
VELKOMMEN TIL
AVANCERET ENERGILAGRING
AARHUS - 30. NOVEMBER 2023

AVANCERET ENERGILAGRING 2023

KONFERENCEN ER STØTTET AF

Uddannelses- og Forskningsstyrelsen

DaCES Danish Center for Energy Storage

energy CLUSTER DENMARK


FÅ NYT OM AVANCERET ENERGILAGRING
DIREKTE I DIN INDBAKKE
TILMELD DIG NYHEDSBREVET AVANCERET ENERGILAGRING PÅ WWW.TEKNOLOGISK.DK/39523

PROGRAM

FORMIDDAG

9.30 - 9.40	**Velkomst v. Lasse Stenhøj Ingvardsen, Teknologisk Institut**
9.40 - 10.10	**Carnot-Battery research at DLR: from theory to demonstration v. Jonas Tombrink, German aerospace center**
10.10 - 10.40	**Status, styrker og synergier for energilagring i Danmark ved DaCES v. Niels Dyreborg Nielsen, DaCes**
10.40 - 10.55	***Pause***
10.55 - 11.20	**Energilagring - hvorfor er det interessant for et kraftvarmeværk v. Jörgen Westerdahl Edström, BEOF**
11.20 - 11.45	**Fossilfri varmeproduktion til industri og kraftvarme med termisk energilagring v. Nis benn, Hyme Energy ApS**
11.45 - 12.10	**Compact Thermal Energy Storage - status, perspectives and research example v. Gerald Englmair, DTU construct**

12.10 - 13.00	***Frokost***
13.00 - 13.35	**Udnyttelse af ladestandere og batterilager til balancering af elnettet v. Andreas Thingvad, Hybrid greentech og Thomas steen Jensen, Københavns Lufthavn**
13.35 - 13.55	**Debat**
13.55 - 14.10	***Pause***
14.10 - 15.10	**Rundvisning i laboratorierne**
15.20 - 15.45	**Potential for optimal operation of Industrial Heat Pumps with Theremal Energy Storage for emissions and cost reduction v. Magnus lyck hansen, viegand maagøe**
15.45 - 16.10	**Avanceret energilagring - forholdet mellem efficiens og effektivitet v. Gunnar Rohde, Teknologisk Institut**
16.10- 16.35	**Refrektioner og afrunding v. Lasse Stenhøj Invardsen, Teknologisk Institut**

AVANCERET ENERGILAGRING

CARNOT-BATTERY RESEARCH AT DLR: FROM THEORY TO DEMONSTRATION

JONAS TOMBRINK, GERMAN AEROSPACE CENTER (DLR)

CARNOT-BATTERY RESEARCH AT DLR: FROM THEORY TO DEMONSTRATION

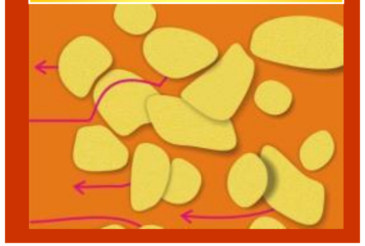
Jonas Tombrink, DLR, Institute of Engineering Thermodynamics

Institute of Engineering Thermodynamics

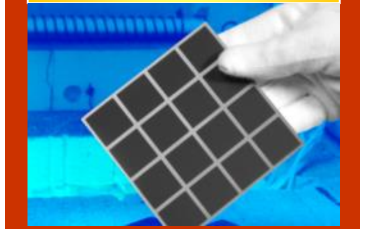
Prof. André Thess, Director

Jörg Piskurek, Vice Director

Computational Electrochemistry
Prof. A. Latz

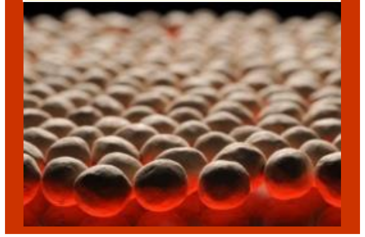


Electrochemical Energy Technology
Prof. A. Friedrich



Energy System Integration
Dr. A. Ansar

Thermal Process Technology
Prof. A. Vandersickel



~ 200 staff in Stuttgart, Köln, Hamburg, and Ulm
~ 27 Mio. EUR annual budget with 50% third party funding

„We are the scientific pathfinder for the energy storage industry“

Institute of Engineering Thermodynamics

Thermal Process Technology

Prof. Annelies Vandersickel

Thermal Power Plant Components

Dr. Stefan Zunft

Regenerator and solid state storage

High temperature heat exchangers

Thermal Systems for Fluids

Dr. Thomas Bauer

Molten salt storage

Thermal Systems with Phase Change

Dr. Andrea Gutierrez

Latent heat storage

PXP storage

Thermo-chemical Systems

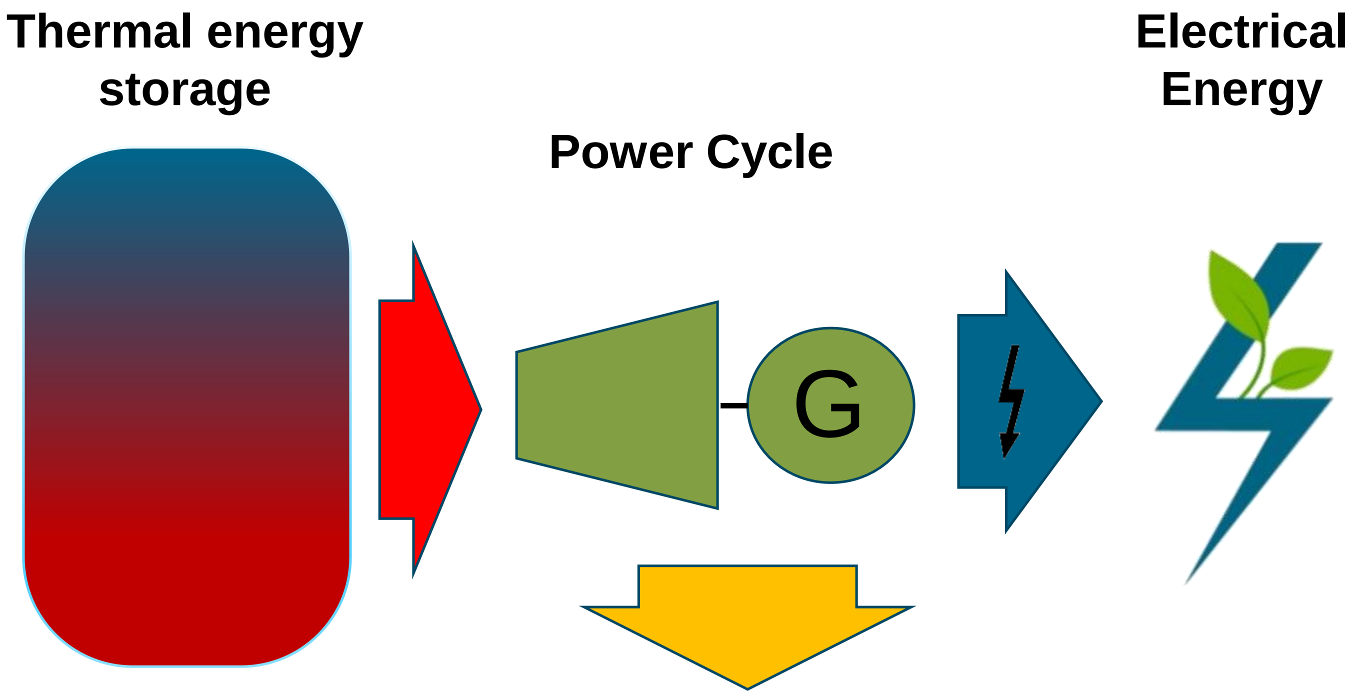
Dr. Marc Linder

Thermochemical Storage

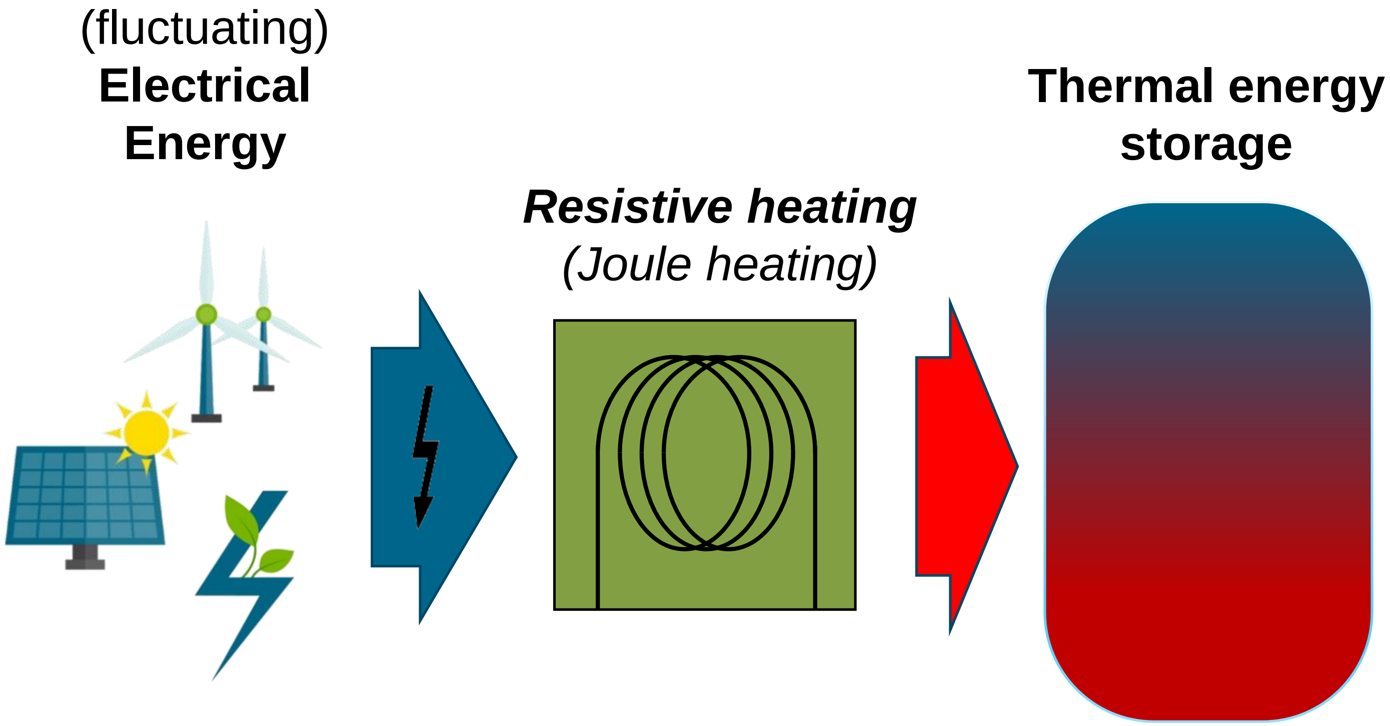
Chemical Heat Pumps

About 60 people located in Stuttgart & Cologne

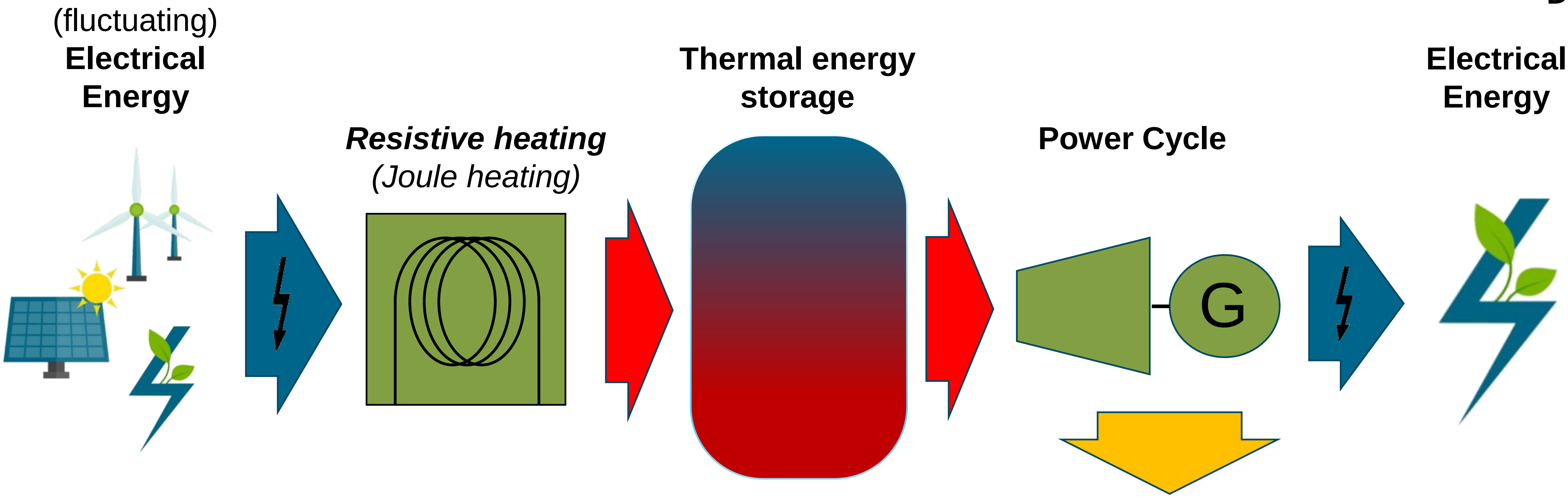
Carnot-Batterie: Power to Heat to Power



Carnot-Batterie: Power to Heat to Power

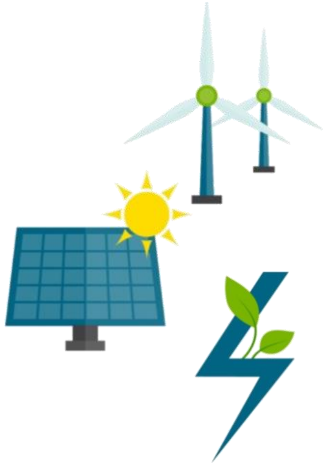


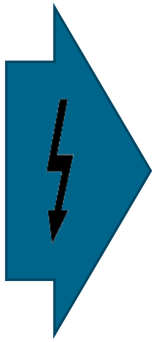
Carnot-Batterie: Power to Heat to Power



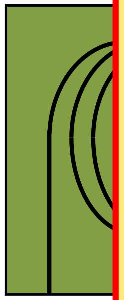
Carnot-Batterie: Power to Heat to Power

(fluctuating)
Electrical Energy





Resist
(Jou

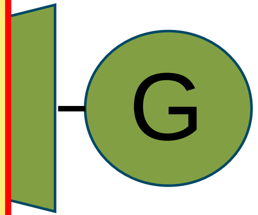


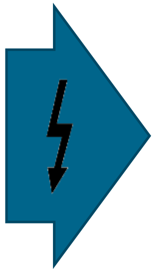
Limited by Carnot efficiency
(also for ideal implementation):

$$\eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}}$$

Real systems: η_{max} < 40 %

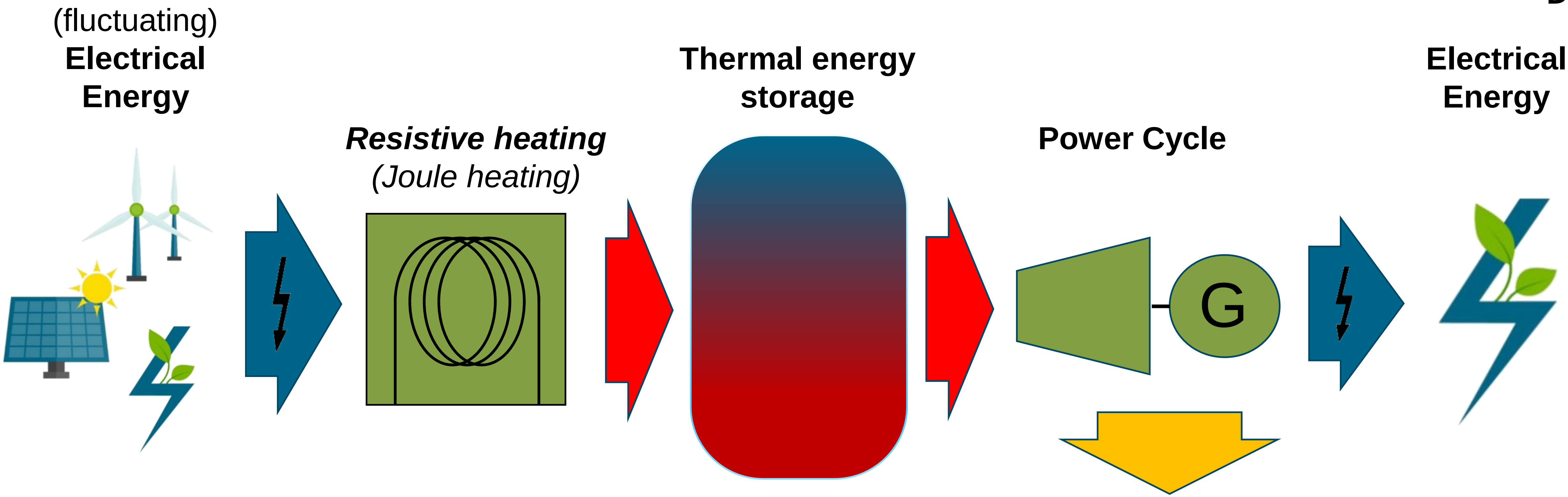
r Cycle



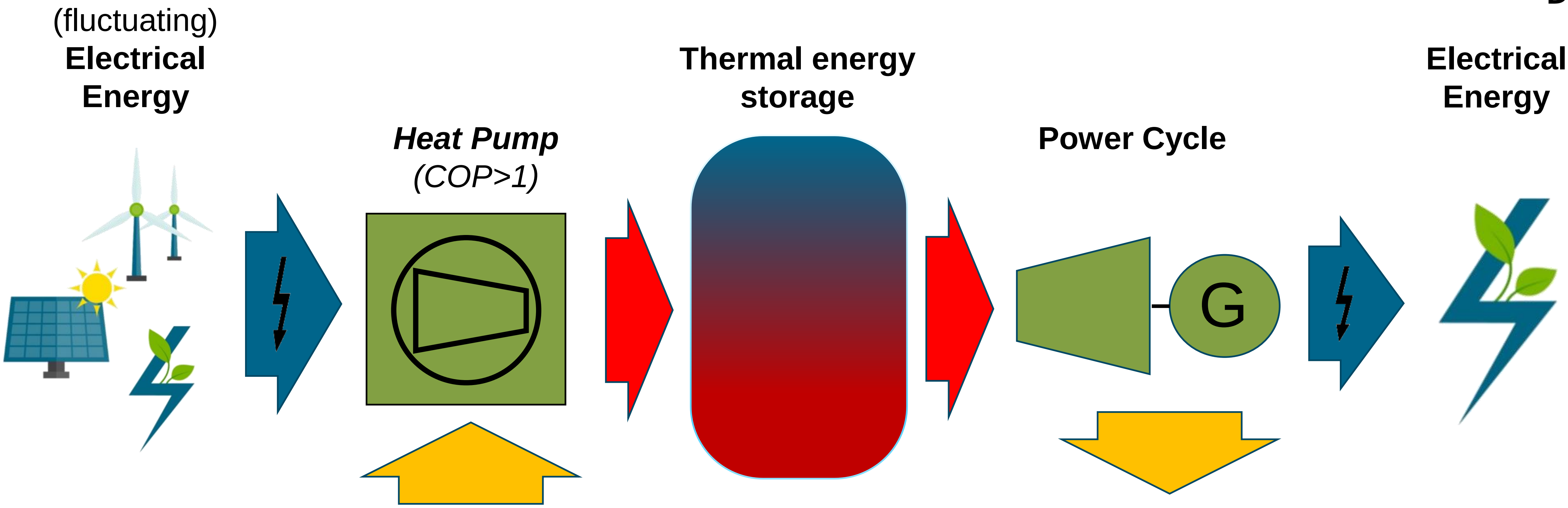


Electrical Energy

Carnot-Batterie: Power to Heat to Power



Carnot-Batterie: Power to Heat to Power



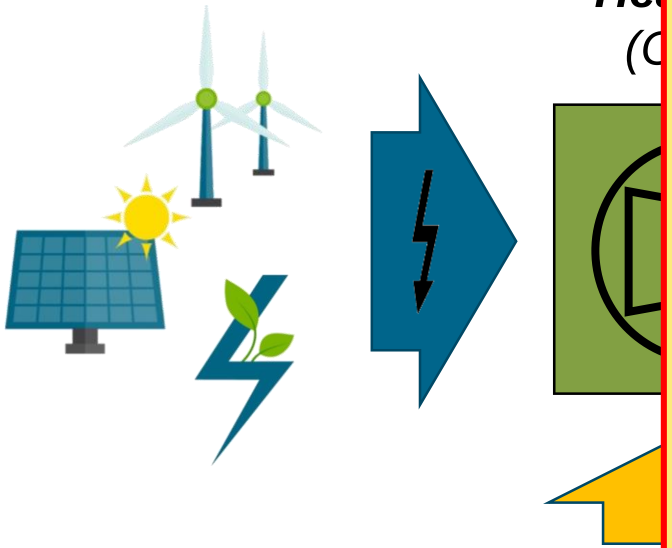
Carnot-Batterie: Power to Heat to Power

(fluctuating)
Electrical Energy

Hea
(C

r Cycle

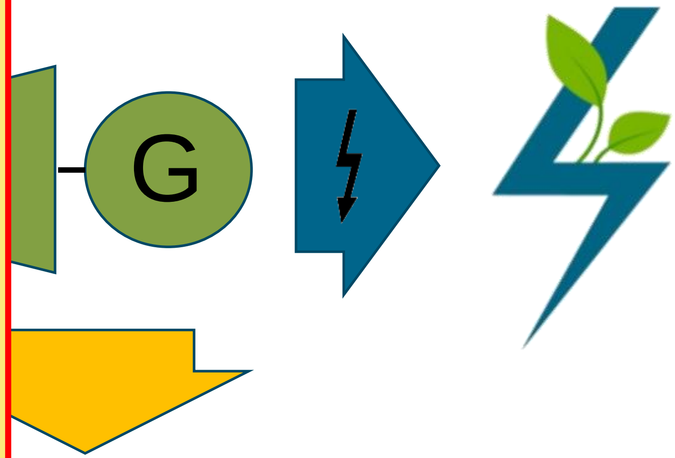
Electrical Energy



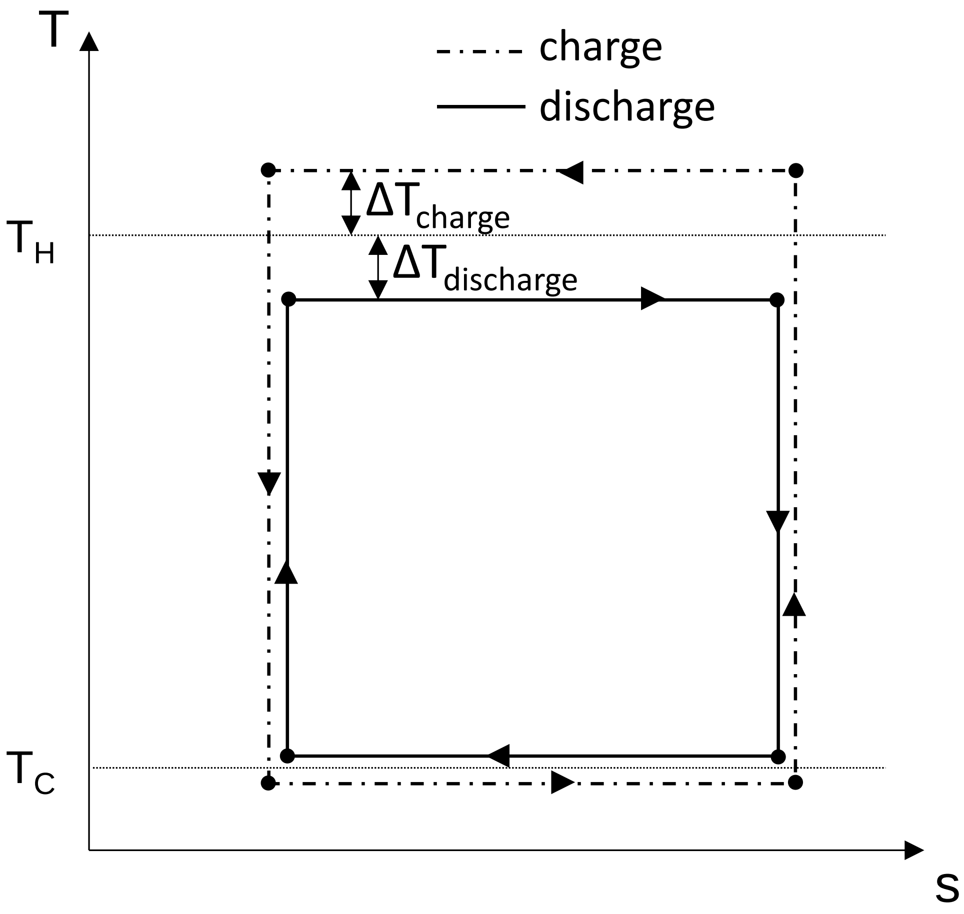
$$\eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}} \quad ; \quad COP = \frac{1}{\eta_{Carnot}}$$

$$\eta_{roundtrip} = COP \cdot \eta_{Carnot} = 1$$

Real systems: $\eta_{max} < 70\ \%$

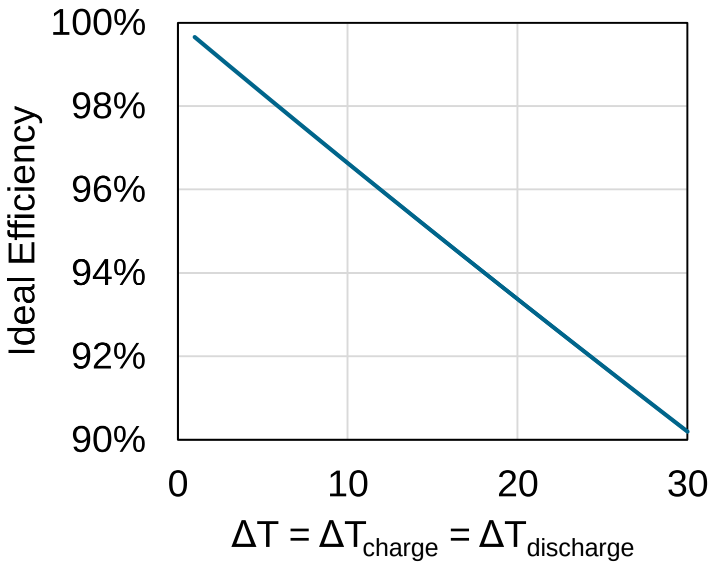


The ideal Carnot-Batterie



Effect of temperature difference on ideal efficiency

T_H = 306 °C, T_C = 15 °C



Rankine and Brayton Carnot Batteries

Rankine Cycle

- Known from coal power plants and conventional heat pumps
- Working fluid conducts phase change from liquid to gaseous
- Higher power density
  - Useful also for smaller machinery

Rankine and Brayton Carnot Batteries

Rankine Cycle

- Known from coal power plants and conventional heat pumps
- Working fluid conducts phase change from liquid to gaseous
- Higher power density
  - Useful also for smaller machinery

Brayton Cycle

- Known from gas turbines
- Only gaseous working fluid
- Lower power density
  - Useful with large machinery

Rankine and Brayton Carnot Batteries

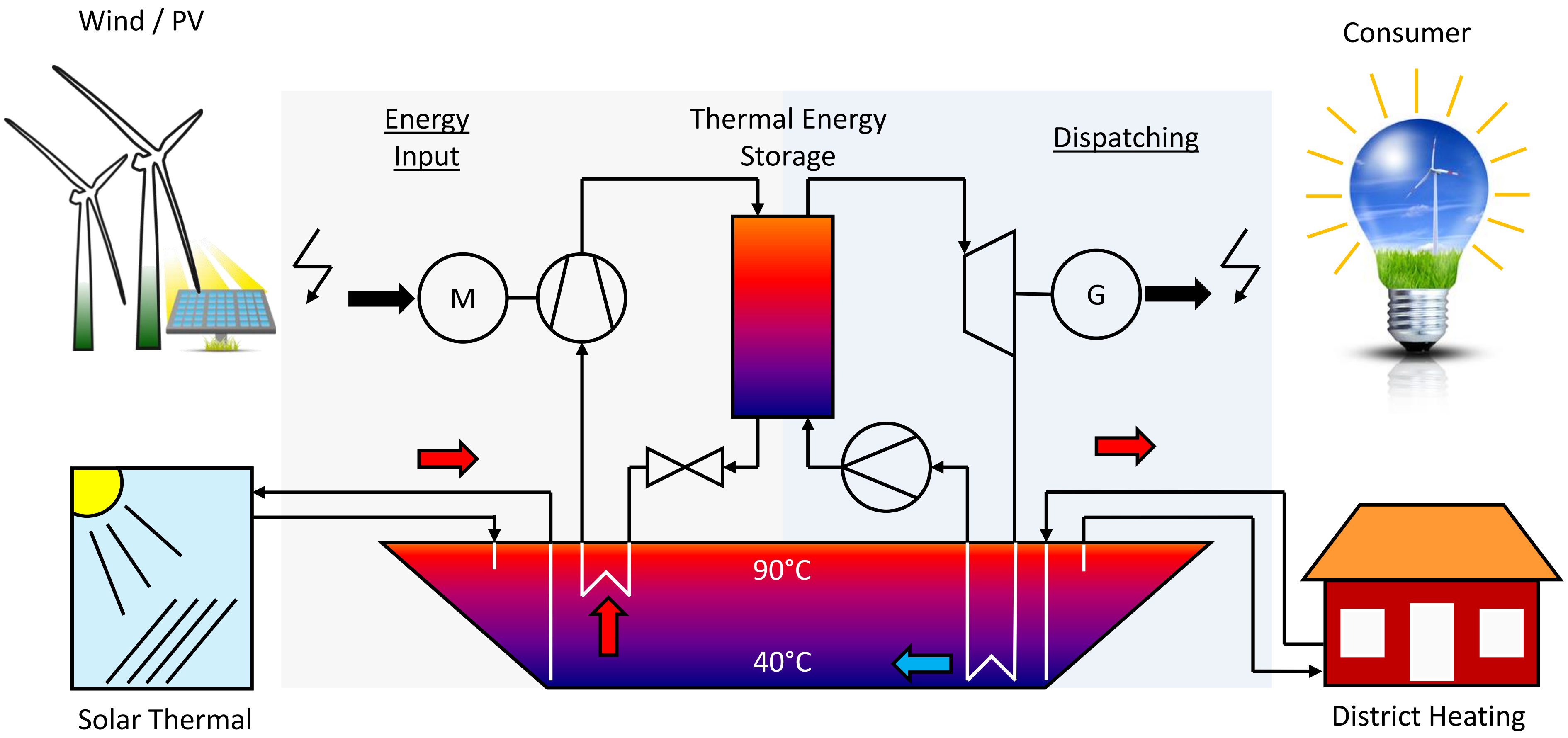
Rankine Cycle

- Known from coal power plants and conventional heat pumps
- Working fluid conducts phase change from liquid to gaseous
- Higher power density
  - Useful also for smaller machinery

Brayton Cycle

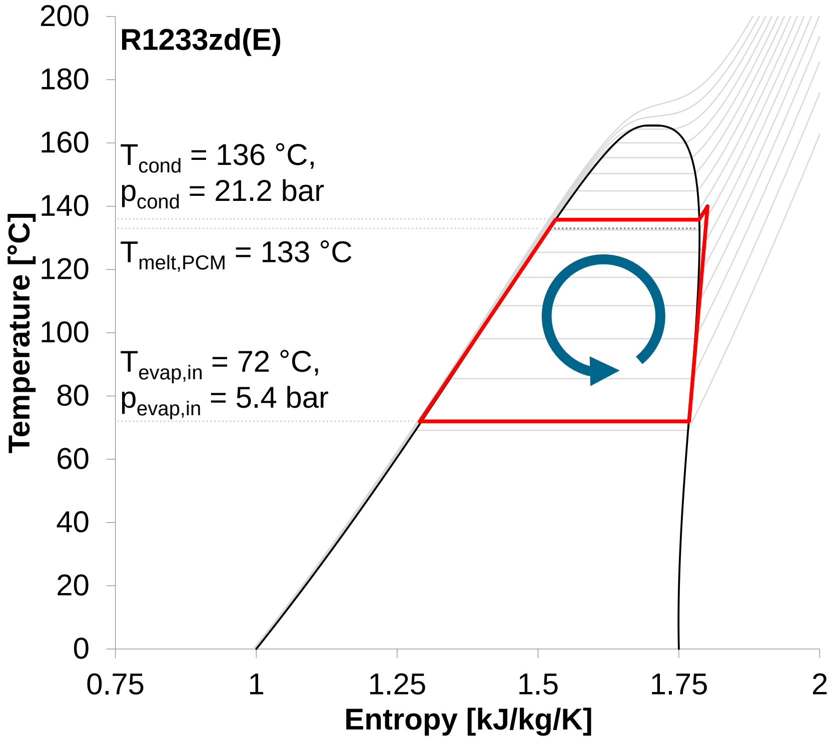
- Known from gas turbines
- Only gaseous working fluid
- Lower power density
  - Useful with large machinery

CHESTER
Compressed Heat Energy STorage for Energy from Renewable Sources



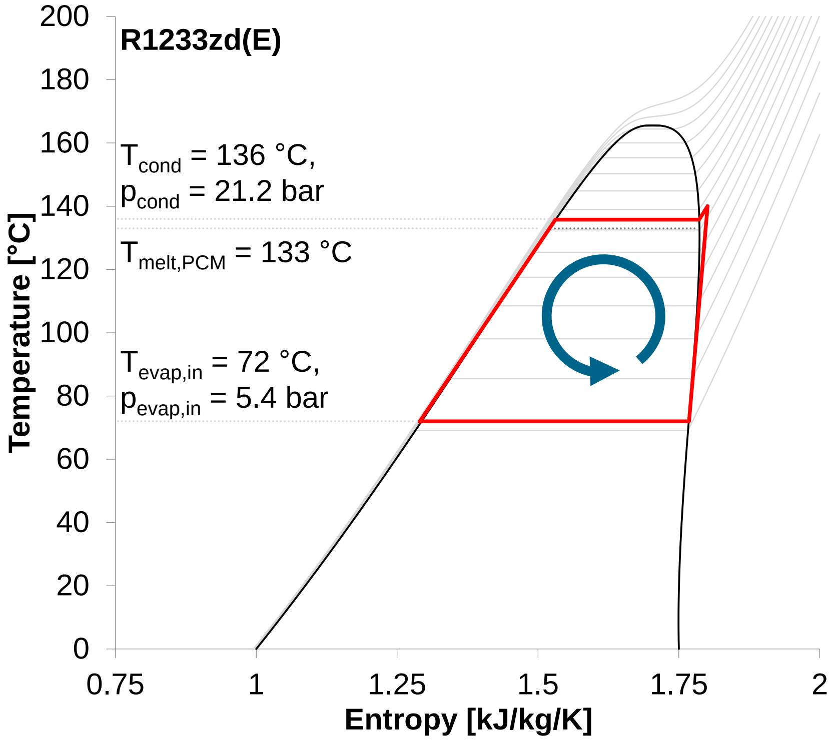
Theoretical T-S-Diagramms

Charging Cycle

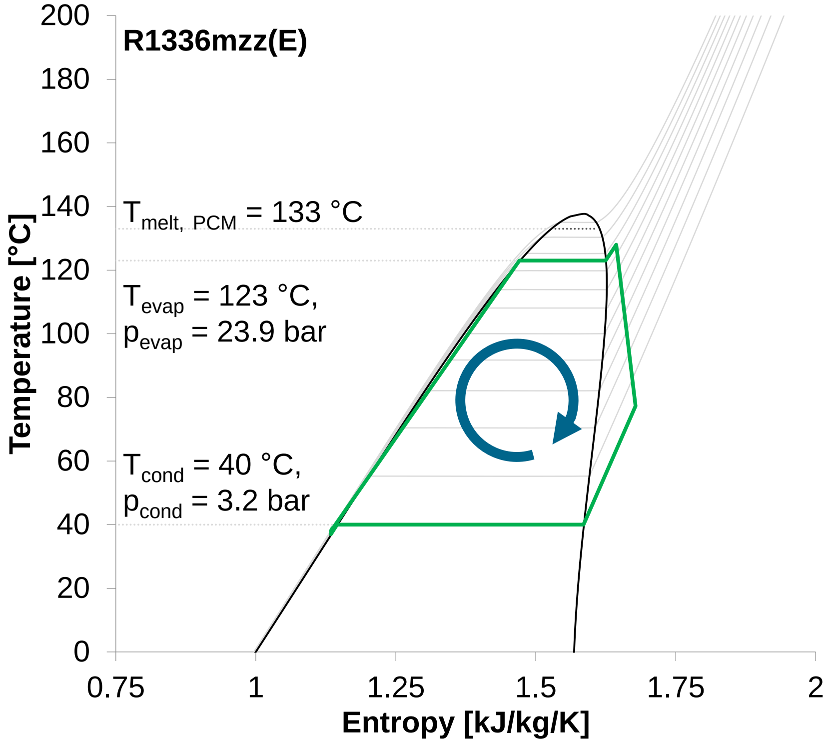


Theoretical T-S-Diagramms

Charging Cycle

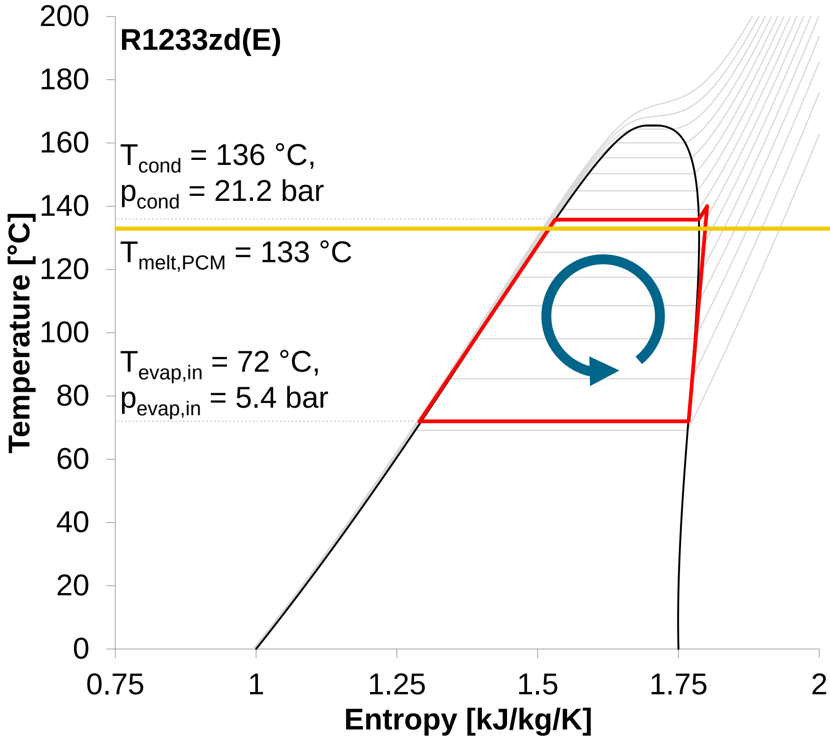


Discharging Cycle

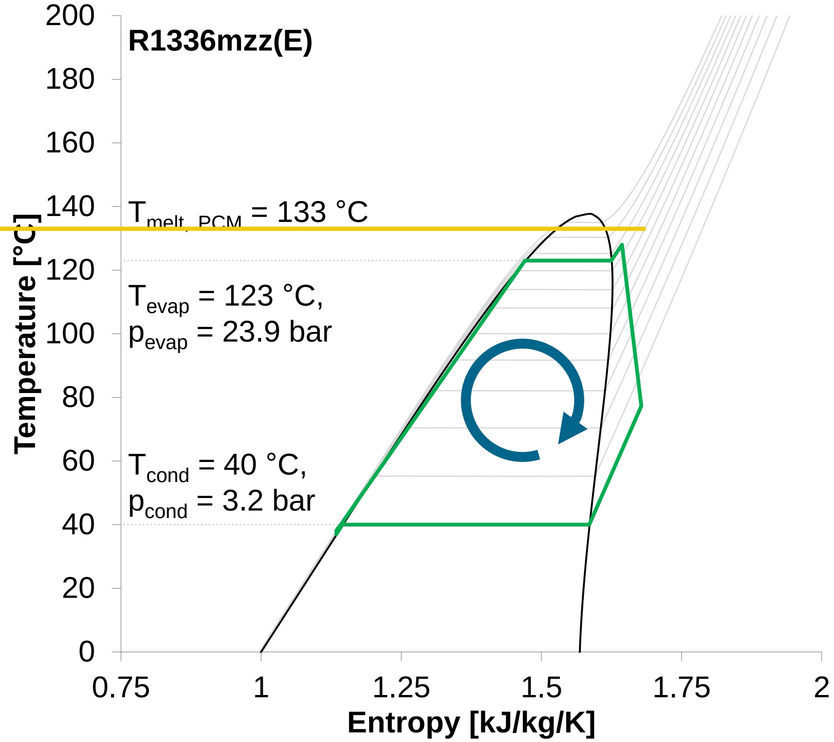


Theoretical T-S-Diagramms

Charging Cycle

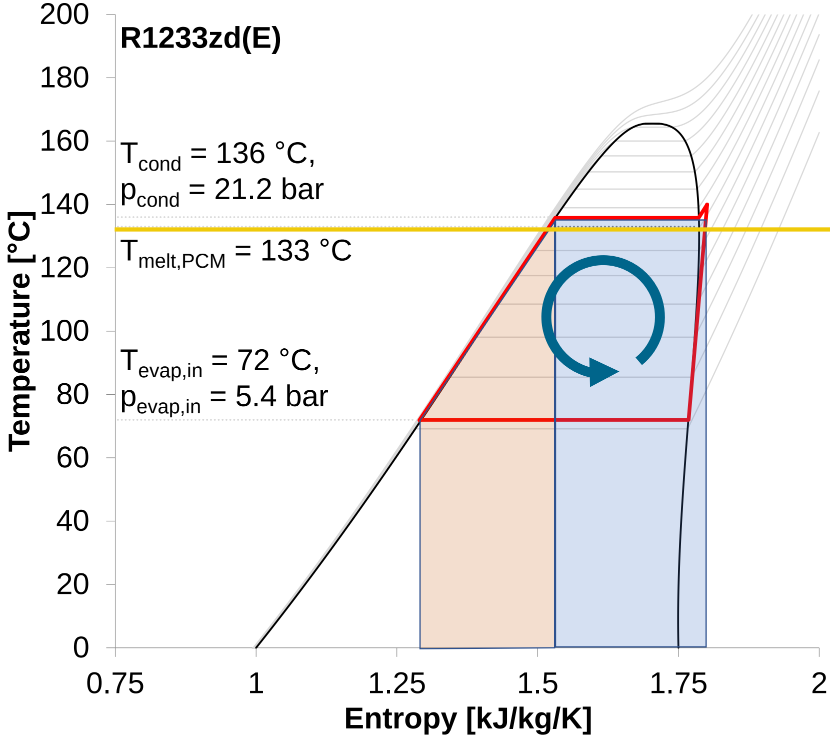


Discharging Cycle

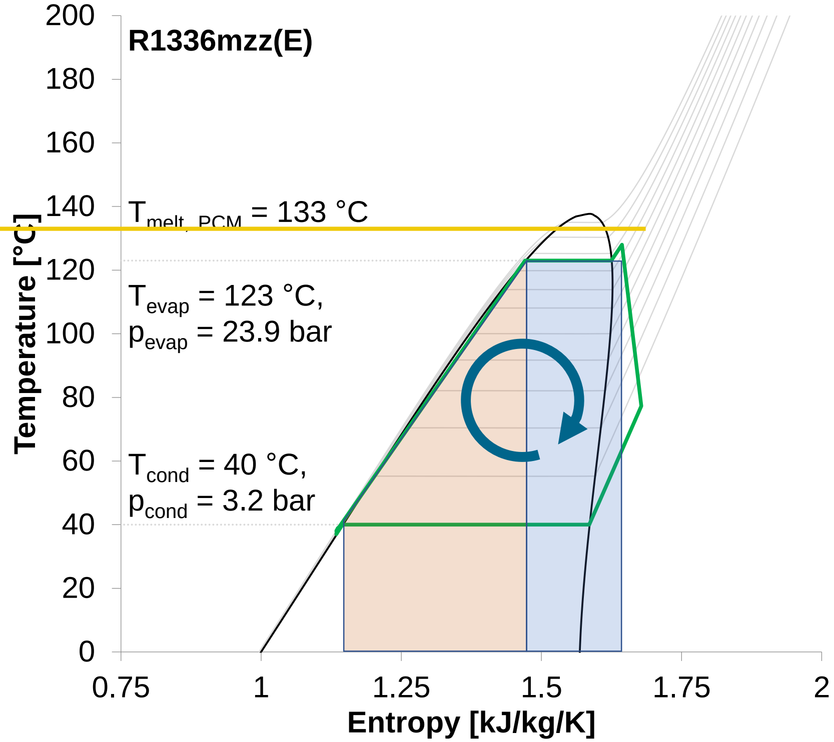


Theoretical T-s-Diagramms

Charging Cycle

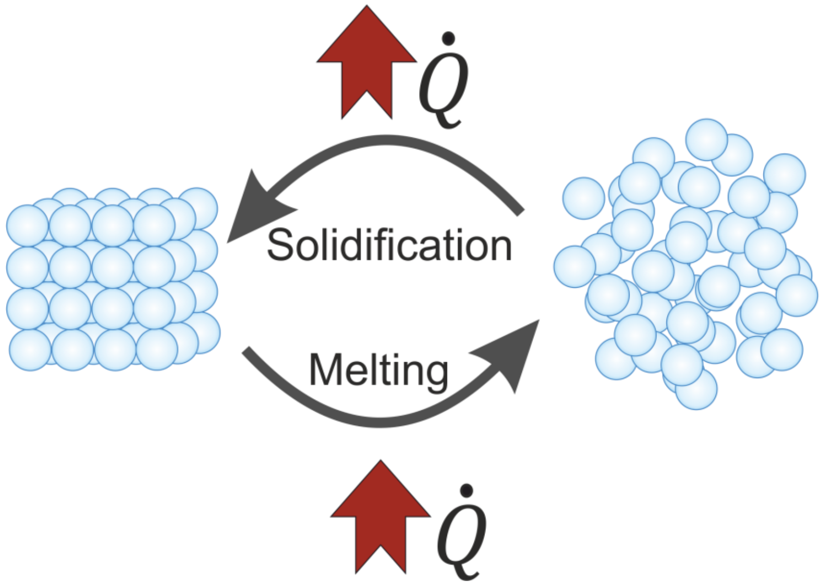


Discharging Cycle



→ **Latent and Sensible Thermal Energy Storage** crucial for optimized efficiency

Latent Heat Thermal Energy Storage



$$Q_{latent} = \Delta h_m$$

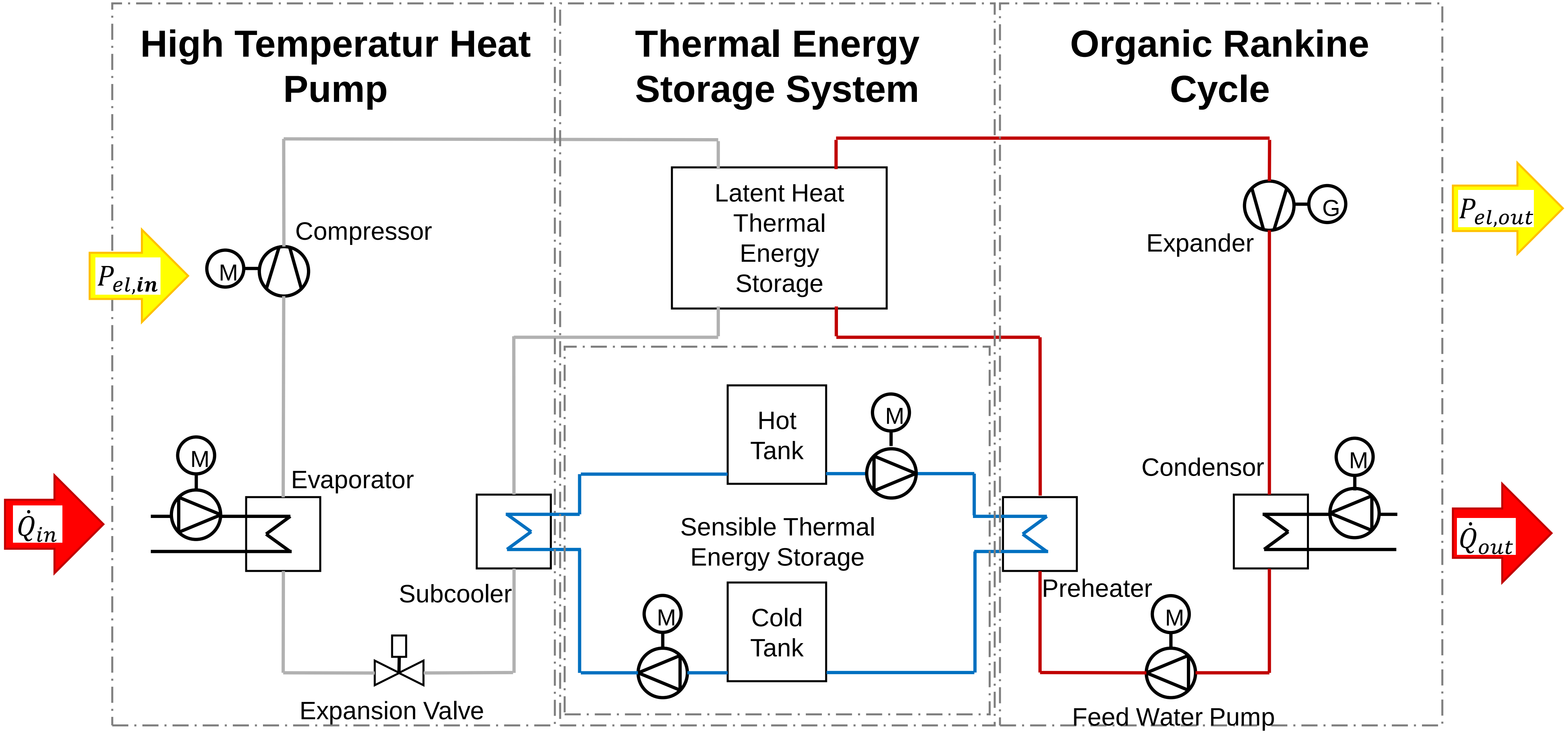
Advantage

- Nearly **Isothermal Conditions**

  → Suitable for steam supply e.g.:
  - for industrial processes or,
  - for Steam/Organic Rankine cycle to generate electricity

- High **Energy Density**

CHESTER - Simplified P&ID

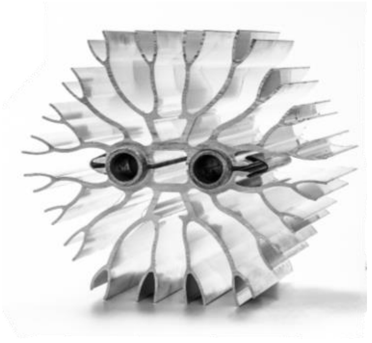


CHESTER – System Overview

High Temperature Heat Pump

- Refrigerant: R1233zd(E)
- Single piston type compressor
- Operating range:
  - Heat source: 70-100ºC
  - Heat sink: 100-150ºC
- Heating: 35 kW_{th} + 25 kW_{th} (cond. / subc.)
- Cond. temperature achieved: 148ºC
- Condenser is the latent heat storage

Combined Latent and Sensible Thermal Energy Storage System



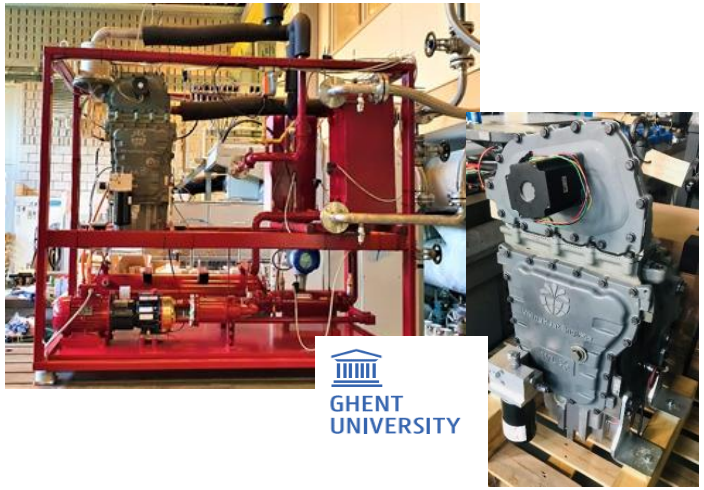
Latent heat-TES:

- Vertical shell-and-tube HX
- Dual-tubes with axial aluminum fins
- Storage capacity: 160 kWh @ 133 ºc
- $LiNO_3/KNO_3$ as storage material

Sensible heat-TES:

- Pressurized two-tank system with a hot and cold water tank
- Pre-heating/subcooling

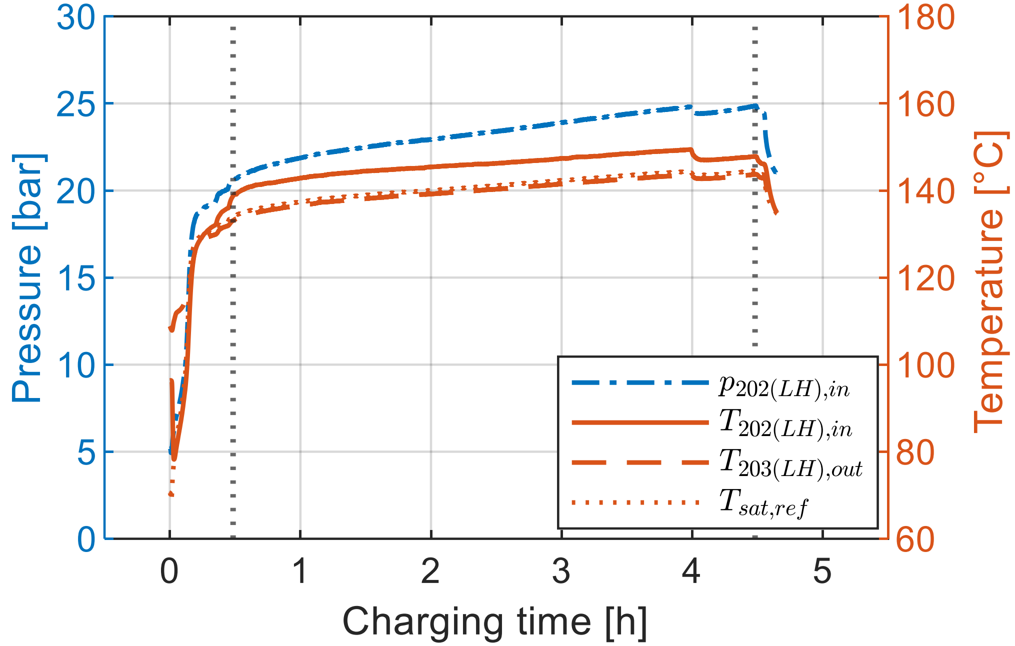
Organic Rankine Cycle

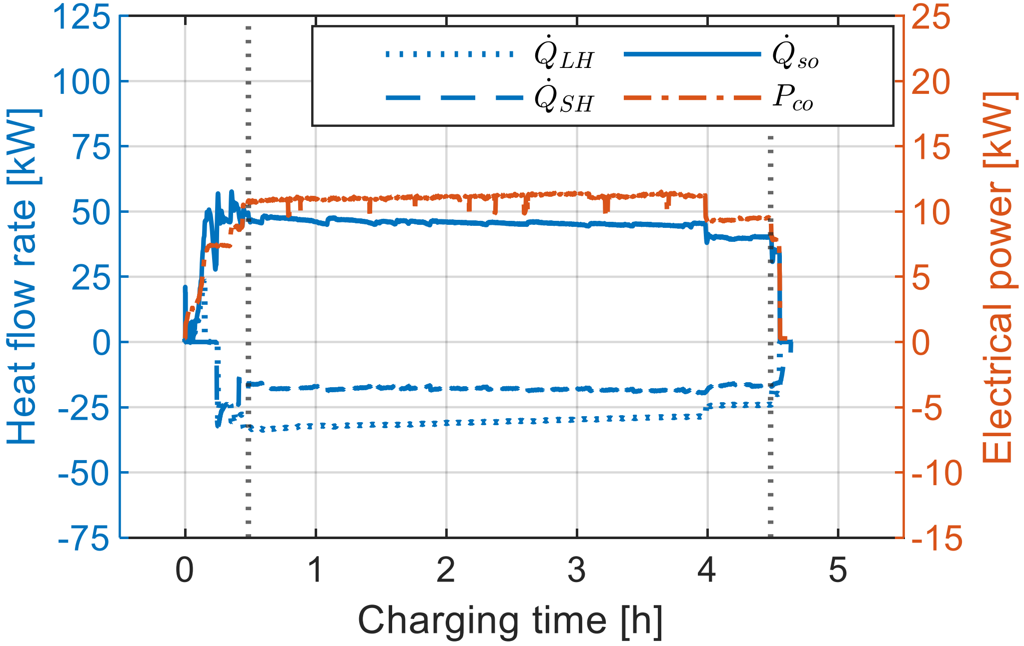


- Refrigerant: R1366mzz(E)
- Single piston expander – variable volume
- Operating range:
  - Heat source: 125 - 135ºC
  - Heat sink: 25 - 45ºC
- 10 kW_{el} nominal power output

High Temperature Heat Pump Operation

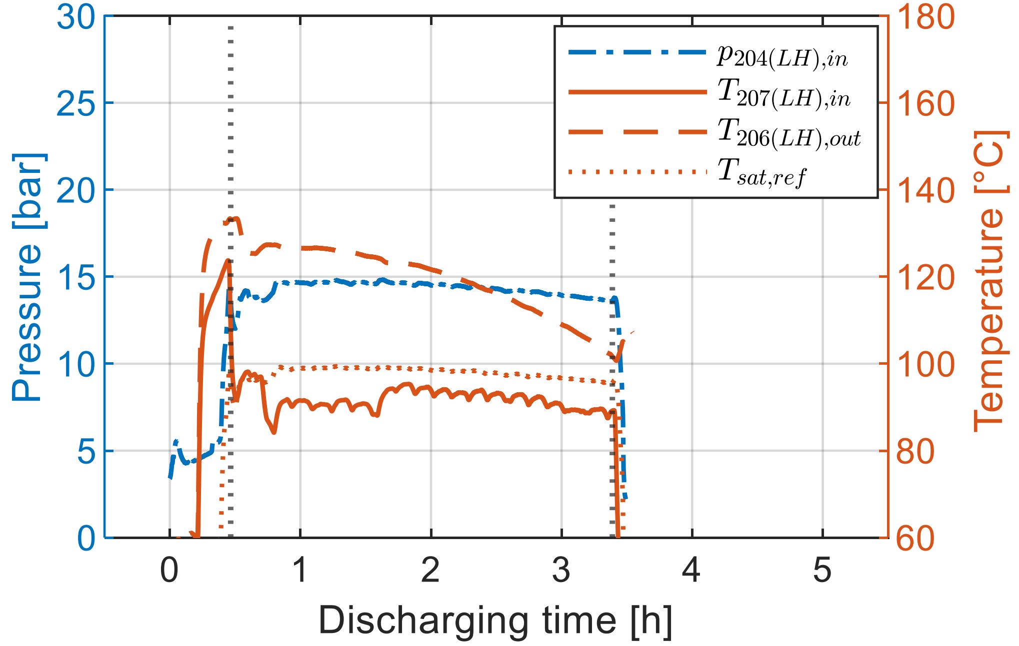
HTHP Operation at 28.06.2022

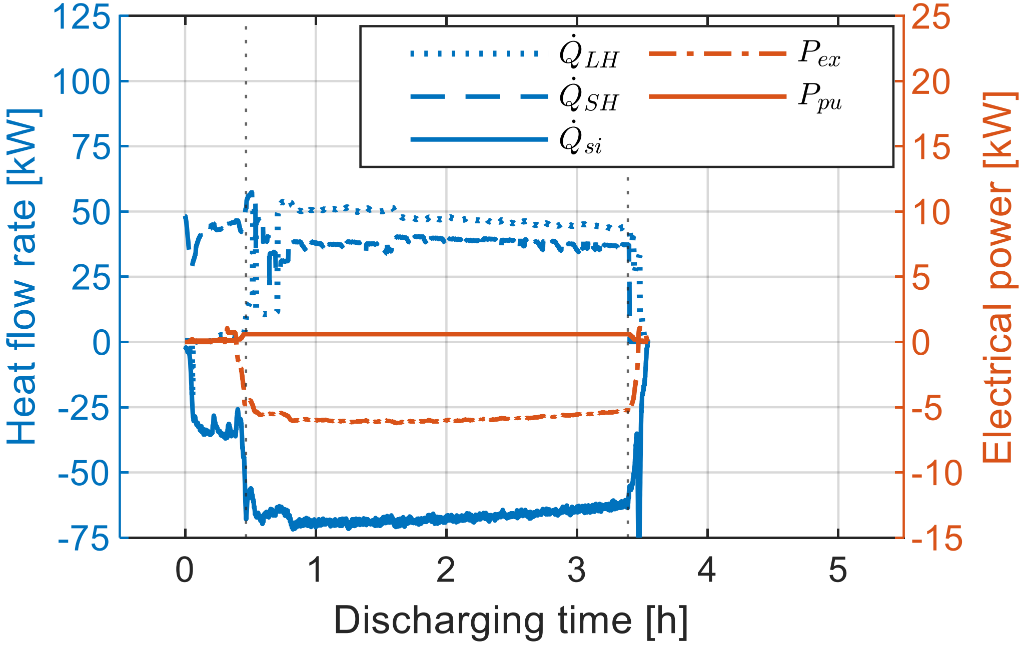




Organic Rankine Cycle Operation

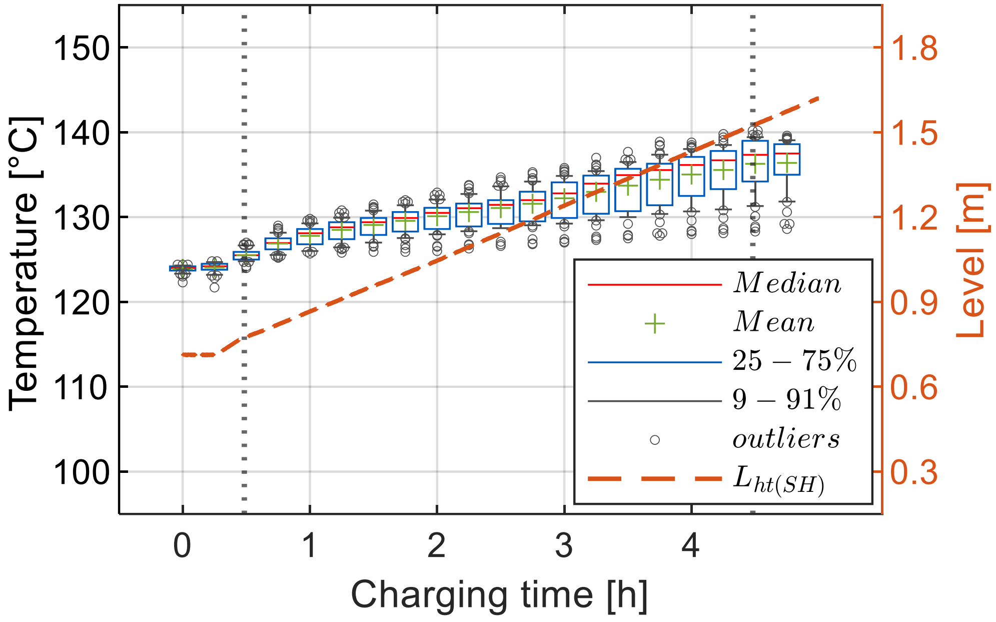
ORC Operation at 10.11.2022



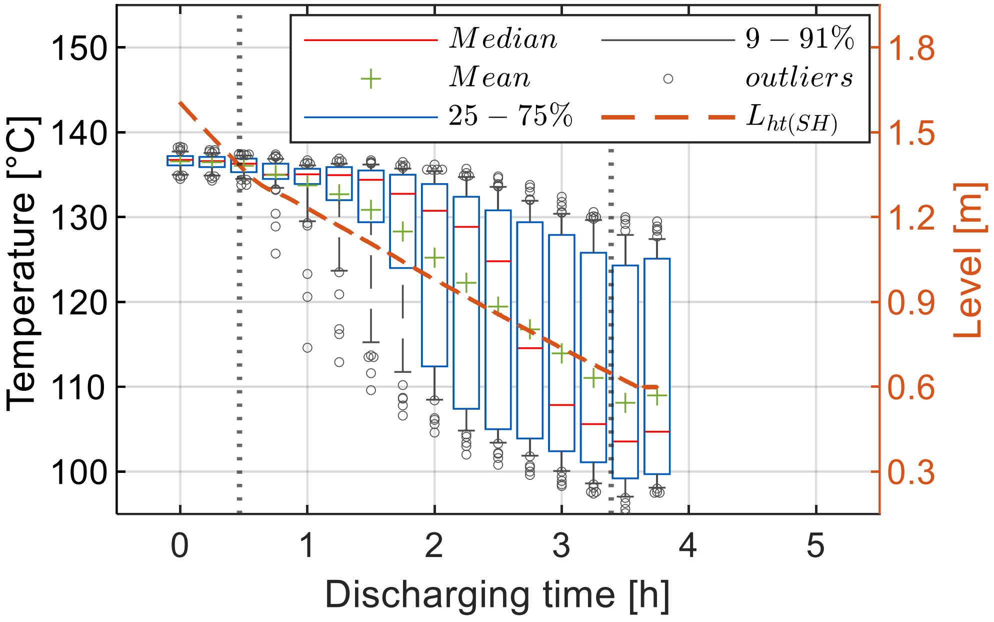


Temperature in Latent Heat Thermal Energy Storage

Charging



Discharging



Roundtrip efficiency

Steady state roundtrip efficiency between 18 % and 37 %

Possible Improvements:

- Improved thermal insulation
- Higher temperatures
- Decreased temperature differences

Rankine and Brayton Carnot Batteries

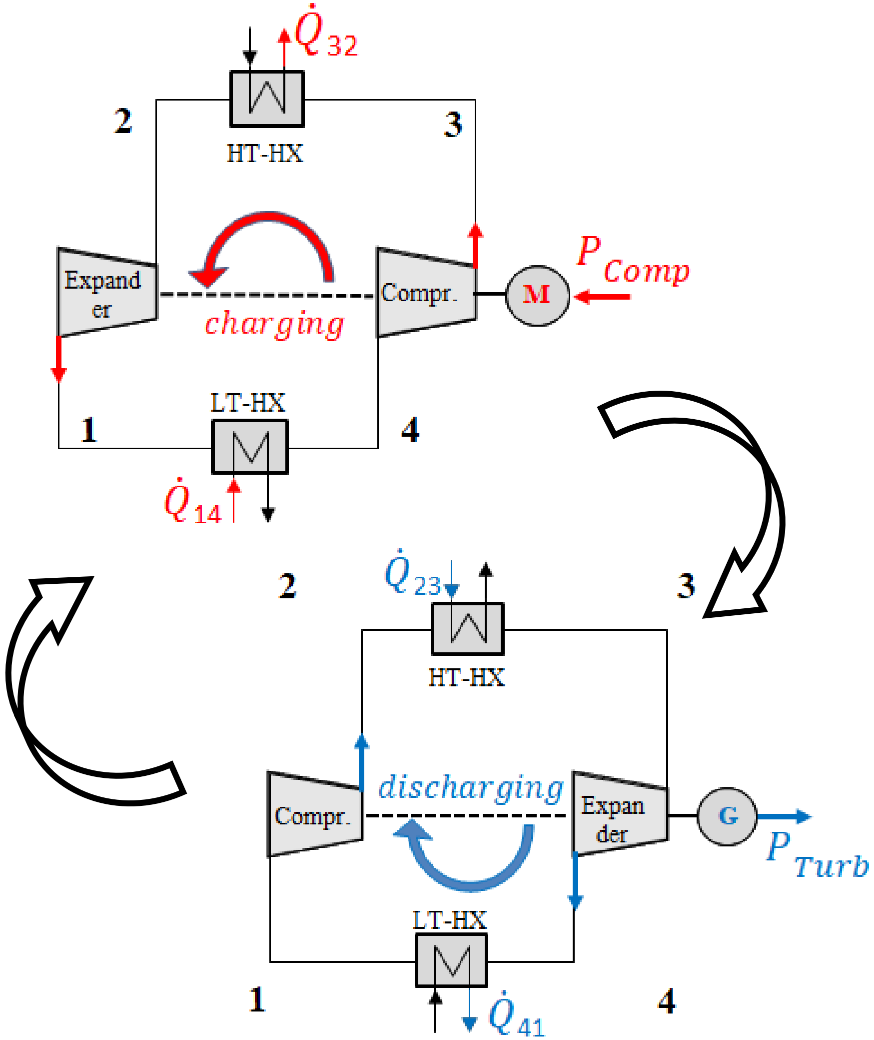
Rankine Cycle

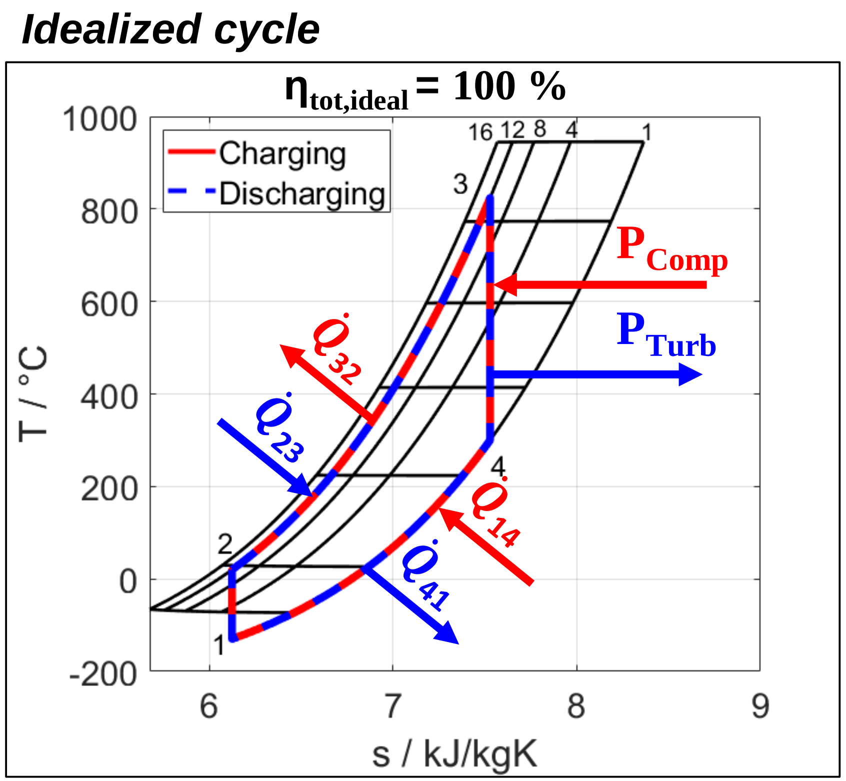
- Known from coal power plants and conventional heat pumps
- Working fluid conducts phase change from liquid to solid
- Higher power density
  - Useful also for smaller machinery

Brayton Cycle

- Known from gas turbines
- Only gaseous working fluid as air, argon, nitrogen, etc.
- Lower power density
  - Useful with large machinery

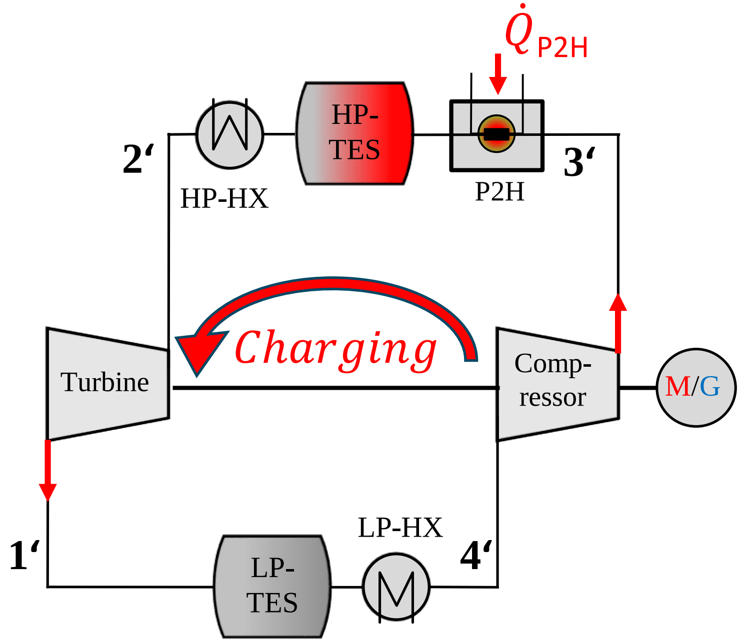
Brayton Carnot Battery
Working principle



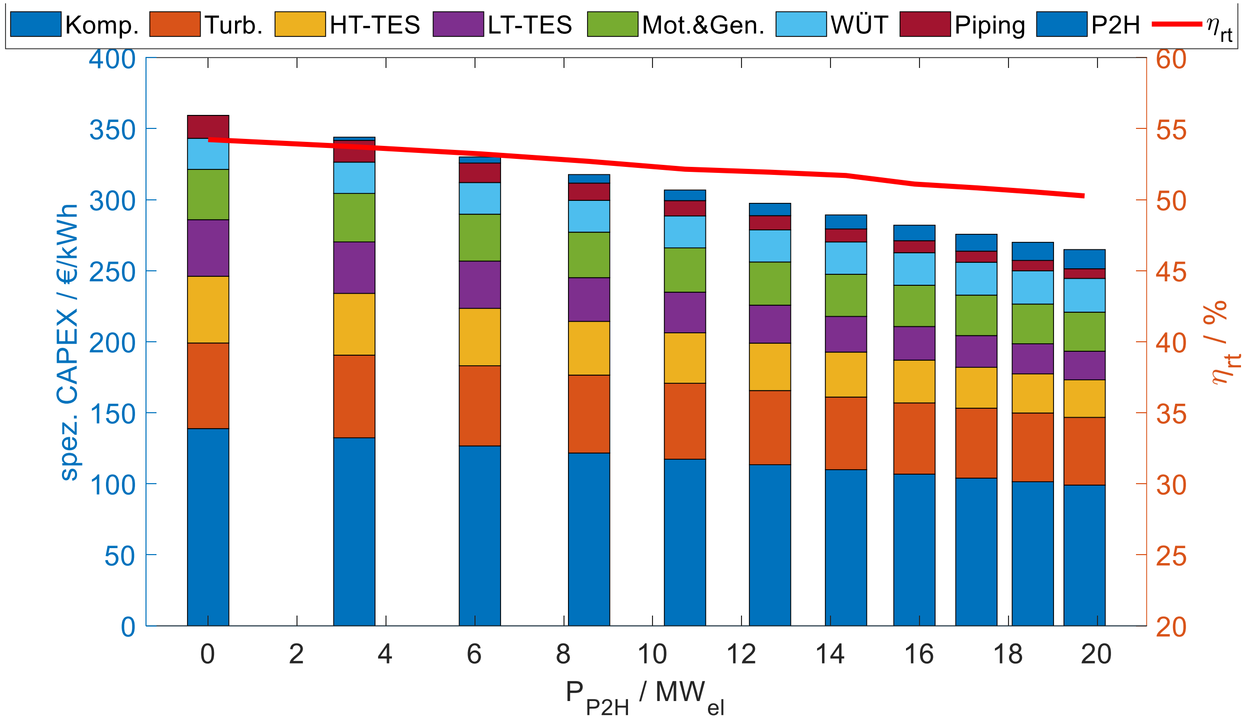


Power-to-heat integration in a Brayton Battery

Cost reduction through additional electrical heating capacity



Belik et al. Techno-economic evaluation of a Brayton Battery configuration with Power-to-Heat extension



Increased integration of electrical heating capacity (P2H) results in:

- Higher energy density for system
  → cost savings (CAPEX↓)
- Higher entropy production with higher losses
  → lower roundtrip efficiency

Impressum

Thema: Carnot-Battery research at DLR: from theory to demonstration

Date: 30.11.2023

Author: Jonas Tombrink, jonas.tombrink@dlr.de

Institute: German Aerospace Center (DLR), Institute of Engineering Thermodynamics

AVANCERET ENERGILAGRING

STATUS, STYRKER OG SYNERGIER FOR ENERGILAGRING I DANMARK VED DaCES

NIELS DYREBORG NIELSEN, DaCES

Dansk Center for Energilagring (DaCES)

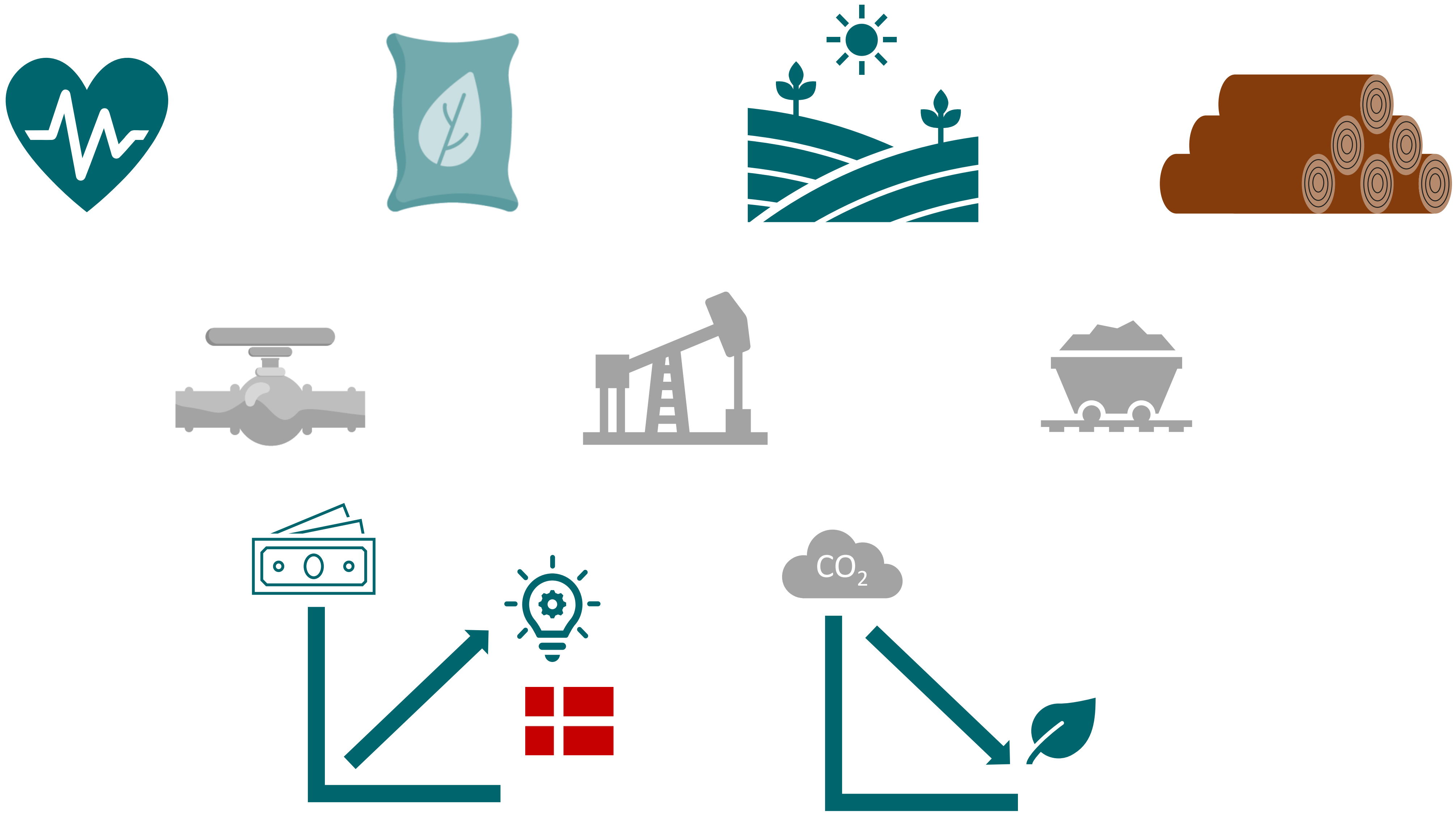
Teknisk chefkonsulent
Niels Dyreborg Nielsen

ndn@daces.dk

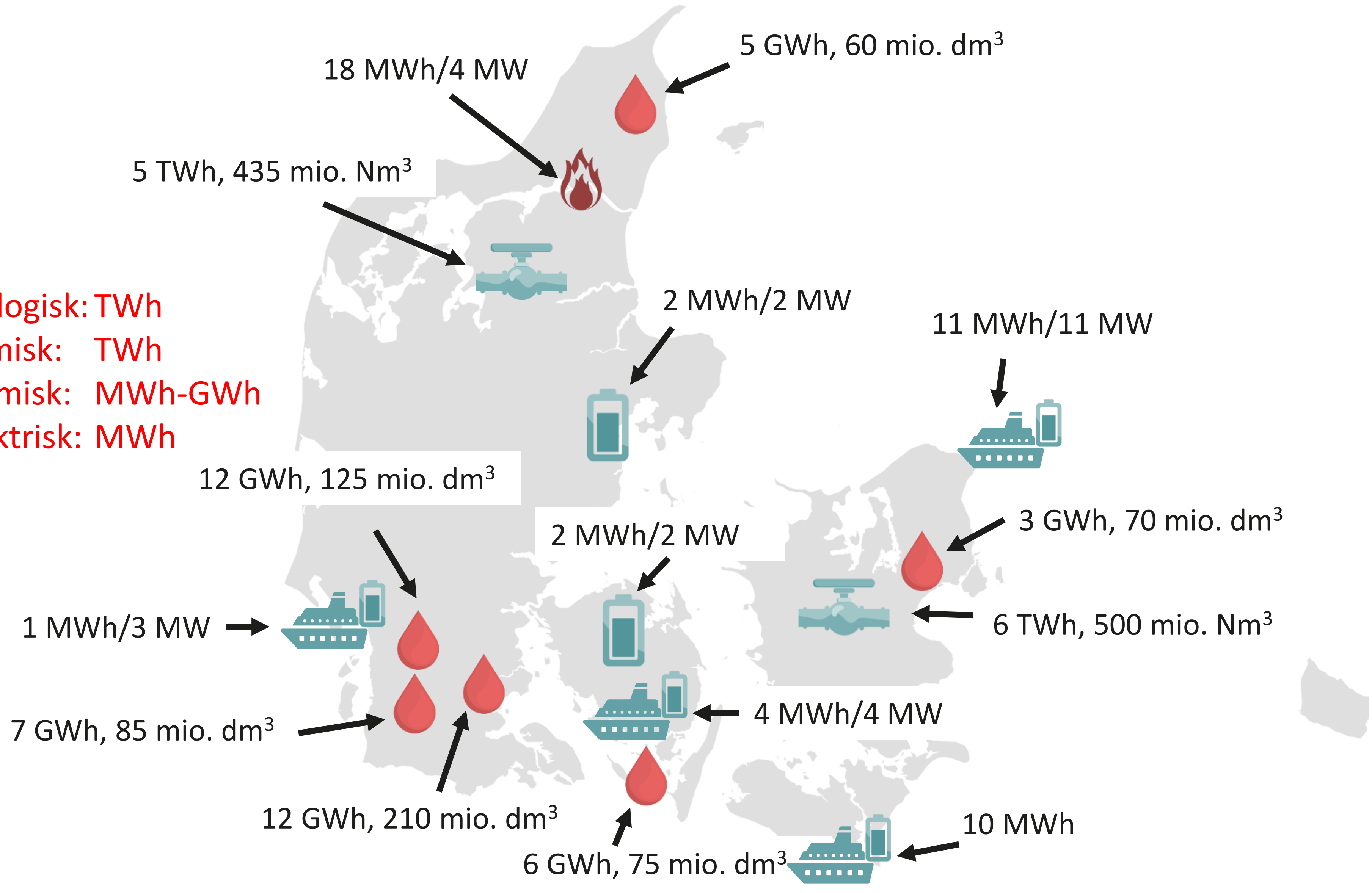
+45 51 70 56 08

DaCES
Danish Center for Energy Storage

Energilagring   Fortid – Nutid – Fremtid



Dansk overblik - Energilagring 2023



Biologisk: TWh
Kemisk: TWh
Termisk: MWh-GWh
Elektrisk: MWh

Projekter i 2024

EWII
Vejle 5x (3 MWh/3,5 MW)

Bornholm
43 MWh/30 MW

Molslinjen
Als 3 MWh/9 MW
Samsø 4 MWh/11 MW

Scandlines
Rødby 10 MWh/35 MW

Bornholm - 2LIPP
0,1 MWh/0,3 MW
0,7 MWh/0,2 MW
20 MWh/4,5 MWh

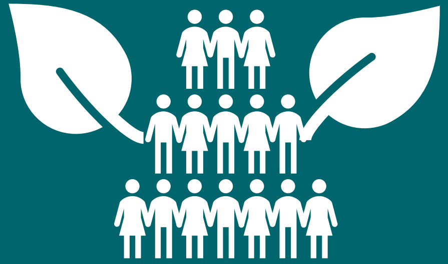
Dansk Center for Energilagring (DaCES)

4-Leaf Consulting – Engineering a Sustainable Future
andel
ATE
ATV – Danish Academy of Technical Sciences
AXCELFUTURE – ERHVERVSLIVETS TÆNKETANK
BATTMAN ENERGY
BIRR
Bitzer
Blue World Technologies
BORNHOLMS ENERGI & FORSYNING
brix.green
CBS
Clever
copenhagen atomics
COWI
Crossbridge ENERGY FREDERICIA
Dall Energy – NEW BIOMASS TECHNOLOGIES
DANISH GRAPHENE
Dansk Batteriselskab – Danish Battery Society
DTU – Technical University of Denmark
Dynelectro
EBO Consult A/S
energy CLUSTER DENMARK
EN2SAVE – www.en2save.dk
ESTECH
European Innovation Council
EXIDE TECHNOLOGIES
FOM TECHNOLOGIES
FORCE TECHNOLOGY
GEUS
GREEN HYDROGEN SYSTEMS
GreenLab
GREENROC MINING PLC
HELIAC
HYBRID GREENTECH – Energy Storage Intelligence
Hydrogen pro
HYDROGEN VALLEY
hyme
iBESS
INDUSTRIENS FOND
innocell
KØBENHAVNS UNIVERSITET
NERVE SMART SYSTEMS
NEXT CONSULT – POWER ENGINEERING
NIRAS
NORDIC ENERGY STORAGE
P2CC – POWER TO CLIMATE CHANGE
PlanEnergi
hlit
RAMBØLL
RESS
SAN Electro Heat
SANISPACES – BATTERY SOLUTIONS
SiOX
SDU – University of Southern Denmark
TEKNOLOGISK INSTITUT
TOPSOE
Vestas
visblue – energy in the flow
XOLTA
Ørsted
AALBORG UNIVERSITY DENMARK
AARHUS UNIVERSITY

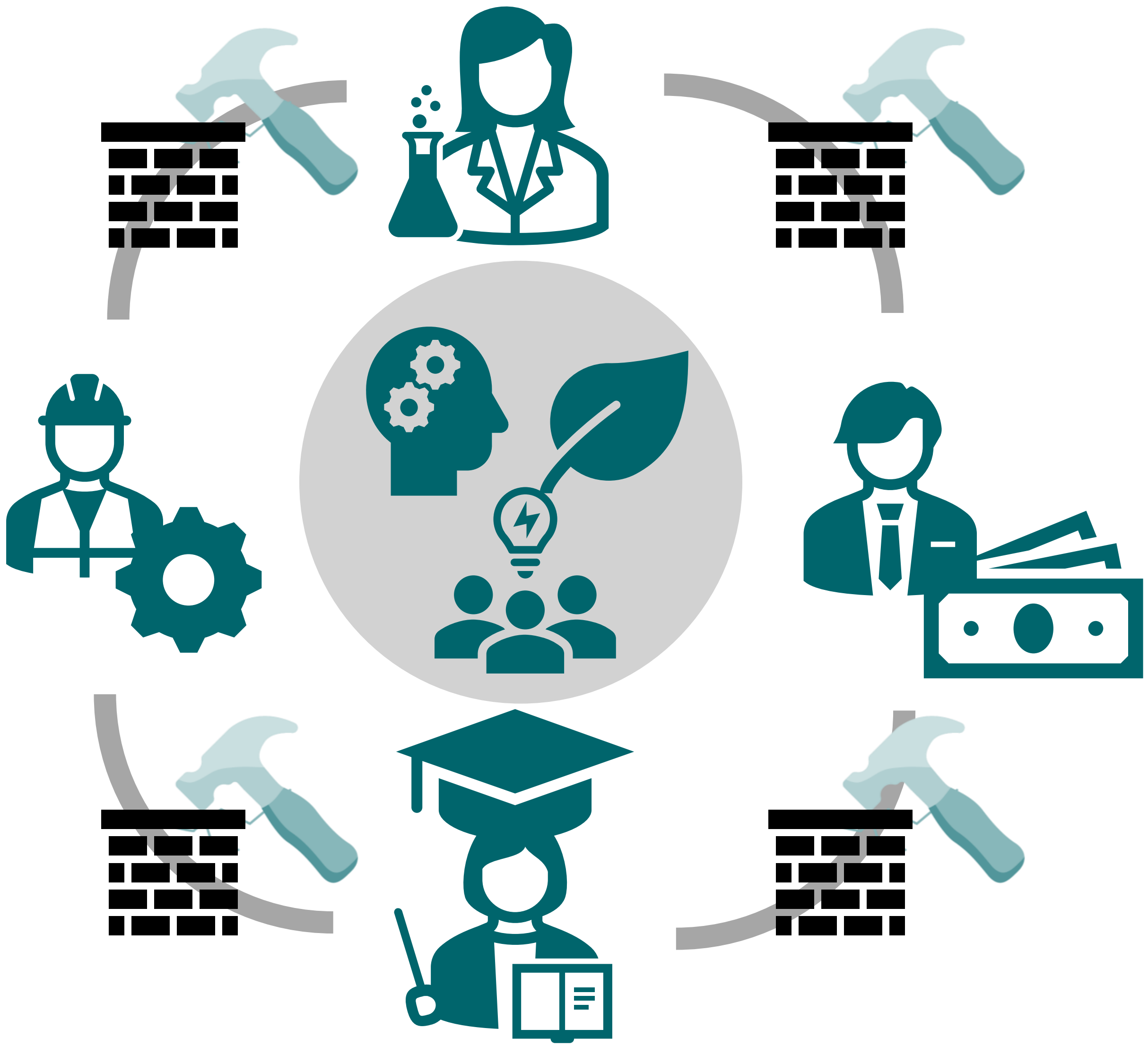
63 medlemmer

Arbejdsgrupper
- Batterier
- Termisk energilagring
- Power-to-X
- Systemintegration
- Uddannelse

Deltag
- www.daces.dk



Vores vision - Energilagring, en dansk styrkeposition!



DaCES aktiviteter 2023

Elektrisk skibsfart workshop

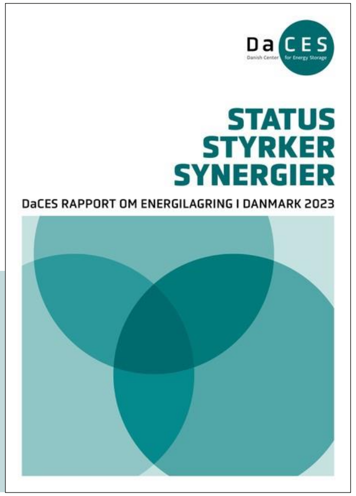
Industri workshop
Økonomi i energilagring
DTU Lyngby 20. marts, 2024

Besøg hos Heliac

DaCES årsdag

Besøg hos Topsoe

Fra tanke til udgivelse



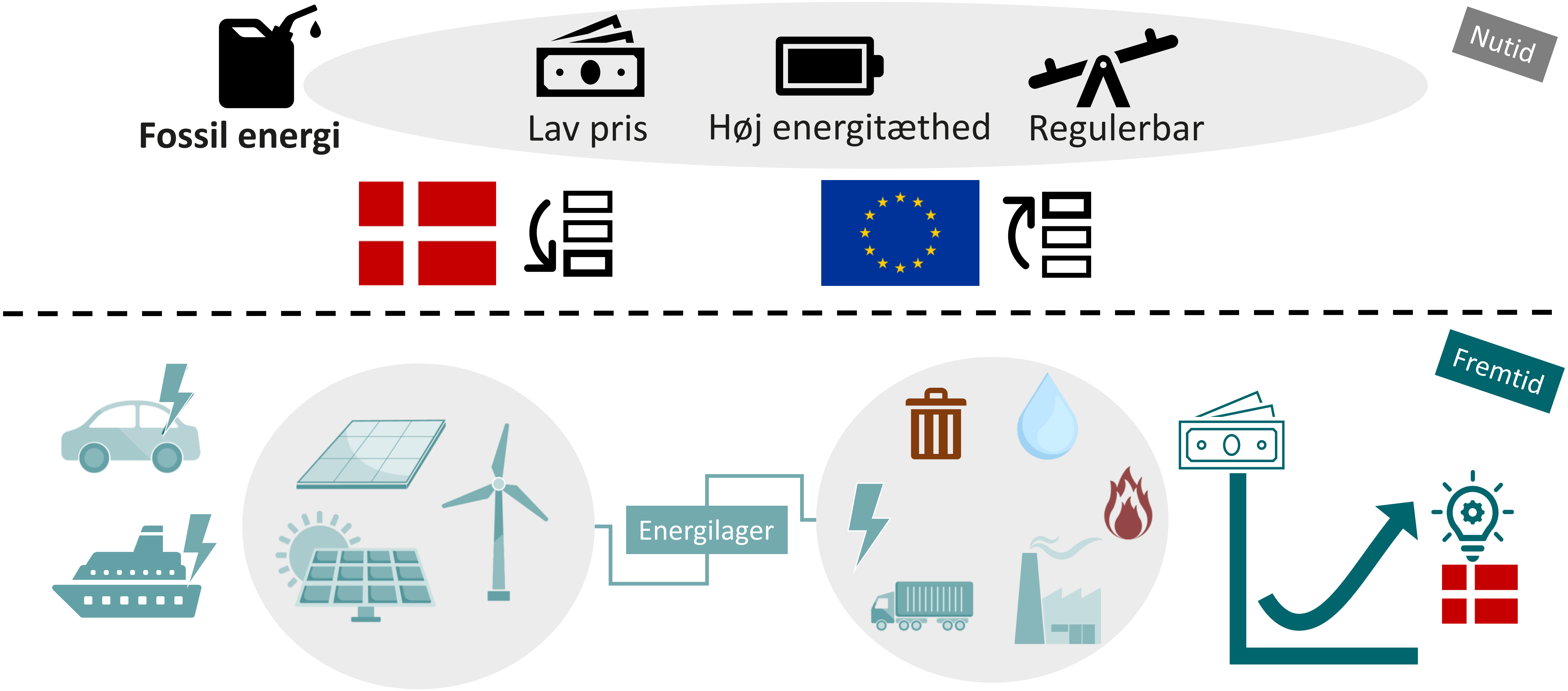
Indhold

Budskab

Metode

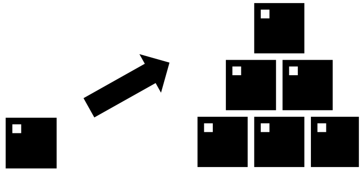
Målgruppe

Energilagring i Danmark – Historisk og potentiale



Termisk energilagring – Overblik

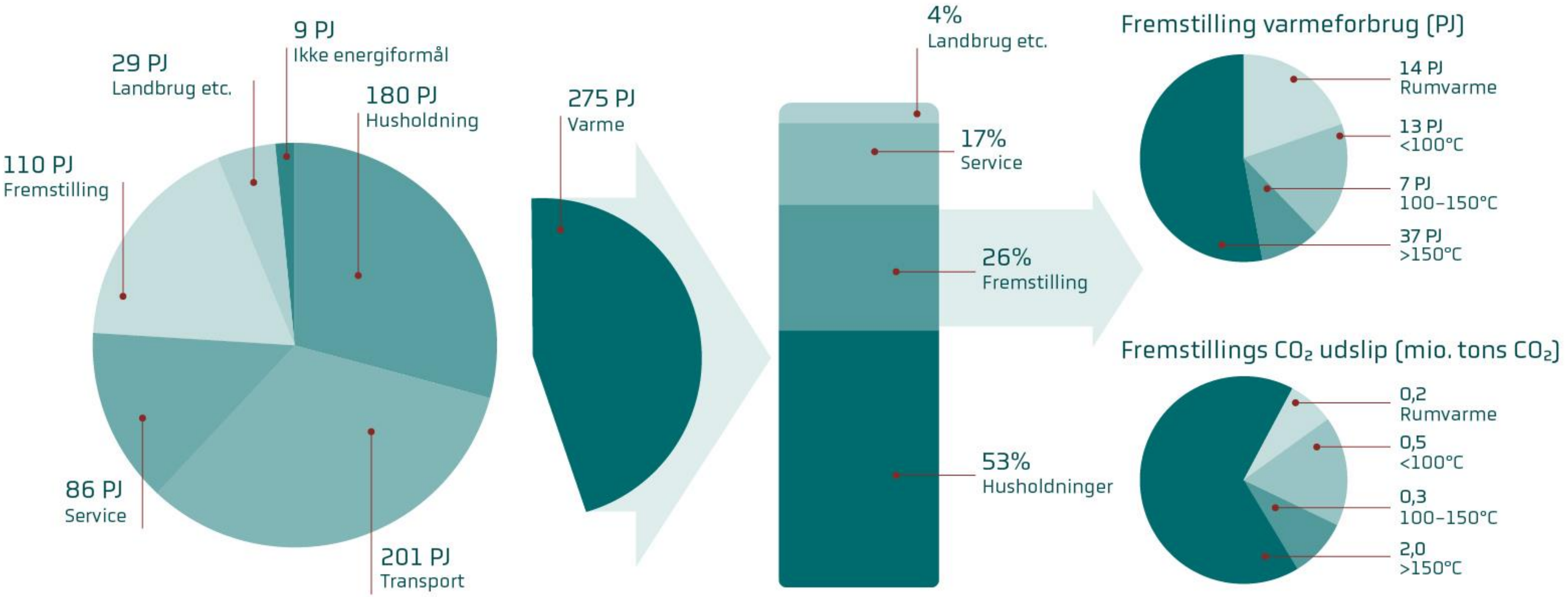
Termisk lagring Vand Olie Sten Salt …



Skalerbar >MWh >timer

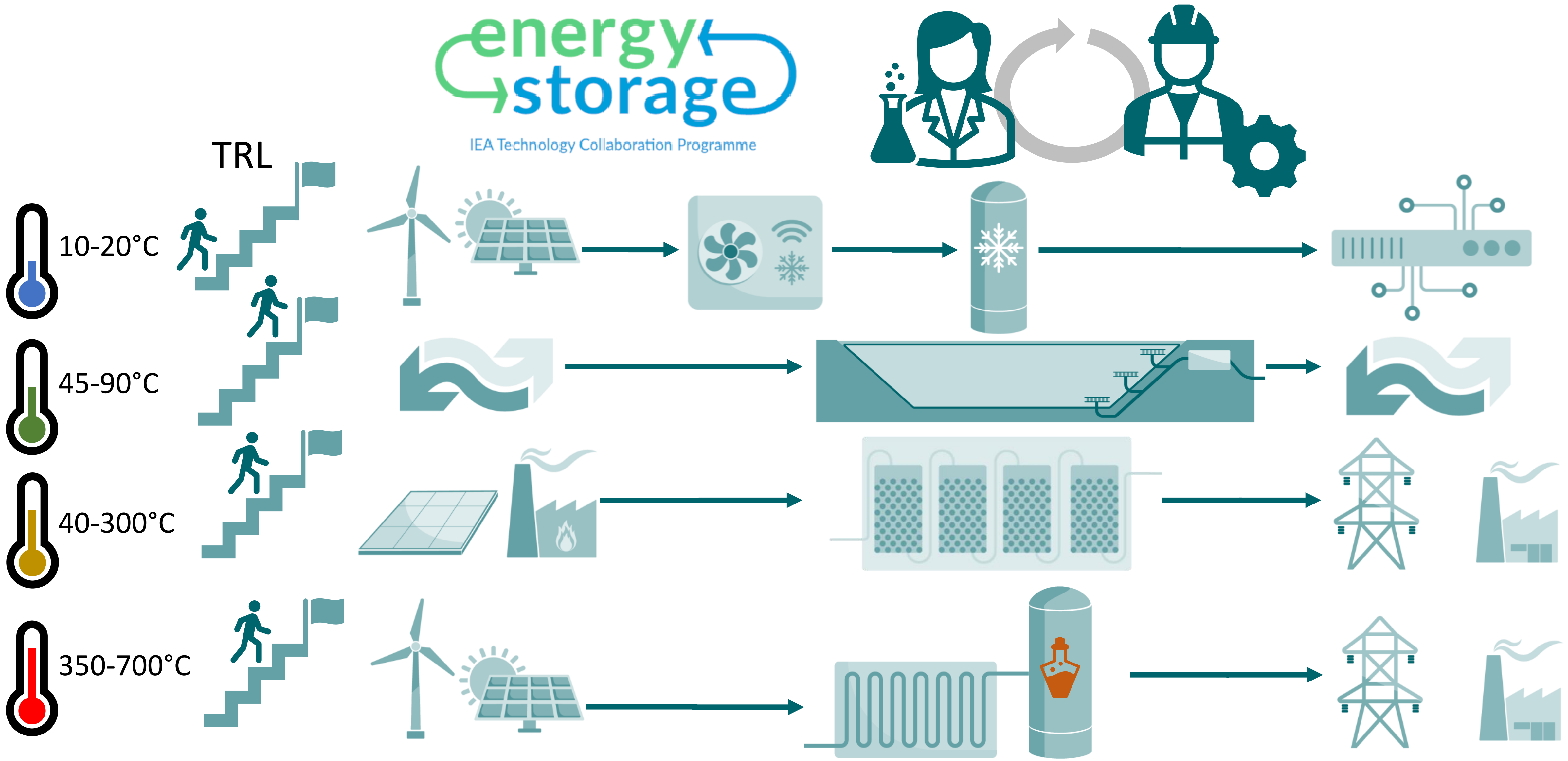
Miljøvenlig

Danmarks energiforbrug 2022 [1]



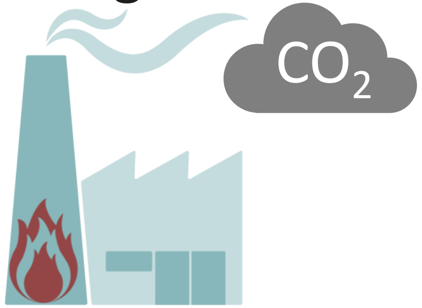
[1] Dataudtræk fra Energistyrelsen, udført juni 2023 for DaCES.

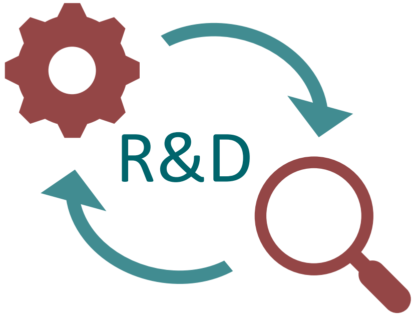
Termisk energilagring – Styrker



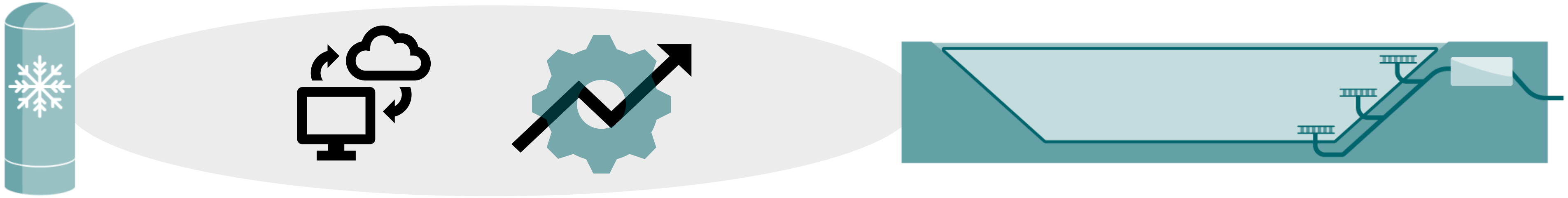
Termisk energilagring – Anbefalinger

1. Invester i udvikling af varmelagre over 100°C

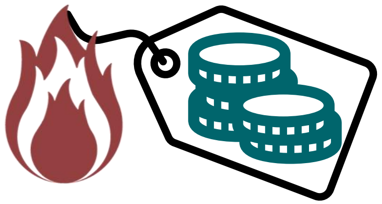




2. Støt optimering af fleksible varme- og kuldelagre under 100°C



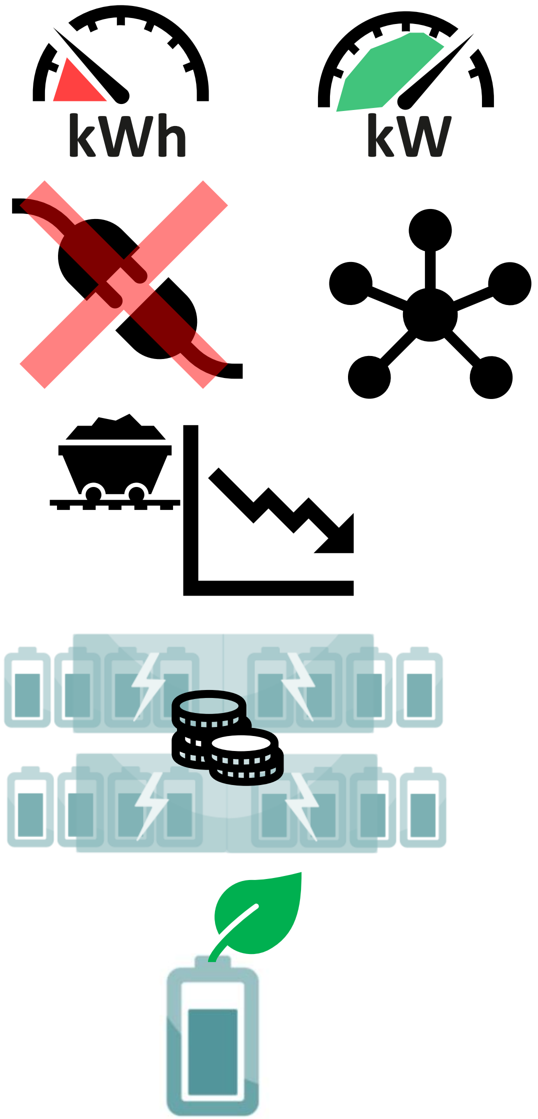
3. Fjern barrierer for overskudsvarme [2]



[2] DI Energi og Rambøll, 2022, Overskudsvarme. Overskudsvarmen er der – hvordan får vi den udnyttet.

Batterier – Overblik

- Energi og effekt
- Kompleksitet
- Råstof
- Storskala lagring urentabel (>MWh, >timer)
- EU: Grøn **nøgle**teknologi



Batterier – Styrker

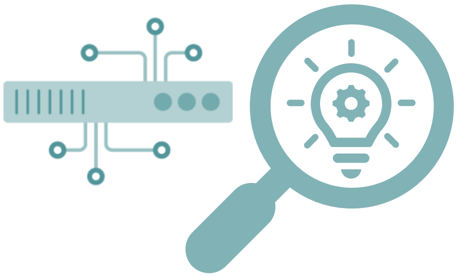
Da CES
Danish Center for Energy Storage

1. Materiale- og syntesekemi

2. Nye, sikre, bæredygtige batterier

3. Integrere batterier med VE

4. Karakterisere og sikkerhedsevaluere



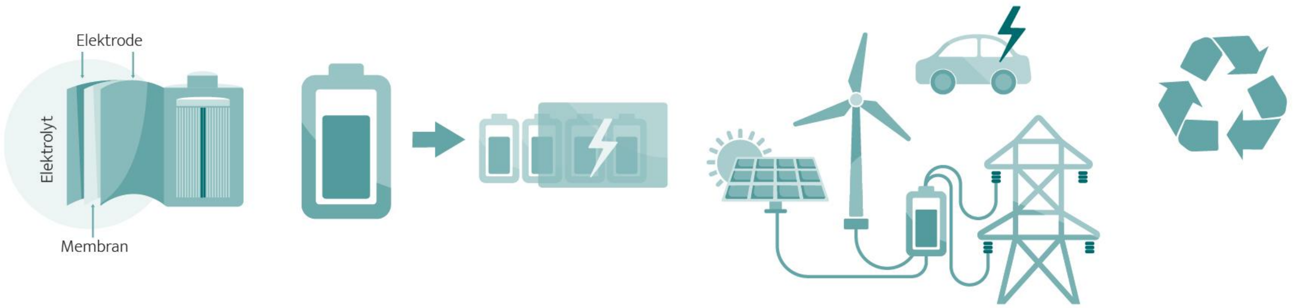
5. Opdage materialer vha. digitale værktøjer

Batteri policy brief

Batterier – Styrker dansk batteriværdikæde

RÅMATERIALER	FUNKTIONELLE MATERIALER	BATTERI-CELLE	BATTERI-PAKKE	APPLIKATION OG INTEGRATION	GENANVENDELSE OG SECOND LIFE

Malm af
- Nikkel
- Kobolt
- Litium
- Mangan
- Grafit



RÅMATERIALER	FUNKTIONELLE MATERIALER	BATTERI-CELLE	BATTERI-PAKKE	APPLIKATION OG INTEGRATION	GENANVENDELSE OG SECOND LIFE
KoBold Metals GEUS – De Nationale Geologiske Undersøgelser for Danmark og Grønland Bluejay mining plc GREENROC MINING PLC	DANISH GRAPHENE FOM TECHNOLOGIES RADISURF KOPPERS innocell TOPSOE visblue energy in the flow	innocell visblue energy in the flow	innocell visblue energy in the flow WS TECHNICALS XOLTA SANISPACES BATTERY SOLUTIONS	**INTEGRATION** Vestas MOLSLINJEN XOLTA Banke FORSEA MAERSK SUPPLY SERVICE SIEMENS Gamesa RENEWABLE ENERGY Midtjyske Jernbaner SANISPACES BATTERY SOLUTIONS **APPLIKATION** Vestas XOLTA Schneider Electric SANISPACES BATTERY SOLUTIONS NERVE SMART SYSTEMS Clever HYBRID GREENTECH iBESS VIKING WIND OK ABB	STENA RECYCLING

4-Leaf Consulting – Engineering a Sustainable Future

AALBORG UNIVERSITET

EBO Consult A/S

AARHUS UNIVERSITET

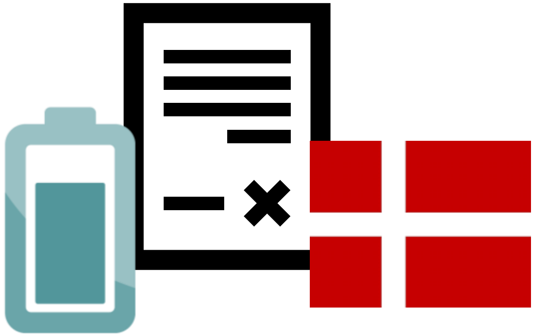
DTU – Technical University of Denmark

GEUS – De Nationale Geologiske Undersøgelser for Danmark og Grønland

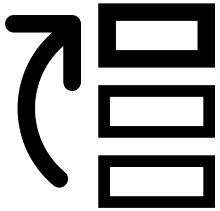
TEKNOLOGISK INSTITUT

SDU

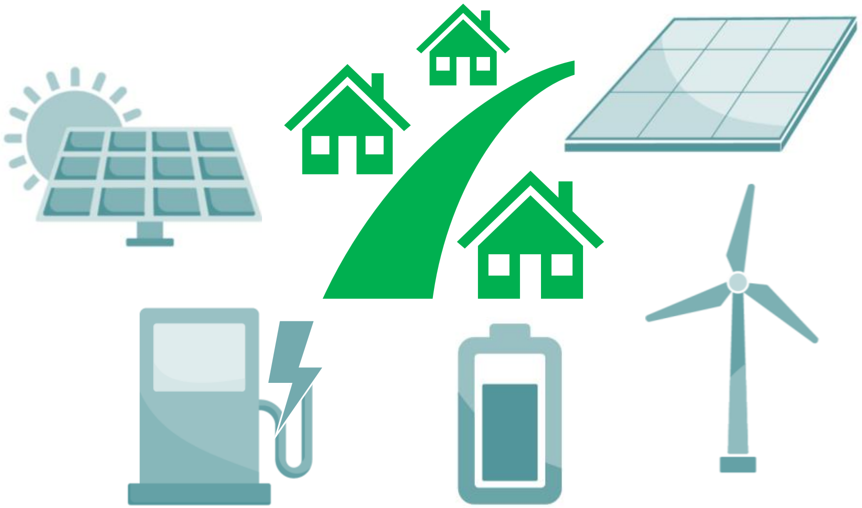
Batterier – Anbefalinger



1. National batteristrategi

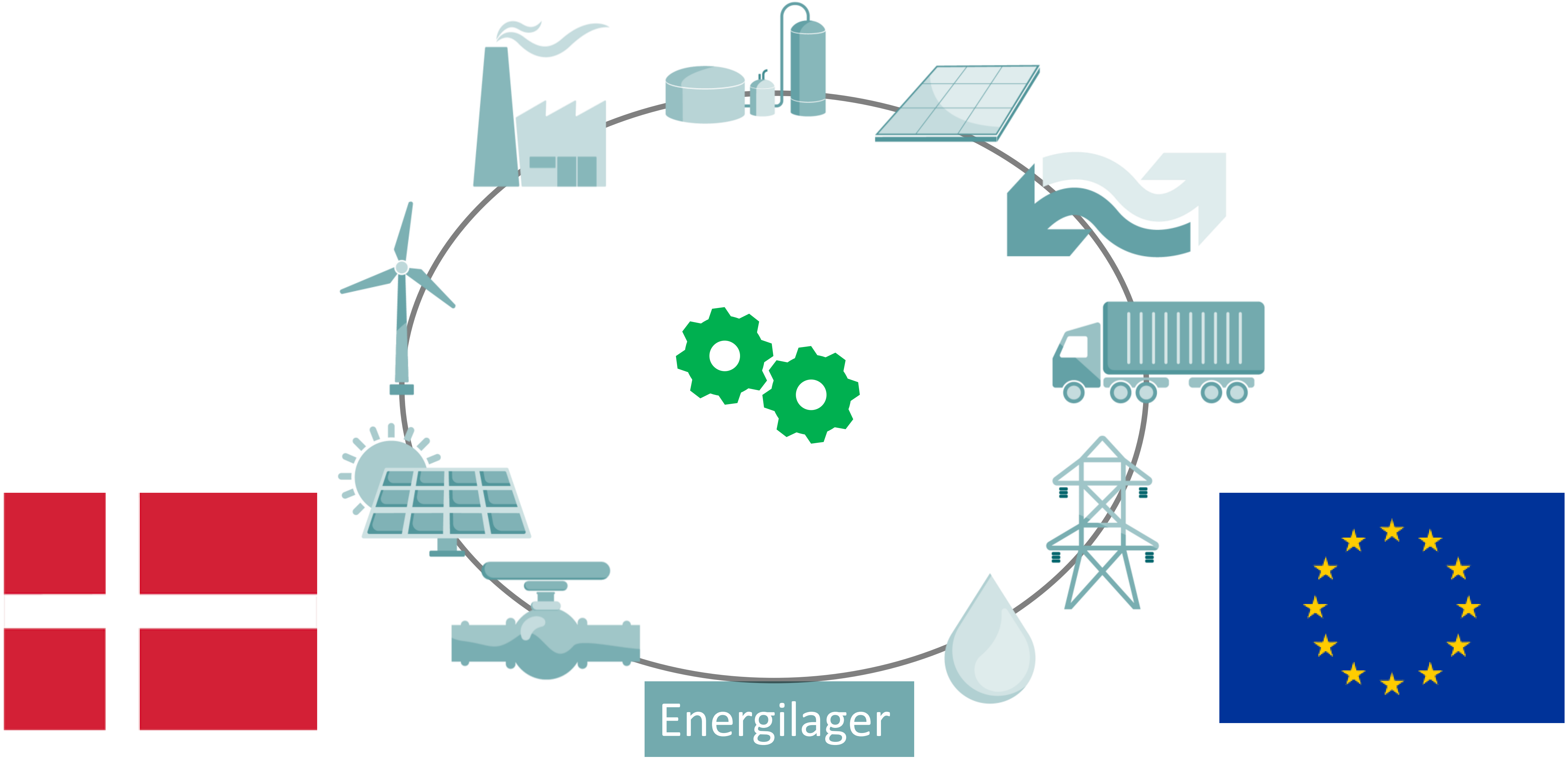


2. Prioriter energilagring inkl. batterier i bevillinger



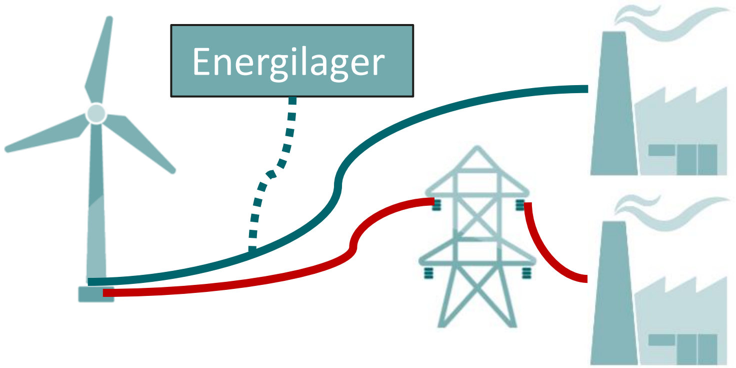
3. Skab vilkår for lokal, fleksibel VE-udnyttelse

Systemintegration – Overblik

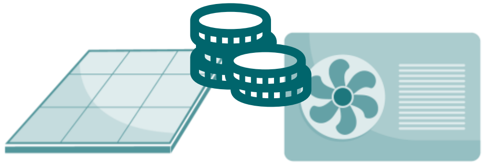


Systemintegration – Potentiale

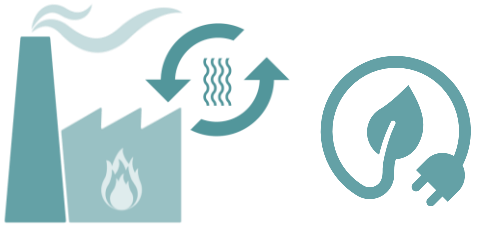
1. Fjern transport



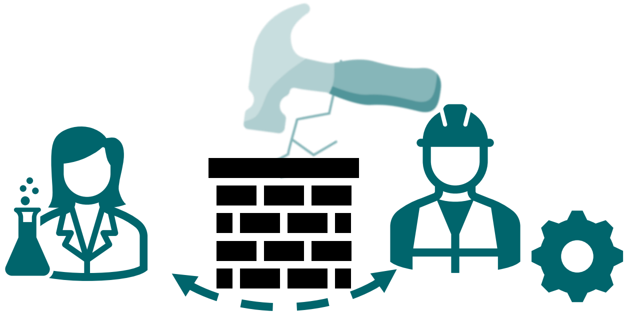
2. Gør energieffektive løsninger rentable



3. Restvarme og elektrificering med styringsværktøjer



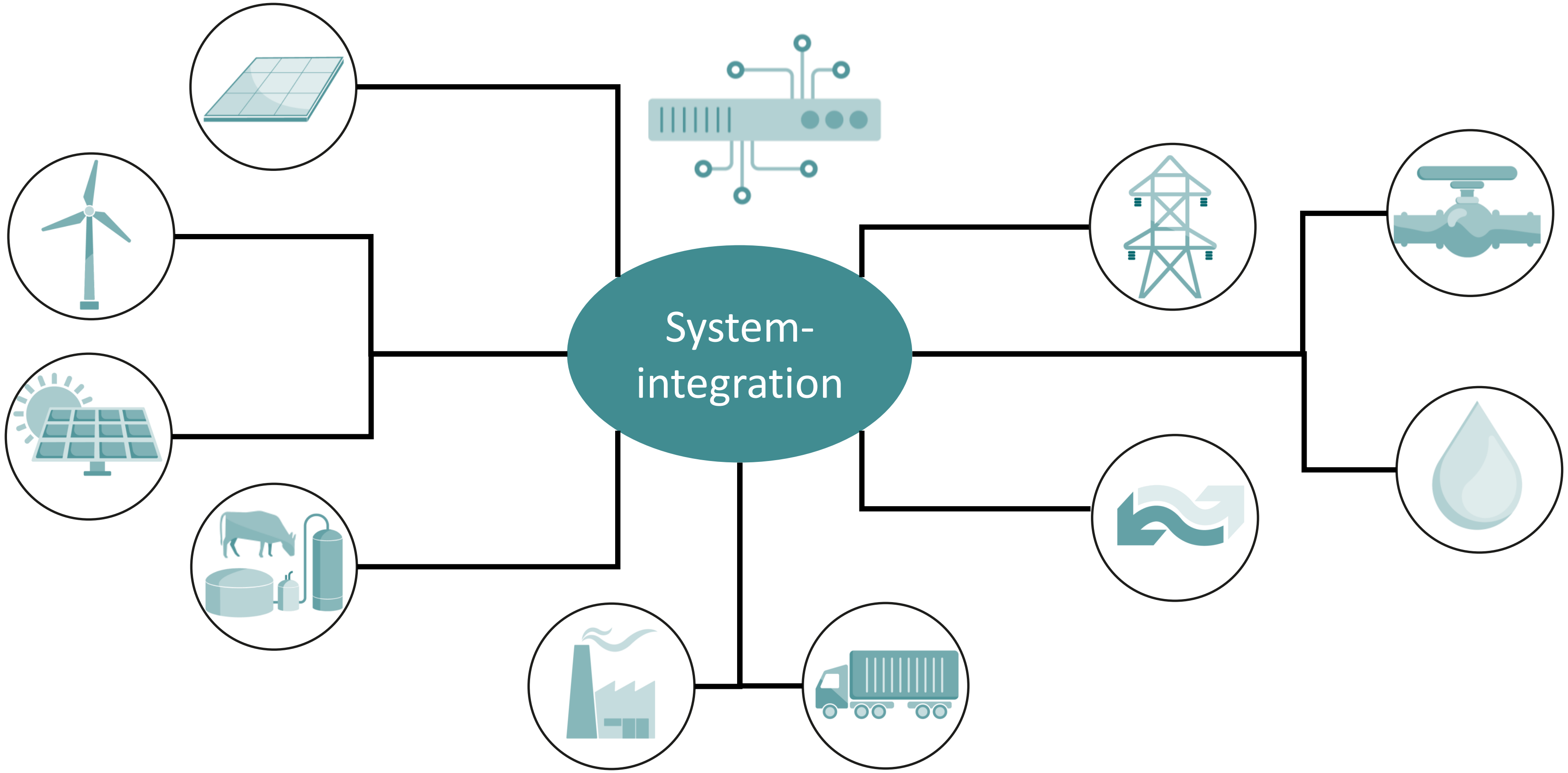
4. Fjern siloer – samarbejde og koordiner på tværs



Systemintegration – Styrker

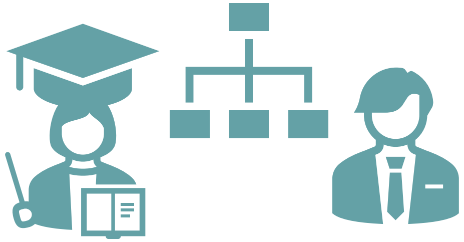
1. Samfundsøkonomisk modellering og optimering af energisystemer

2. Koble teknologier og energiinfrastruktur effektivt



Systemintegration – Anbefalinger

1. Udvikle og demonstrere systemintegrationsløsninger



2. Strategisk og koordineret energiplanlægning i Danmark

3. Tilpas løbende rammer for effektiv VE-integration

4. Opdater ENS’ katalog for energilagring

Spørgsmål – Feedback - Kontakt

Uden **energilagring**

Ingen omkostningseffektiv, forsyningssikker og grøn omstilling!

Kontakt

Bliv medlem

Niels Dyreborg Nielsen,
ndn@daces.dk
Teknisk chefkonsulent, DaCES

DaCES rapport 2023

AVANCERET ENERGILAGRING

ENERGILAGRING - HVORFOR ER DET INTERESSANT FOR ET KRAFTVARMEVÆRK?

JÖRGEN EDSTRÖM, BORNHOLMS ENERGI & FORSYNING (BEOF)

Energilagring - hvorfor er det interessant for et kraftvarmeværk?
BORNHOLMS ENERGI & FORSYNING
Jörgen Edström
30/11/2023

Fremtidens robuste elsystem

”Kraftvarmeværkerne bliver nogle gange glemt, men er også fremover et afgørende supplement til sol og vind, der kan fastholde Danmarks elforsyningssikkerhed i verdensklasse.”

Mogens Lykketoft og Jesper Frost Rasmussen, hhv. formand, Energinet Danmark og Dansk Fjernvarme.

FORRETNINGSOMRÅDE EL- OG VARMEPRODUKTION

Vi producerer el til det nordiske elmarked og varme til Rønne på et flisfyret kraftvarme-anlæg (Blok 6) på 35 MW.

Vi producerer el på vindkraft og ejer 1/3 af kapaciteten på Bornholm – i alt 12 vindmøller med en samlet kapacitet på 12,5 MW .

Vi sikrer Bornholms elforsyning i ø-drift efter aftale med Energinet. Det sker ved en række nødanlæg:

- 1 X Blok 5 oliekedel i alt 25 MW
- 4 x dieselmotorer – i alt 19,2 MW
- 10 x dieselmotorer – i alt 15 MW

BORNHOLMS ENERGI & FORSYNING

Hvad fokuserer BEOF på?

El- og varmeproduktion

- At udfase fossile brændsler ved normaldrift
- At undersøge muligheder for nye teknologier til produktion af el- og fjernvarme
- At vi fortsat er øens sikkerhedsnet ved behov for ø-drift
- At have en langsigtet plan i 2025 for reduktion af biomasse og indfasning af ny teknologi
- At fokusere på det fleksible elmarked og lagring – både på kort og lang sigt

BORNHOLMS ENERGI & FORSYNING

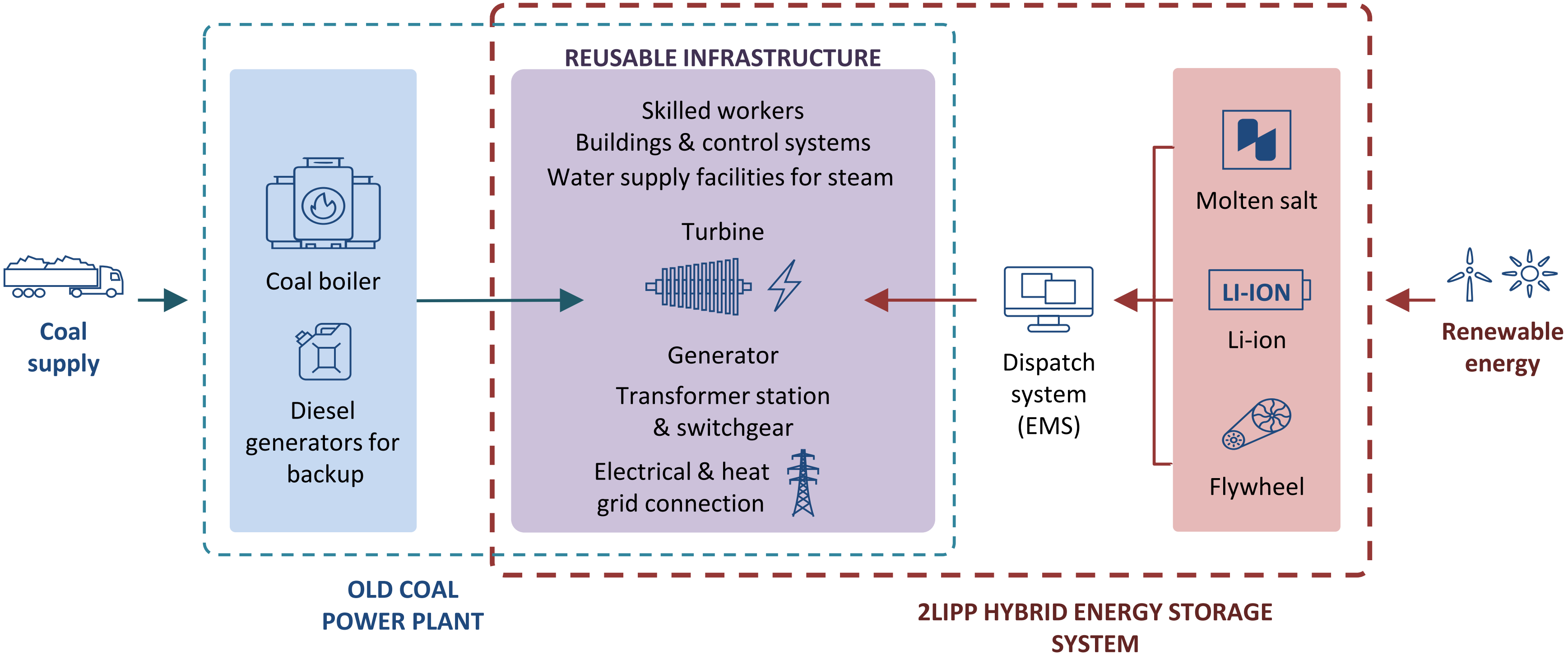
2LiPP Projektet

Demonstrationsanlæg på kraftvarmeværket i Rønne, som skal teste et hybridlager med en kombination af tre teknologier, der kan skabe fremtidens grønne kraftvarmeværk med fokus på genbrug af eksisterende infrastruktur.

Teknologierne er:

- Højtemperatur saltlager med dampturbine
- Batterilager bestående af brugte bilbatterier
- Højteknologisk svinghjul
- Energy Management System, som optimerer teknologierne ud mod el-markederne

2LiPP Concept



BORNHOLMS ENERGI & FORSYNING

Energilagring - hvorfor er det interessant for BEOF?

- Bornholm som testø

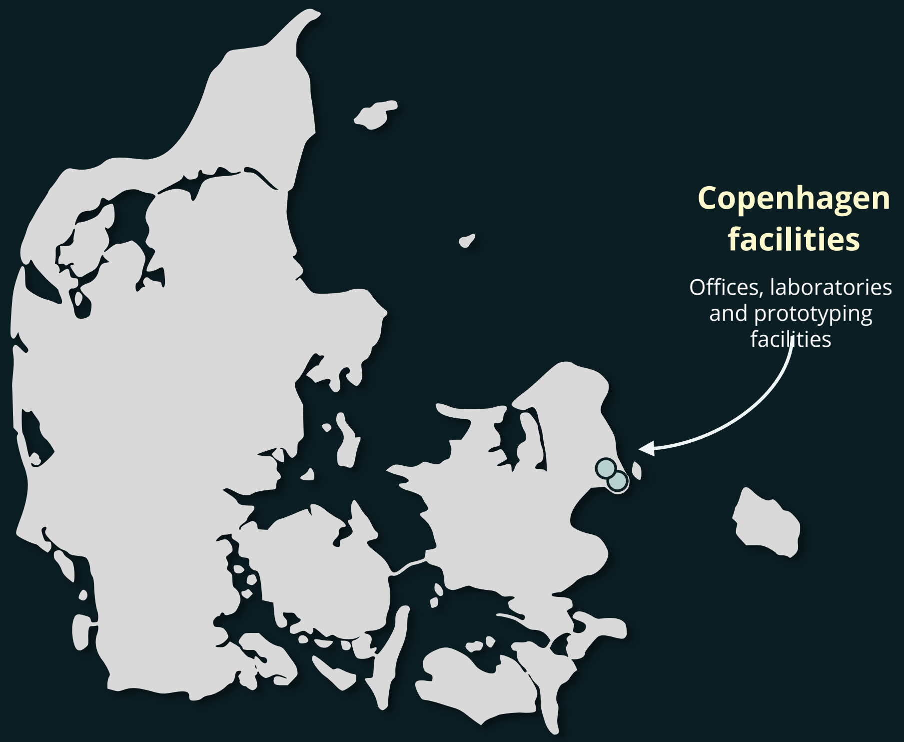
- Fremtidens grønne kraftvarmeværk
  - Produktion af el og varme
  - Fremtidens elmarked – balance og lagring
  - Arbejdspladser


AVANCERET
ENERGILAGRING
FOSSILFRI VARMEPRODUKTION TIL INDUSTRI
OG KRAFTVARME MED TERMISK ENERGILAGRING
NIS BENN, HYME

hyme

Sustainable. Available.

Make sustainable energy available. Always.



Titanhus Facilities

- Offices
- 330 m^2 molten salt laboratories

Amager Facilities

- Large scale salt components testing
- Prototyping

The Hymates team working on the mission

+30 headcount

15+ nationalities

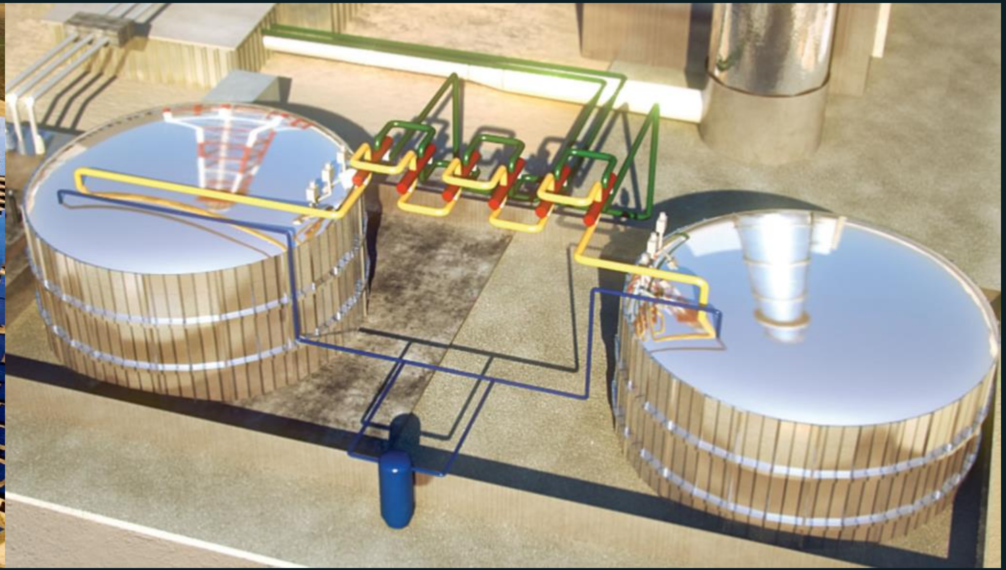
~33% female staff

Ages from 23 – 68

Why molten salts?

Molten salts are generally

- Good at storing heat = high energy density
- Good at transporting heat = high thermal conductivity
- Liquid at high temperatures with low vapour pressure = easy and safe to operate
- Abundant = quite cheap and no supply chain problems
- High technological readiness



Why hydroxide salts?

Truly sustainable | Abundant material, sustainably made from salt water, no reliance on critical raw materials

Superior properties | Excellent thermophysical properties results in very high energy density and best-in-class heat transfer

Inexpensive | Cheapest of all molten salt candidates

15-30 % plant CAPEX reductions possible

Clean and safe | Non-toxic, non-flammable and low pressure

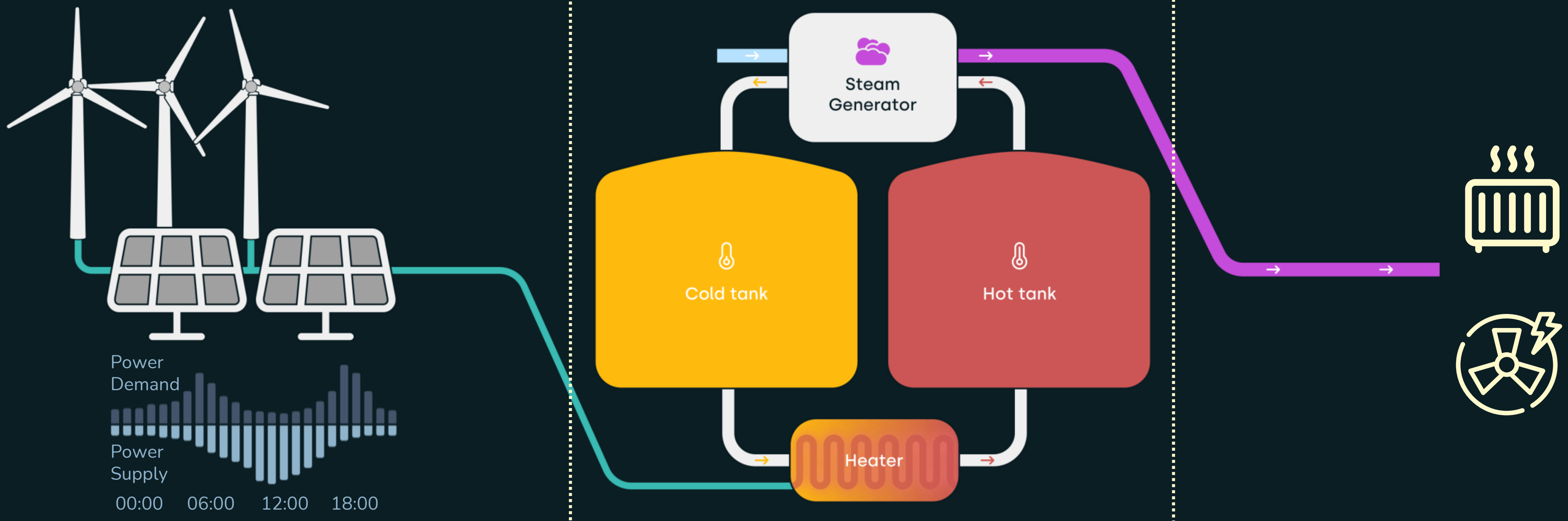
Standard environmental approval

How Hyme turns power into on-demand power and heat

Charge from grid or renewables

Hyme patented solution

Decarbonizes industry and utilities and strengthens the energy system



- Charge to full capacity in 6-8 hours

- From 50 MWh to 1 GWh in a single, hot tank.
- Autonomous operations from heaters to steam generator

- Up to +24-hours constant steam-discharge at high volume and constant temperature.

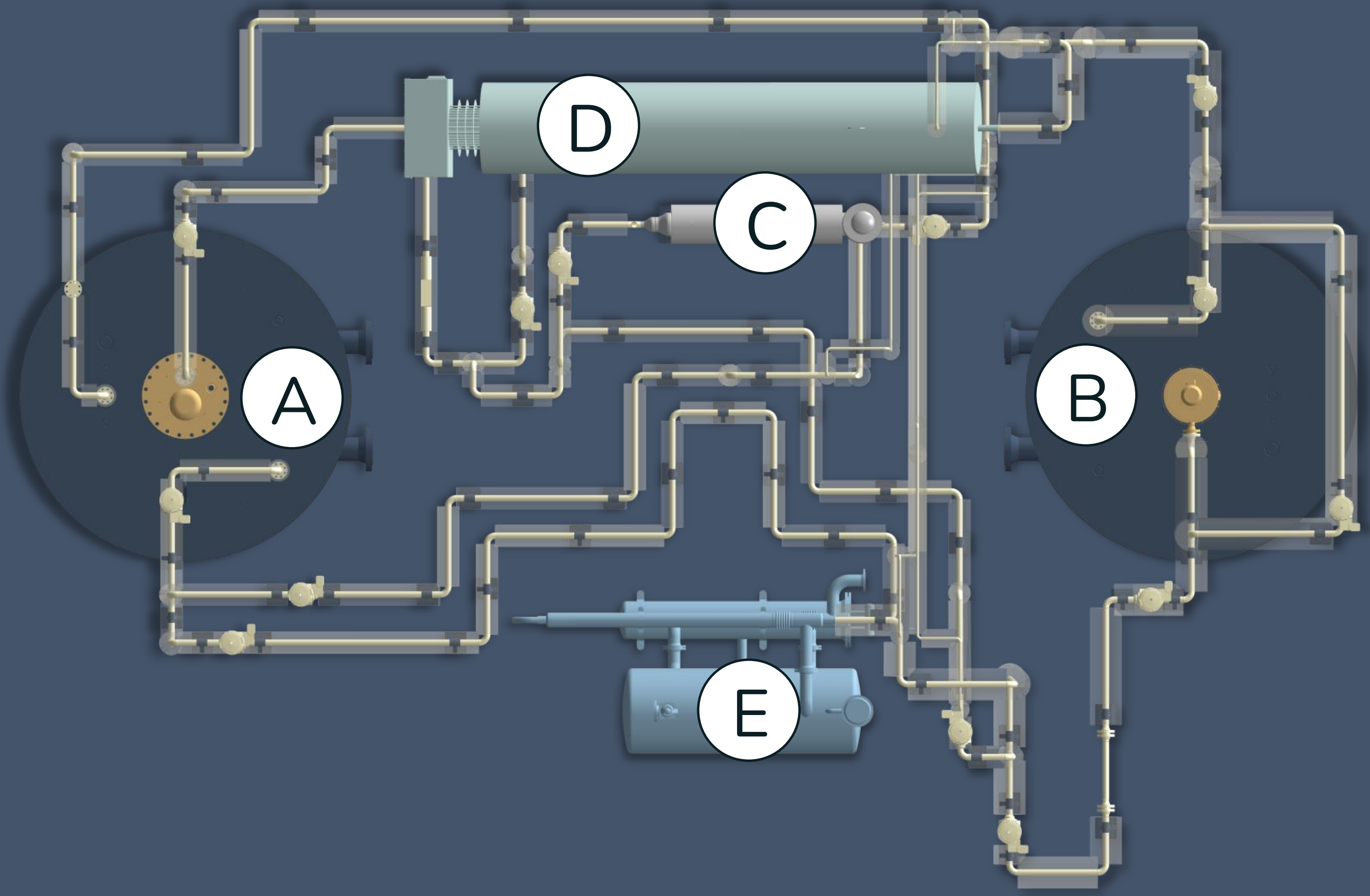
From technology to product – step 1

The world's first hydroxide molten salt energy storage plant

MOSS project implemented with partners.

The main components

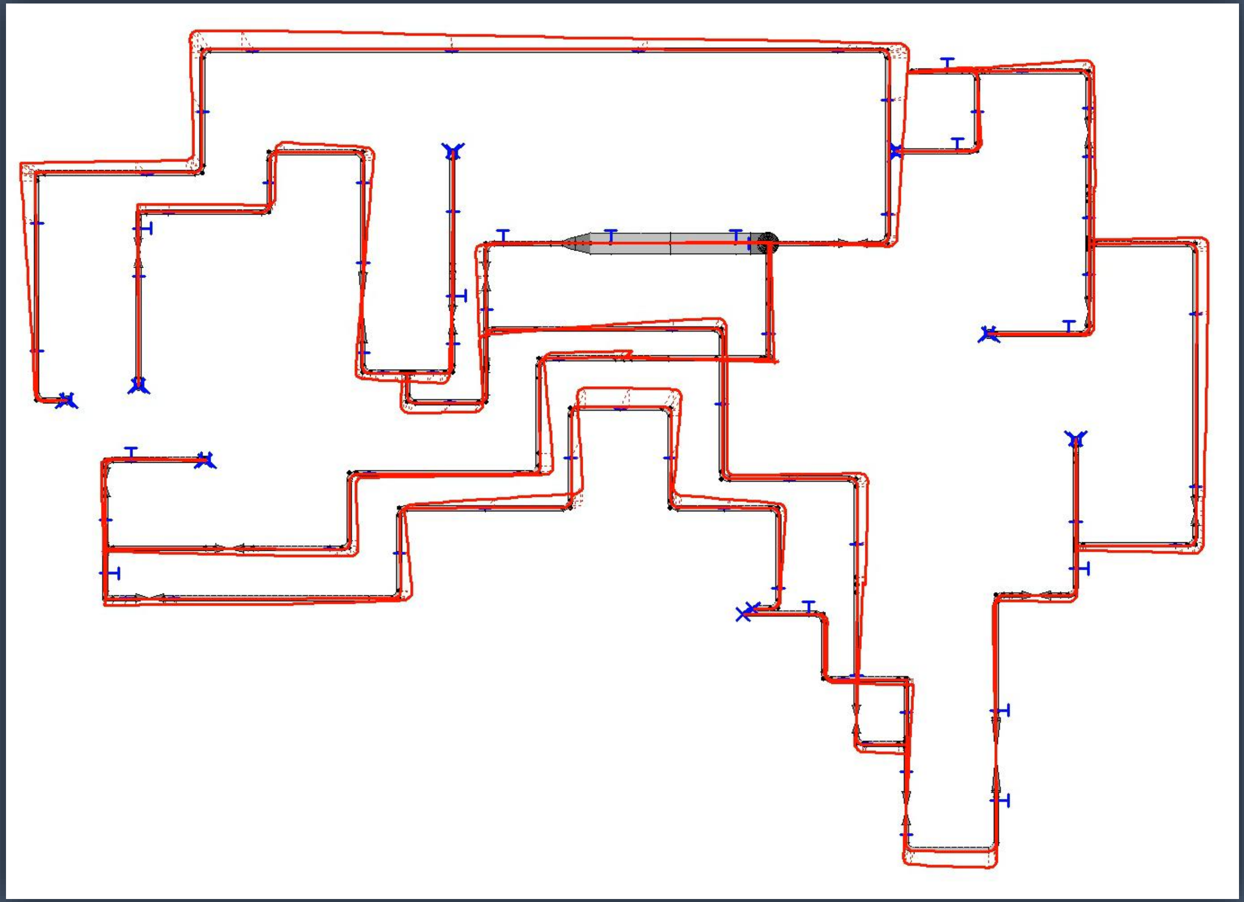
- A: Cold tank
- B: Hot tank
- C: CCU
- D: Electric heater
- E: Steam generator



One example of a challenge

Pipe stress calculation

- Thermal expansion of pipes when heated from 15°C to 650°C
- Expansion is approximately 10 mm/m at this ΔT
- Fixed at connections to equipment
- Animation is exaggerated x 5

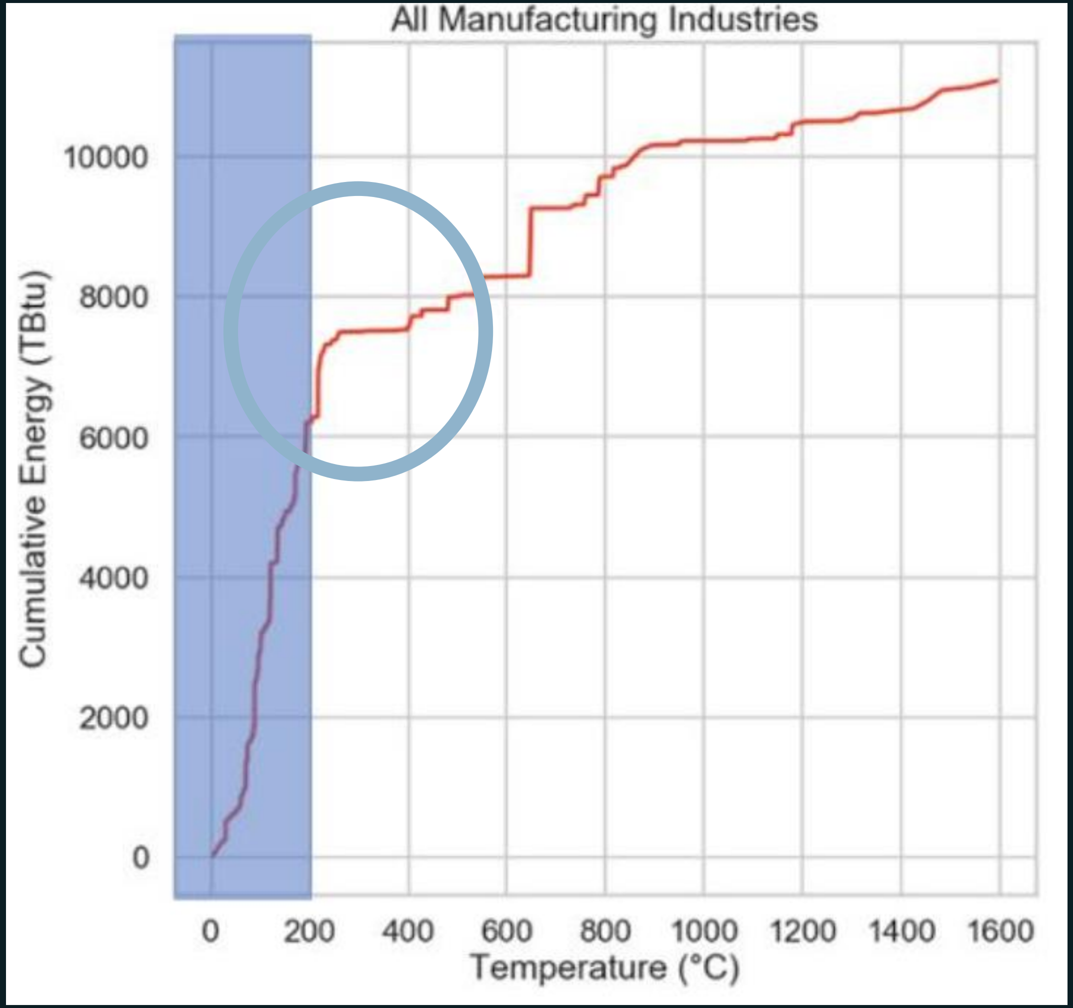


Hyme plant 1.0

Hyme delivers value to two distinct customer segments

Customer segment	Main use-case	Application
Industrial process heat 	Delivering green, high temperature heat on demand by replacing fossil enabled heat	• Chemicals and petrochemicals • Paper, pulp and print • Food and beverages

Industrial process heat



50 °C 160/200 °C

Heat pumps

100 °C ~300 °C

Electric boiler

160 °C 250 °C

Hyme – steam after cogeneration

200/250 °C 585 °C

Hyme - direct steam

Case illustration:
Large scale industrial heat for dairy production

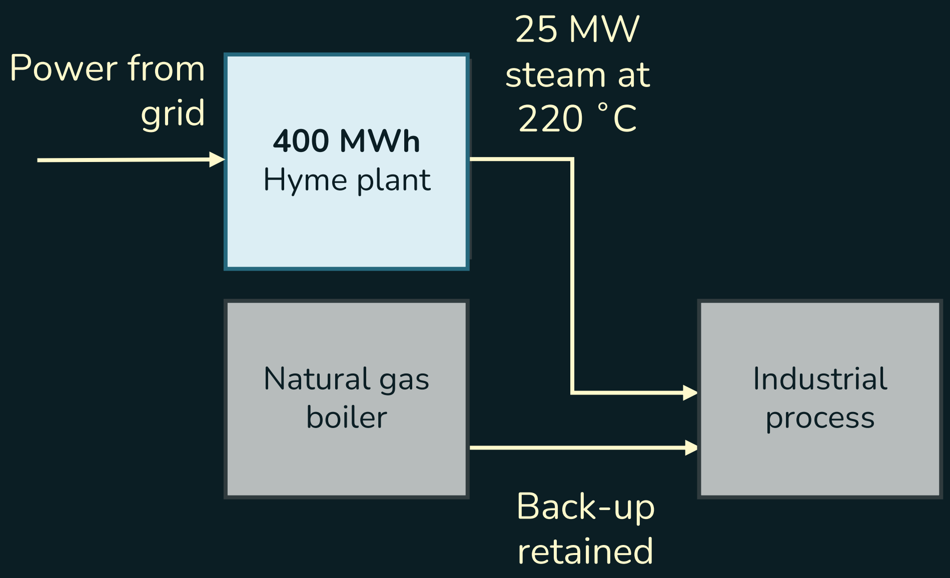
Situation

- Industrial process heat.
- Most have 24/7 operations – or very close to it.
- Storage duration is typically for 18-30 hours of operation.
- We are aiming to cover 60- 80 % of the hours of a year at slightly more than half cost of natural gas.

Proposed Hyme solution

75 MW charge – 400 MWh storage – 25 MW output

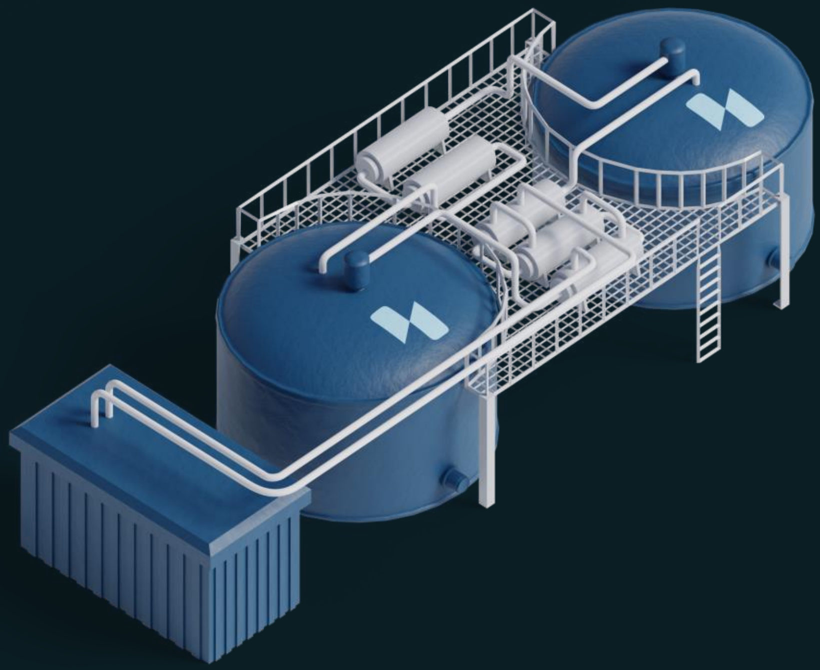
Delivering 5.000 out of ~6.000 yearly operating hours



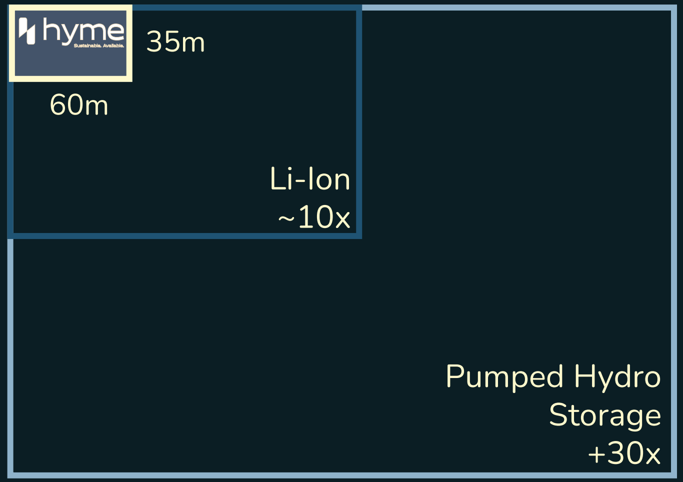
Hyme delivers value to two distinct customer segments

Customer segment		Main use-case	Application
Industrial process heat		Delivering green, high temperature heat on demand by replacing fossil enabled heat	• Chemicals and petrochemicals • Paper, pulp and print • Food and beverages
Legacy power and cogeneration plant owners		Delivering secure, baseload energy from '2nd life' green combined heat and power plants	• Turn cogeneration or power plants into green backbone of grid stability

What does a large Hyme plant look like?

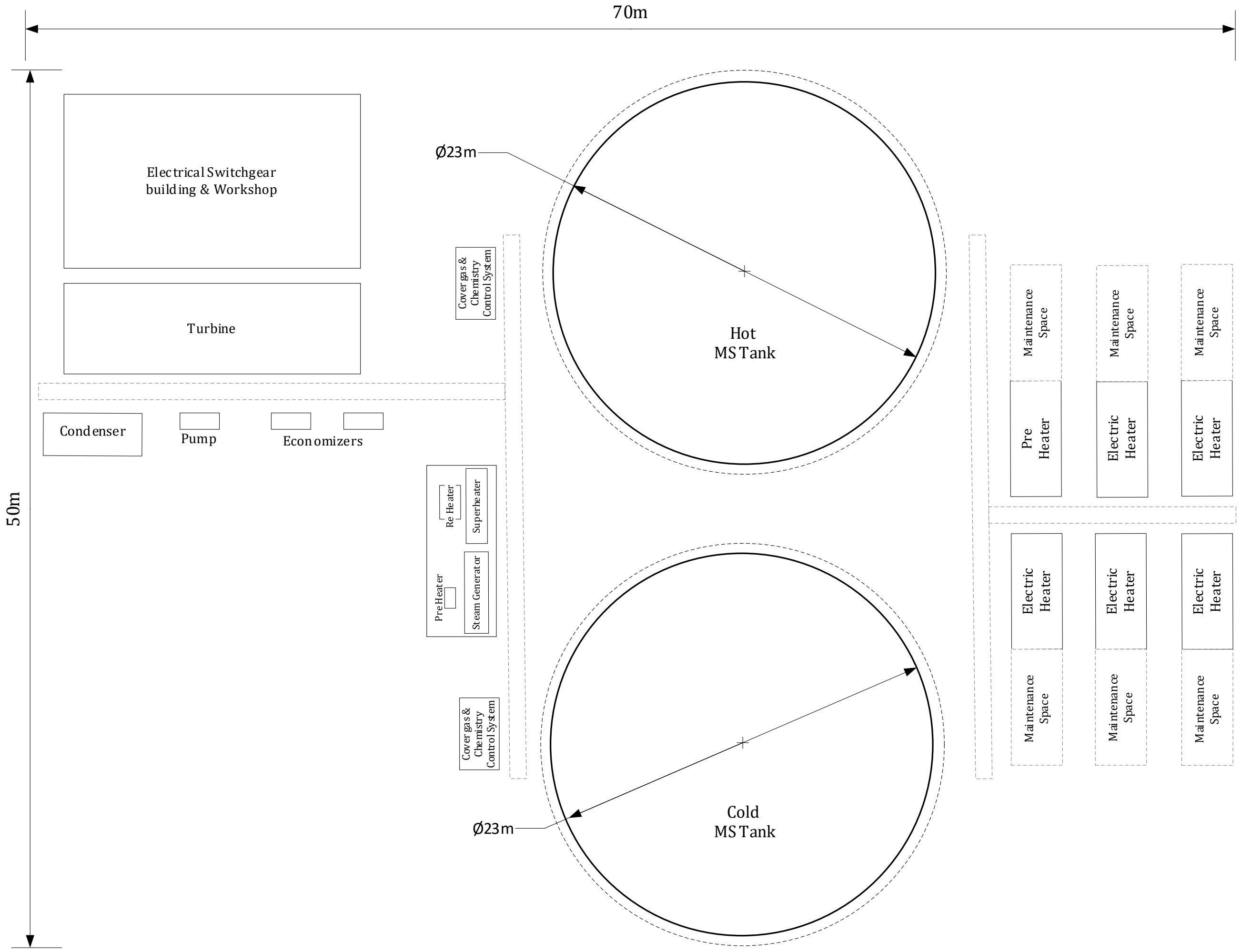


1 GWh footprint comparison



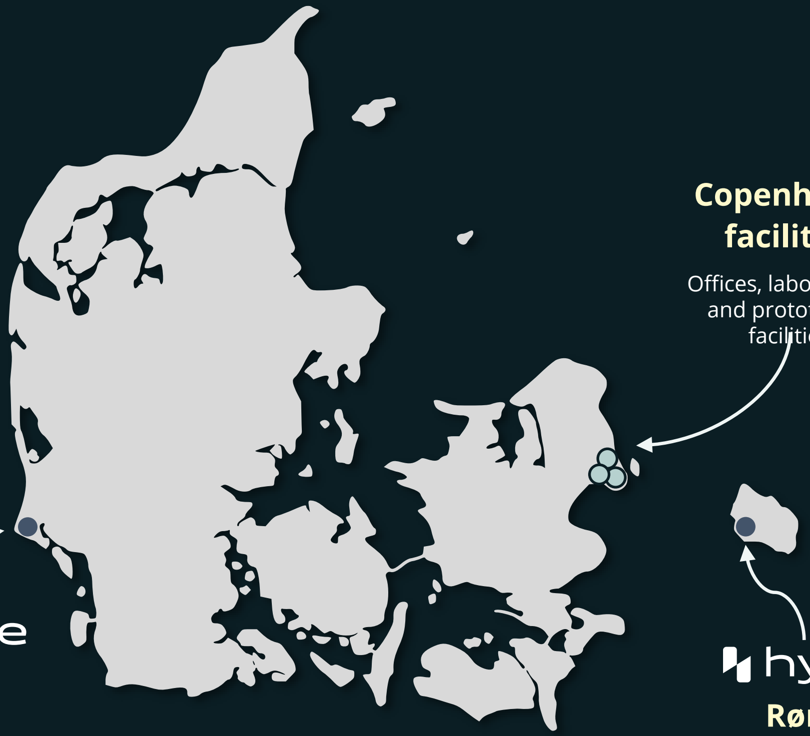
Hyme TES 1,3 GWh Storage footprint - Greenfield

70 x 50 m – for complete plant with power block, switch gear etc.



Equipment	Key Size Parameters
Hot Molten Salt Tank	Dimensions: 23 m diameter x 13 m height
Hot Molten Salt Pump	Power 50 HP Discharge Pressure 5 bar Flowrate 348 m3/h
Cold Molten Salt Tank	Dimensions: 23 m Ø x 13 m height
Cold Molten Salt Pump	Power 75 HP Discharge Pressure 7 bar Flowrate 314 m3/h
Electric Heaters	Total Heat Load 113 MWt 690 V 50Hz
Pre Heater	Tube and Shell Heat Exchanger Dimensions: 1,2m L x 0,5m Ø
Steam Generator	Tube and Shell Heat Exchanger Dimensions: 5m L x 1,4m Ø
Super Heater	Tube and Shell Heat Exchanger Dimensions: 4,6m L x 1,1m Ø
Re Heater	Tube and Shell Heat Exchanger Dimensions: 2,1m L x 1,1m Ø

From technology to product – final step



Copenhagen facilities

Offices, laboratories and prototyping facilities

hyme

Esbjerg site

The world's first hydroxide molten salt energy storage plant

hyme

Rønne site

Fully integrated into operations and energy markets

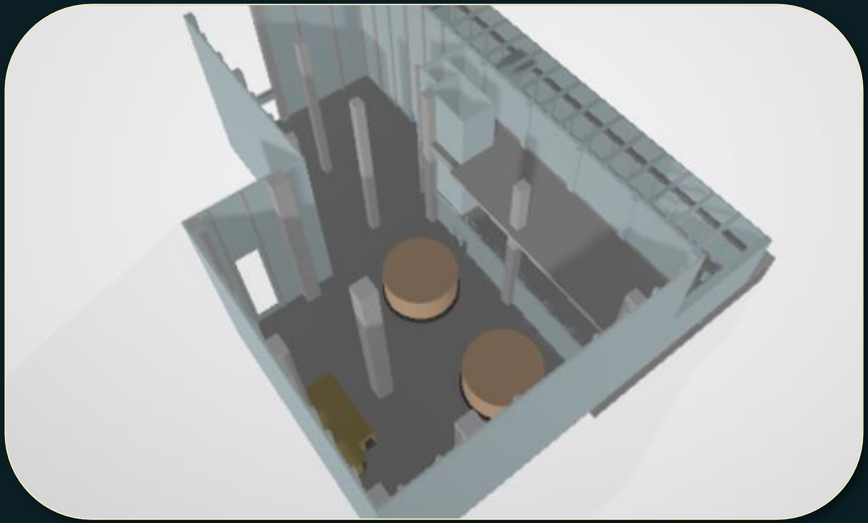
2LIPP project on Bornholm at BEOF, Rønne

Plant specifications

- ~20 MWh of storage
- 5 MW charge
- 4 MW output steam for power, steam and district heating
- Final design still under way

Goals

- Easily replicable design developed
- Easy to operate
- O & M procedures and training fully developed
- Participation in flexibility markets – tests of FCR, aFRR and mFRR
- Initiate operations in 2025
- No harm to humans or environment in construction or operation



hyme
Sustainable. Available.

Thank you!

Nis Benn
Chief Commercial Officer
Co-founder of Hyme
nvb@hyme.energy

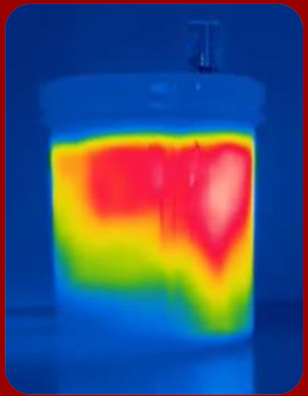
AVANCERET ENERGILAGRING

COMPACT THERMAL ENERGY STORAGE – STATUS, PERSPECTIVES AND RESEARCH EXAMPLE

GERALD ENGLMAIR, DTU CONSTRUCT

Compact Thermal Energy Storage

- Status, perspectives and research example



Gerald Englmair, PhD
Assistant Professor
Technical University of Denmark
Department of Civil and Mechanical Engineering (Construct)
Email: gereng@dtu.dk

DTU Construct: Thermal Storage as key component for solar (renewable) energy supply

Solar resources

Solar thermal collectors

Solar heating plants

Large-scale heat storage, compact heat storage

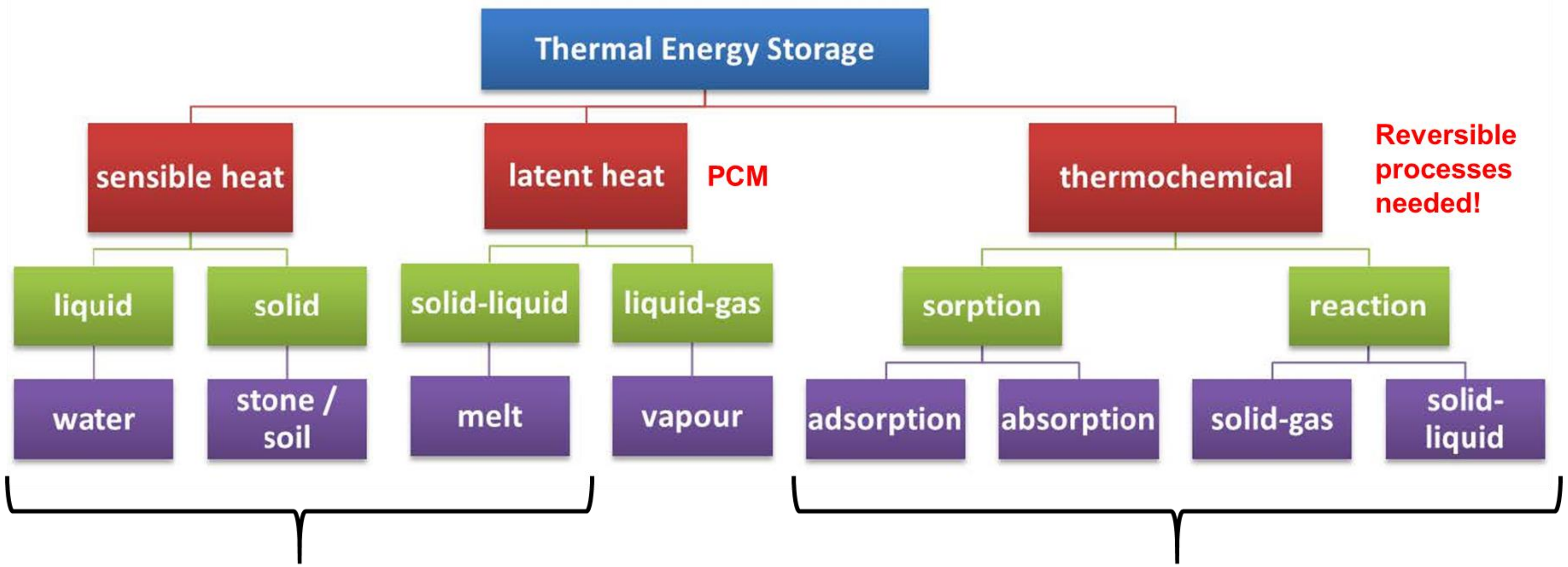
Cold storage, solar cooling

Solar energy systems for combined heat and electricity production (PVT)

Scientific staff, November 2023

Simon Furbo, associate professor, sifu@dtu.dk
Jianhua Fan, associate professor, jifa@dtu.dk
Janne Dragsted, associate professor, jadr@dtu.dk
Gerald Englmair, assistant professor, gereng@dtu.dk
Elsabet Nielsen, senior researcher, elsa@dtu.dk
Weiqiang Kong, senior researcher, weiko@dtu.dk
Mark Dannemand, senior researcher, markd@dtu.dk
Adam Rasmus Jensen, researcher, arajen@dtu.dk
Ioannis Sifnaios, Postdoc, iosif@dtu.dk
Yutong Xiang, PhD student, yutxi@dtu.dk
Meng Gao, PhD student, menga@dtu.dk

Thermal Energy Storage Mechanisms



Solutions on market

Low storage density

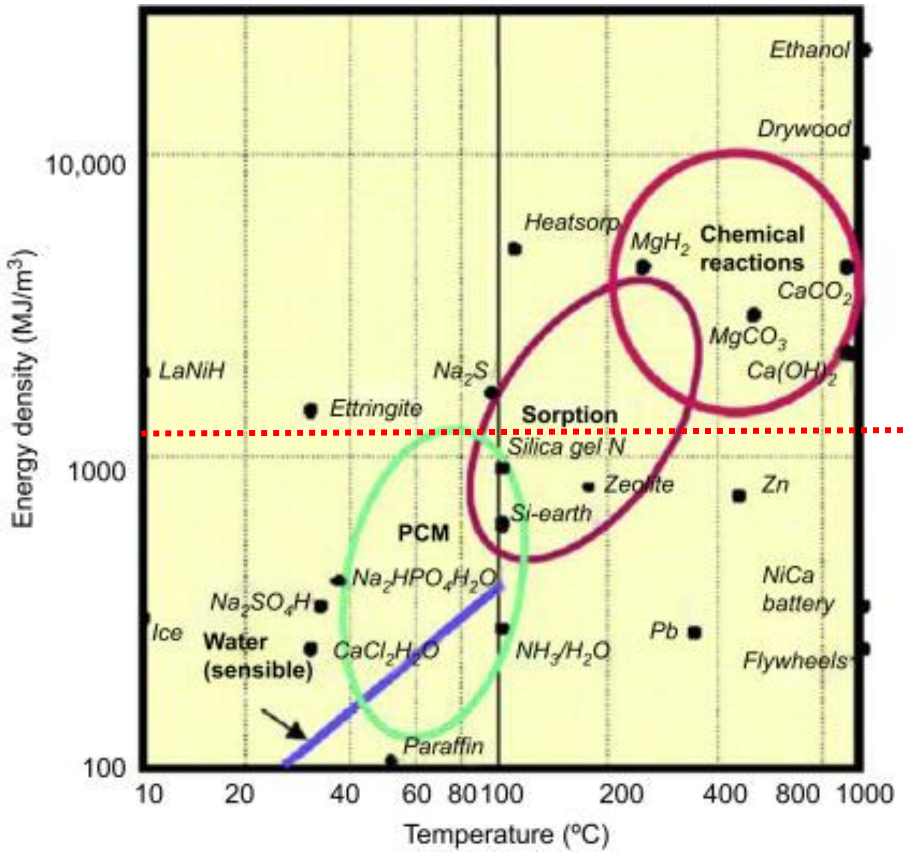
Mainly research (niche applications exist)

Compact:

TCM
(e.g. zeolite+water, NaOH+water)

PCM
(e.g. ice, paraffins, salt hydrates)

Material energy density ≠ storage density



	Stoarge energy density	Factor
Water *	60 kWh/m³	1
Latent	50 -120 kWh/m³	1 – 2
Adsorption	120 - 180 kWh/m³	2 – 3
Reaction	200 - 600 kWh/m³	4 – 10

5-10 for small ΔT

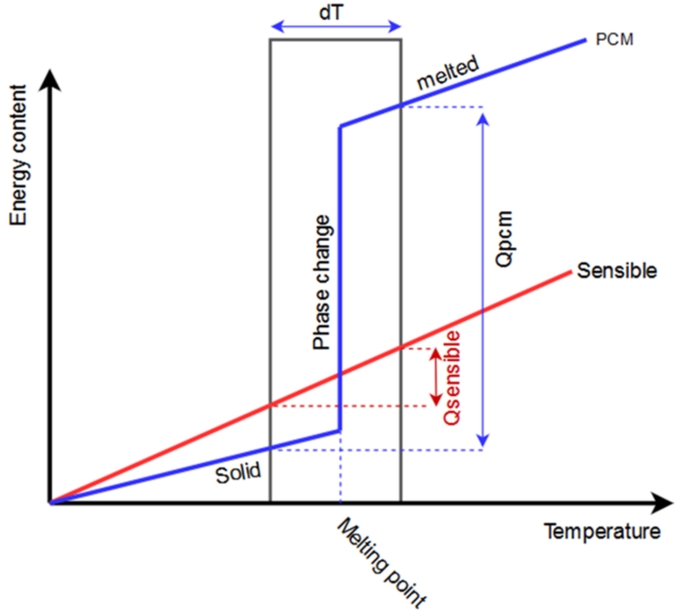
* with ΔT = 50 K

Lithium-ion batteries
= 1400 MJ/m³ = 390 kWh/m³

Compact Thermal Energy Storage (CTES)

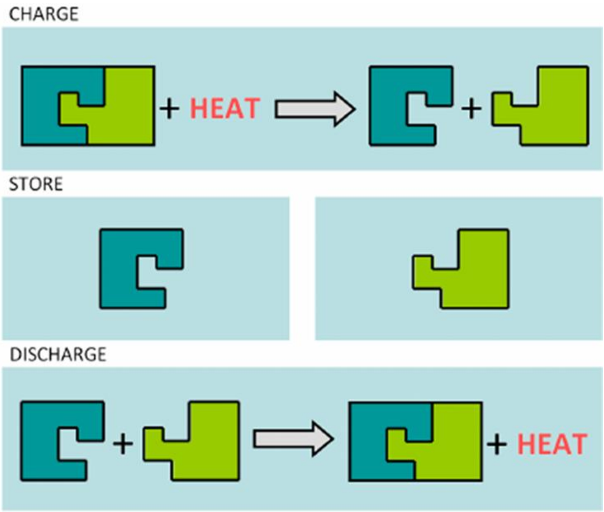
Phase Change Materials (PCM)

- **Capacity in small temperature range**
  → space requirements
  → near constant temperature



Thermo Chemical Materials (TCM)

- **Reversible processes**
  → High temperature
  → High storage density (but more complex)



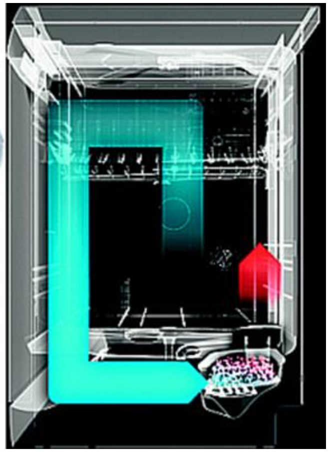
Compact Thermal Energy Storage (CTES)

Phase Change Materials (PCM)

- **Increase of chiller/heat pump operation flexibility**
  → use of solar and wind power (cheaper)
  → additional supply safety
- **Applications through added value**
  → Thermal comfort
  → Transportation of sensitive goods

Thermo Chemical Materials (TCM)

- **Novel application fields**
  → Industry & sector-coupling
  → Household applications; devices, humidity control, etc.



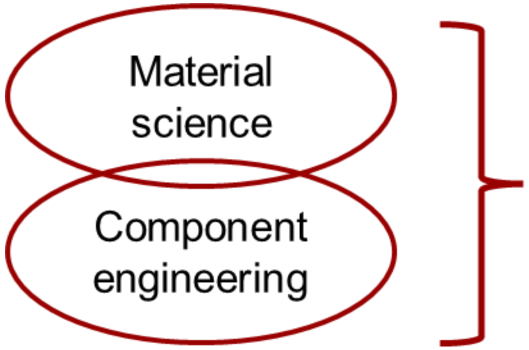
IEA ES Task 40 "Compact Thermal Energy Storage; Materials within Components within Systems"

>80 experts from >30 institutes

…..continuation in IEA Task collaboration since over 10 years.

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Joint Task



Application-orientated development

Utilization of synergy in between research fields

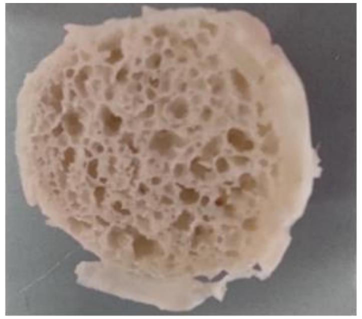
energy storage
IEA Technology Collaboration Programme

IEA ES Task 40 "Compact Thermal Energy Storage; Materials within Components within Systems"

Subtask A: Material Characterization and Database

Standardized measurement procedures and tests
… thermal conductivity, heat capacity, density, etc.

Thermal Analyzer for Thermogravimetry, AIT

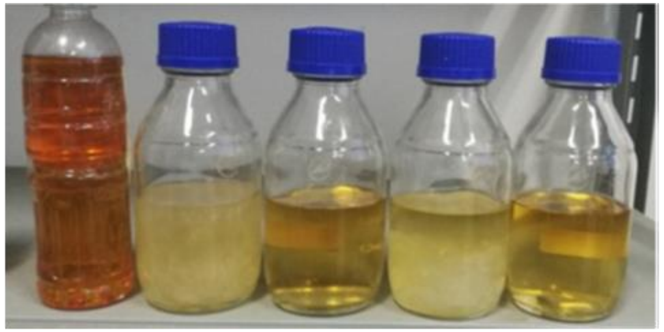


Zeolite foam, University of Messina

Source: https://task58.iea-shc.org/photos

Subtask B: Material Improvement

Exploring potential materials, Performance improvement
(e.g. enhanced thermal conductivity, temperature stability, etc.)



Testing of additives at DTU Construct

IEA ES Task 40 "Compact Thermal Energy Storage; Materials within Components within Systems"

Subtask D: Stability of PCM and TCM

Reviewing material degradation mechanisms

Developing recommendations for stability testing

Subtask E: Effective Component Performance

Heat exchanger design

Storage performance testing & analysis

Testing of 10 heat stores with PCM;
long-term stability testing at DTU Construct

IEA ES Task 40 "Compact Thermal Energy Storage; Materials within Components within Systems"

Subtask C: State of Charge – SoC Determination

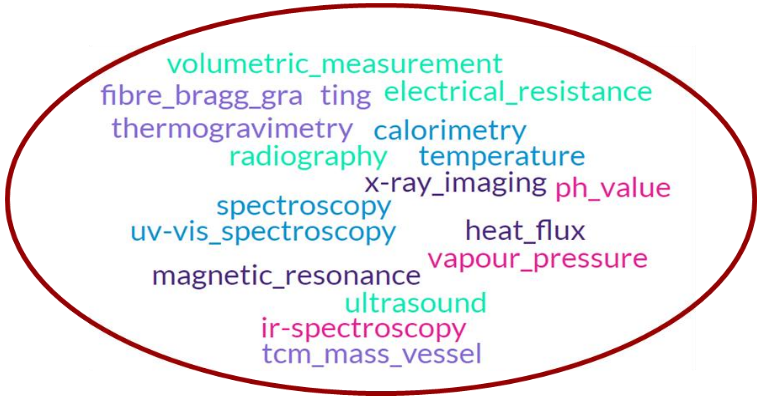
Lead: Gerald Englmair, DTU Construct

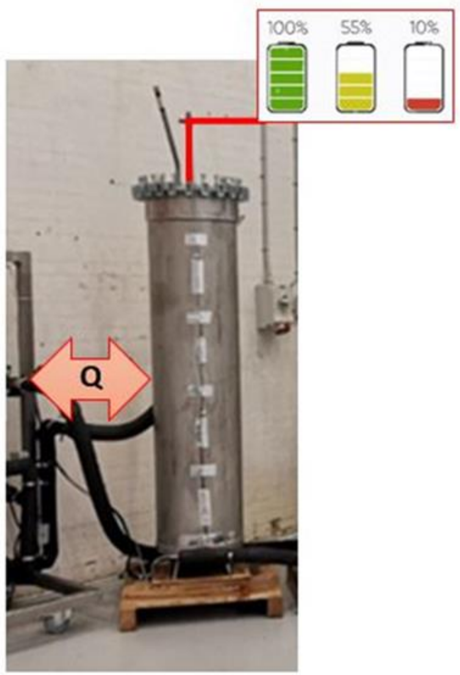
Reliable and instantaneous SoC determination via material bulk response

Analogy: electrical batteries

Prerequisite for **flexibility (reserve market access) of heating and cooling systems**

Reported techniques (material level):

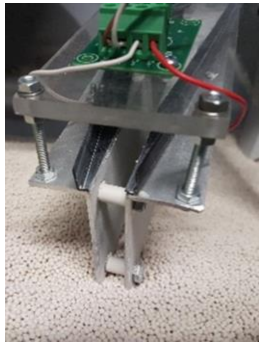




"Thermal battery"

Schematic illustration, DTU Construct

IEA ES Task 40 "Compact Thermal Energy Storage; Materials within Components within Systems"

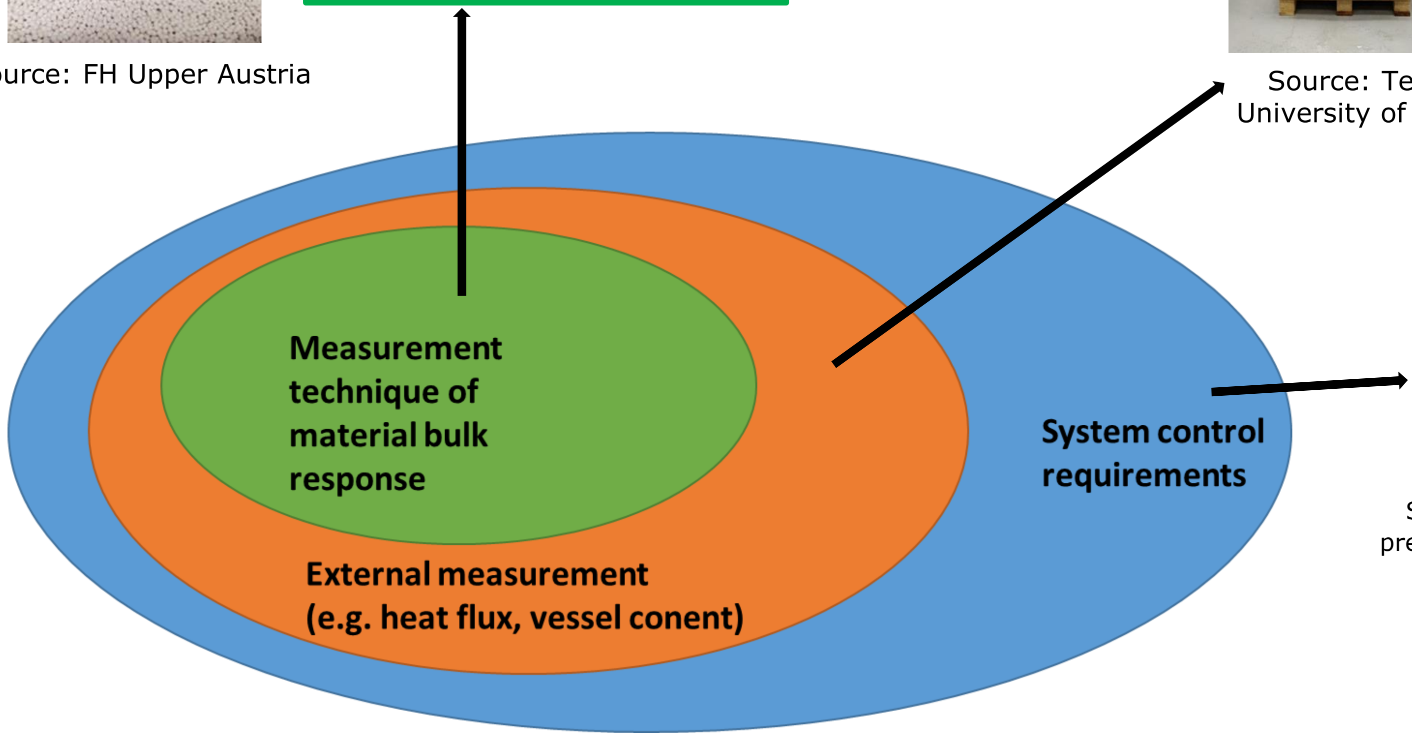


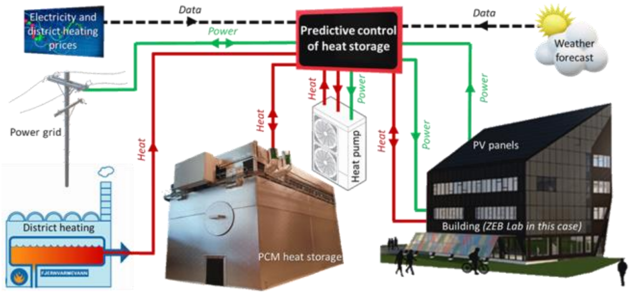
Source: FH Upper Austria

1. Material laboratory: Material response with charging/ discharging can be reproduced

Source: Technical University of Denmark

2. Pilot testing: Correlation of material response to heat flux → Calibration at test stand





Source: SINTEF; https://www.sintef.no/en/projects/2021/presav-prediktive-styringsstrategier-til-aktiv-varmelagring-i-zeb-laboratoriet/

3. Reliable, instantaneous SoC determination enables CTES operation in flexible systems

CTES Technology Position

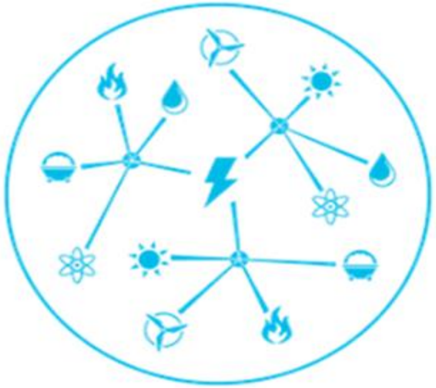
Applications

- Distributed power-to-heat
- Data Center Cooling
- Thermal comfort in buildings
- Heat recovery in industrial processes
- Thermal storage in combination with drying or steam production (e.g. dishwasher)

Drivers

- **Distributed thermal storage** enables better utilization of excess energy (PV, wind) with existing infrastructure
- **Higher volatility of arbitrage prices** → added value → monetary value
- Need for diversification of energy supply for **increased security of supply**
- Lowering the material and component **costs**

Technology Position Paper: Compact Thermal Energy Storage.
van Helden, Wim; Fumey, Benjamin; Englmair, Gerald et al. International Energy Agency, 2023. 7 p.

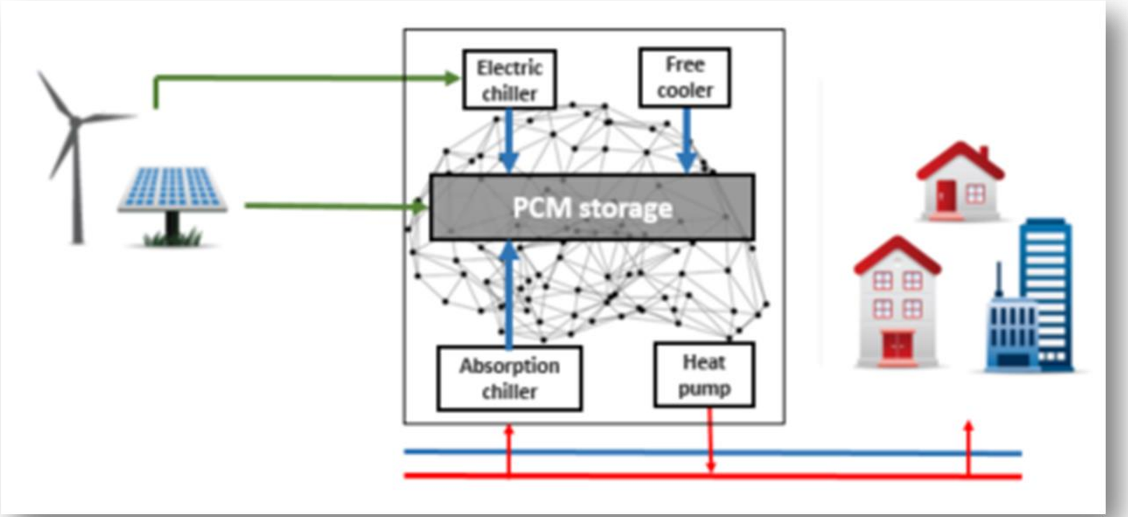


Research example: https://cool-data.dtu.dk/

Cool-Data
Innovation Fund Denmark

"Cool-Data develops, assesses and implements an **AI**-based **modular**, **flexible**, **secure** and **reliable** integrated cooling energy system for data centers"

Integrated technical solution:



DTU Compute
DTU Construct
DTU Management

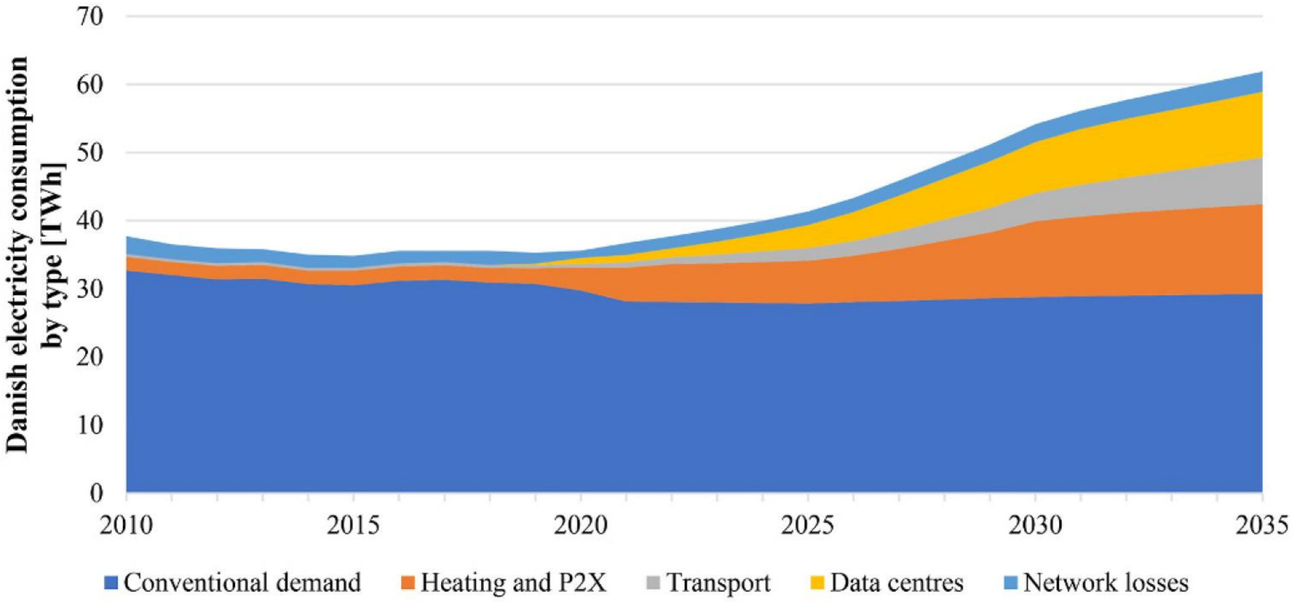
GEV
Vi møder dig med go' energi

NAVIAIR

centerdenmark
intelligent energy

ENERGY COOL®
more cooling - less energy

Exemplary driver: Data center electricity consumption



Historic (up to 2020) and projected electricity use by type in Denmark [Danish Energy Agency, 2022]

Data centres are estimated to have consumed 200-250 TWh in 2020 → 1% of global electricity demand

More information: J. Monsalves, C. Bergaentzlé, D. Keles.
Impacts of flexible-cooling and waste-heat recovery from data centres on energy systems:
A Danish case study. Submitted in March 2023 to the journal "Energy".

Benefits of flexible server room cooling

- Reduction of RES curtailment
- Grid stability
- Lower electricity cost
- Decarbonization of the electricity sector

Source: J. Monsalves, C. Bergaentzlé, M. Backer, 2022

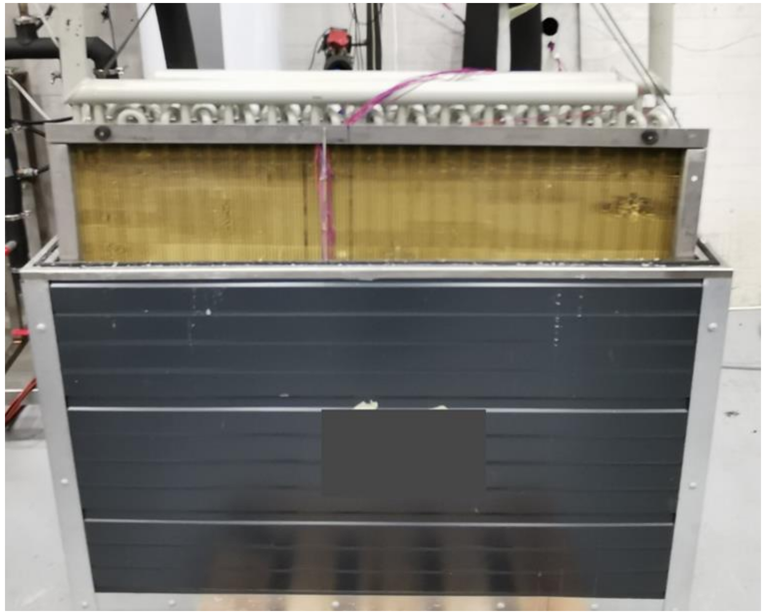
PCM cold storage for flexible cooling

Pilot storage with finned heat exchanger:

- Metal heat exchanger = safe choice
- PCM volume: 115 liter
- PCM mass: 153 kg
- Salt hydrate + thickening agent

- **Potential of >50 kWh per m^3 storage** (including heat exchanger)
- **Volume reduction to water tank: factor 5<** (higher in smaller temperature interval)

Use of certified products

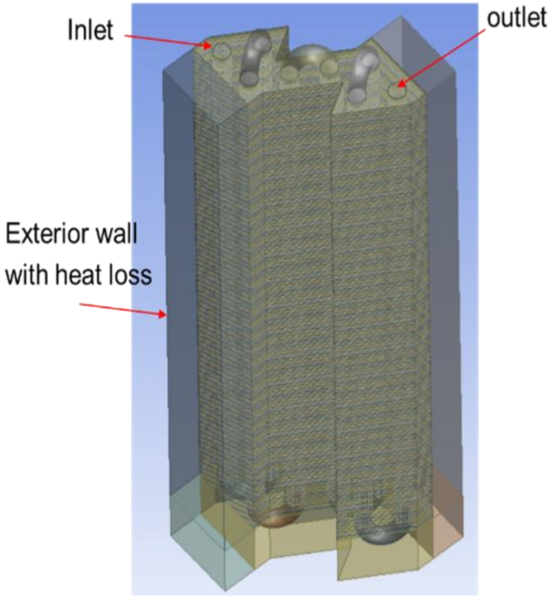


Maximal energy PCM volume via immersed heat exchanger design

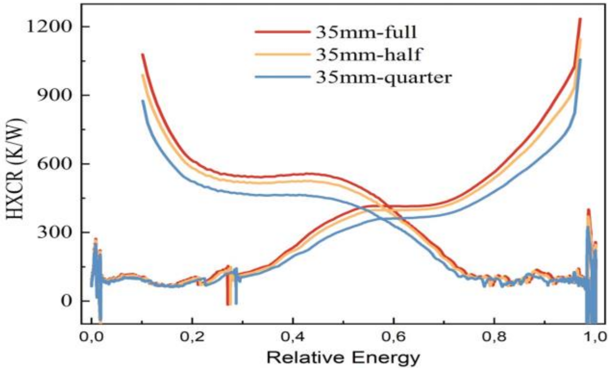
PCM cold storage for flexible cooling

1st prototype:
115 L PCM

7.5 kWh



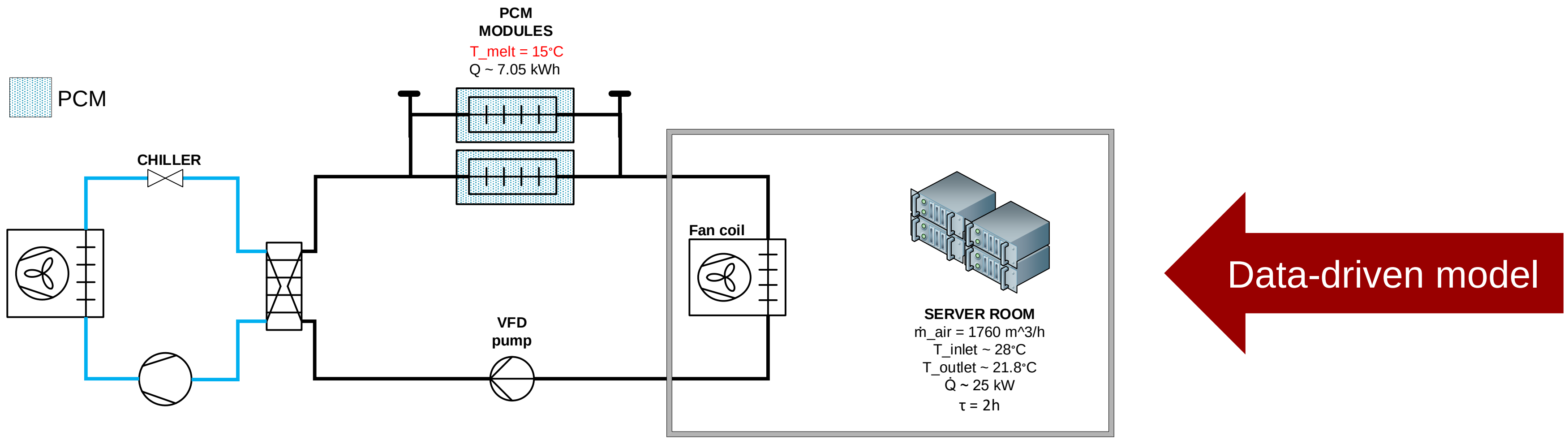
Validated CFD model



2nd prototype:
230 L PCM

15 kWh

PCM cold storage for flexible cooling



2nd prototype:

230 L PCM

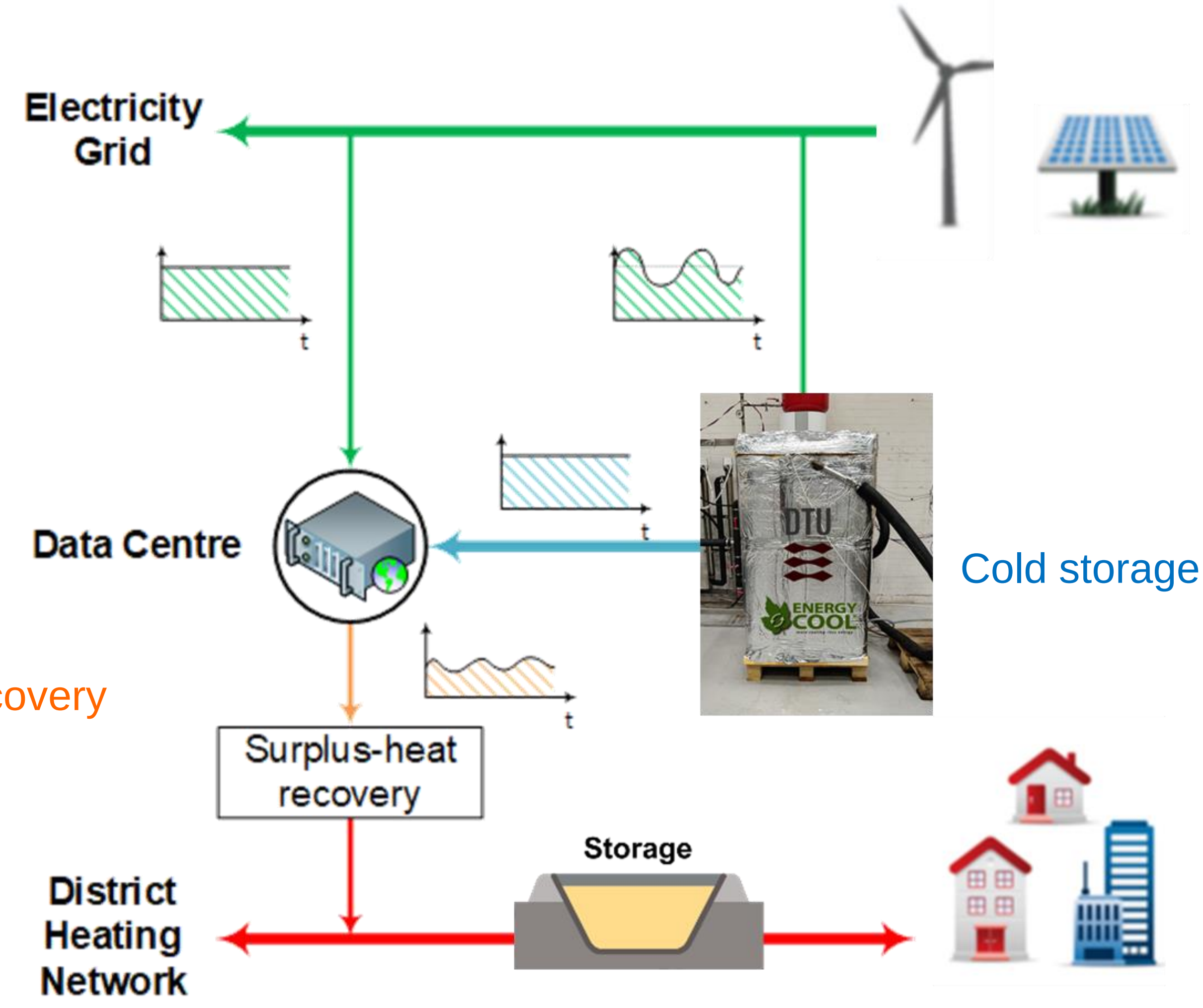
15 kWh

Development of predictive system control algorithm for server room cooing

First paper: Zhu, Y., Englmair, G., Huang, H., Dragsted, J., Yuan, Y., Fan, J., & Furbo, S. (2023). Numerical investigations of a latent thermal energy storage for data center cooling. Applied Thermal Engineering, 236 Part B, [121598]. https://doi.org/10.1016/j.applthermaleng.2023.121598

PCM cold storage for flexible cooling

Cool-Data



How can the system benefit be translated into a business case?

Cold storage – daily utilization (decentralized)

Continuous heat recovery

Large heat storage – weekly utilization (centralized)

IEA Energy Storage Task 41 ”Economics of Energy Storage”

Benefit → **Value** → **Business Case**

Benefit: Flexibility, Reliability, Mobility, Autarky, …

Value: How much would somebody pay for the benefit?

Business Case: Who pays for the benefit?

How can the system benefit be translated into a business case?

Danish Industry workshop with DaCES:
Time: March 20, 2024; 11.30 – 17:30h
Place: DTU Bulding 101, Meeting center.
Registration here

SCAN ME

energy storage
IEA Technology Collaboration Programme

DTU Technical University of Denmark

DaCES Danish Centre for Energy Storage

PlanEnergi

EUDP

AVANCERET ENERGILAGRING

UDNYTTELSE AF LADESTANDERE OG BATTERILAGER TIL BALANCERING AF ELNETTET

ANDREAS THINGVAD, HYBRID GREENTECH &
THOMAS STEEN JENSEN, KØBENHAVNS LUFTHAVN

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

CPH
LITHUANIAN AIRPORTS VNO KUN PLQ
THE CAREPORT
ADR Aeroporti di Roma
IATA
air bp
CENTRALNY PORT KOMUNIKACYJNY
UNIVERSITÀ DI PARMA
RSB Roundtable on Sustainable Biomaterials www.rsb.org
AIRBUS
SAS
TUHH Technische Universität Hamburg
DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center
Brændstoflageret BKL Københavns Lufthavn I/S
DANISH TECHNOLOGICAL INSTITUTE
NISA Nordic Initiative for Sustainable Aviation
BMGI Consulting
Hybrid Greentech Energy Storage Intelligence

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

Udnyttelse af ladestandere og batterilager til balancering af elnettet

v. Andreas Barnekov Thingvad, Hybrid Greentech
Thomas Steen Jensen, Københavns Lufthavn

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

KLIMASTRATEGI

- Ground operations:
  Net-Zero 2030

- Omstilling af flåde
  - Interne
  - Eksterne

- Opladningsinfrastruktur
  - 1350 ladepunkter bestilt
  - Nov. 2023: 400+ installeret

This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 957824

FLÅDEOVERBLIK

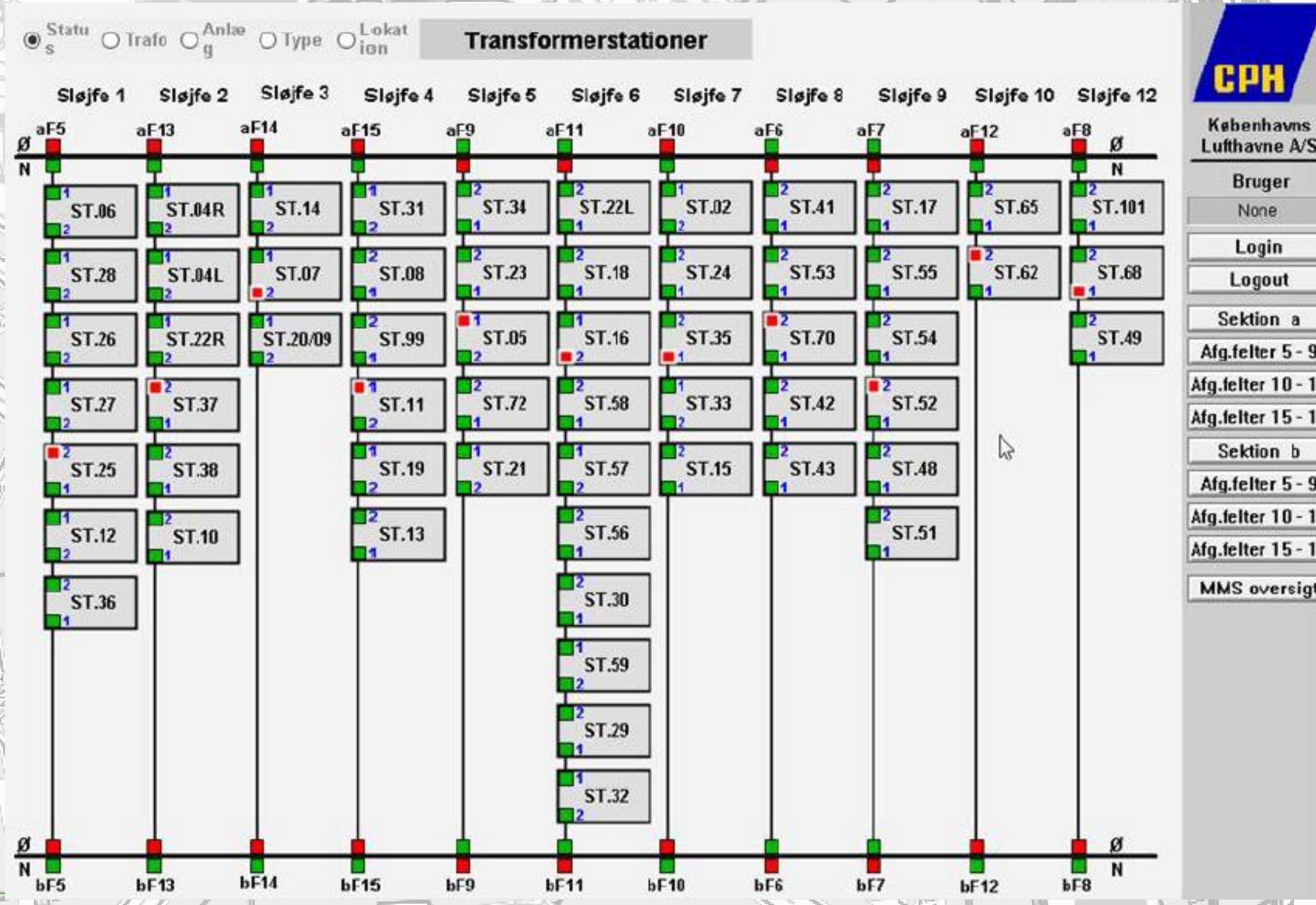
- CPH køretøjer
  - Små: 200+
  - Store: 80+
  - Special: 300+

This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

EL-INFRASTRUKTUR

- Hovedtilslutning
- Distrubutionsnet
- Transformerstationer
- Nødforsyning
- Elforbrug
- Peaks
- Share



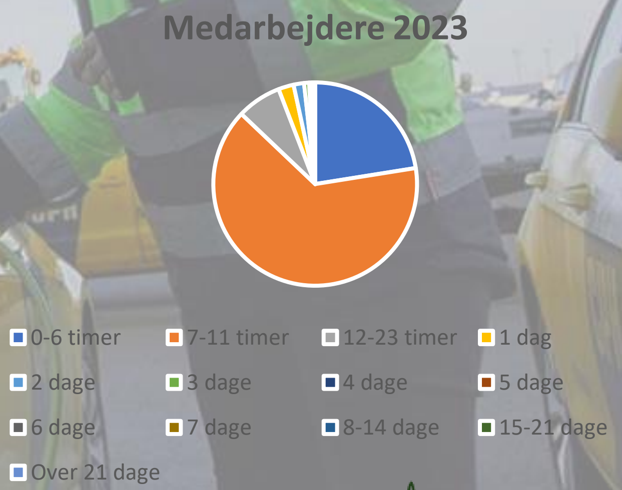
This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

PERSONALEKØRETØJER
MEDARBEJDERPARKERING

- Brugsmønster
- System for booking
- De travle timer: 7-17
- Tilsluttet ladestander

- Parkeringsarealer
- P1
  - 7-11 timer
  - 8-14 dage: 20 %
- Potentialer



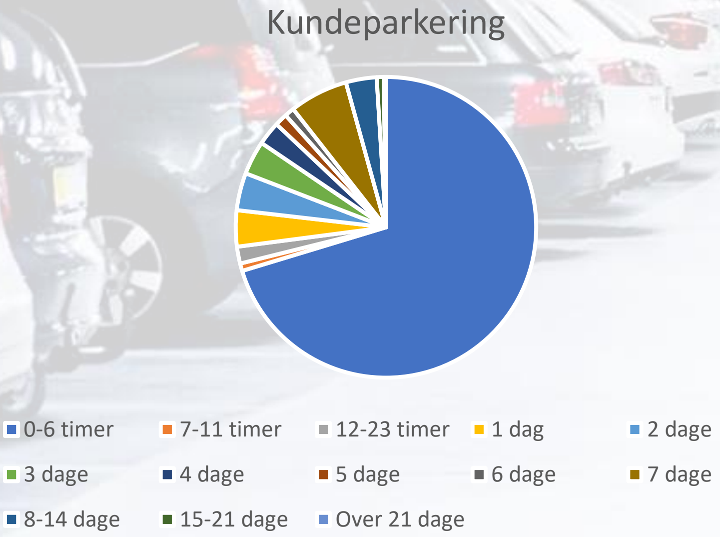
This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

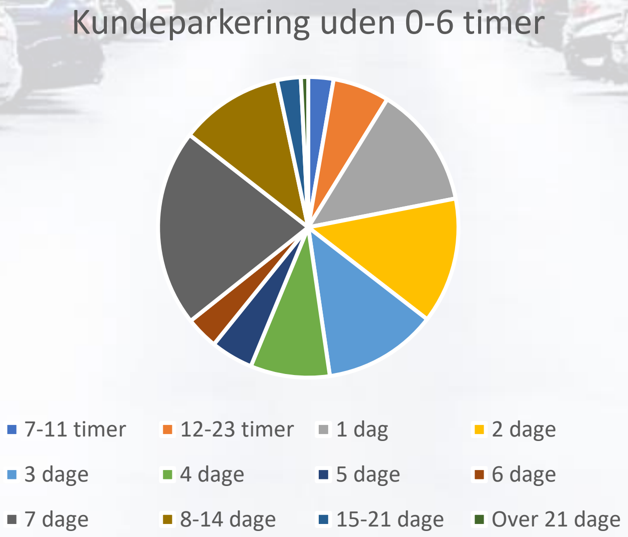
KUNDEPARKERING

- 2023

1.5 mio.



0.5 mio.



This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

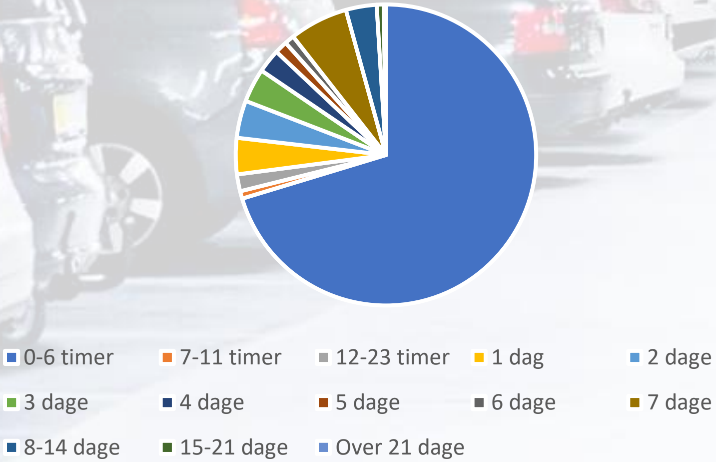
ALIGHT
SUSTAINABLE AVIATION

KUNDEPARKERING

- 2023

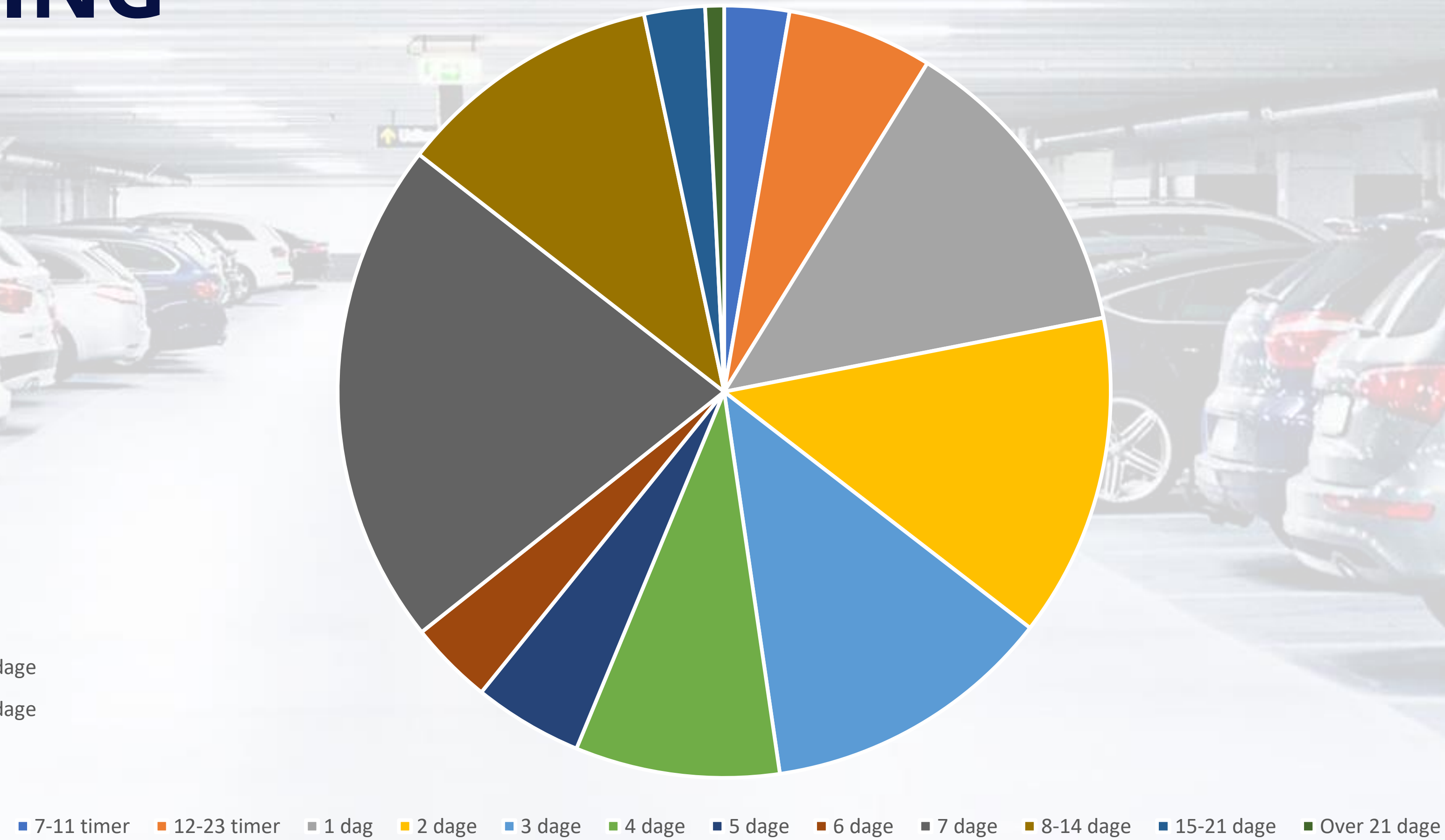
1.5 mio.

Kundeparkering



0.5 mio.

Kundeparkering uden 0-6 timer



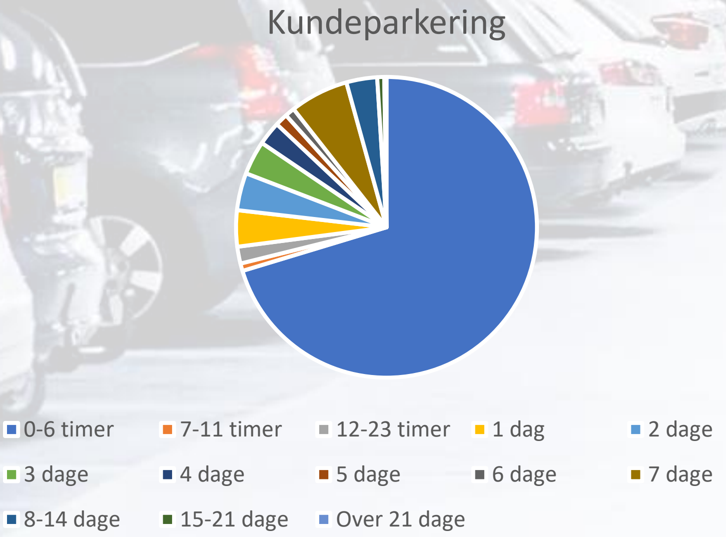
This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

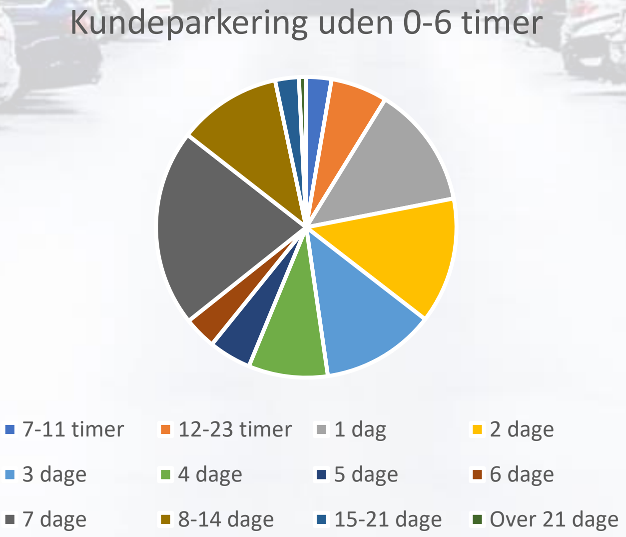
KUNDEPARKERING

- 2023

1.5 mio.



0.5 mio.



0.35 mio.

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

FREMTIDIGE UDFORDRINGER

- Større andel af elektrificeret udstyr
- Ny flyteknologi
  - EL
  - Brintteknologi
- RefuelEU

Udfordret infrastruktur

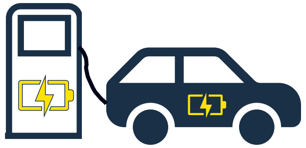
Potentielle løsninger

- Battery Energy Storage Systems
- Demand response
- V2G

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

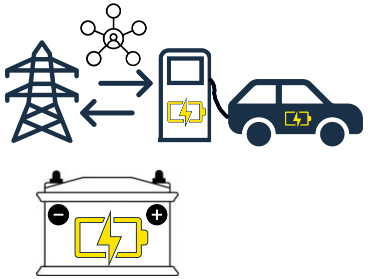
Indhold

1. Smart charging
   a) CO_2
   b) *Elspotpriser*



2. Systemydelser til elnettet
   a) *Energinets værktøjskasse*
   b) *Kombinerede porteføljer*
   c) *Økonomiske potentialer*
   d) *Regulerkraft*

3. Eksempel: *Drift af EV-portefølje under aktivering af systemydelse*
4. Eksempel: *Drift af batterisystem ved arbitragehandel og systemydelser*



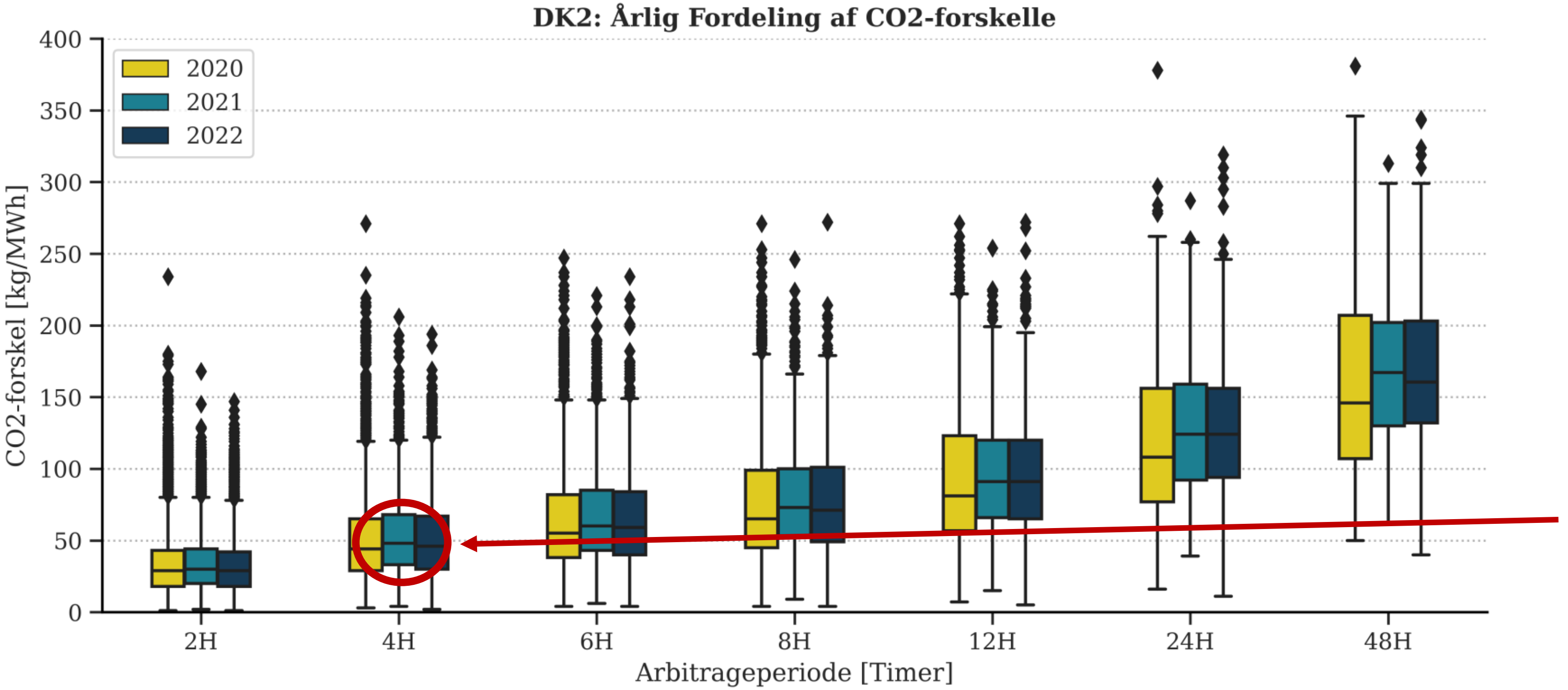
5. Konklusion

HYBRID GREENTECH
Energy Storage Intelligence

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

Potentiale for CO_2-besparelse ved forskudsopladning



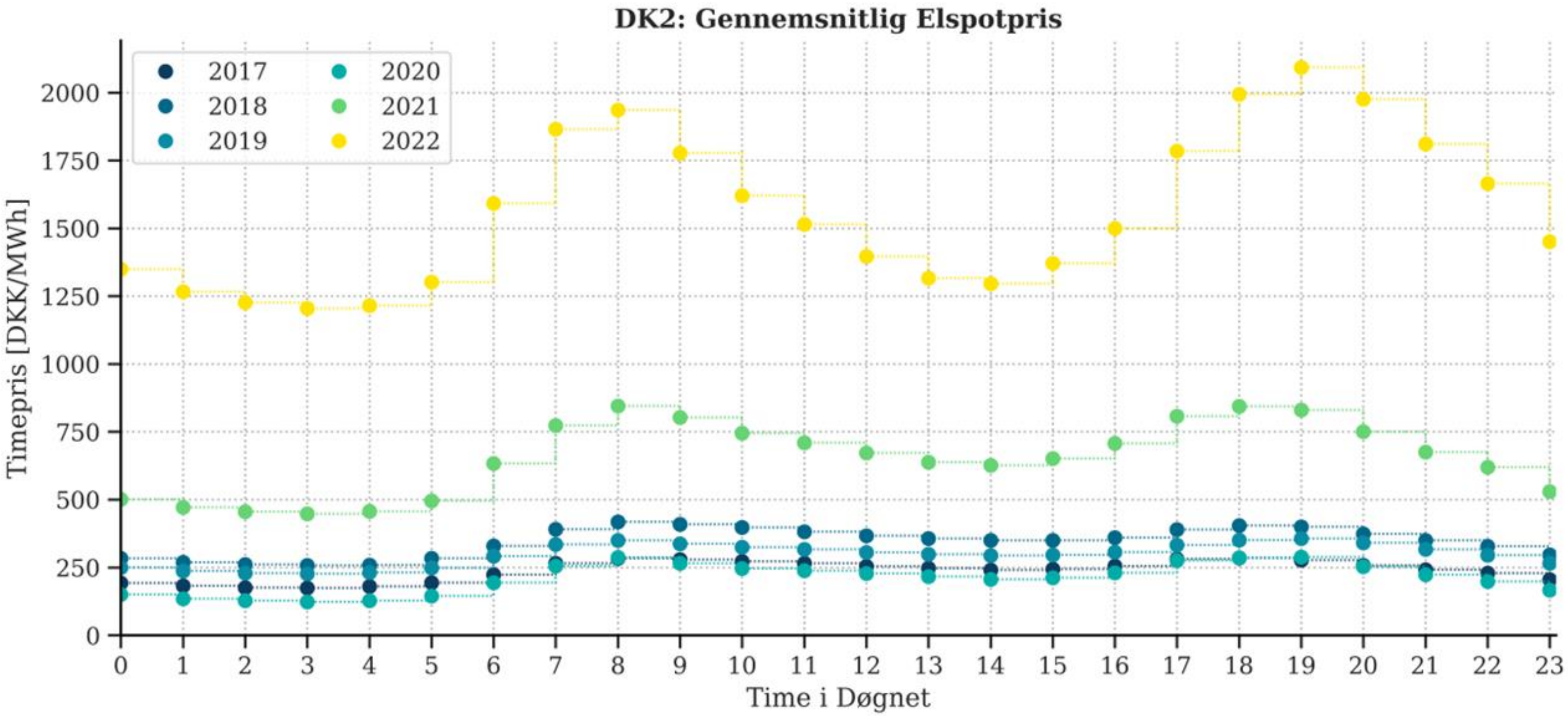
Fremrykning af opladning på få timer kan potentielt spare adskillige kg CO_2.

Medianværdien for *fire timers* justering kan være op til 2,5 kg for 50 kWh.

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

Potentiale for besparelse på elspotpris ved *smart charging*

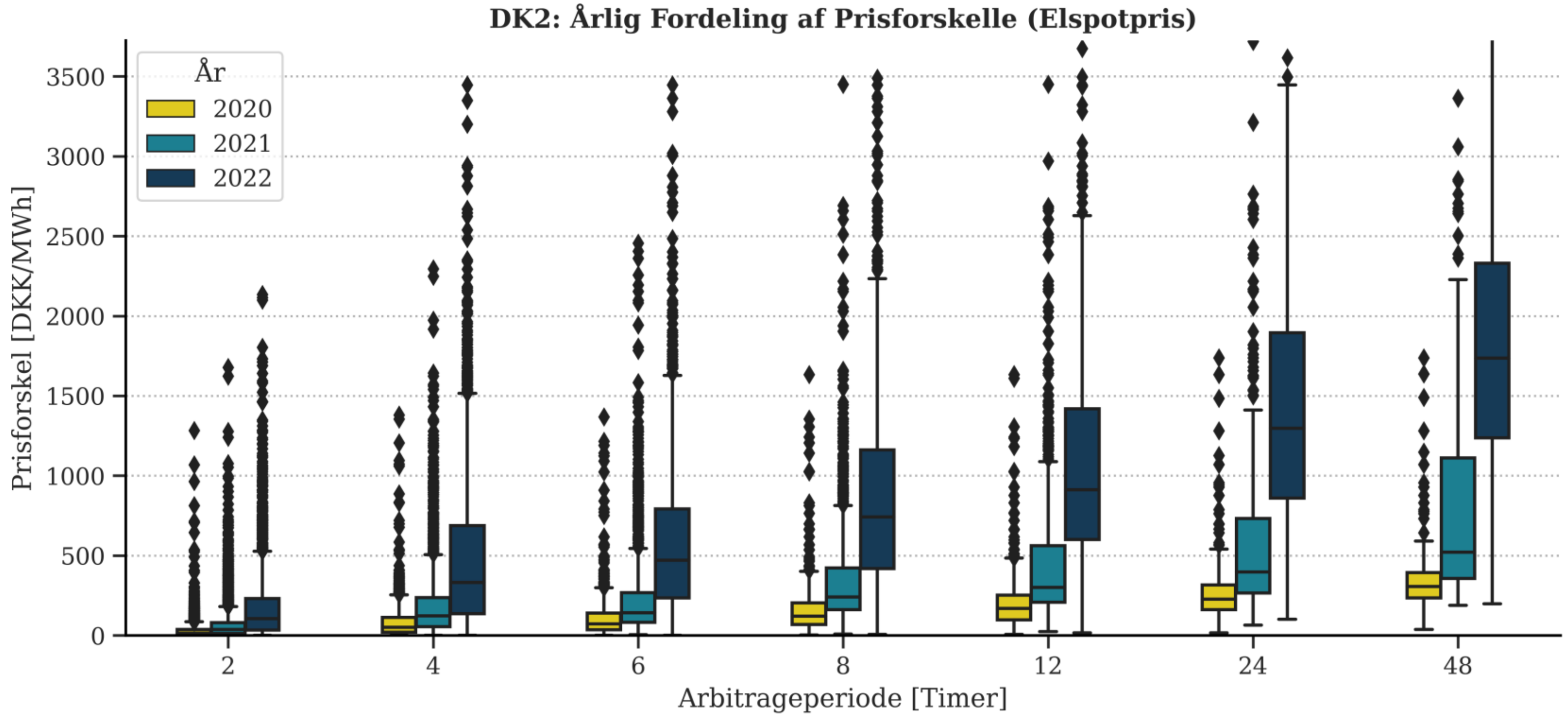


Elspotprisen har i de seneste år haft tendens til at være stærkt varierende over døgnets timer.

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

Potentiale for besparelse på elspotpris ved *smart charging*



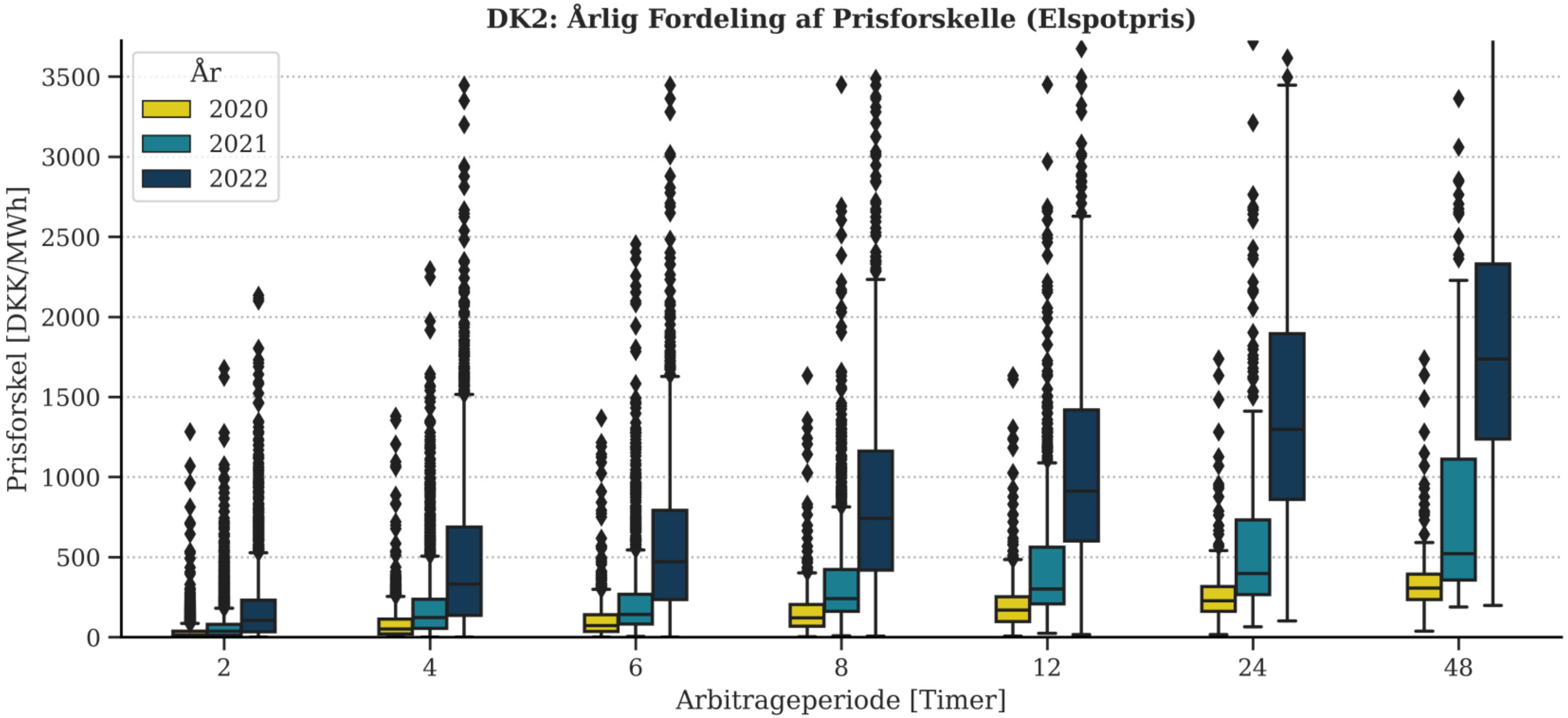
2021 og 2022 havde store prisforskelle over relativt korte perioder.

Ved prismiljøer som disse år, kan der være store besparelse ved at rykke opladningen blot *fire timer*.

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

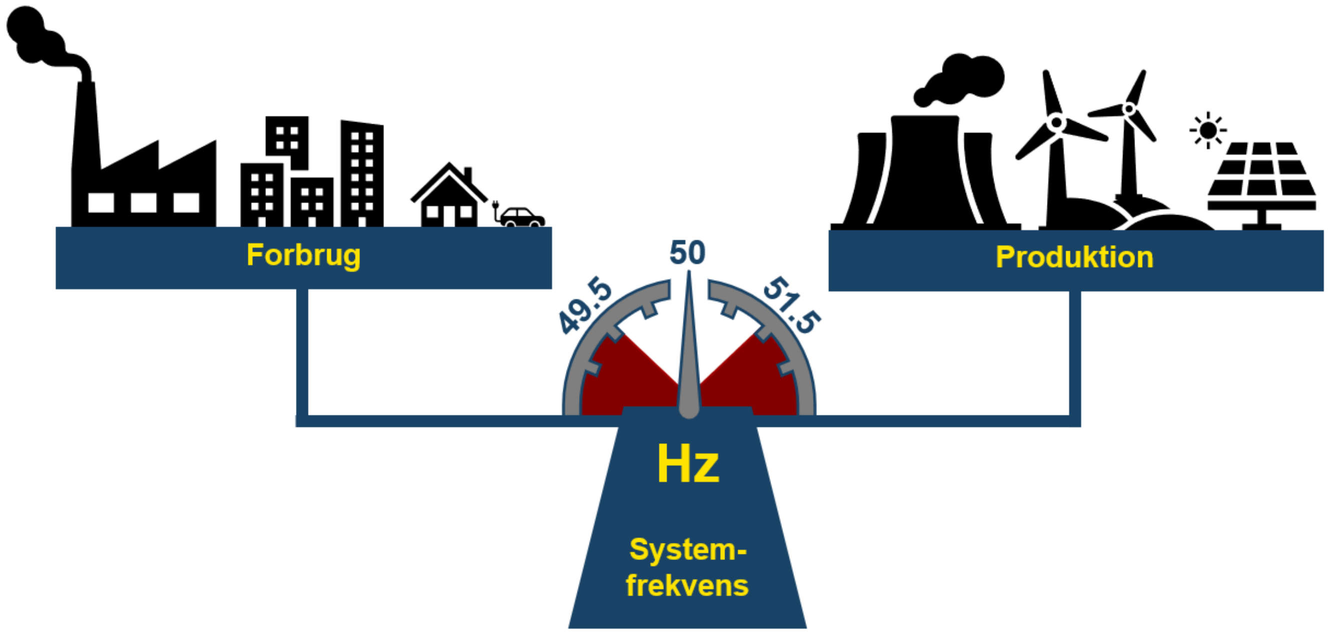
Potentiale for besparelse på elspotpris ved *smart charging*



Hvis 1000 elbiler, sat til at oplade 20 kWh hver, rykkes med *otte timer*, ville der som *medianværdi i 2021* kunne spares:

$$250 \frac{\text{DKK}}{\text{MWh}} \cdot \frac{20 \text{ kWh}}{1000} \cdot 1000 = 5000 \text{ DKK}$$

Forsyningssikkerhed kræver stabilisering af elnettet

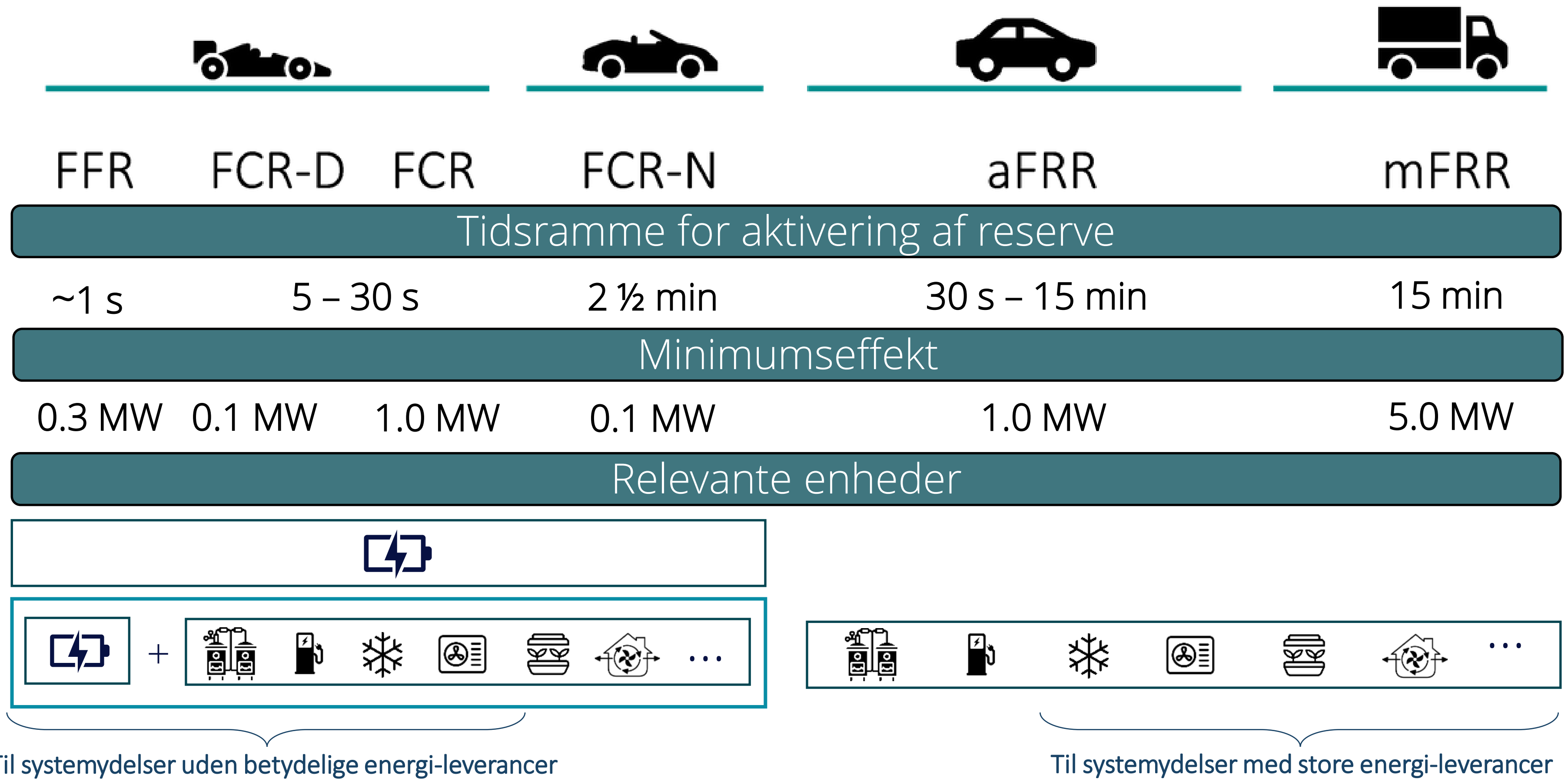


Forbrug og produktion skal være i *balance hvert sekund*. Derfor har Energinet en værktøjskasse af forskellige ***reserver***, der hjælper med at balancere elnettet.

ALIGHT SUSTAINABLE AVIATION

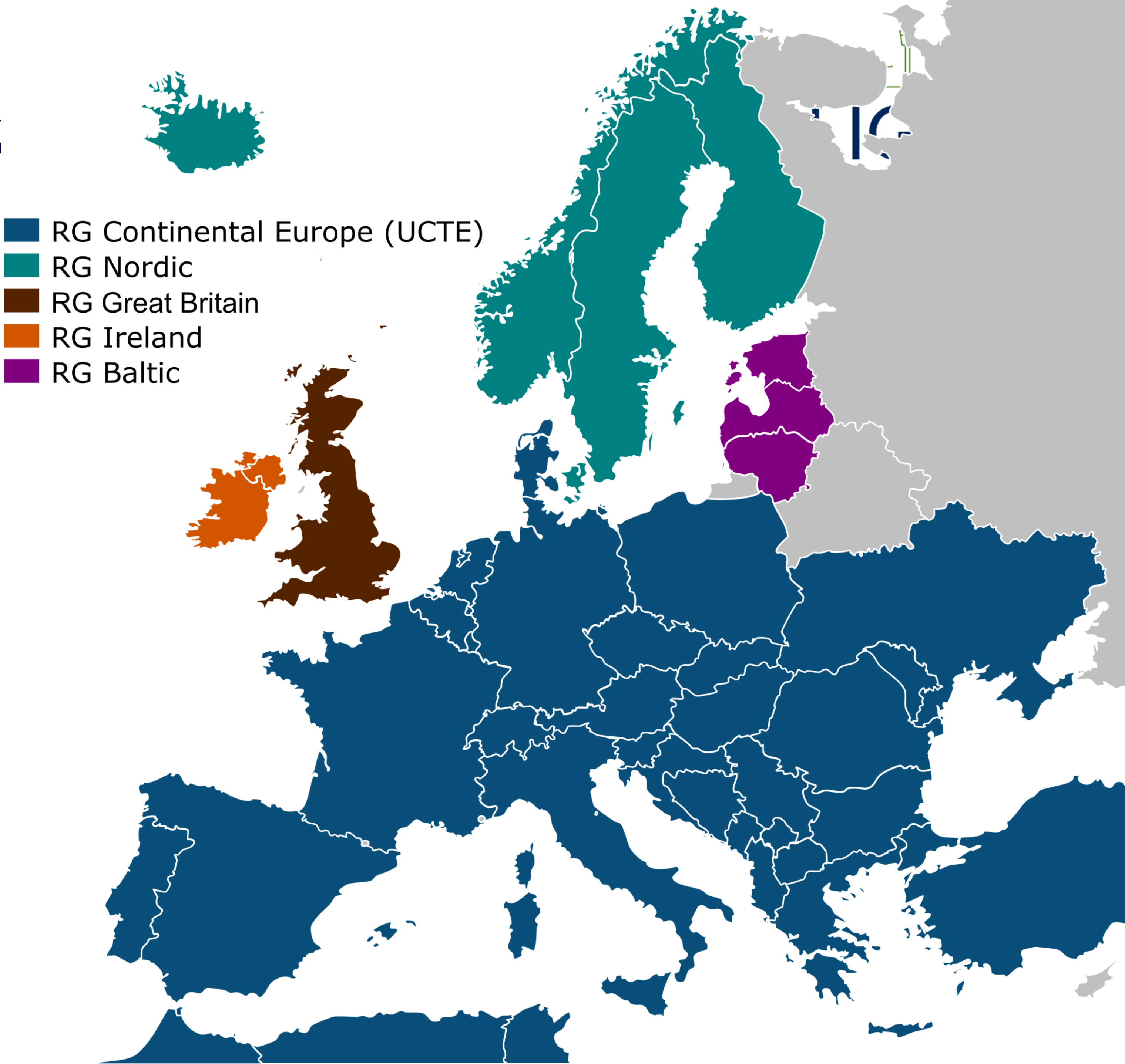
HYBRID|GREENTECH Energy Storage Intelligence

Energinets værktøjskasse til at balancere elnettet



Tilpasset fra Energinet:
https://energinet.dk/El/Systemydelser/Introduktion-til-Systemydelser/Oversigt-over-systemydelser
https://energinet.dk/Om-nyheder/Nyheder/2022/11/01/Behovet-for-systemydelser-vil-vokse-markant

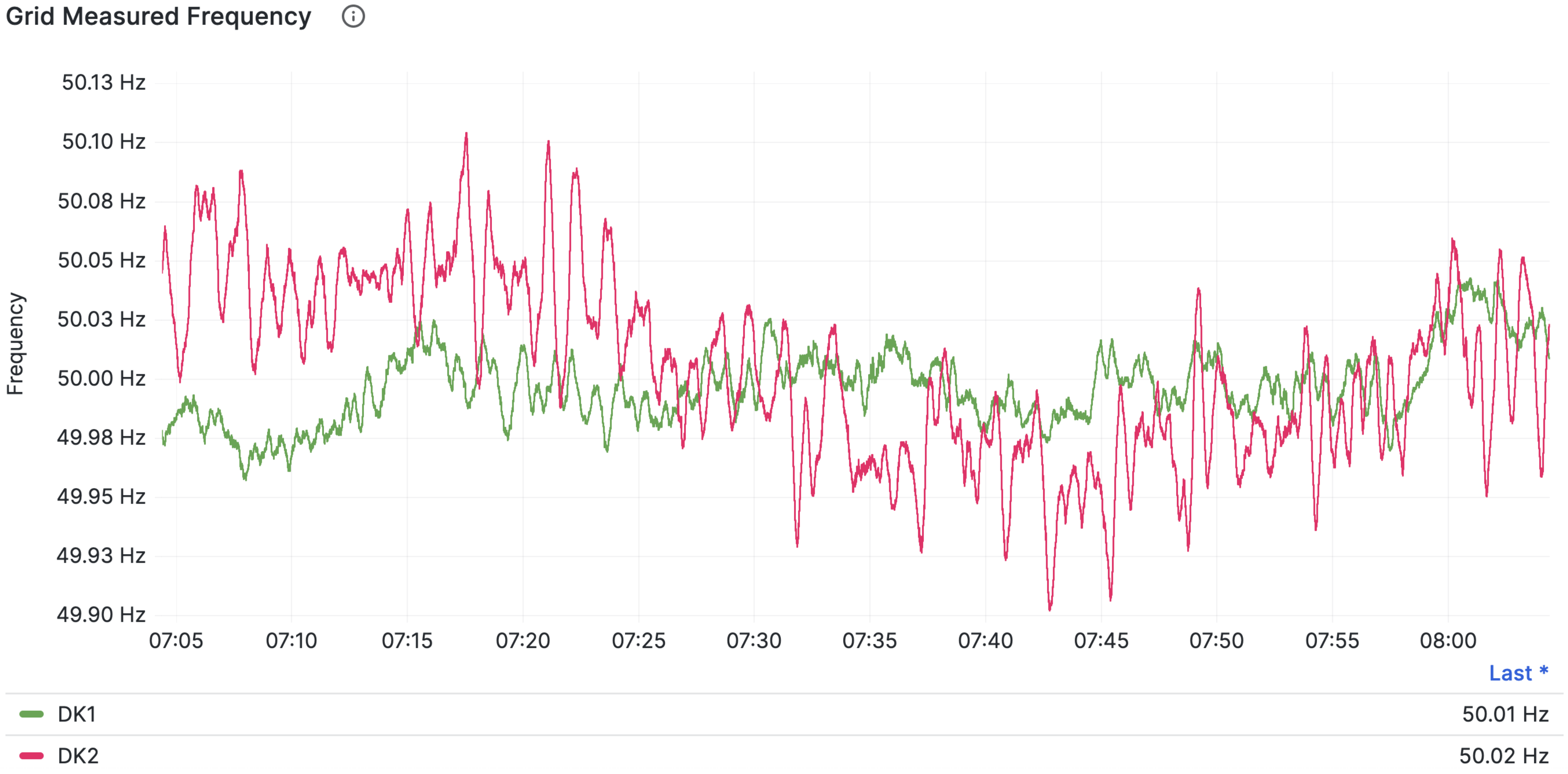
One country with two power systems



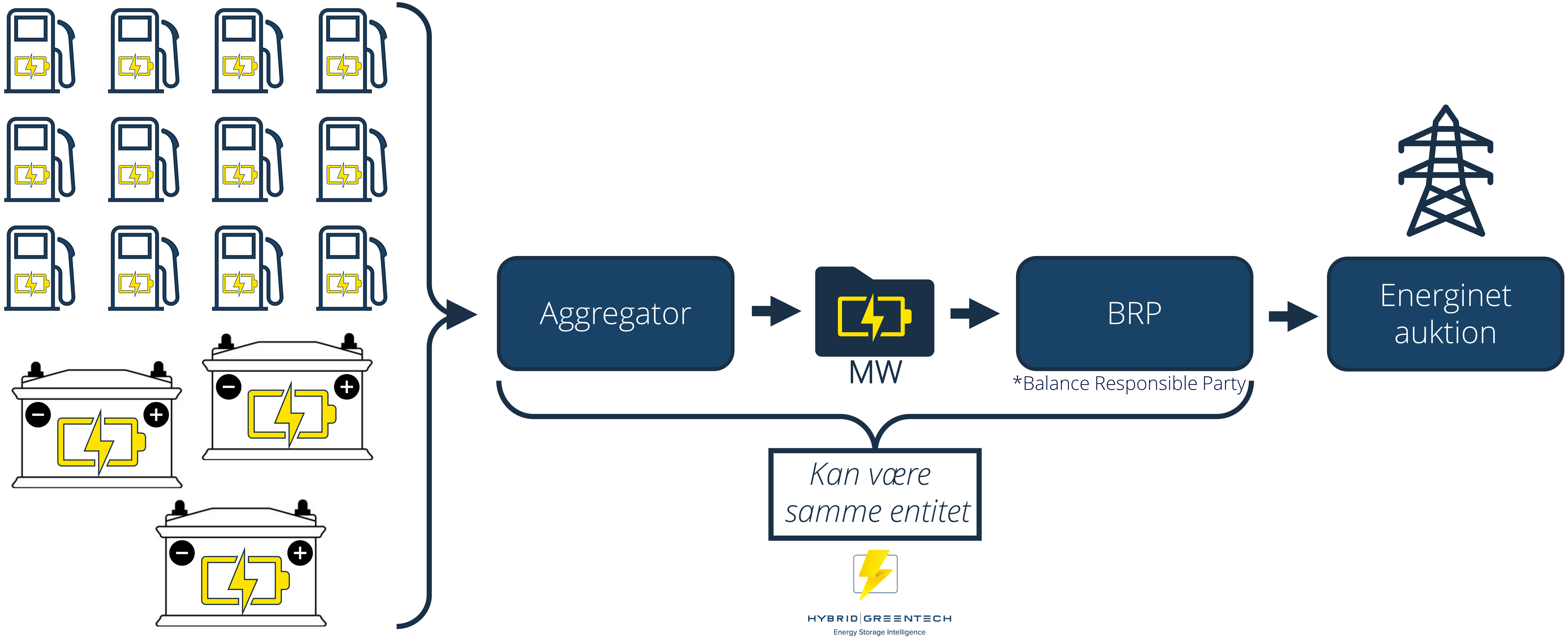
- DK1 is in RG-Continental Europe
  - Frequency Containment Reserve (Regelleistung)
  - aFRR (PICASSO)
  - mFRR (MARI)

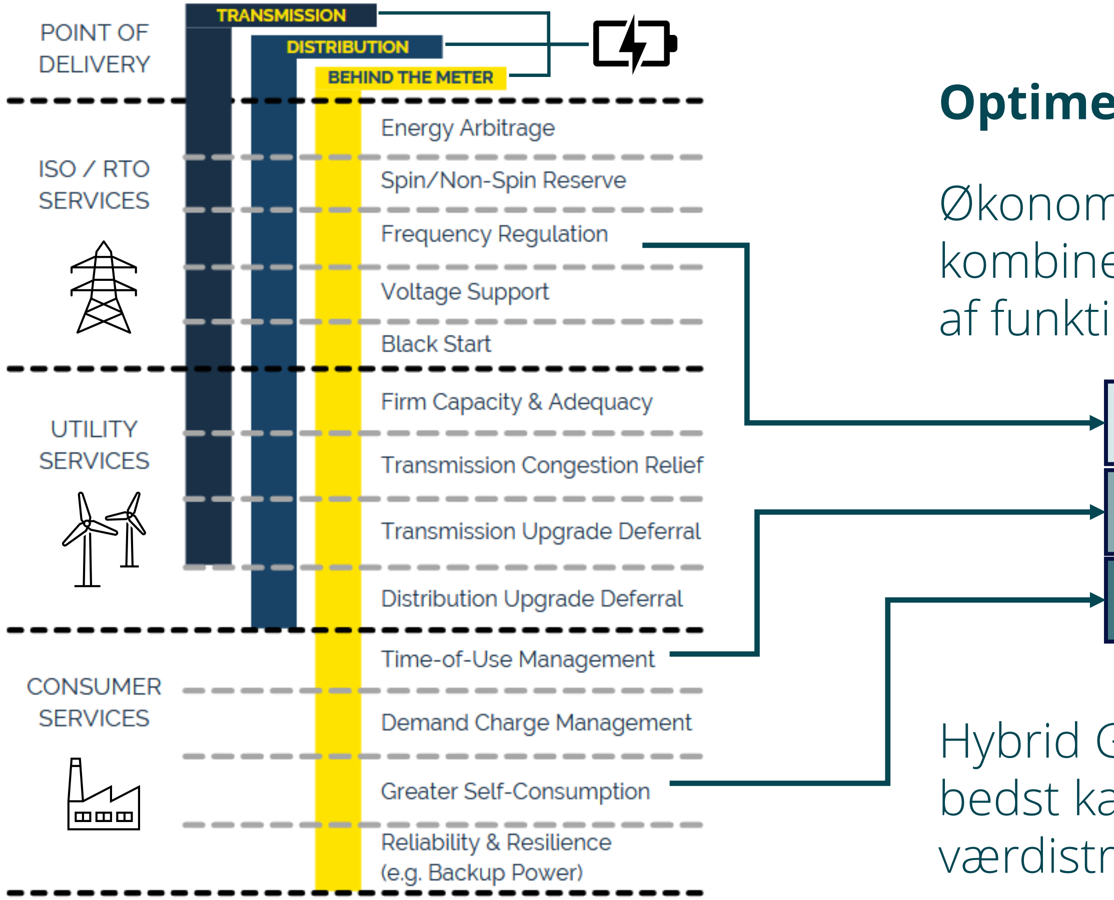
- DK2 is in RG-Nordic
  - FCR-N (Nordic MMS)
  - FCR-D up and down (Nordic MMS)
  - FFR (National)
  - aFRR (PICASSO)
  - mFRR (MARI)

Netfrekvensen her til morgen



Kombineret portefølje





Optimering af indtægt fra diverse værdistrømme

Økonomien bag BESS-enheder forbedres markant, når ydelser kan kombineres for at optimere og udnytte enhedens komplette række af funktioner.

Værdistrømme

- Frekvensregulering
- Time-of-use styring
- Øget egetforbrug

Hybrid Greentech kan evaluere, hvordan en BESS eller EV-portefølje bedst kan generere indtægt på timebasis ved at kombinere værdistrømme fra diverse ydelser.

Daily operation

The EMS calculates an optimal schedule with an optimisation horison of 24 hours.

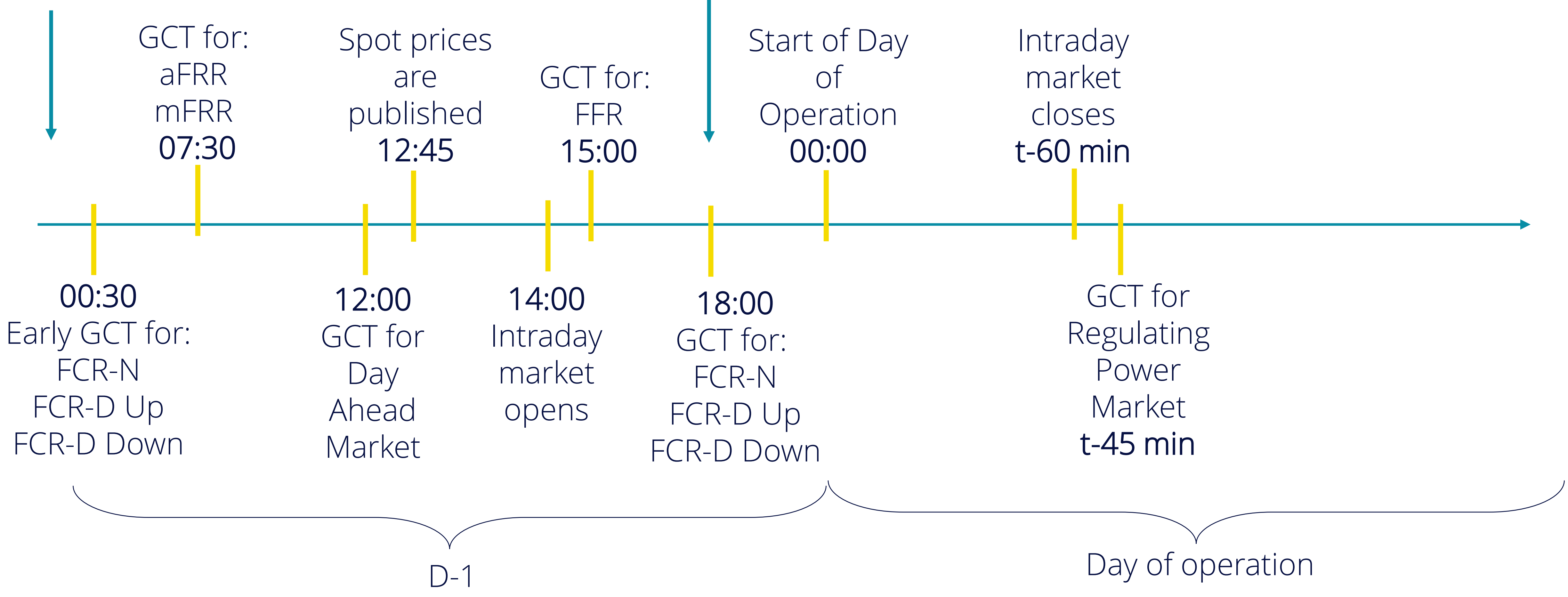
It is **recalculated** every minute based on updates on: **SOC**, **production**, **consumption** and **forecasts**

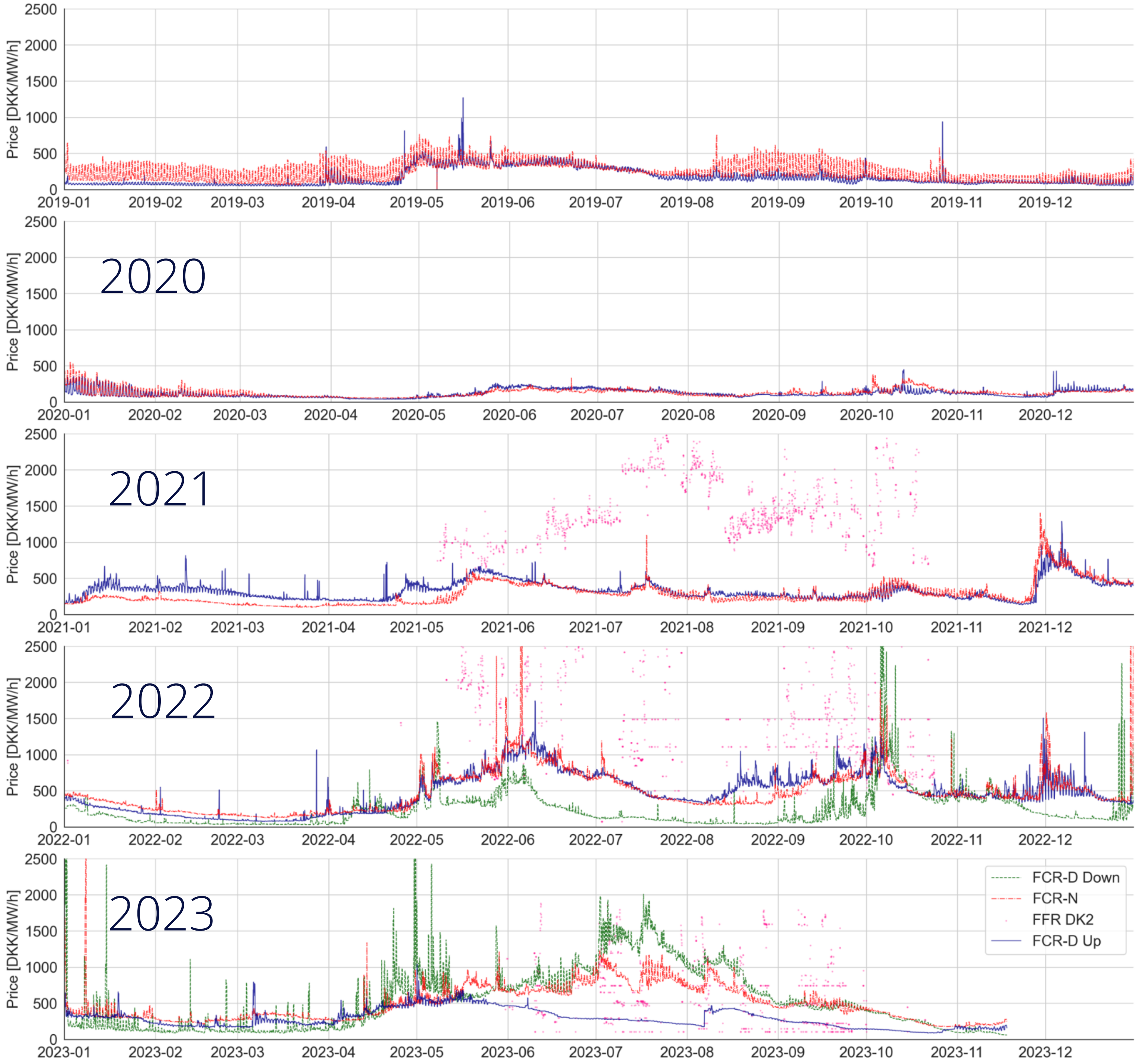
Forecast:
- Spot price
- Power capacity for each market
- Price and cost of each market
- Decide on markets including FFR

Commit capacity and prices

Forecast :
- Power capacity for each market

Commit remaining capacity and prices

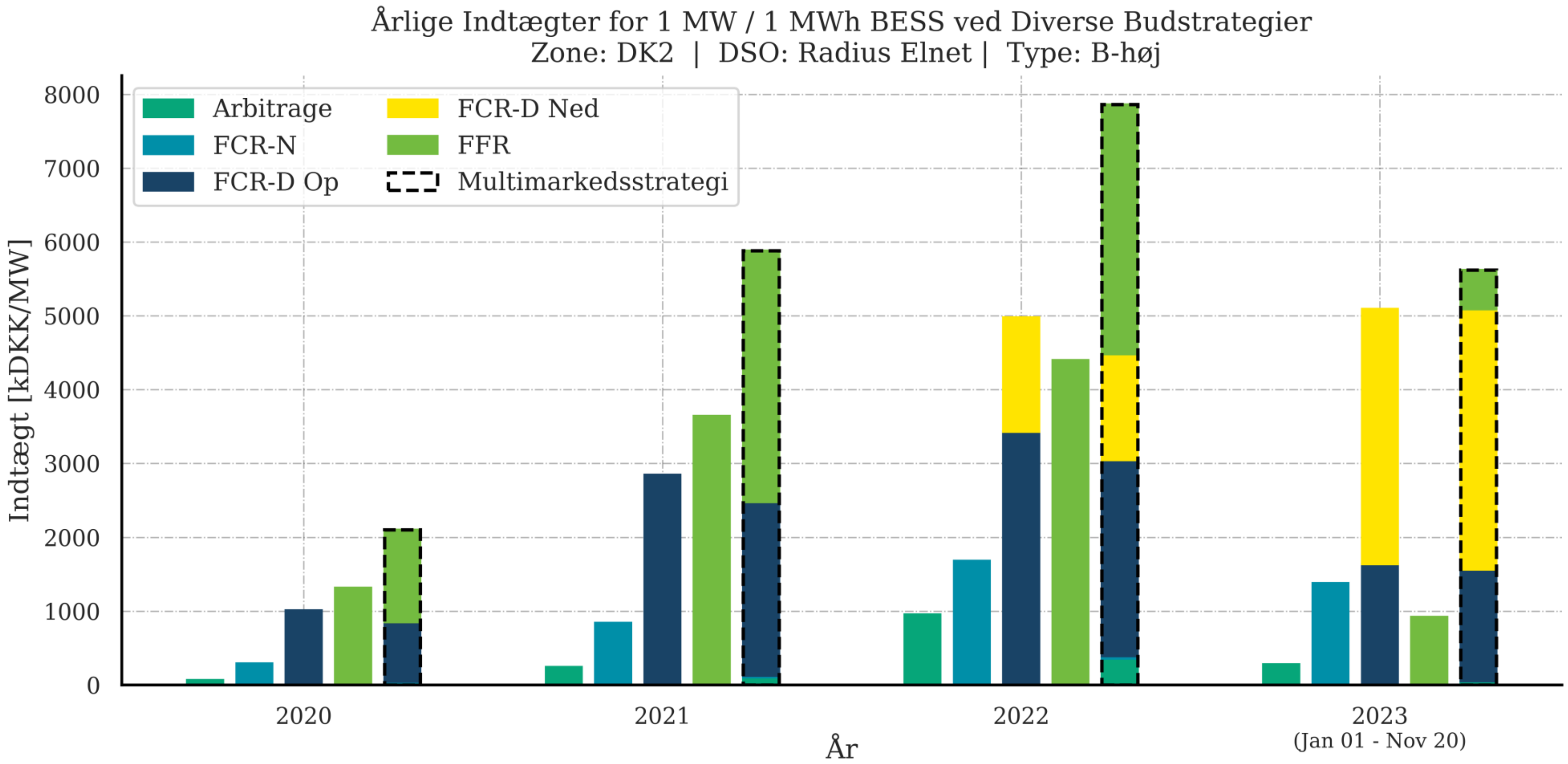




ALIGHT
SUSTAINABLE AVIATION

Optimal ***kombination af markeder*** på timebasis giver de bedste indtægter.

Økonomisk værdi af systemydelser

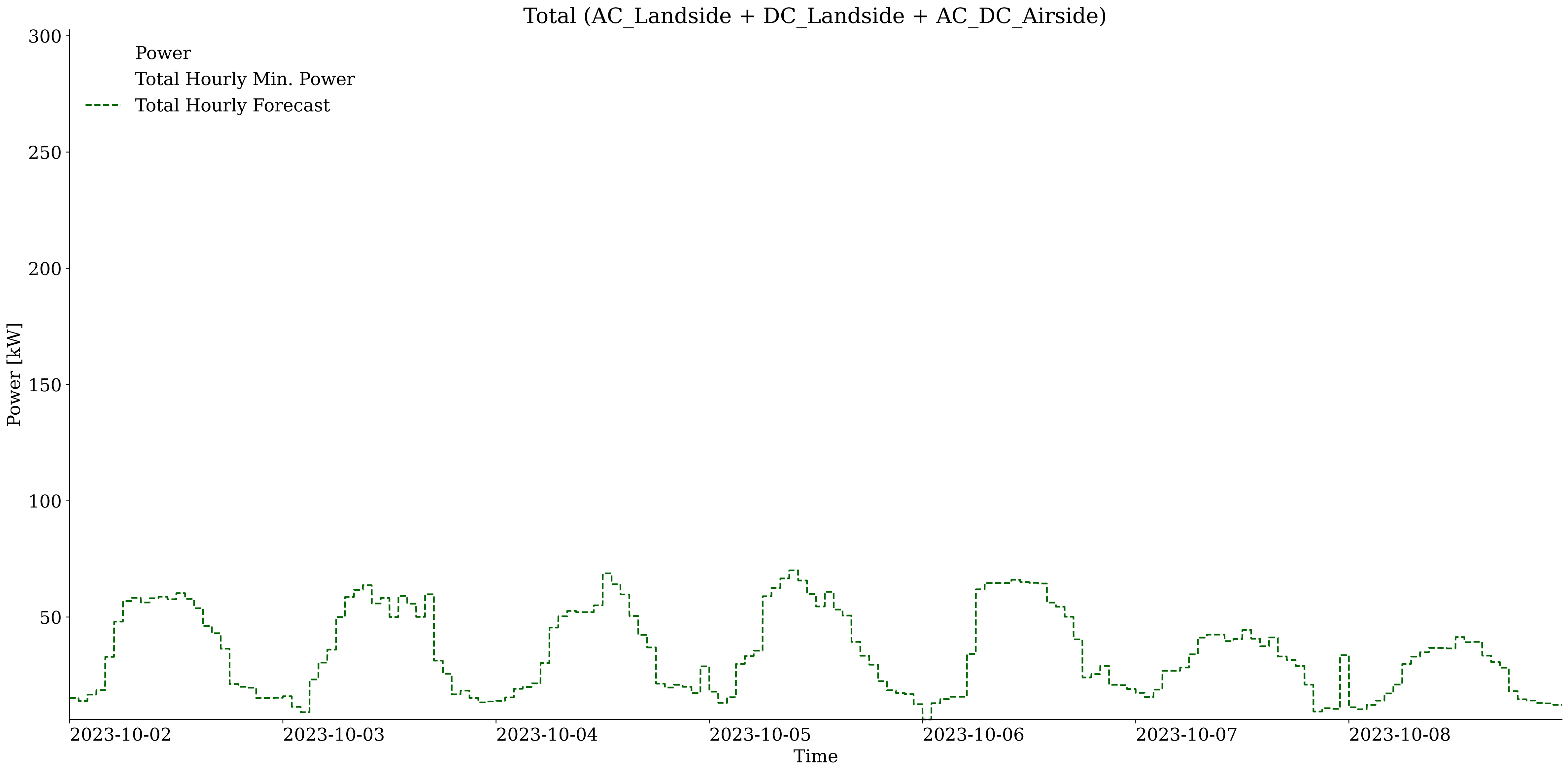


Historisk indtjening:

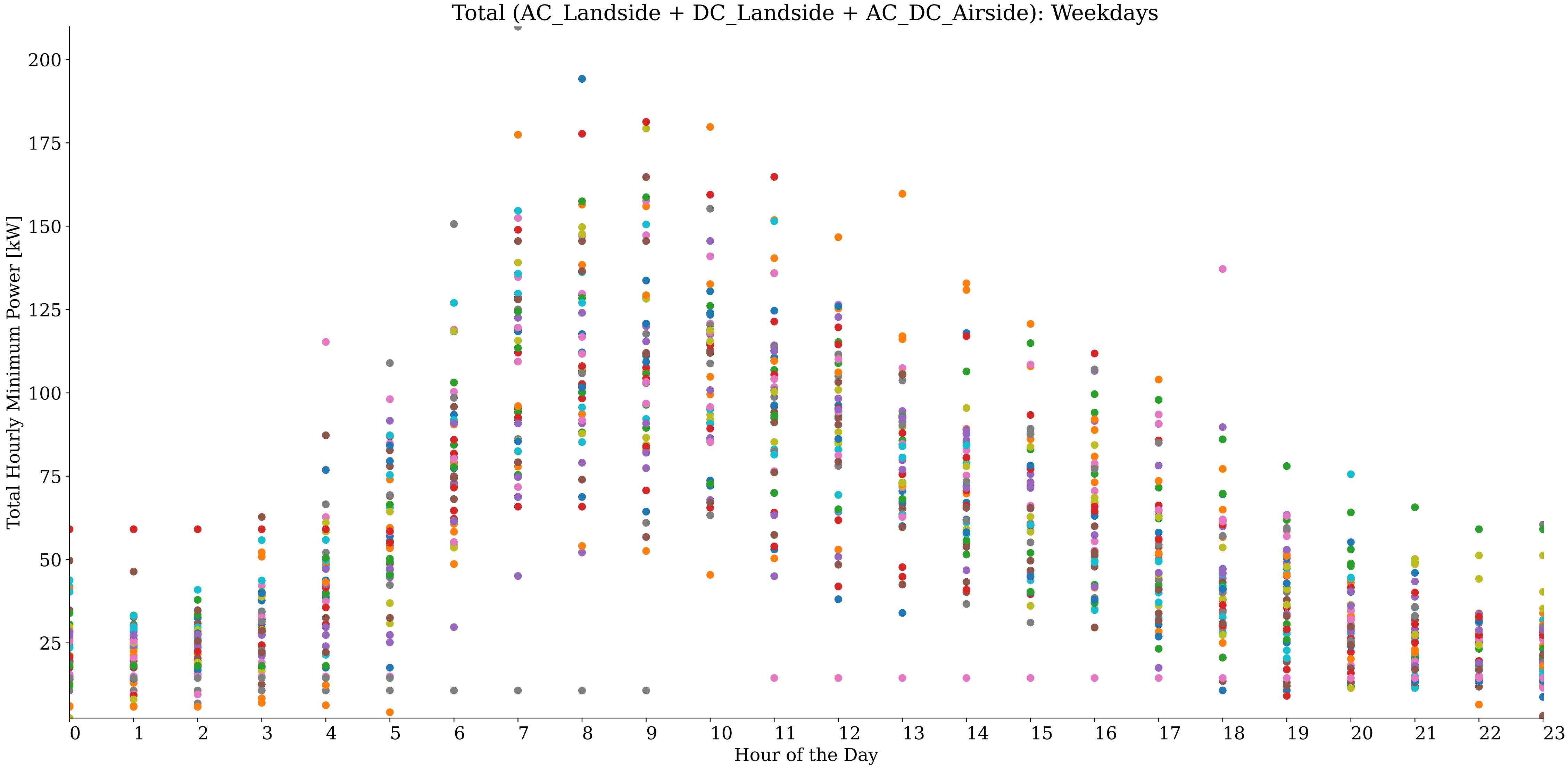
1 MW/1 MWh batteri med 90% round-trip effektivitet.

Inklusiv omkostning til op- og afladningstab og tariffer.

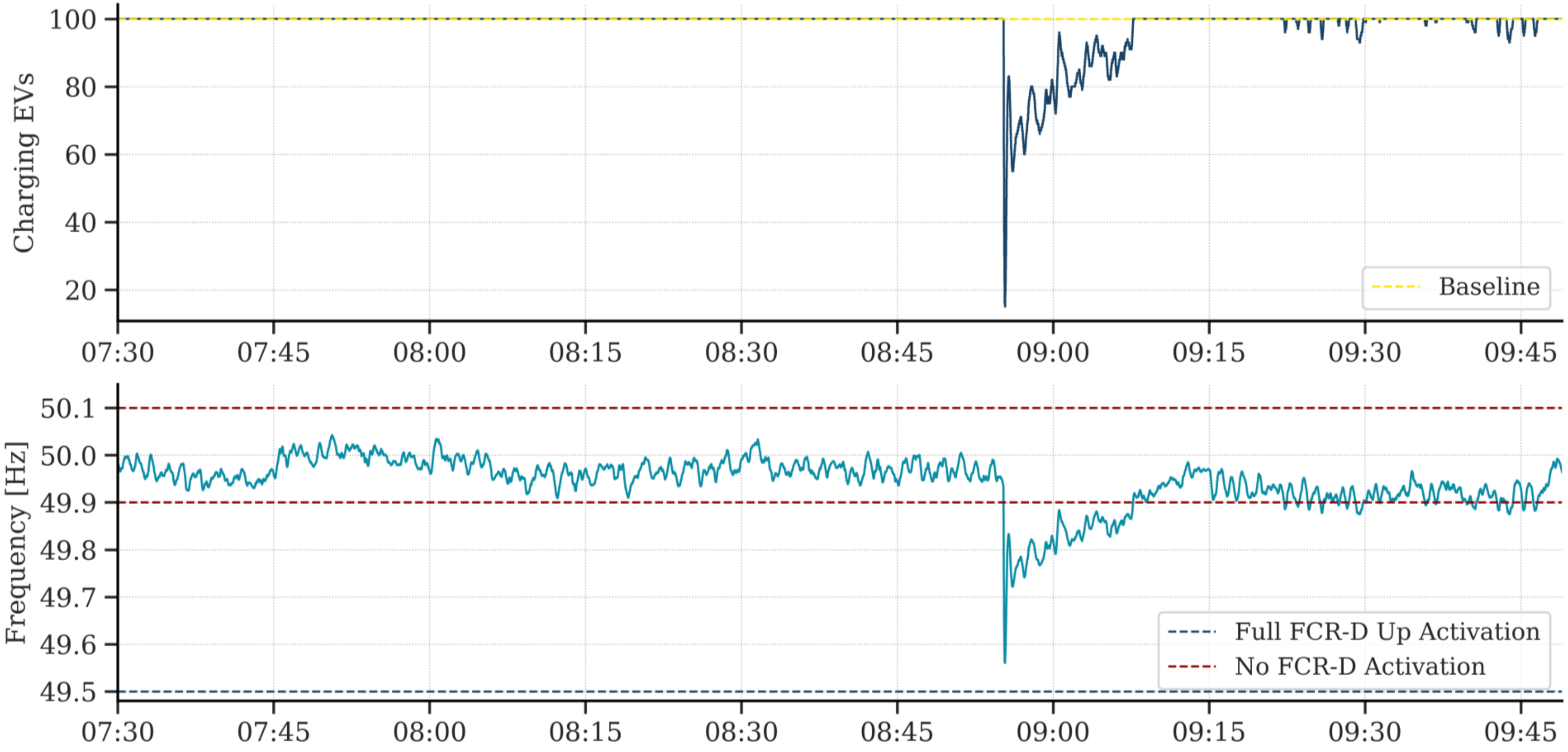
Consumption from chargers



Dagligt opladsningsmønster



Eksempel på leverance af FCR-D med elbiler



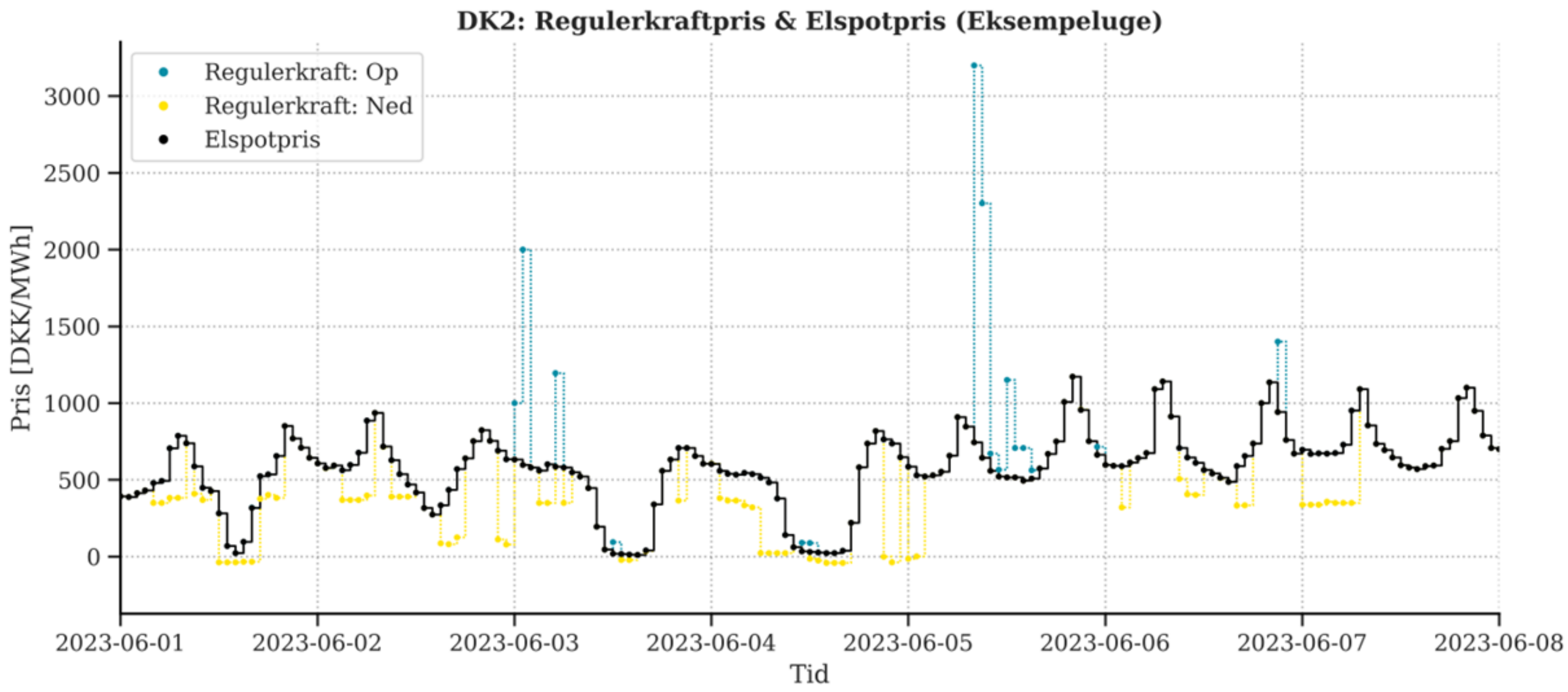
Leverance af *FCR-D Op* med
baseline på 100 elbiler styret ved *ON/OFF-kontrollogik*.

Ladningsprocessen er *uforstyrret* det meste af tiden.

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

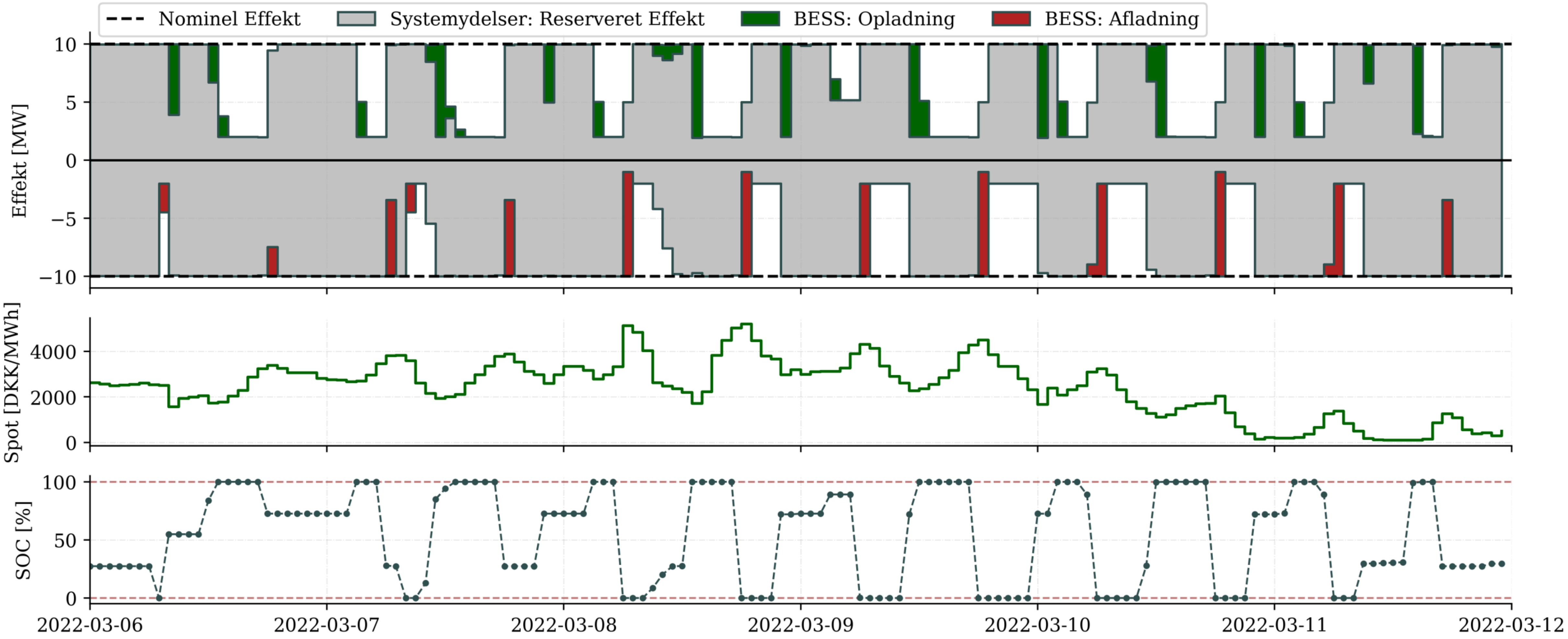
Levering af regulerkraft med ladestandere

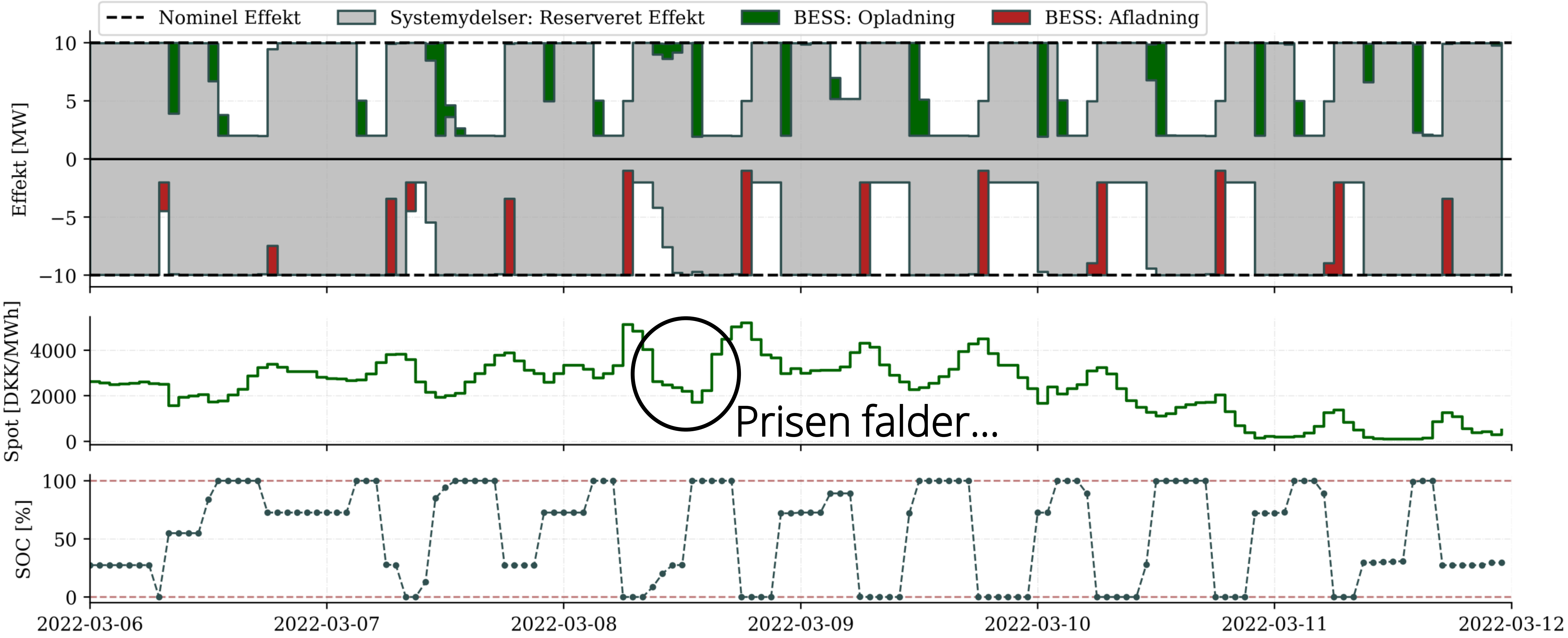


Eksempel på budstrategi:

- Jeg vil gerne **øge** mit energiforbrug, hvis prisen er **50%** under spot prisen.
- Jeg vil gerne **reducere** mit energiforbrug, hvis prisen er **50%** over spot prisen.

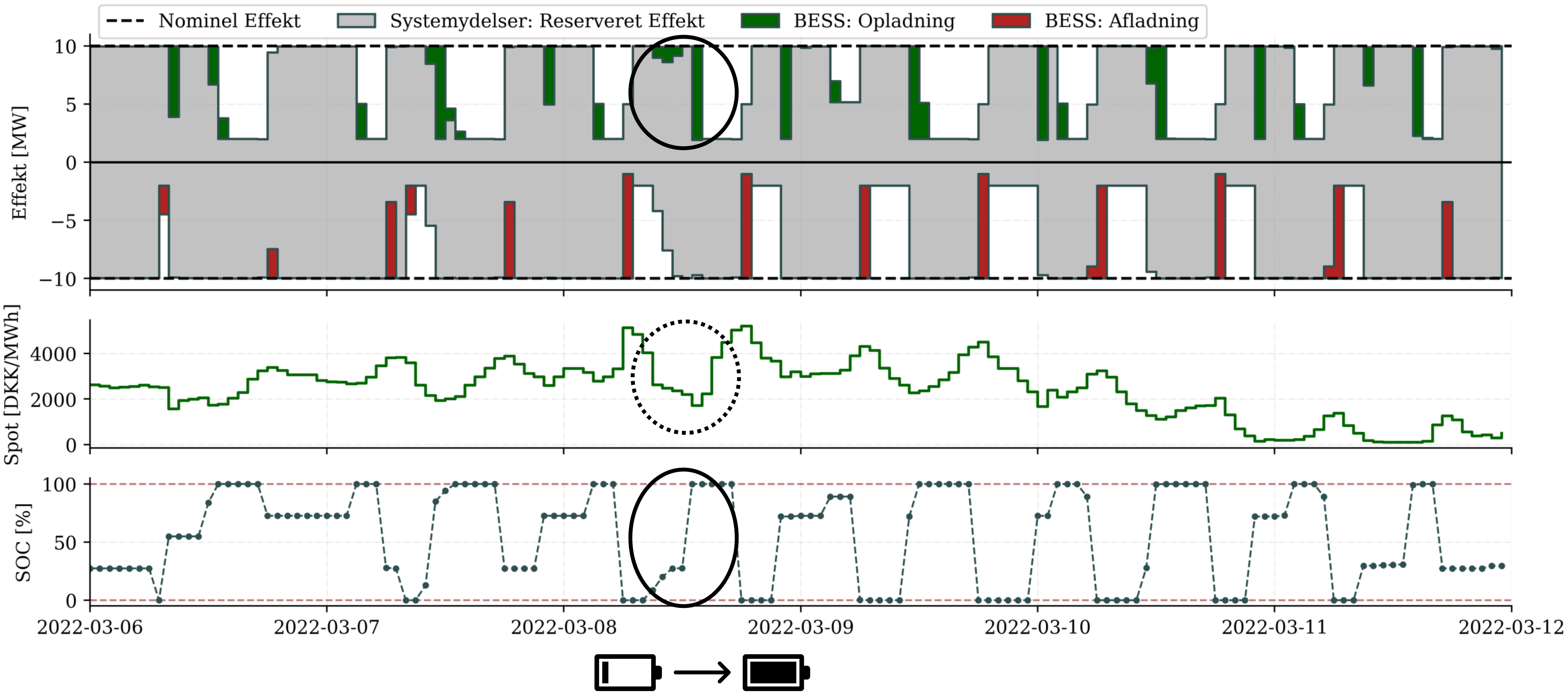
Eksempel på batteridrift: FCR & Arbitrage

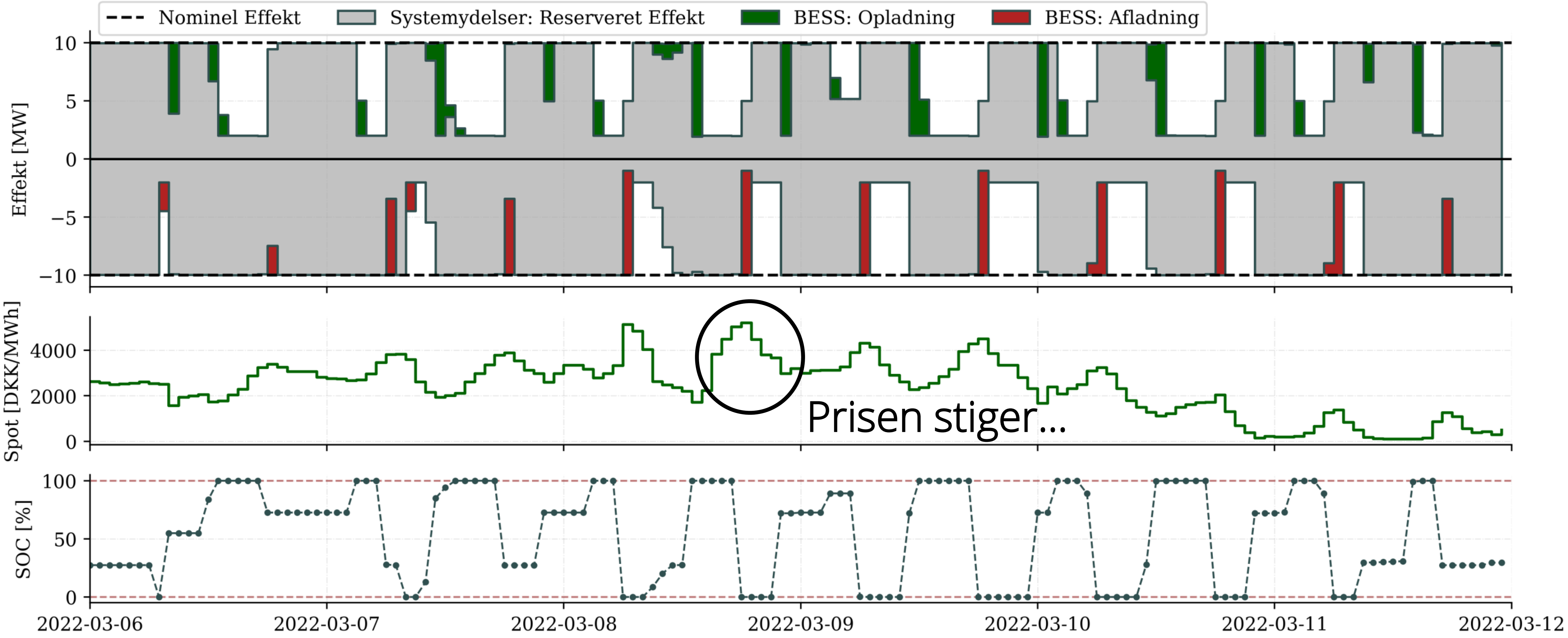




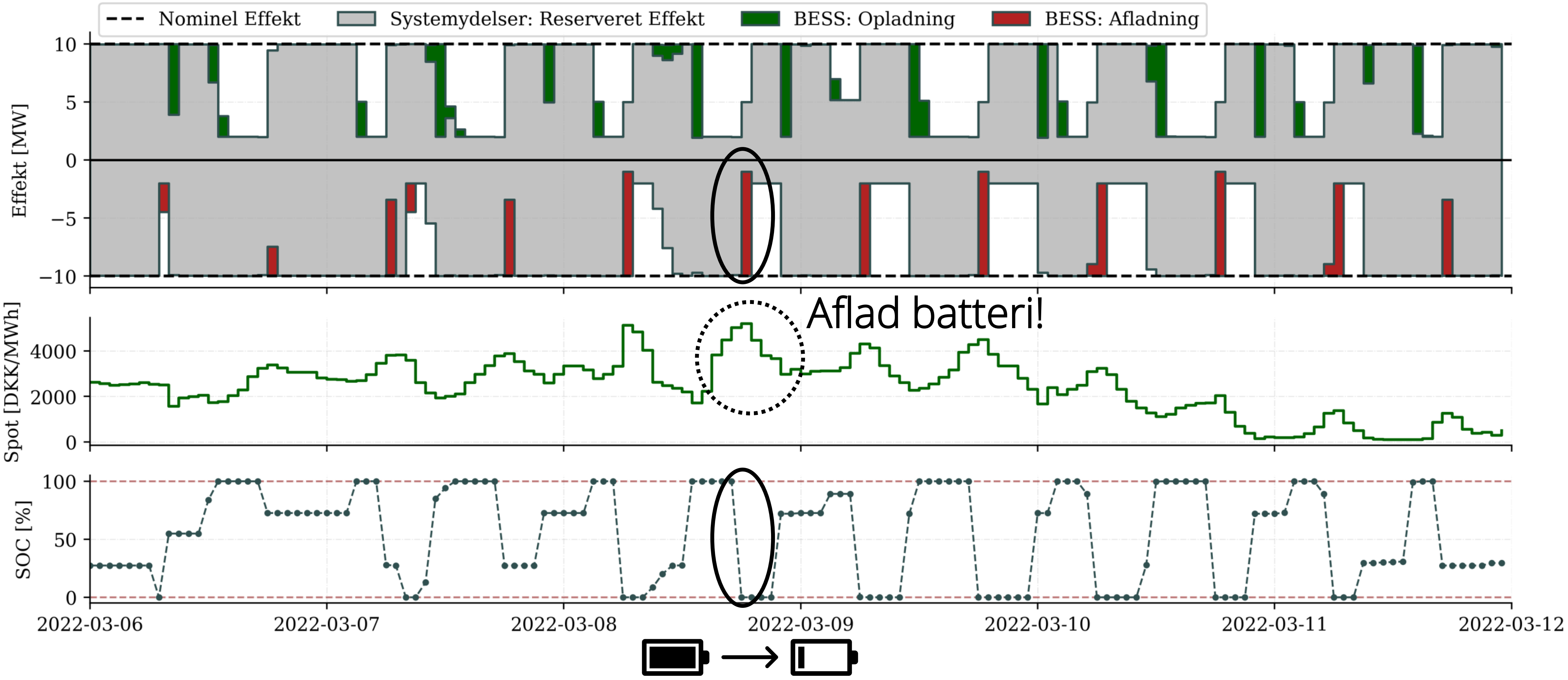
Nominel Effekt
Systemydelser: Reserveret Effekt
BESS: Opladning
BESS: Afladning
Effekt [MW]
Spot [DKK/MWh]
SOC [%]
Prisen falder…
2022-03-06
2022-03-07
2022-03-08
2022-03-09
2022-03-10
2022-03-11
2022-03-12

Oplad batteri!





Nominel Effekt
Systemydelser: Reserveret Effekt
BESS: Opladning
BESS: Afladning
Effekt [MW]
10
5
0
−5
−10
Spot [DKK/MWh]
4000
2000
0
Prisen stiger…
SOC [%]
100
50
0
2022-03-06
2022-03-07
2022-03-08
2022-03-09
2022-03-10
2022-03-11
2022-03-12

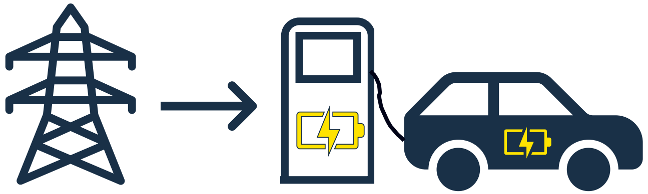
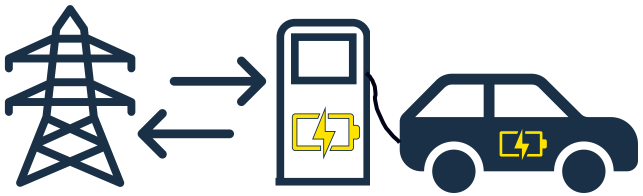


Nominel Effekt
Systemydelser: Reserveret Effekt
BESS: Opladning
BESS: Afladning
Effekt [MW]
Spot [DKK/MWh]
SOC [%]
Aflad batteri!
2022-03-06
2022-03-07
2022-03-08
2022-03-09
2022-03-10
2022-03-11
2022-03-12

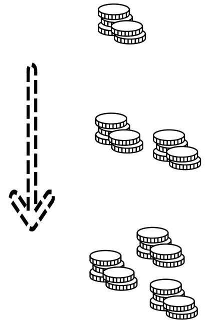
This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

ALIGHT
SUSTAINABLE AVIATION

Konklusion

Unidirektional ladning		V2G-ladning
		
✓	Smart Charging	✓
✗	Arbitrage	✓
*(✓)	Frekvensydelser	✓

…



* *Levering af nedregulering (f.eks. FCR-D Ned) kræver i dette tilfælde, at opladningens baseline nedjusteres, så opladningens effektforbrug kan øges ved aktivering af reserven.*

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 957824

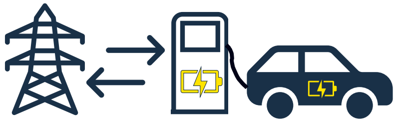
Konklusion

- Smart charging og intelligent kontrol har stærkt potentiale for at:
  - *Mindske CO2-indholdet* på tværs af use-cases
  - *Skabe besparelser* ved opladning

- Leverance af især *FCR-D og FFR* kan *øge indtægter markant* med *minimal indflydelse* på driften af enhederne

- Et *større antal enheder* kan bydes ind i reservemarkederne som en *kombineret portefølje*

- *V2G*-funktionalitet kan *øge fleksibiliteten og potentialet* markant



White paper er ude nu.

AVANCERET ENERGILAGRING

POTENTIAL FOR OPTIMAL OPERATION OF INDUSTRIAL HEAT PUMPS WITH THERMAL ENERGY STORAGE FOR EMISSIONS AND COST REDUCTION

MAGNUS LYCK HANSEN, VIEGAND MAAGØE

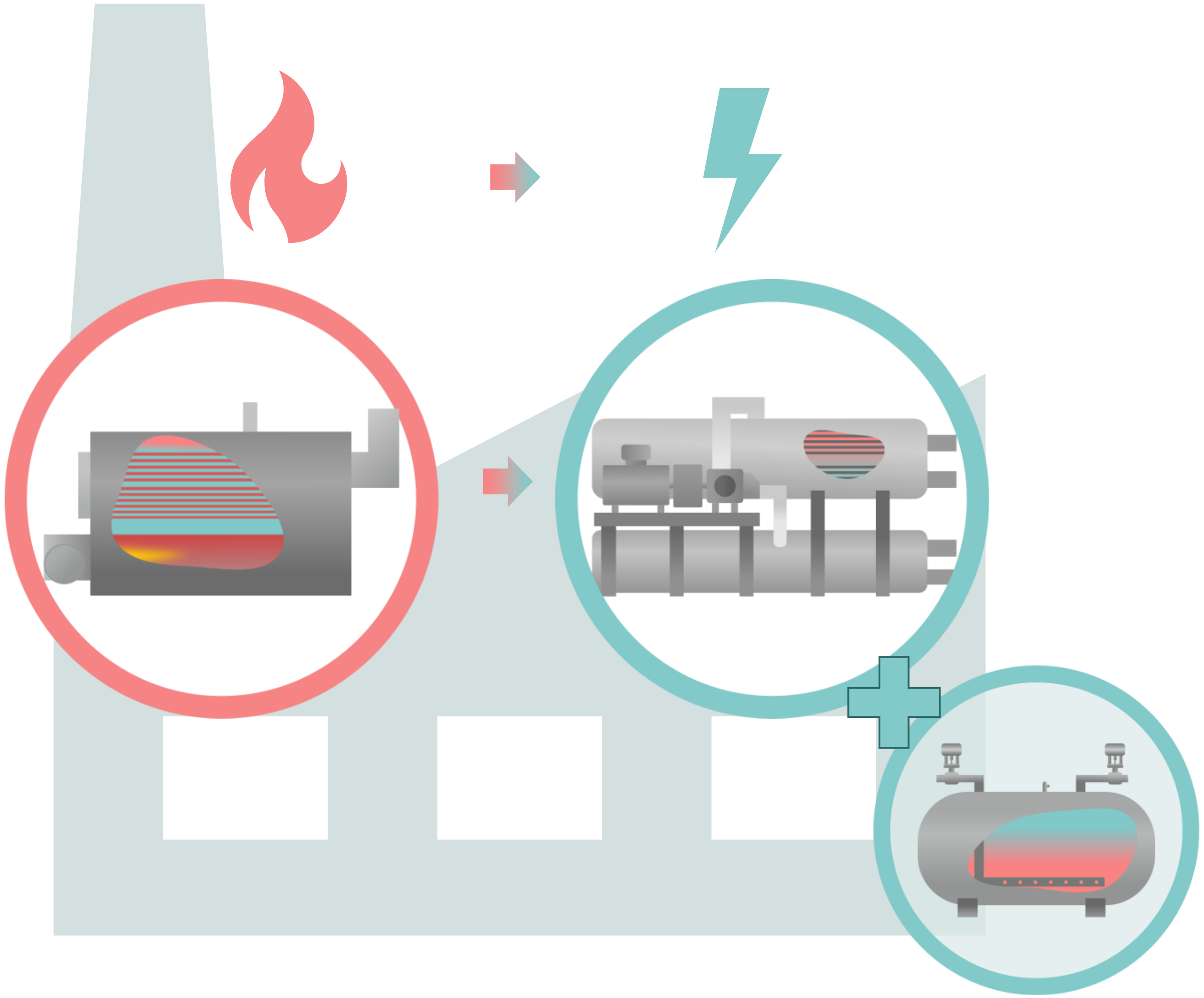
DTU

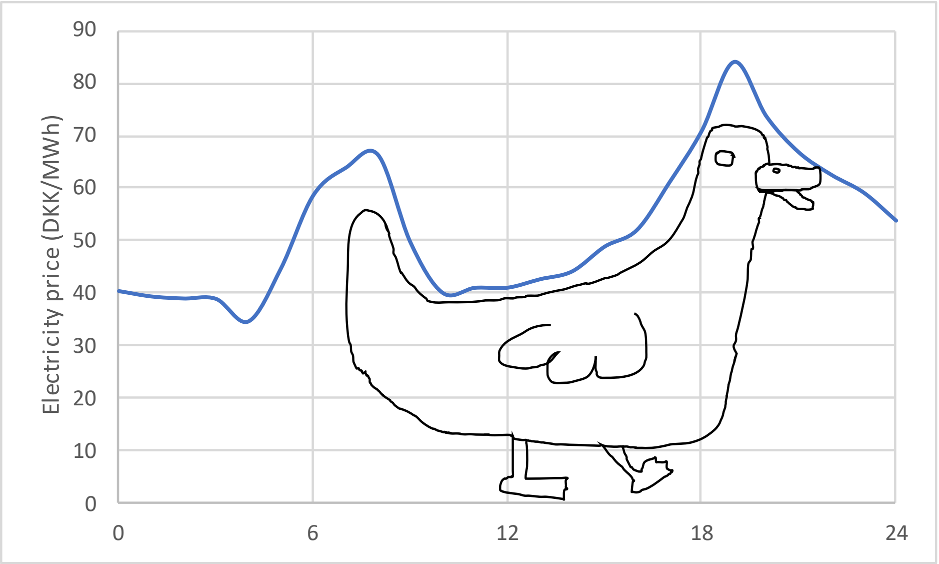
Roger Padullés, Technical University of Denmark

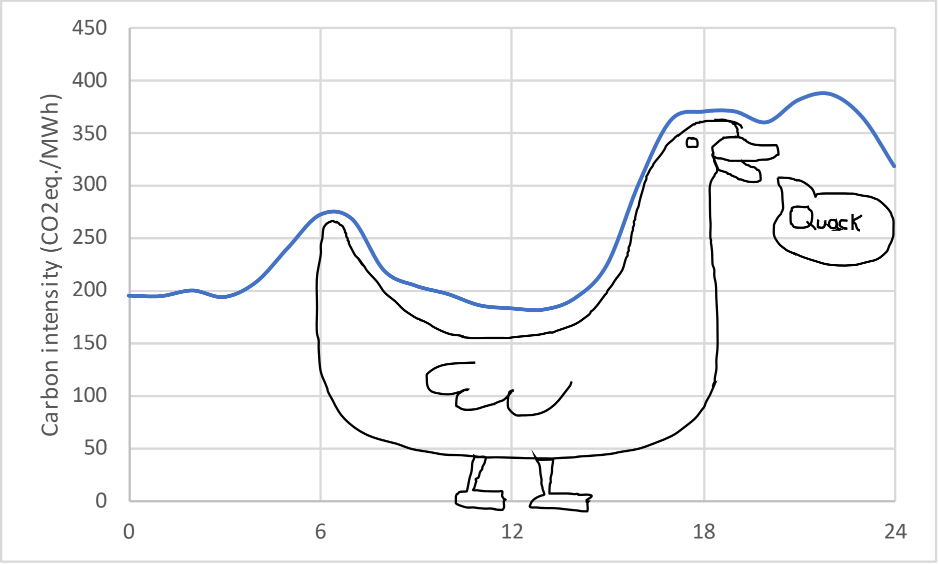
Potential for optimal operation of Industrial Heat Pumps with Thermal Energy Storage for emissions and cost reduction

Presented by Magnus Lyck Hansen, Viegand Maagøe

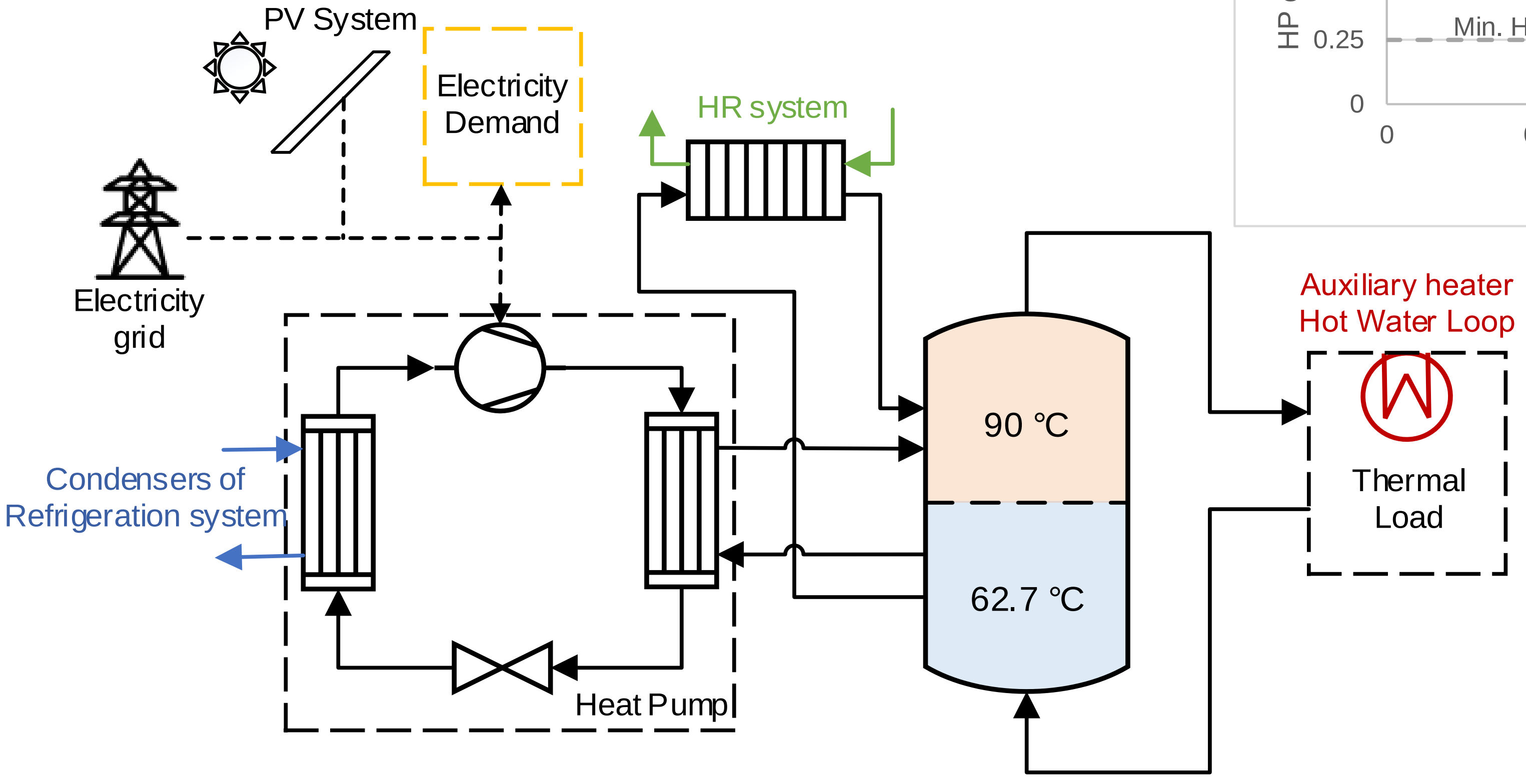
Background and motivation







Case Study



Smart control considering:

- Price/CO2 fluctuations
- Solar radiation
- Actual load and HR

- How important is a smart control of the heat pump to optimize cost and/or CO2?
- Which are the most important parameters to estimate this potential?
- How does the optimal size of the HP+Tank system differ if load-shifting is considered?

Method

Indexed by time:

- Electricity price / CO_2 intensity grid
- Gas price / CO_2 emissions gas
- Load
- Heat recovery
- Electricity consumption
- PV output

Single value parameters:

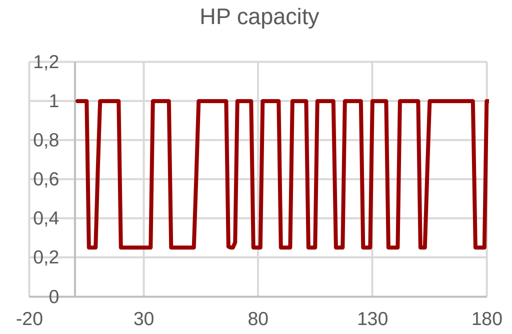
- Tank capacity
- HP max. capacity
- **COP (Jensen et al. 2018)**
- Max. ramp up/ramp down
- Min. HP load

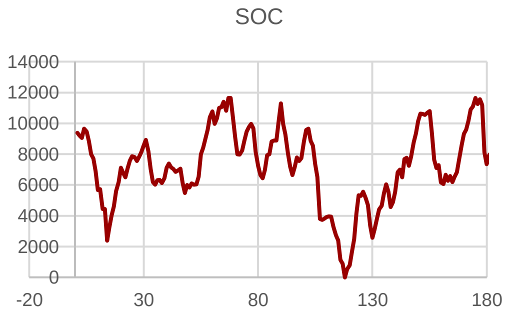
Optimal size of the system

PYOMO LP MODEL

- Optimize operation cost
- Optimize carbon emissions

State of charge
HP capacity
Boiler output
Electricity sold
Electricity purchase

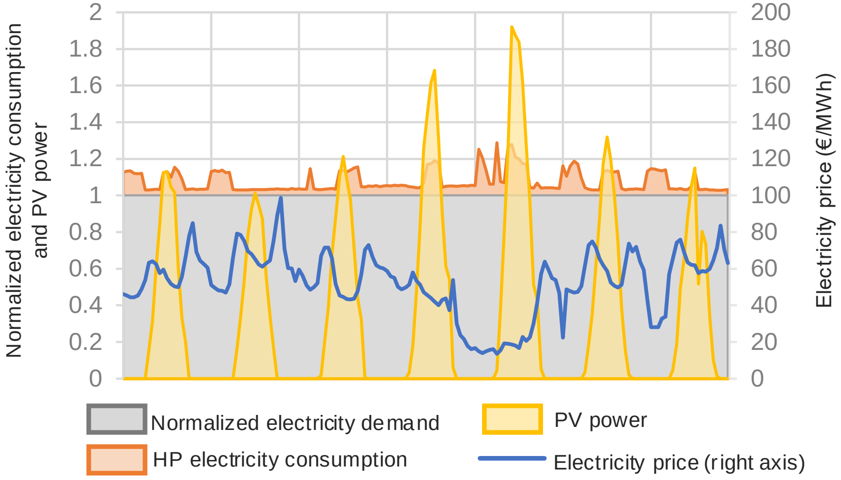


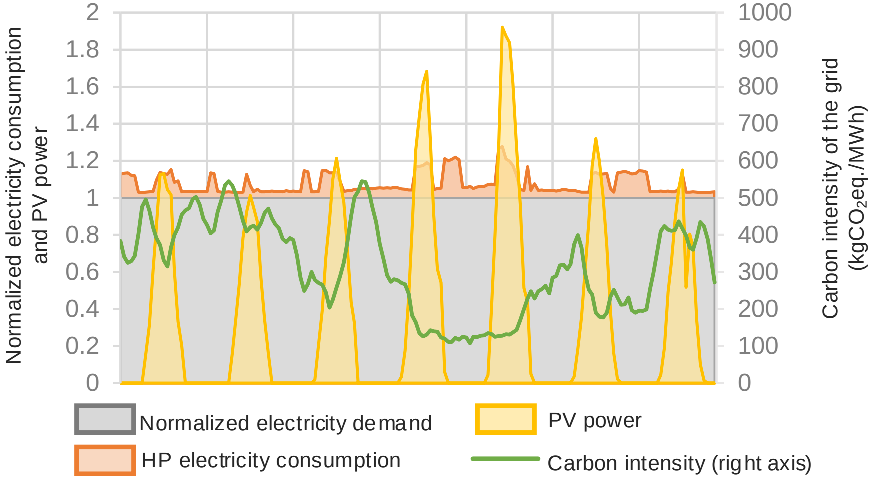


Uncertainty and sensitivity analysis
Monte Carlo simulations and SRC method

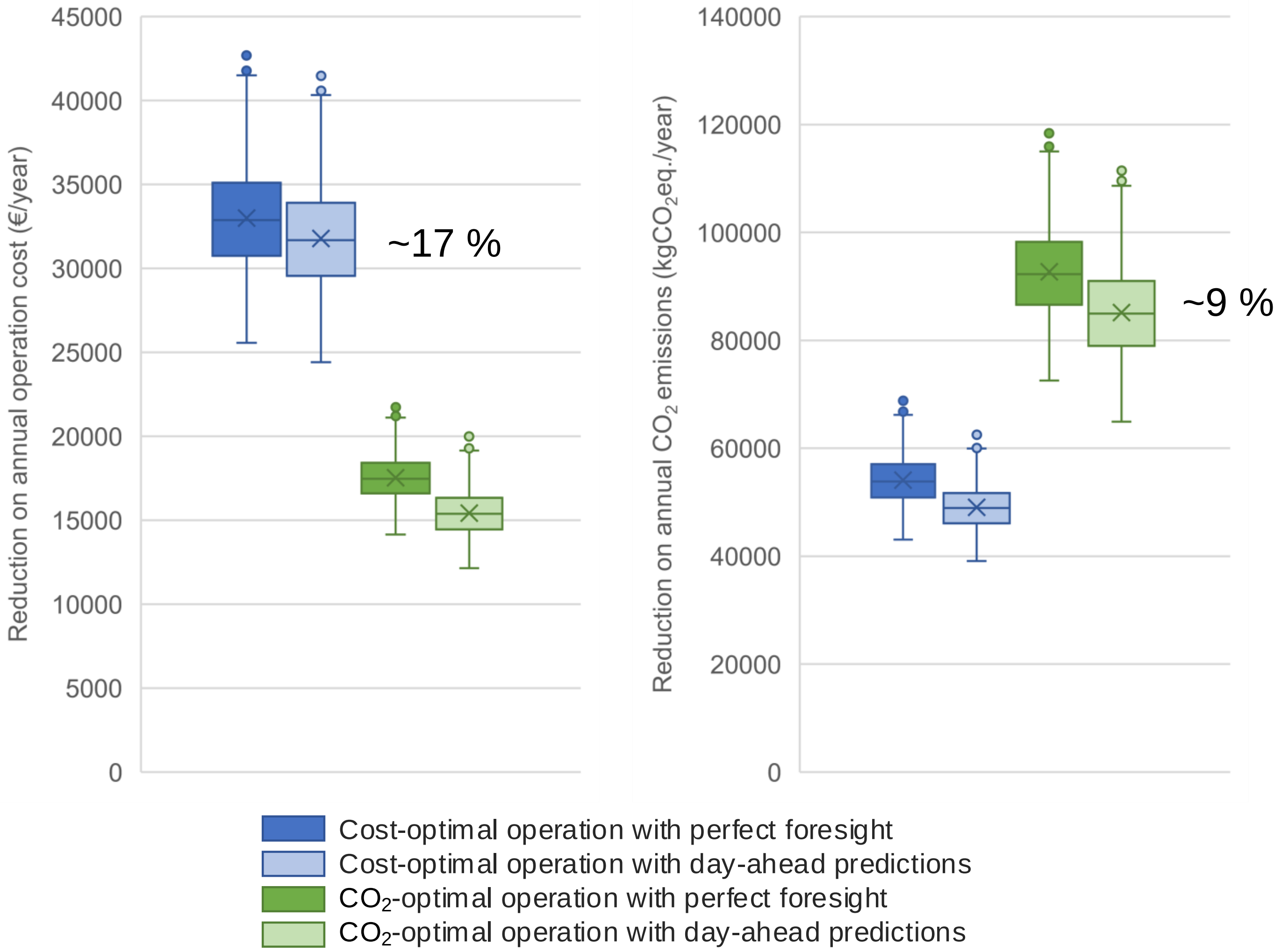
Parameter	Mean value	Type of deviation	Deviation
$Q_{HP,max}$	1.75 MW	Uniform, absolute	0.01 MW
V_{tank}	375 m^3	Uniform, absolute	1 m^3
T_{source}	35 °C	Uniform, absolute	3 K
$T_{sink,in}$	62.7 °C	Uniform, absolute	1 K
$T_{sink,out}$	90 °C	Uniform, absolute	1 K
$\eta_{is,c}$	75 %	Normal, absolute	5 %
f_Q	10 %	Normal, absolute	5 %
ΔT_{pp}	5 K	Uniform, absolute	3 K
Error on COP approx.	0 %	Normal, relative	10 %
η_{Boiler}	95 %	Normal, absolute	5 %
$x_{min,load}$	25 %	Uniform, absolute	10 %
$x_{ramp-up}$	90 %	Uniform, absolute	10 %
$x_{ramp-down}$	90 %	Uniform, absolute	10 %

Results – example of HP behaviour





Results – potential for CO2 and cost reduction



Results – Sensitivity analysis

What assumptions are important to estimate the saving potential?

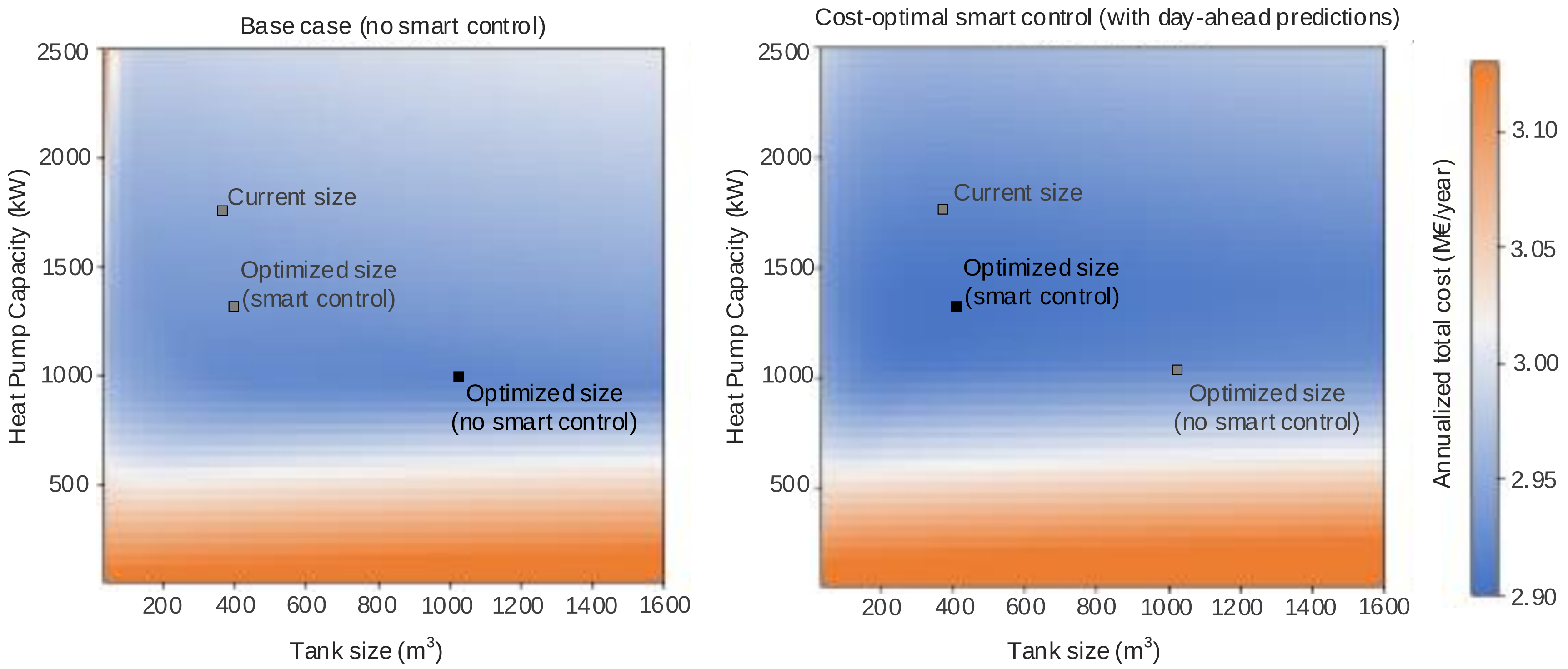
	Cost reduction (Cost-optimal operation with day-ahead predictions)	Cost reduction (CO_2-optimal with day-ahead predictions)	Emissions reduction (Cost-optimal operation with day-ahead predictions)	Emissions reduction (CO_2-optimal with day-ahead predictions)
$Q_{\mathrm{HP,max}}$	0.003	0.017	0.003	0.010
V_{tank}	0.007	0.004	0.006	0.007
T_{source}	-0.157	-0.174	-0.150	-0.173
$T_{\mathrm{sink,in}}$	-0.014	-0.021	-0.020	-0.016
$T_{\mathrm{sink,out}}$	0.058	0.066	0.061	0.062
$\eta_{is,c}$	-0.517	-0.571	-0.493	-0.569
f_Q	0.125	0.136	0.118	0.137
$\Delta \mathrm{T}_{pp}$	0.289	0.319	0.276	0.318
Error from Eq. 1	-0.305	-0.336	-0.290	-0.337
η_{Boiler}	0.005	0.005	0.005	0.006
$x_{\mathrm{min.load}}$	-0.694	-0.607	-0.725	-0.610
$x_{\mathrm{ramp-up}}$	0.000	-0.002	-0.001	-0.002
$x_{\mathrm{ramp-}down}$	-0.002	-0.002	-0.002	-0.003
R^2	0.995	0.991	0.994	0.992

Define COP of HP

Minimum HP load,

Is it possible to turn OFF?

Optimal system size



If smart control is implemented:

- Design size of tank can be reduced → better use of storage capacity
- Capacity of HP should be increased → To deliver same amount of heat but concentrated in lower-price hours

Conclusions

Smart heat pump operation when combined with a heat storage

- Can reduce operation costs (by up to 17% in studied case)
- Can reduce CO2 emissions (by up to 9% in studied case)
- Day-ahead predictions are enough for significant reduction.
- Different size of the system: a bigger HP and a smaller tank is possible

Limitation and future work:

- More detailed TES model. Faster charge/discharge could increase mixing losses.
- More detailed HP model. Dynamics of the system and variable COP with part-load.

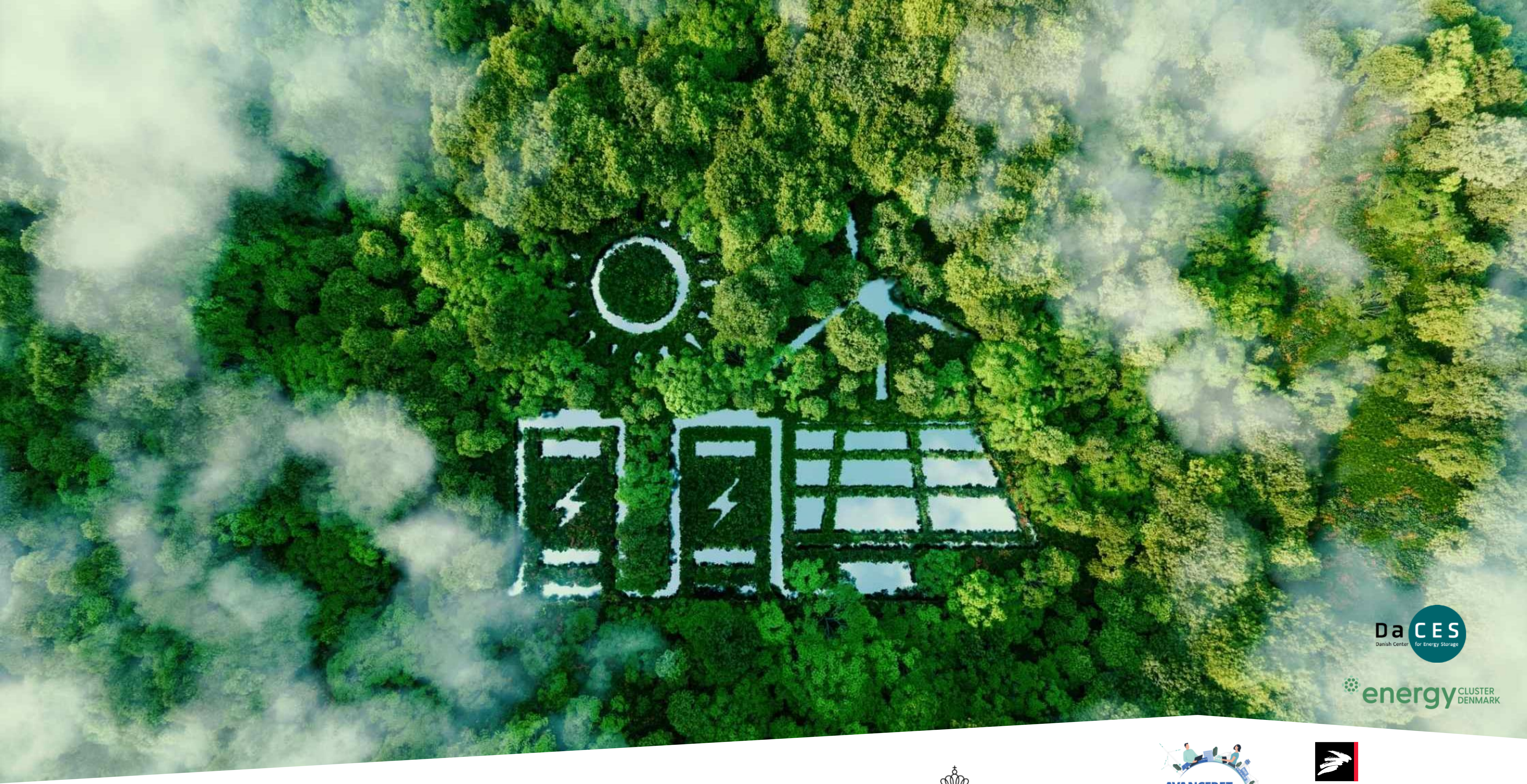
Thank you for your attention!

Acknowledgements:

AVANCERET ENERGILAGRING

AVANCERET ENERGILAGRING – FORHOLDET MELLEM EFFICIENS OG EFFEKTIVITET

GUNNAR ROHDE, TEKNOLOGISK INSTITUT



DaCES Danish Center for Energy Storage

energy CLUSTER DENMARK

Uddannelses- og Forskningsstyrelsen

AVANCERET ENERGILAGRING KONFERENCE 2023

DANISH TECHNOLOGICAL INSTITUTE

Gunnar Rohde | 30.11.2023

Advanced Energy Storage

Effectiveness versus Efficiency

DaCES Danish Center for Energy Storage

energy CLUSTER DENMARK

Uddannelses- og Forskningsstyrelsen

AVANCERET ENERGILAGRING KONFERENCE 2023

DANISH TECHNOLOGICAL INSTITUTE

Agenda

1. Effectiveness and Efficiency of Energy Systems
2. The Energy System Today and in the Future
3. Consequences and Relevance for/of Energy Storage
4. Too Much is not Good Enough
5. Conclusion & Outlook

Uddannelses- og Forskningsstyrelsen

AVANCERET ENERGILAGRING KONFERENCE 2023

DANISH TECHNOLOGICAL INSTITUTE

Energy Effectiveness

- Why is something being done?
- Aligns with goals and objectives
- How can the future be improved?
- Requires external views
- Not easy to define and/or measure
- Requires subjective visioning

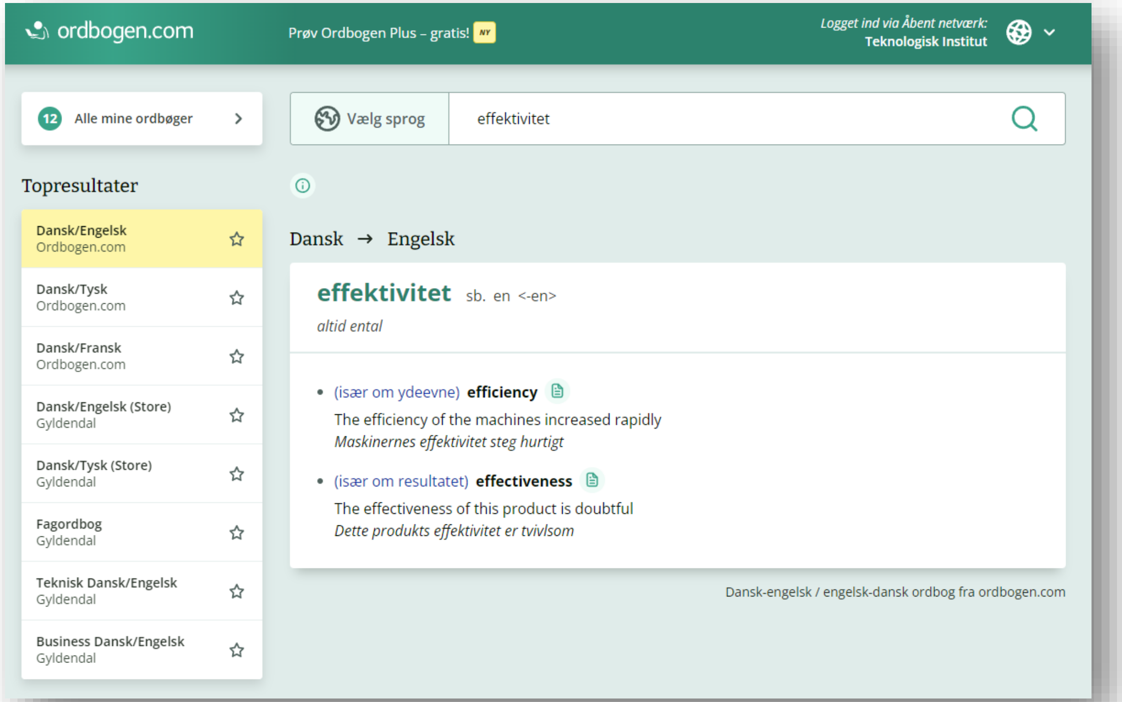
➔ *Doing the right things*

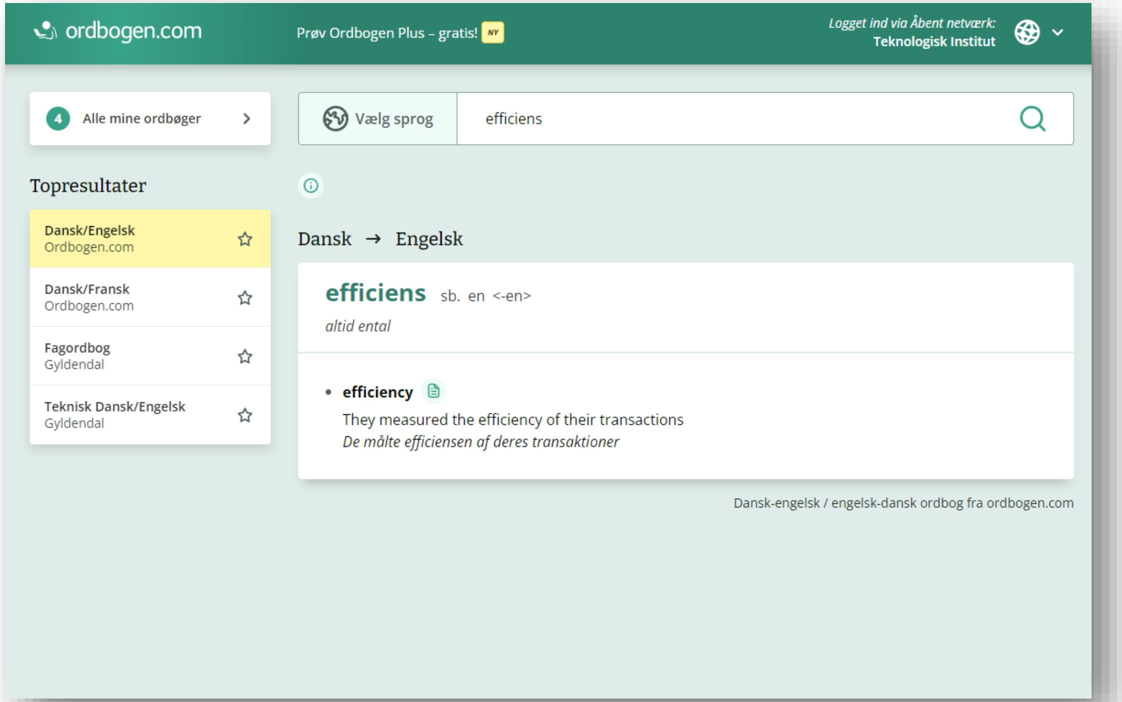
Energy Efficiency

- What needs to be done?
- Focusses on the process
- What can be improved now?
- Internal views are sufficient
- Easily measurable by specific metrics
- Objective analysis is sufficient

➔ *Doing the things right*

Effectiveness and Efficiency *in the Danish Language*





Uddannelses- og Forskningsstyrelsen

AVANCERET ENERGILAGRING KONFERENCE 2023

DANISH TECHNOLOGICAL INSTITUTE

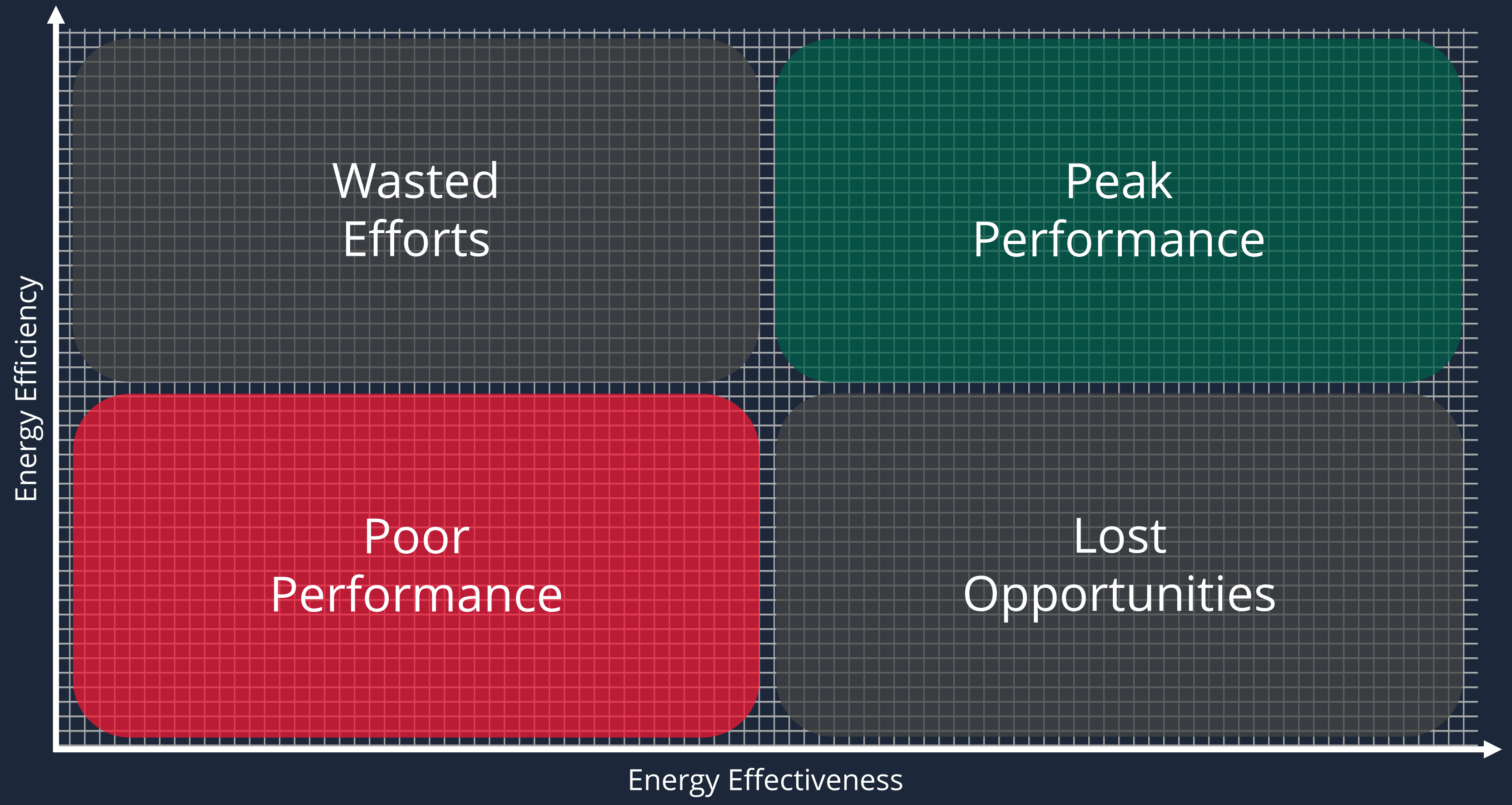
Effectiveness and Efficiency of Energy Systems

Energy Effectiveness

→ *Doing the right things*

Energy Efficiency

→ *Doing the things right*

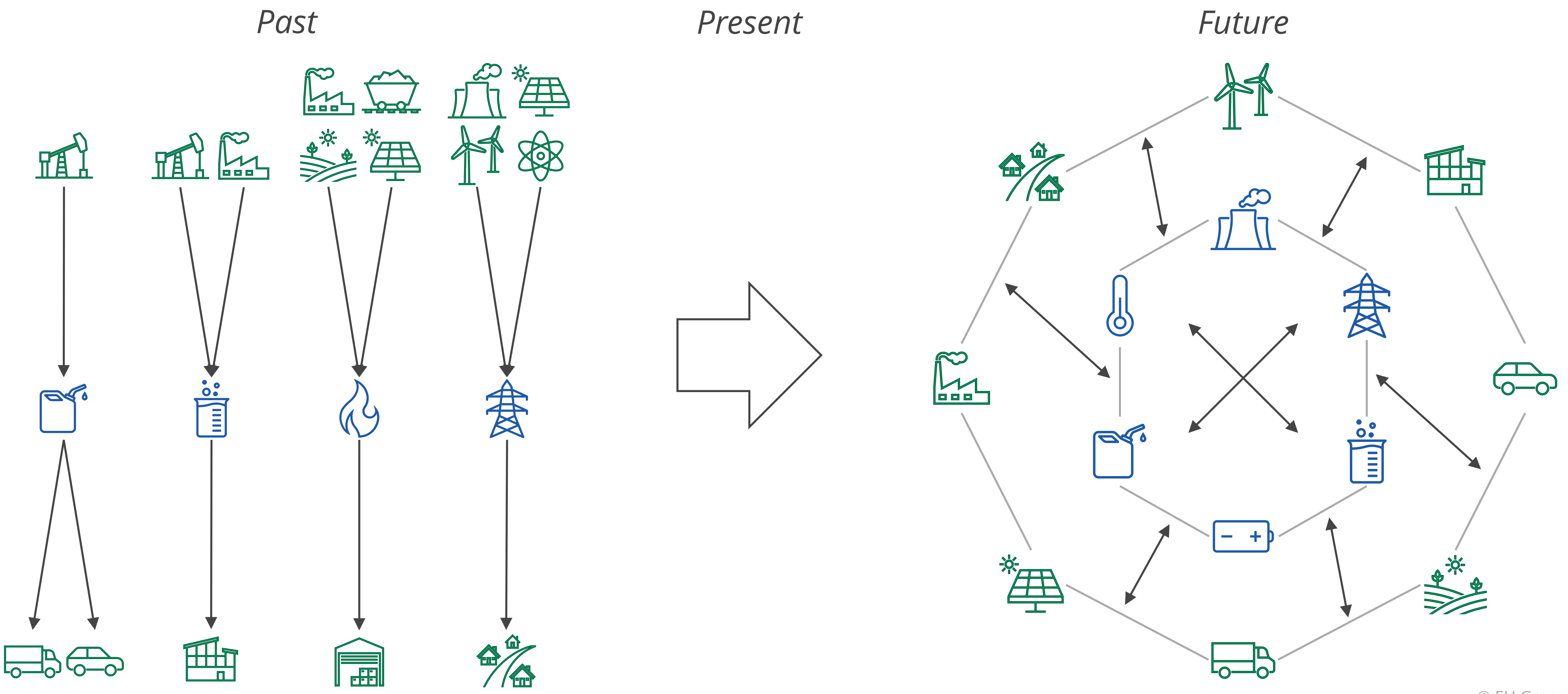


Uddannelses- og Forskningsstyrelsen

AVANCERET ENERGILAGRING KONFERENCE 2023

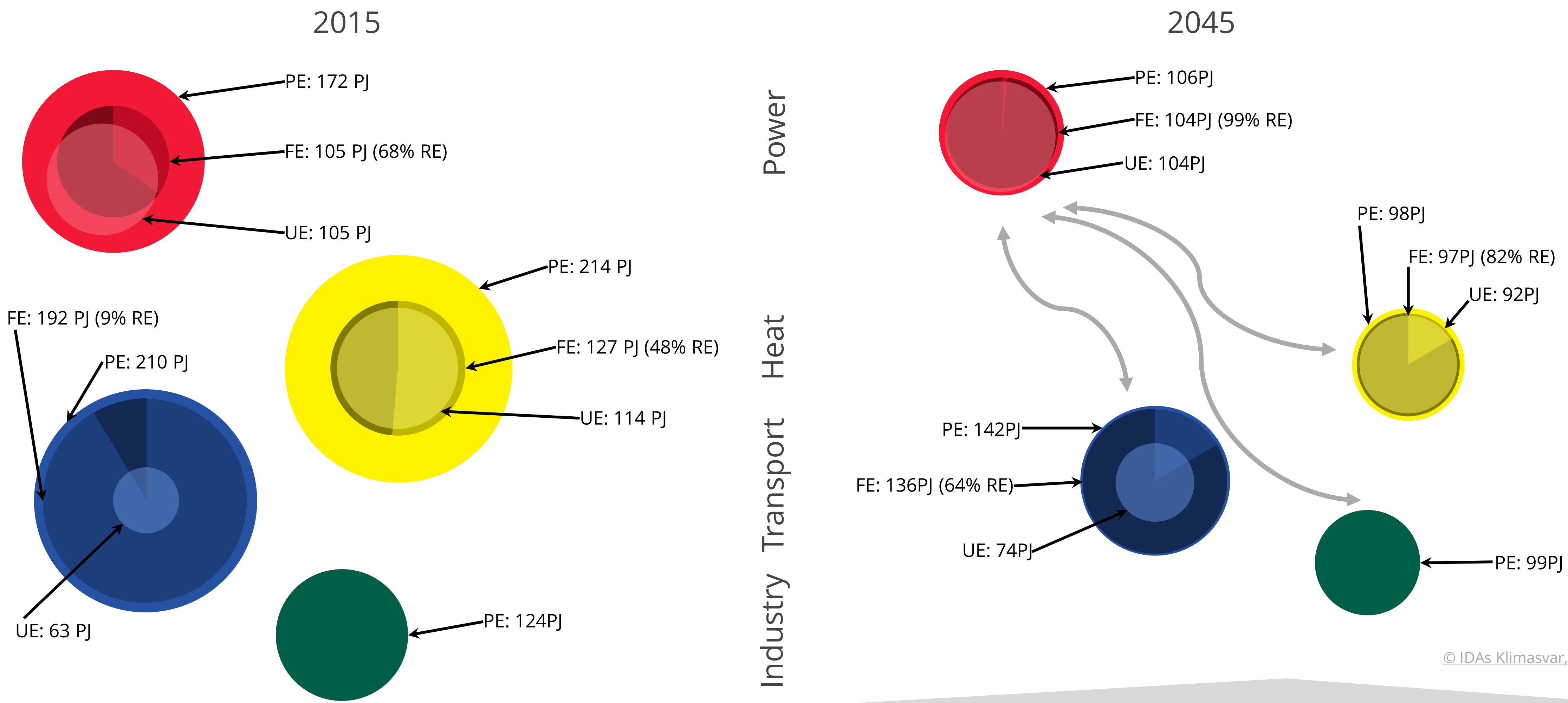
DANISH TECHNOLOGICAL INSTITUTE

The Energy System Today and in the Future

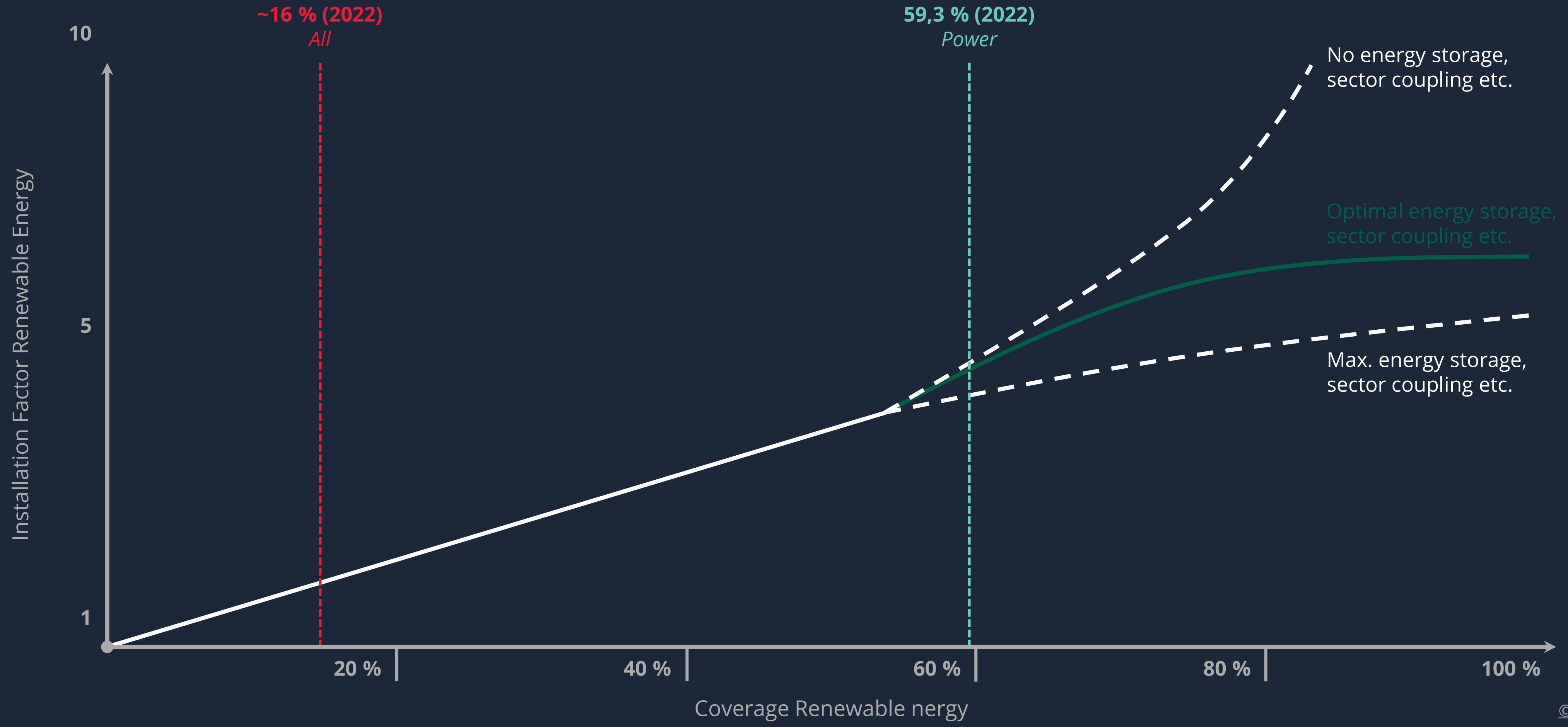


© EU Green Deal, 2021

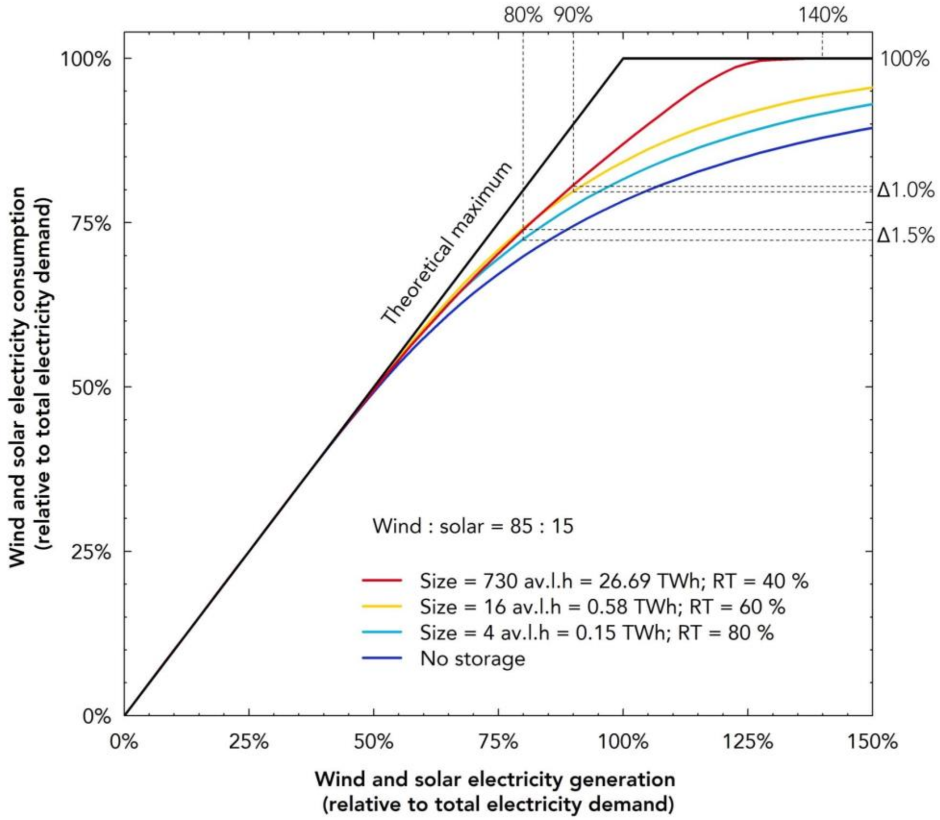
Consequences and Relevance for/of Energy Storage



Consequences and Relevance for/of Energy Storage



Too Much is not Good Enough



- Up to ca. 50% renewable power coverage, energy storage can be avoided by flexibility/sector coupling
- Up to ca. 80% renewable power coverage, small distributed energy storage many charging cycles
- For 100% renewable power generation, seasonal storage is required

➔ *Less energy storage capacity can sometimes store more energy*

Uddannelses- og Forskningsstyrelsen
AVANCERET ENERGILAGRING KONFERENCE 2023
DANISH TECHNOLOGICAL INSTITUTE

Conclusion

1. Effectiveness ☞ Efficiency ☞ Electrification ☞ Electrochemistry
2. Energy storage must be part of each of these steps – but only where it really makes sense
3. Energy storage shall reduce emissions and cost as well as avoid shortages and overcapacity
4. Flexibility and sector coupling can act as virtual energy storage
5. Too much energy storage capacity might interfere the energy transition

➔ Energy storage is *required* for the green transition, but not *sufficient*

Outlook

Sufficiency

"Efficiency without ~~Effectiveness~~ is lost"

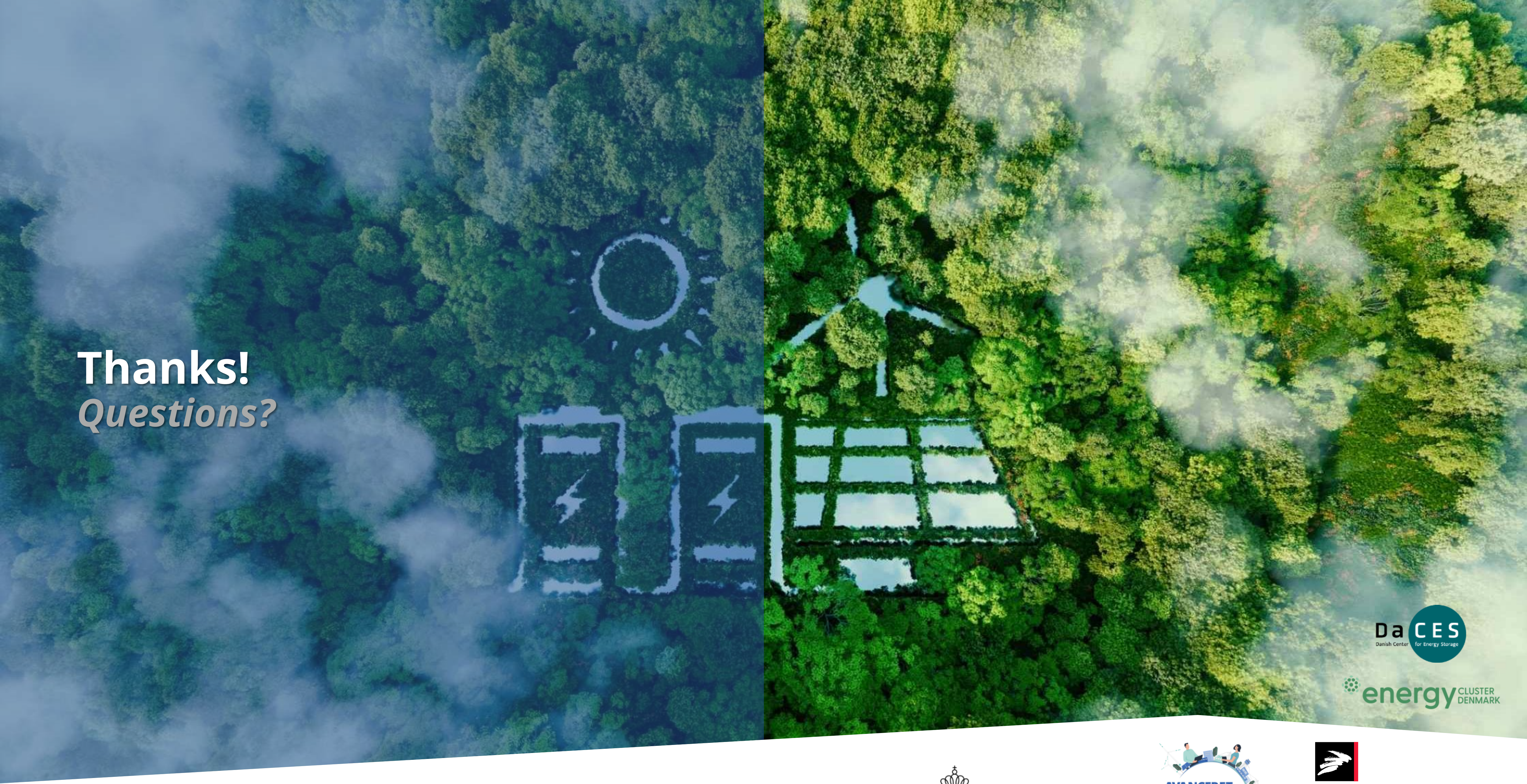
IPCC AR6, 2022

~~IPCC AR4, 2007~~

Uddannelses- og Forskningsstyrelsen

AVANCERET ENERGILAGRING KONFERENCE 2023

DANISH TECHNOLOGICAL INSTITUTE



Thanks!
Questions?

DaCES Danish Center for Energy Storage

energy CLUSTER DENMARK

Uddannelses- og Forskningsstyrelsen

AVANCERET ENERGILAGRING KONFERENCE 2023

DANISH TECHNOLOGICAL INSTITUTE


PÅ GENSYN
I 2024
AVANCERET ENERGILAGRING
TAASTRUP - 28. NOVEMBER 2024