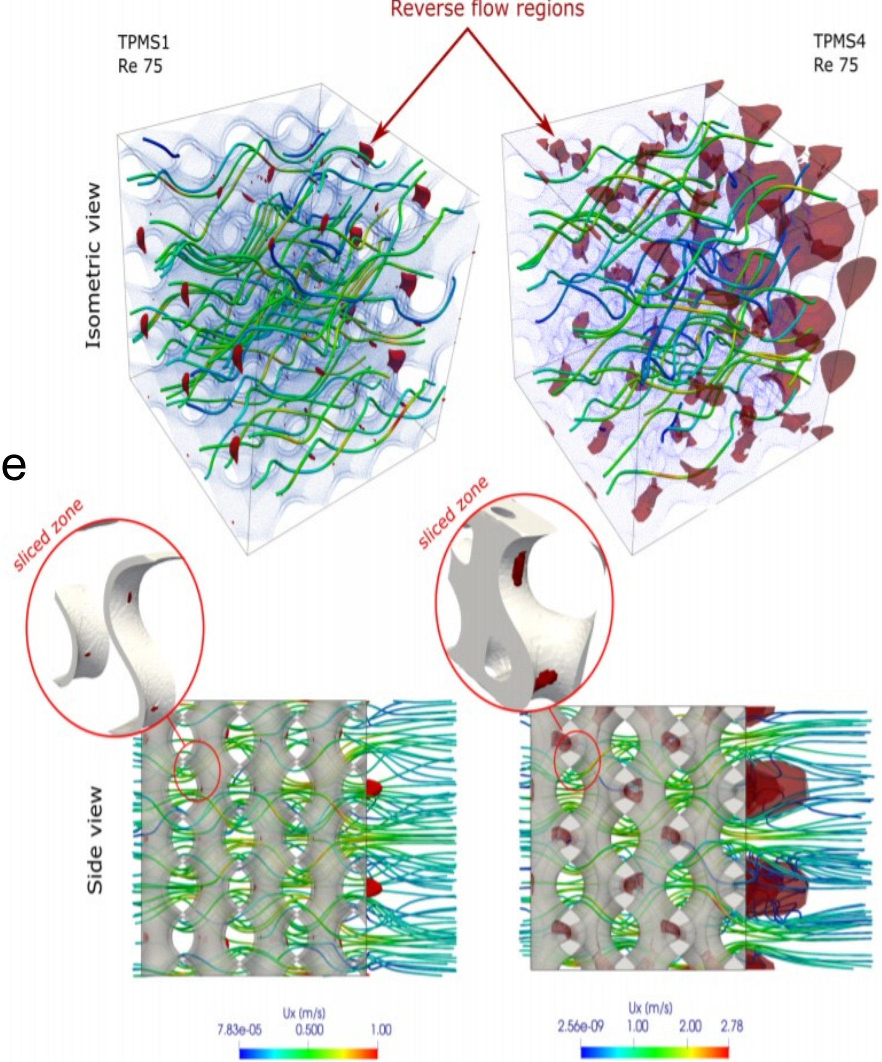
- Low reverse flow regions
- High heat-transfer rate even at low Re
- Many interesting observations
- Quantification of these behaviors



Applied Thermal Engineering 212 (2022) 118448

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/ate

Research paper

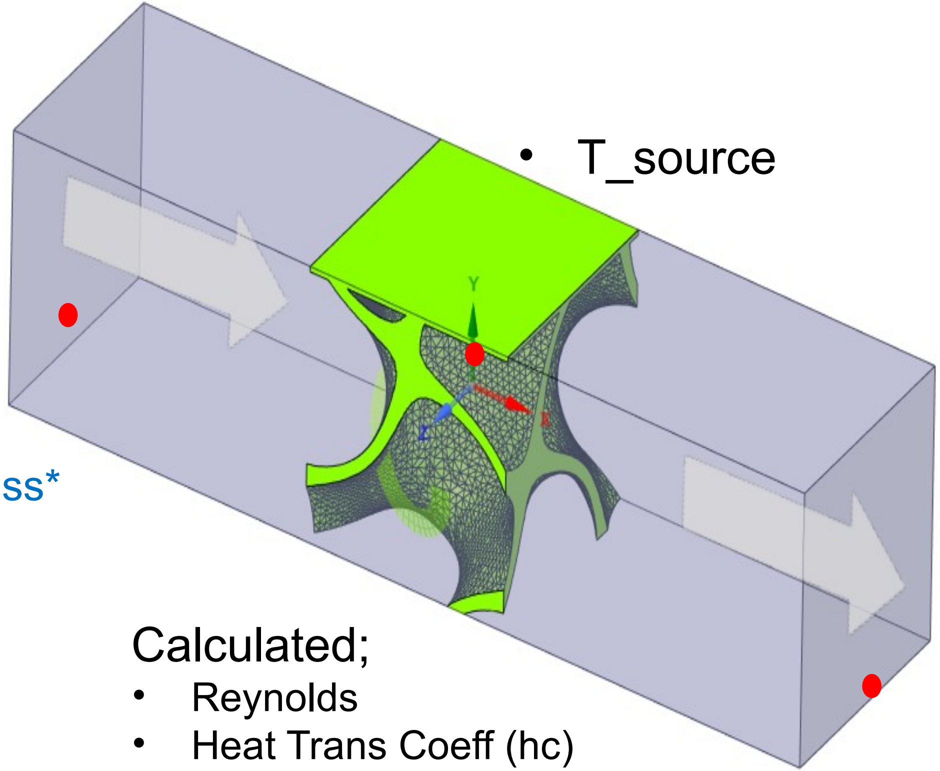
Multi-objective optimization of TPMS-based heat exchangers for low-temperature waste heat recovery

Reza Attarzadeh [a,*], Seyed-Hosein Attarzadeh-Niaki [b], Christophe Duwig [a]

[a] *Department of Chemical Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden*
[b] *Faculty of Computer Science and Engineering, Shahid Beheshti University (SBU), Tehran, Iran*

DOE & Optimization

- U_in
- T_in
- P_in
- Density
- Viscosity
- TPMS thickness*
- TPMS length*



- T_source

- U_out
- T_out
- P_out

Calculated;
- Reynolds
- Heat Trans Coeff (hc)
- Nussult (Nu)
- ΔT = T_source-T_out
- ΔP = P_out – P_in

* Excluded

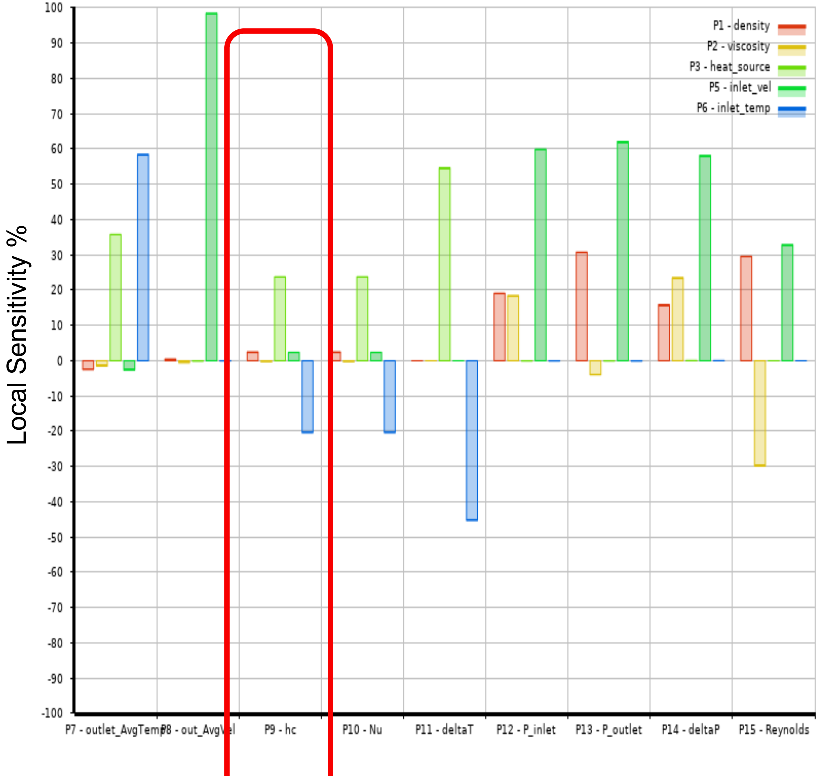
Summary of OP design

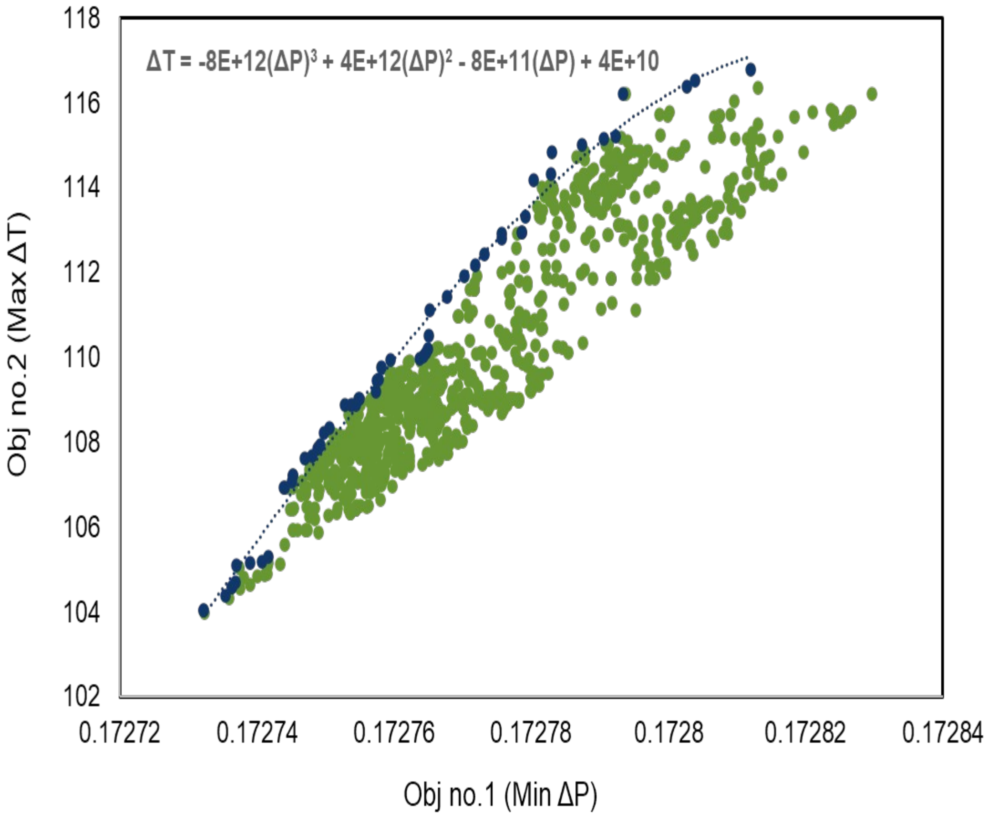
Optimization Study	
Maximize	Goal is to Maximize Temperature difference
Minimize	Goal is to Minimize Pressure difference
<= 150	Strict Constraint, Reynolds less than or equals to 150

Optimization Method	
MOGA	Multi-Objective Genetic Algorithm
Configuration	Generate 7000 samples initially, 1400 samples per iteration
Status	Converged after 28797 evaluations.

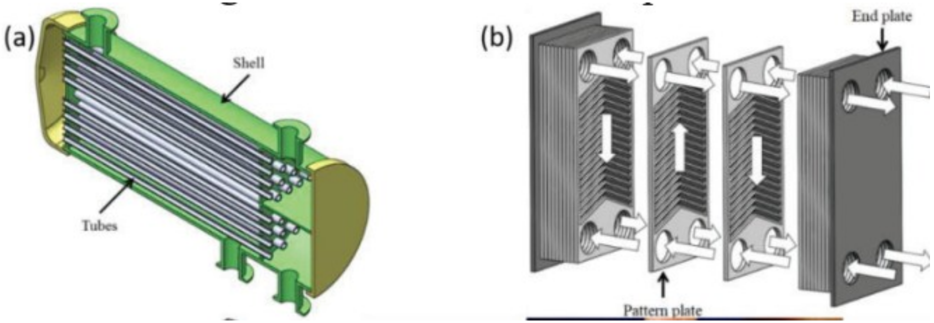
Sensitivity and Pareto front

Heat transfer Coefficient (hc)

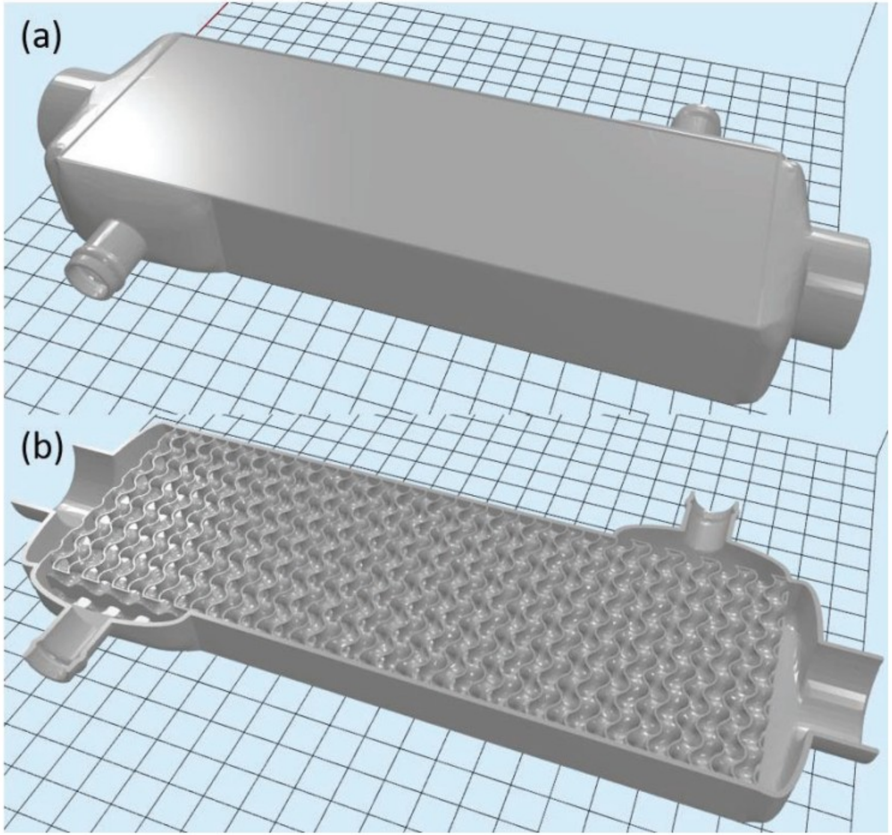




Next step 2 fluids TPMS



Present solutions



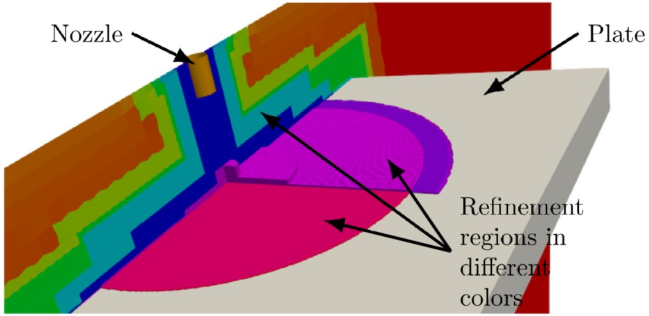
Increasing h – playing with turbulence

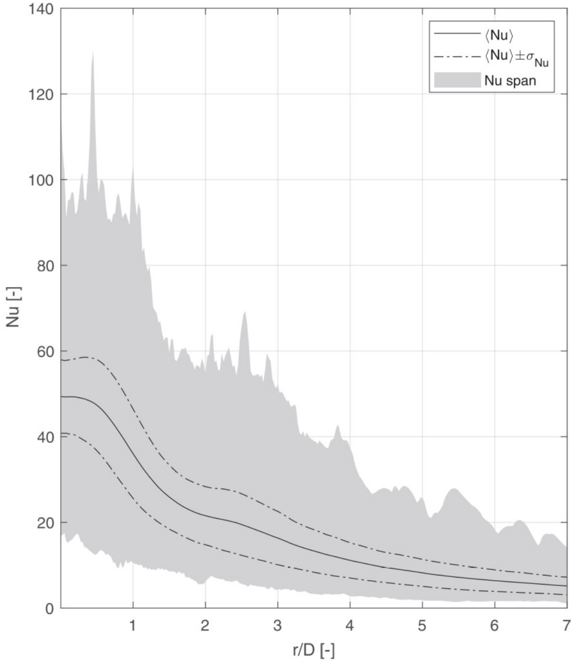
Relaminarization is often a problem

Heat-transfer is driven by turbulence and in particular by large scale structures

We look at the flow with high-fidelity simulations

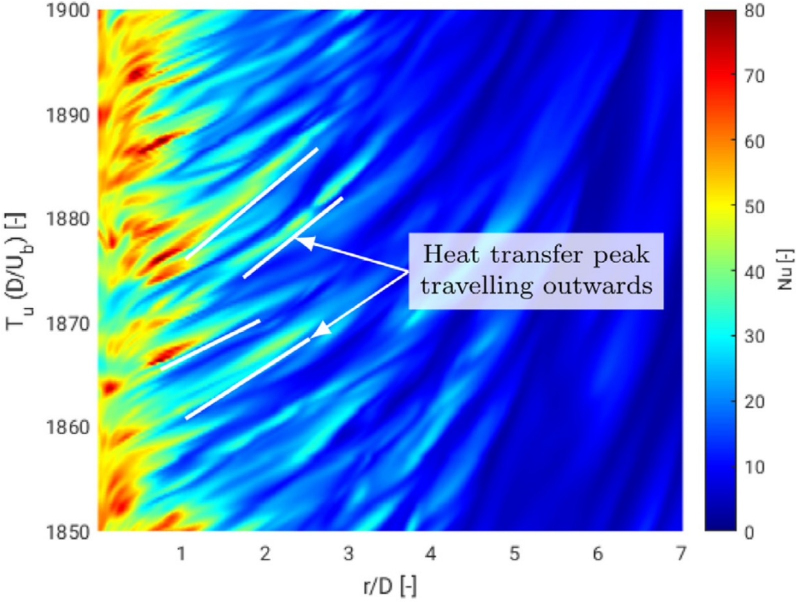
K. Rönnberg and C. Duwig International Journal of Heat and Mass Transfer 173 (2021) 121197

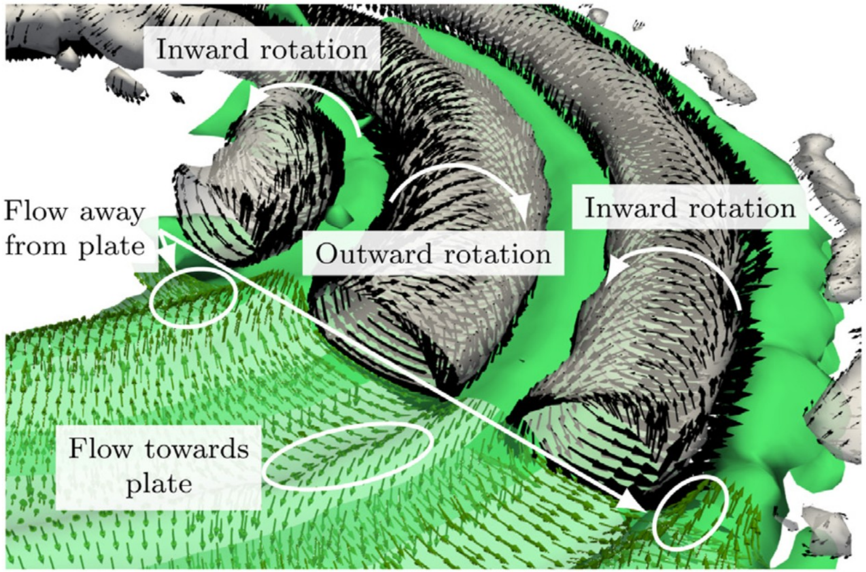




Increasing h – playing with turbulence

High Nu is correlated with outward travelling vortices





K. Rönnberg and C. Duwig International Journal of Heat and Mass Transfer 173 (2021) 121197

Increasing h - Reactive fluids

Reversible equilibrium reactions

$$A_{n(g)} \rightleftarrows {}^{n}/_{m}\ A_{m(g)}$$

Reaction is endothermic – it takes energy to break the large molecule

Reaction is pushed right by higher temperatures and left by higher pressures

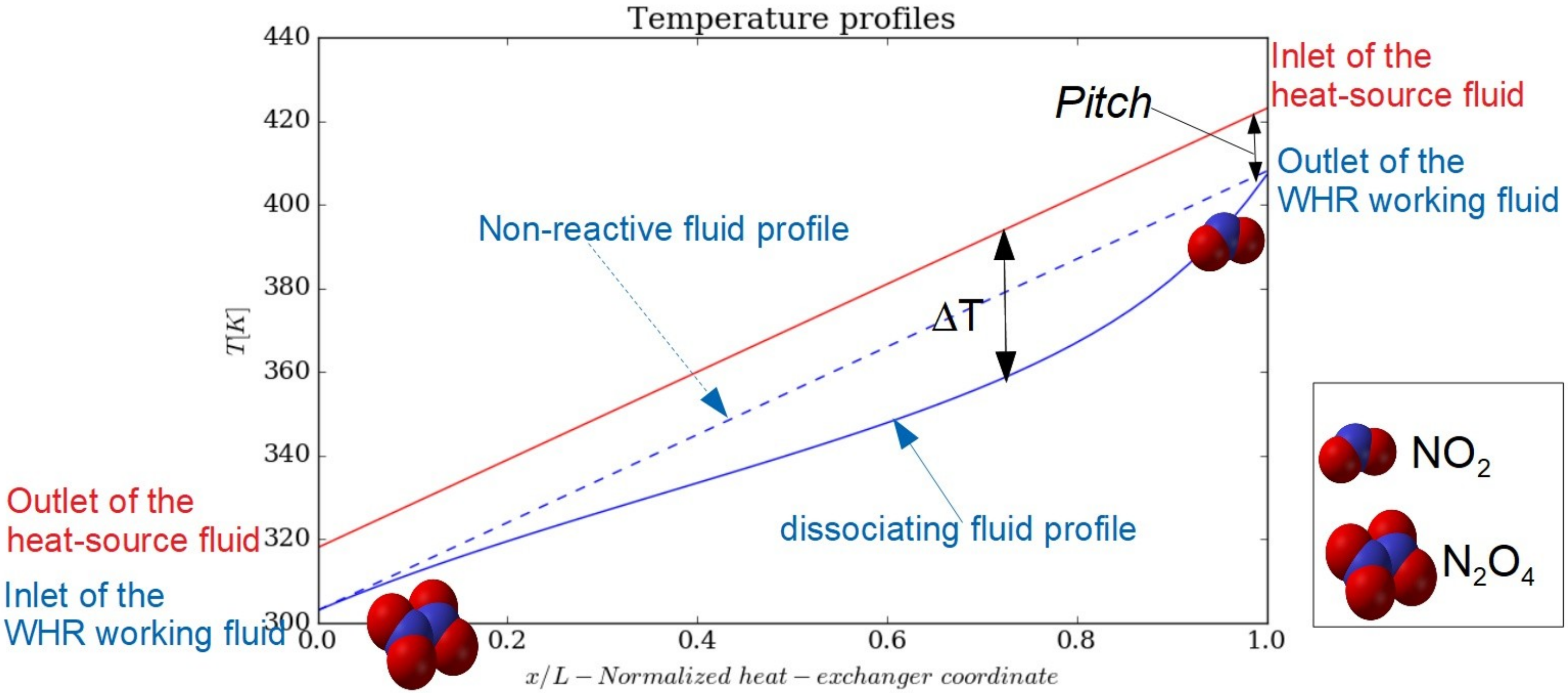
It is gas phase all the time

Example

- N2O4 = 2 NO2 = 2 NO + O2
- NOCl = NO + ½ Cl2

Reactive fluids

Temperature profiles in an HTX



Effect of dissociation reactions on heat-transfer

International Journal of Heat and Mass Transfer 182 (2022) 121946

Contents lists available at ScienceDirect

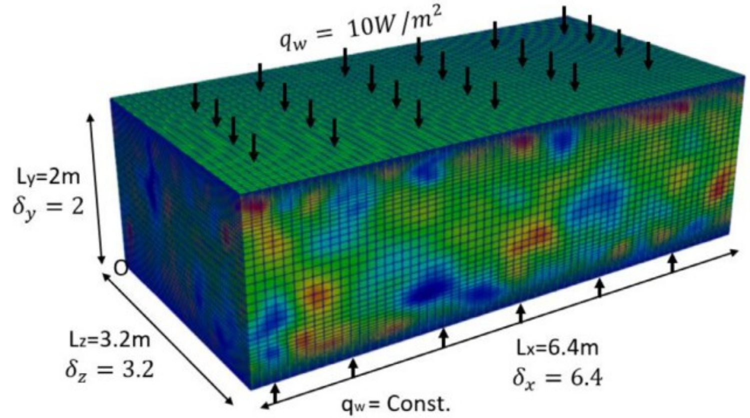
International Journal of Heat and Mass Transfer

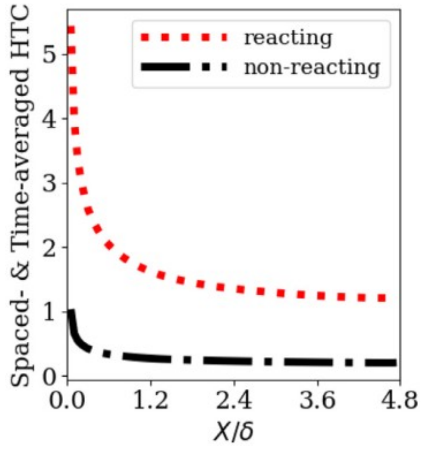
journal homepage: www.elsevier.com/locate/hmt

Identification of heat transfer intensification mechanism by reversible N_2O_4 decomposition using direct numerical simulation

Kai Zhang*, Yazhou Shen, Christophe Duwig

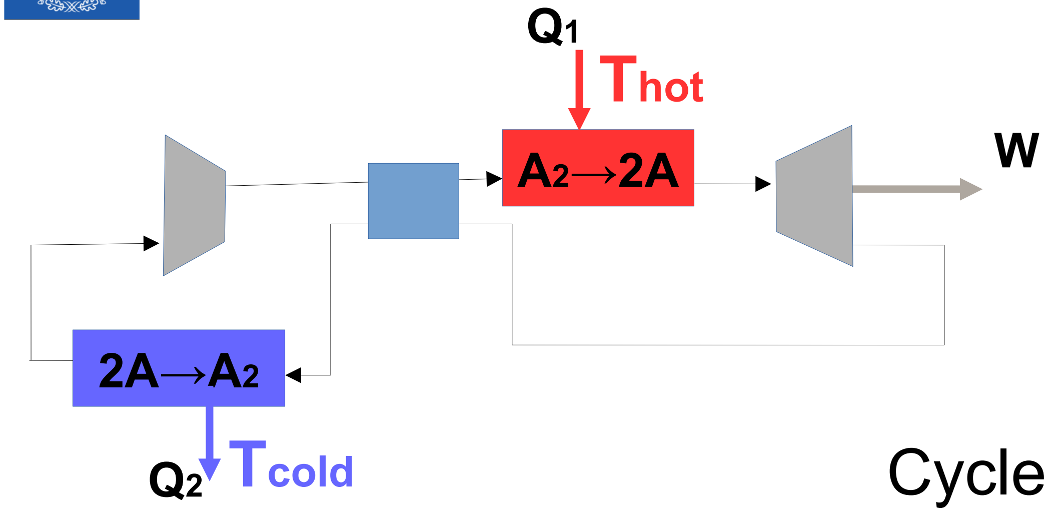
Department of Chemical Engineering, Royal Institute of Technology (KTH), Brinellvägen 8, 114 28 Stockholm, Sweden





Boosts Heat-transfer by +500%

Impact on the thermodynamic cycle



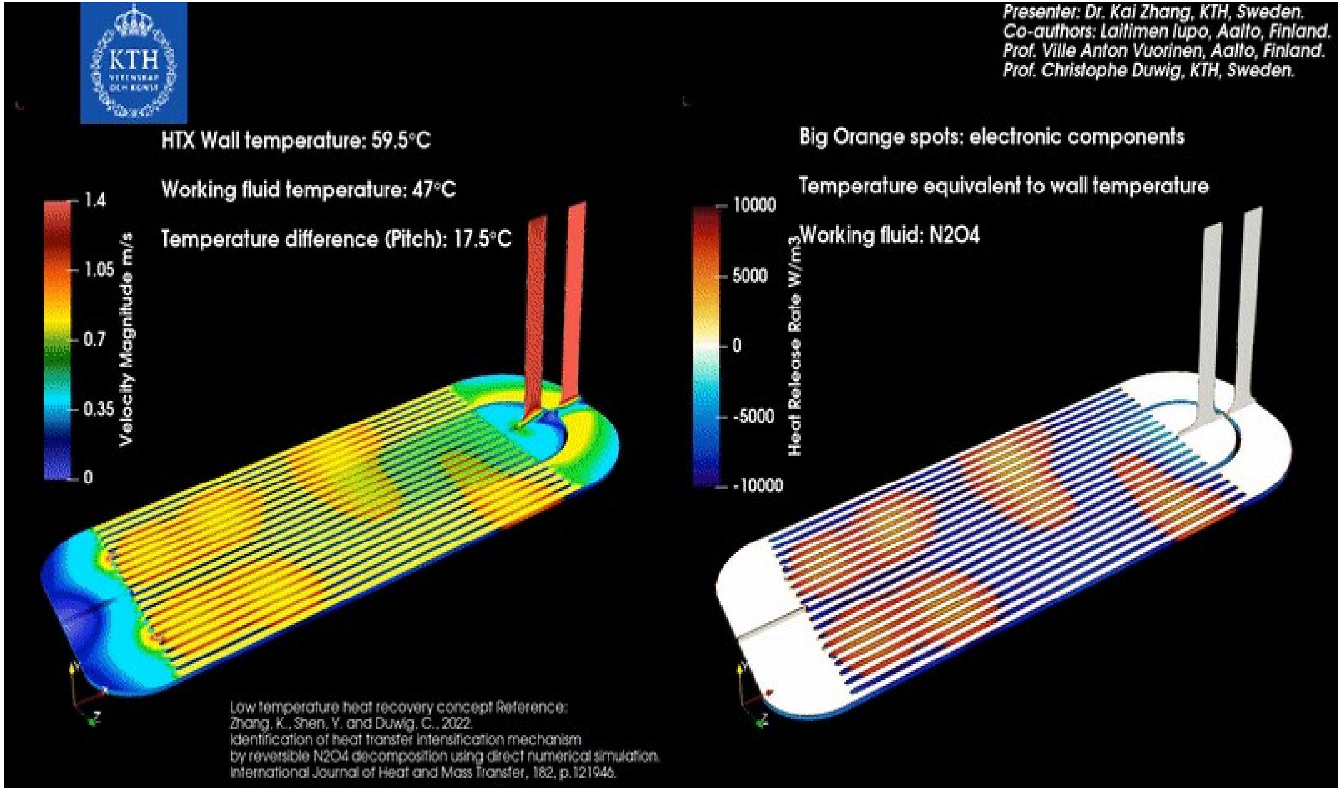
Cycle efficiency N_2O_4

- η= 0.09 @Thot = 363K
- η= 0.12 @Thot = 393K

Rapid response to transient

Potentially very compact HTX

Electronic cooling



Presenter: Dr. Kai Zhang, KTH, Sweden.
Co-authors: Laitimen Iupo, Aalto, Finland.
Prof. Ville Anton Vuorinen, Aalto, Finland.
Prof. Christophe Duwig, KTH, Sweden.

HTX Wall temperature: 59.5°C

Working fluid temperature: 47°C

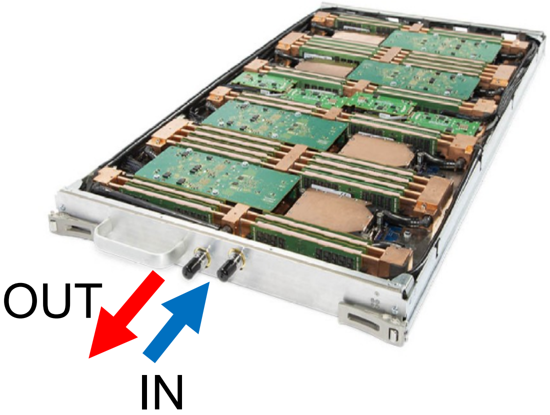
Temperature difference (Pitch): 17.5°C

Big Orange spots: electronic components

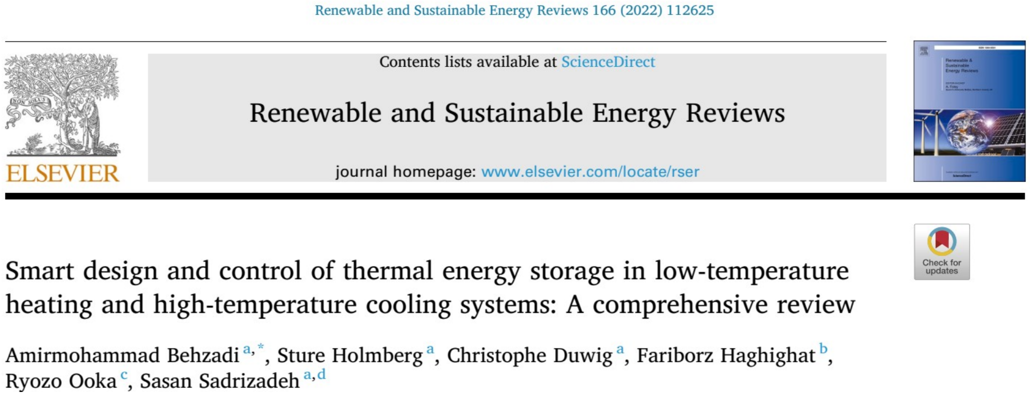
Temperature equivalent to wall temperature

Working fluid: N2O4

Low temperature heat recovery concept Reference:
Zhang, K., Shen, Y. and Duwig, C., 2022.
Identification of heat transfer intensification mechanism
by reversible N2O4 decomposition using direct numerical simulation.
International Journal of Heat and Mass Transfer, 182, p.121946.



Applications to the built environment



Renewable and Sustainable Energy Reviews 166 (2022) 112625

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Smart design and control of thermal energy storage in low-temperature heating and high-temperature cooling systems: A comprehensive review

Amirmohammad Behzadi[a,*], Sture Holmberg[a], Christophe Duwig[a], Fariborz Haghighat[b], Ryozo Ooka[c], Sasan Sadrizadeh[a,d]

Project in the frame of the IEA Annex 37 - Smart Design and Control of Energy Storage Systems

Results in Engineering 16 (2022) 100619

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Heating energy implications of utilizing gas-phase air cleaners in buildings' centralized air handling units

Behrouz Nourozi[a,*], Sture Holmberg[a], Christophe Duwig[a], Alireza Afshari[b], Pawel Wargocki[c], Bjarne Olesen[c], Sasan Sadrizadeh[a,d,**]

Project in the frame of the IEA Annex 78 - Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications

Re-using cleaned indoor air to reduce losses

Energiforsk Värmeklustret

- Happy to hear your areas of interest
- Calls of interests
  - Swedish Energy Agency Termo
  - Swedish Energy Agency E2B2 (energy efficient buildings)
  - Vinnova (Eurostars, ….)
  - …..
- Track for collaboration
  - Heat-Exchanger technology (additive manufacturing)
  - Heat-Harvesting from electric/ electronic systems/ low temp. sources
  - Decarbonize processes
  - PCM – heat storage (flexible buildings)

Contact:
duwig@kth.se

KTH Energy Platform

TOWARDS THE ENERGY OF THE FUTURE

THE INVISIBLE REVOLUTION BEHIND THE ELECTRICAL SOCKET

Energi finns överallt. Vi tar för givet att den finns tillhands när vi vill värma upp våra hem, laga mat, använda våra datorer, mobiltelefoner, rulltrappor, lyftkranar, röntgenapparater, bussar, tåg, flygplan och bilar. Den är en självklar, ofta osynlig – och tyvärr ohållbar del av våra liv.

Idag vet vi att världens energisystem måste omvandlas i grunden. Det är en förutsättning för att vi ska kunna bromsa klimatförändringarna och skapa ett hållbart samhälle. Och vi har alla viktiga roller att spela i omvandlingen. Men hur förändrar vi något som vi inte kan se?

I den här antologin delar några av Sveriges ledande energiforskare sin syn på kända och mindre kända utmaningar och lösningar kring framtidens energi. Syftet är att stimulera samtal och konstruktiv debatt för att vi ska kunna ta oss an utmaningarna i en öppen dialog där fakta och kunskap formar vår framtid.

Boken är skriven av forskare anslutna till **KTH:s Energiplattform**, i samarbete med den ideella organisationen **Vetenskap & Allmänhet, VA**.

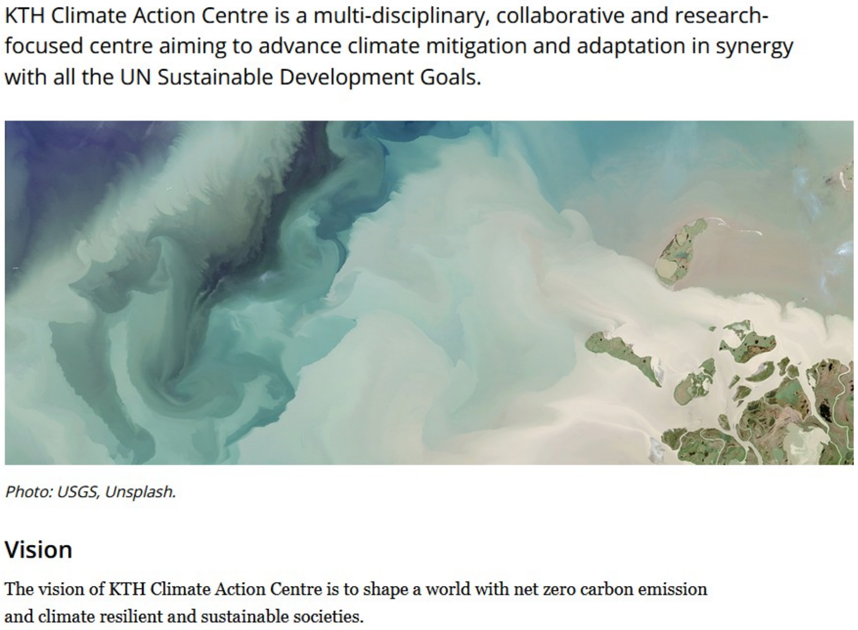
Vetenskap & Allmänhet
VA – PUBLIC & SCIENCE

9 789180 275958

www.energiantologi.se

Thank you and see you next time at the KTH Climate Action House

Source google Maps



KTH Climate Action Centre is a multi-disciplinary, collaborative and research-focused centre aiming to advance climate mitigation and adaptation in synergy with all the UN Sustainable Development Goals.

Photo: USGS, Unsplash.

Vision

The vision of KTH Climate Action Centre is to shape a world with net zero carbon emission and climate resilient and sustainable societies.