

WP2.3 Distribuerade kyllager i fjärrkylanät

Distributed Cold Storages in District Cooling (DC)

DC optimization opportunities with cold storages combining power-to-cold

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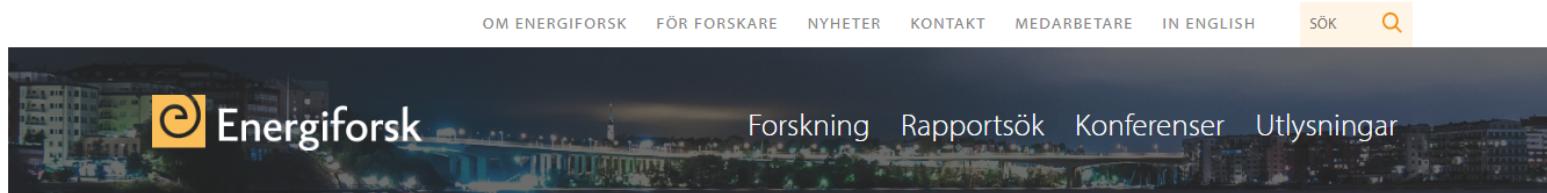
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- **Activity Overview**
- **Results and discussion- DC optimization with Cold Storage (Case study: Norrenergi AB)**
 - Swedish context of DC and Cold storages
 - DC optimization with distributed (and centralized) cold storages
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 - Cost benefits analysis
 - IEA ECES Annex 35 on Flexible Sector Coupling
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- **Concluding summary**
- **Discussion**

Introduction & Aim



OM ENERGIFORSK FÖR FORSKARE NYHETER KONTAKT MEDARBETARE IN ENGLISH SÖK

Energiforsk Forskning Rapportsök Konferenser Utlysningar

Termiska energilager Om programmet Organisation Stormöte 30 januari Illustrerande systembilder

PROJEKT

Distribuerade kyllager i fjärrkylanät

En ökad efterfrågan på kyla väntas i hela Europa också i Sverige. Det beror på ett varmare klimat, bättre isolerade byggnader och ett ökat krav på komfort. Vi vänjer oss vid ett behagligt klimat och tolererar inte stora variationer. Det här projektet handlar om hur kyllager ute i fjärrkylanäten kan bidra till en jämn och effektiv produktion av kyla som maximerar andelen naturlig kyla i systemet.

f t in

Målet är att möta upp och minskar

Med hjälp beskrivas. I antal MWh undersöks att absorbera

Projektet ut det nät som fjärrkyla kö

Resultaten

Projektet s som ett del medel av ir

Optimization of the DC systems and networks with distributed cold storages coupled with power-to-cold and renewable energy

lager kan, kan

ngsteknik, opplasteffekt, spektiv ts möjighet

första hand leverantörer av

ylasystem.

på KTH, ingår har beviljats med övriga

Om projektet

PROJEKTLEDARE Saman Nimali Gunasekara och Viktorija Martin, KTH

UPPDRAFGIVARE Energimyndigheten, Energiforsk och Norreenergi

BUDGET 3 562 500 kr

TID maj 2018 - december 2020

<https://www.energiforsk.se/program/termiska-energilager/projekt/distribuerade-kyllager-i-fjarkylanat/>

Activity Overview

2.3.1

2.3.2

2.3.3

2.3.4

1. System description & method-

A. SOA: DC & distributed cold storages (& power-to-cold) in Sweden

B. International inspirations for cold storage

2. Techno-economic performance evaluation

A. Case-study analysis of Norrenergi AB's DC system

B. Choose and learn suitable software tools for this DC-system study

C. Benchmark, then compare & optimize the DC system with the integration of cold storages & other options

D. Overall performance analysis

E. Results analysis in the overall Swedish context

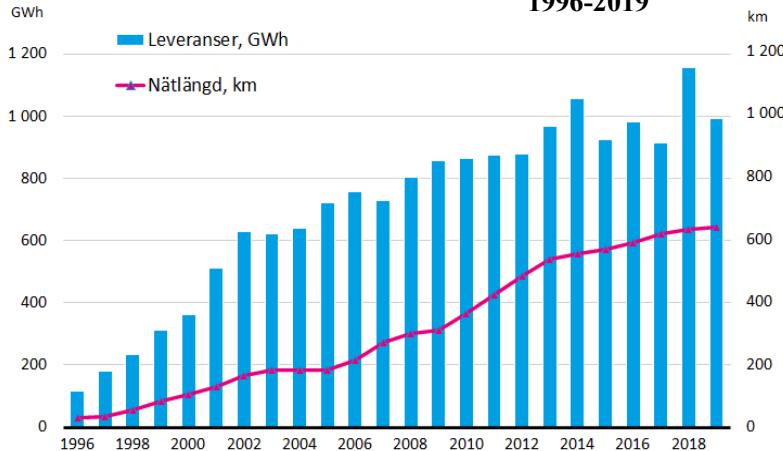
3. Benefit analysis

4. Reporting & communication

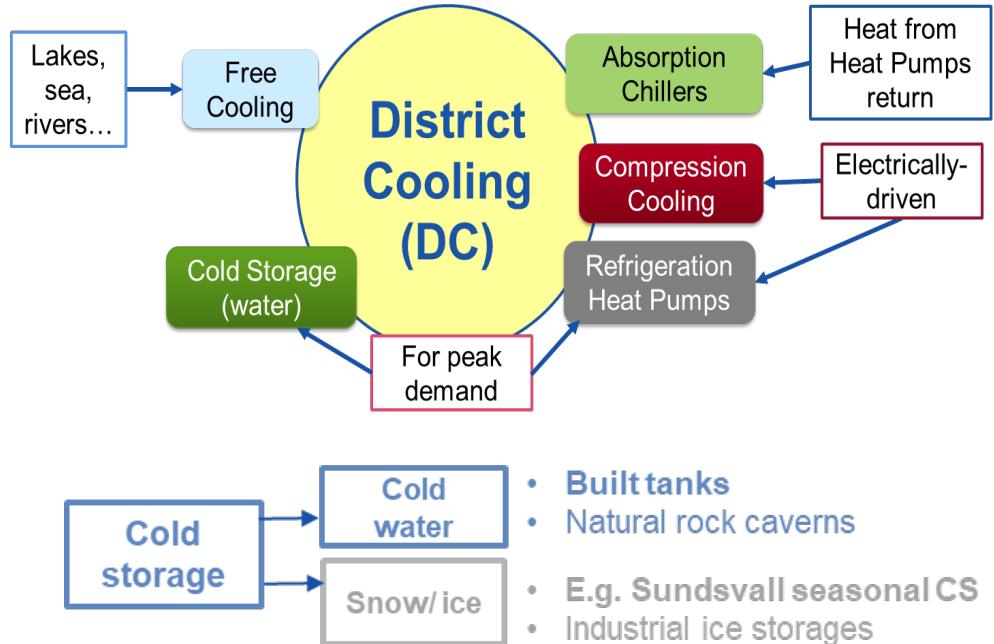
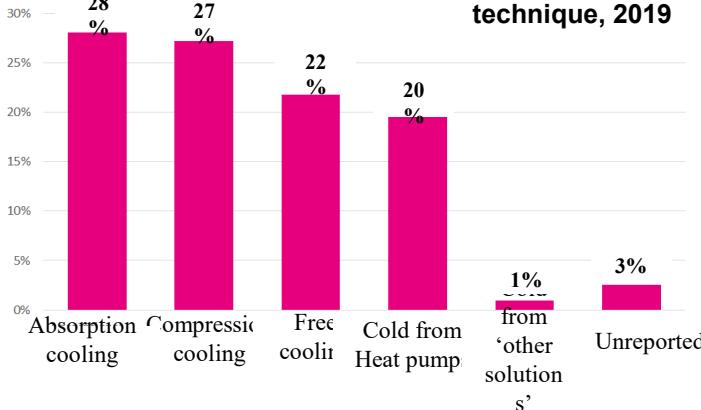
- Reports
- Workshops
- IEA Annex meetings
- International conferences
- Journal publications

Results: DC and Cold Storage in Sweden today

District cooling: supply and network lengths,
1996-2019



District cooling production per production technique, 2019



1 TWh cold supply vs.
2-5 TWh demand (by 2016)

Energiföretagen, 2020 (<https://www.energiforetagen.se/statistik/fjärrvälestatistik/>)

Profu, 2013. "Sammanställd statistik över 2012 års fjärrvärmepriser,"

C. Tullin, 2016. "Heat generation from biomass in Sweden," in *Renewable Heating and Cooling*, Amsterdam, Elsevier, pp. 241-265.

S. N. Gunasekara, V. Martin, T. Edén, F. Sedeqi, M. Tavares and P. S. Mayo Nardone, "Distributed cold storages for district cooling in Sweden- The current context and opportunities for the cold supply expansion," in Eurotherm Seminar #112- Advances in Thermal Energy Storage, Lleida, 2018

Presented @



Slutkonferens 2021 – 01 – 19

[norrenergi](#)

Swedish
Energy Agency



Energiforsk

Results: DC and Cold Storage in Sweden today....

International inspirations...

The Pearl of Qatar

- Electrically driven chillers, 457 MW cooling capacity
- Can use water of poor quality (including sewage water)

Nagoya JR Station DHC

- Ice (phase change materials- PCMs) storage of 49 MWh
- Ice macro-encapsulated in plastic balls, 1226 m³
- PtC peak shaving using night-time cheap electricity
- Adapted to scarce space limitations by design

Climaespaço DHC

- Partially-underground chilled water storage tank
- 15,000 m³ (from a tri-generation plant), 35 MW cooling
- Less requirements of insulation

Enerstore PtC Berlin (SaltX-Vattenfall)

- Thermochemical heat storage (TCS) system: CaO-H₂O
- 10 MWh capacity, charging/discharging power 1/3 MW
- Using renewable intermittent electricity (e.g. from solar & wind) is expected



Presented @



Energiföretagen, 2020 (<https://www.energiforetagen.se/statistik/fjärrkylestatistik/>)
Profu, 2013. "Sammanställd statistik över 2012 års fjärrvärmepriser.,"

C. Tullin, 2016. "Heat generation from biomass in Sweden," in *Renewable Heating and Cooling*, Amsterdam, Elsevier, pp. 241-265.

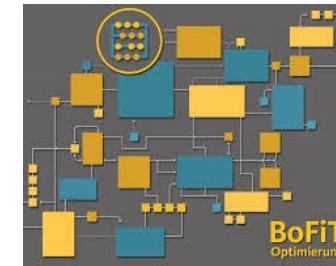
S. N. Gunasekara, V. Martin, T. Edén, F. Sedeqi, M. Tavares and P. S. Mayo Nardone, "Distributed cold storages for district cooling in Sweden- The current context and opportunities for the cold supply expansion," in Eurotherm Seminar #112- Advances in Thermal Energy Storage, Lleida, 2018

Case Study - Norrenergi AB's DC system



Cold production plant	Technology	Installed capacity [MW]	COP
Solnaverket	Heat pumps	18	3
	Compression chillers	10	5
	Cold storage	10	-
Total Solnaverket		38	
Frösundaverket	Free cooling	12.6	10
	Compression chillers	10	5
Total Frösundaverket		22.6	
Sundbybergsverket	Compression chillers	12.5	5
Total Sundbybergsverket		12.5	
Total DC system installed capacity		73.1	

Results: Norrenergi AB's DC system and network dynamics optimization with CSs



Preliminary study-
DC system
optimization with
distributed CSs
with power-to-cold

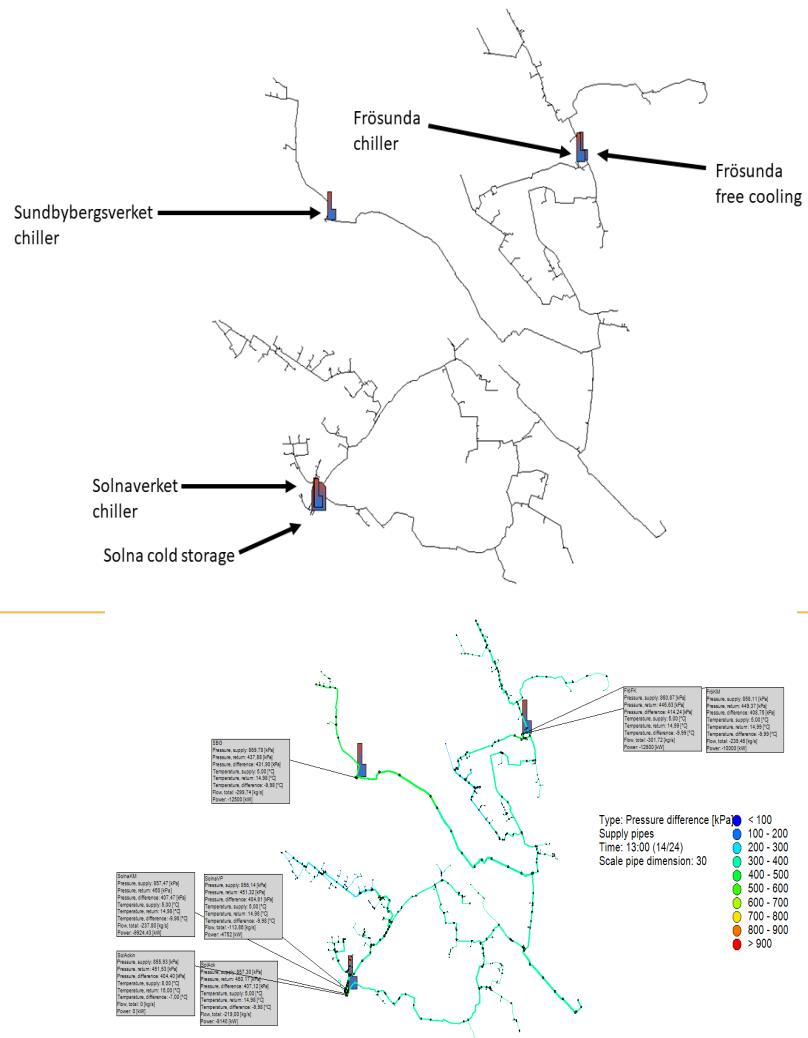
Cost savings in new CSs (e.g. of 15 MW capacity) than with the base case

Yifru. W. Biramo,
"Optimization of Distributed Cooling and Cold Storage in Sweden," MSc. Thesis. KTH Royal Institute of Technology, Stockholm, 2019.

DC network dynamics optimization with distributed CSs to minimize differential pressure bottlenecks



Results: Norrenergi AB's DC network dynamics optimization

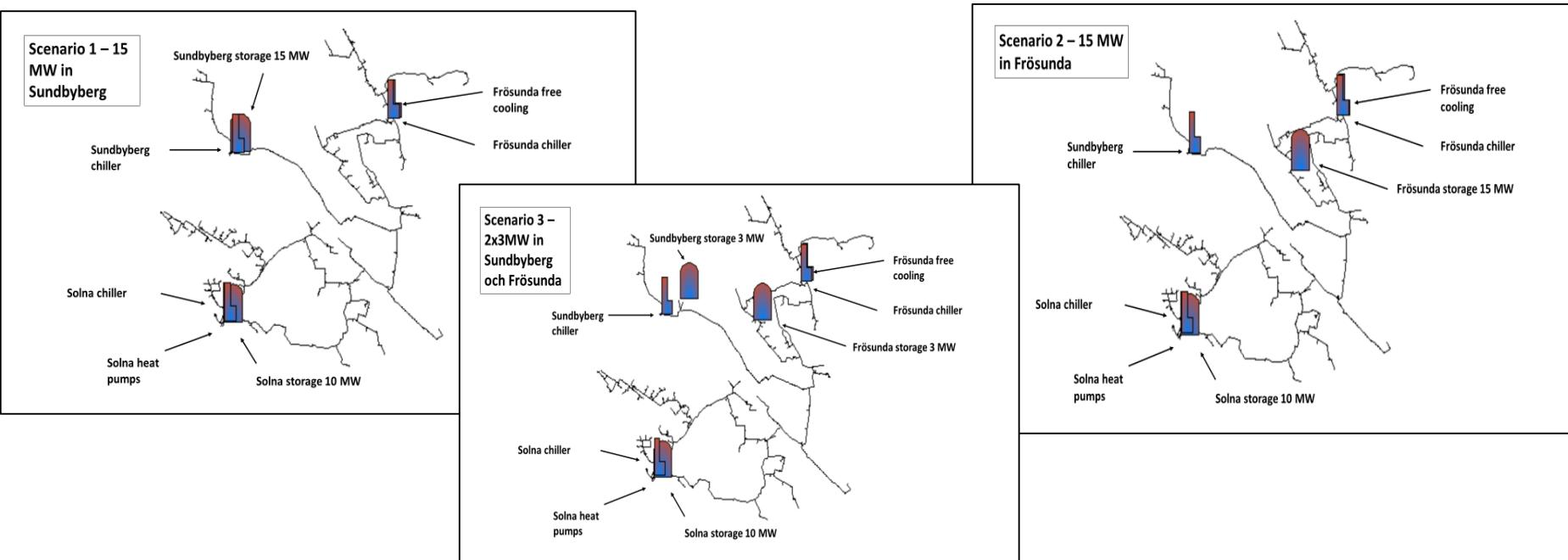


DC network dynamics optimization with distributed cold storages

- Optimization criteria: grid **differential pressure** (within 100-800 kPa)
 - Hourly resolution, 24 hours**
 - Temperature** a secondary result
- Optimal CS combination:** Base case and 3 scenarios of new cold storages (central and distributed) ([MSc thesis Zinar Bilek](#))
 - BC:** one 10 MW CS at Solnaverket
 - Sc1 & 2:** one new 15 MW CS (Sundbybergsv./Frösunda)
 - Sc3:** two new 3 MW CSs (Frösunda & Sundbyb.)
- Optimal capacity and benefits analysis**
 - Model refinements
 - Optimal CS capacity determination** (6 more scenarios, 2 CSs of 3-7.5 MW)
 - Comparison of alternatives to CS
 - Cost benefits analysis

Results: Norrenergi AB's DC network dynamics optimization

Optimal CS combination determination

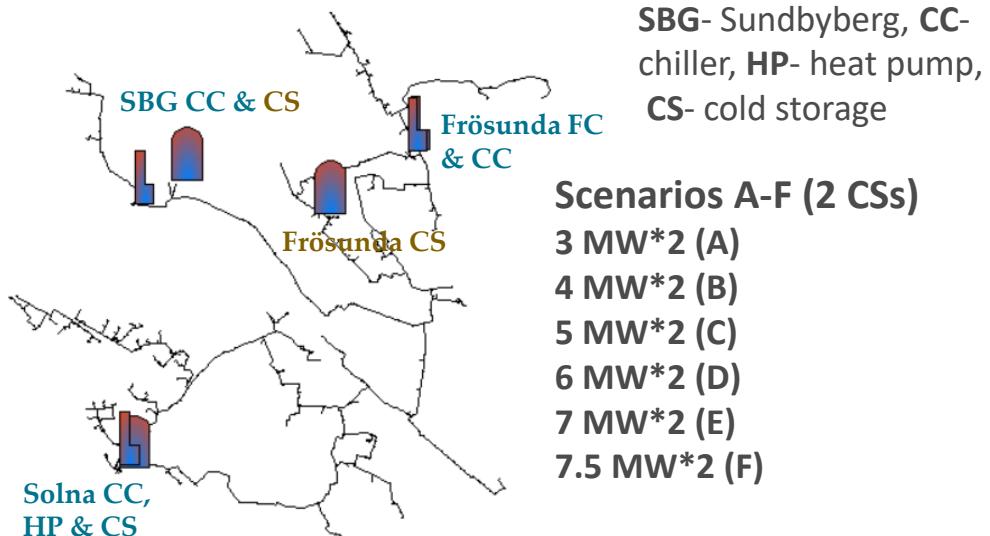
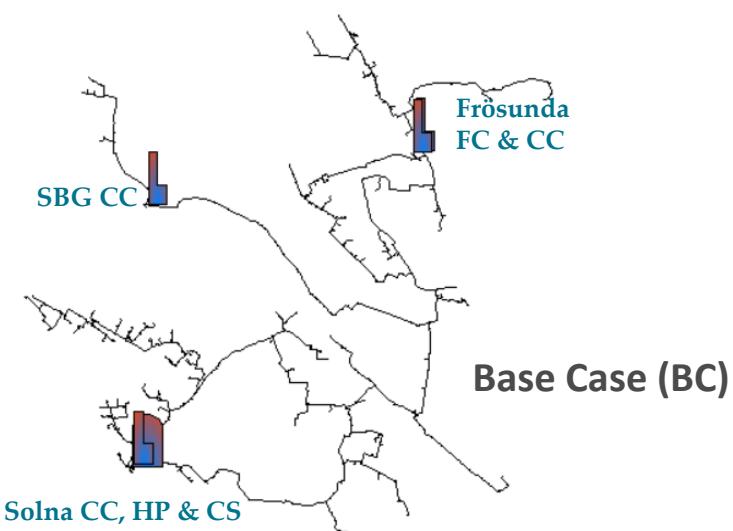


Scenario	Base case	Scenario 1	Scenario 2	Scenario 3
Daily production cost (SEK)	125 600	122 300	119 900	120 400
Daily cost savings	-	2.7%	4.8%	4.3%
KPI (SEK/MWh)	115.2	112.1	110.0	110.3

Zinar Bilek, "[Performance assessment in district cooling networks using distributed cold storages – A case study](#)," MSc. Thesis. KTH Royal Institute of Technology, Stockholm, 2020.

Results: Norrenergi AB's DC network dynamics optimization

Optimal capacity determination of the two CSs (3-7.5 MW each)



Key Performance Indicators (KPIs):

KPI,1- the unit cost of cold produced (SEK/MWh,cold)

KPI,2- the ratio of unit cost of cold of a scenario and that of BC

KPI,3- the unit cost of electricity to produce the cold (SEK/MWh,electricity)

KPI,4- the unit cold produced per used amount of electricity (MWh,cold/ MWh,electricity)

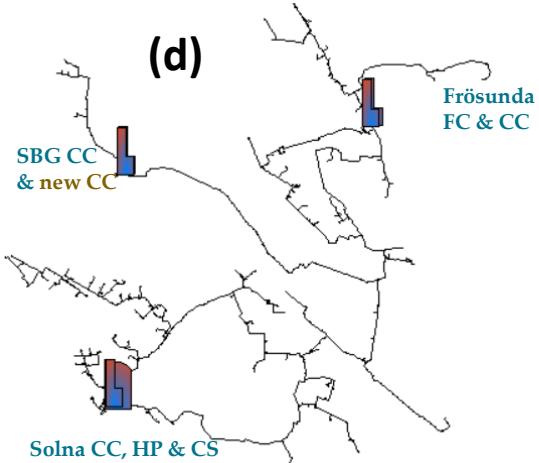
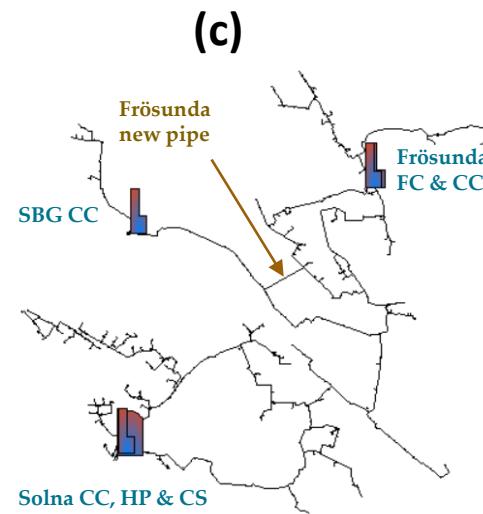
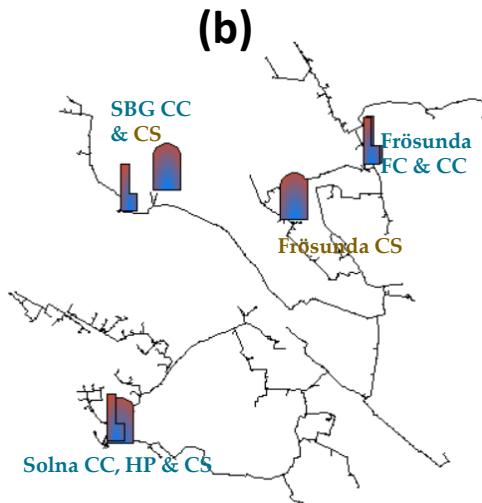
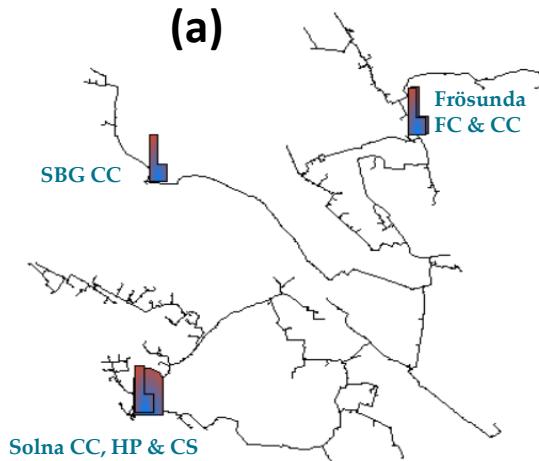
Results: Norrenergi AB's DC network dynamics optimization

case	BC	ScA (3*2)	ScB (4*2)	ScC (5*2)	ScD (6*2)	ScE (7*2)	ScF (7.5*2)
Total cold produced (MWh)	964	965	965	966	965	965	965
Total El consumed to produce that cold (MWh)	167	163	163	163	163	163	163
Total cold production cost (SEK)	101792	97604	97270	96889	96480	96160	95977
KPI,1. Unit Cost of cold produced (SEK/MWh,cold)	105.6	101.1	100.7	100.3	99.9	99.6	99.4
KPI,2. The ratio of unit cost of cold of a Sc. as compared to BC	1	0.958	0.954	0.951	0.947	0.943	0.942
KPI,3. Unit Cost of El to produce cold (SEK/MWh,El)	608	599	597	595	592	590	589
KPI 4, unit cold produced per used el (MWh,Cold/MWh,El)	5.76	5.93	5.93	5.93	5.93	5.93	5.93
Max diff. pressure observed (kPa)	705	662	680	694	709	763	742
Min diff. pressure observed (kPa)	250	250	250	250	250	250	250

Results: Norrenergi AB's DC network dynamics optimization

110% Demand- Alternatives Analysis

SBG- Sundbyberg, CC- chiller, HP- heat pump, CS- cold storage



- (a) **Base Case** (today's system)
- (b) **Two additional CSs (7.5 MW each, 5000 m³)** in Sundbyberg and Frösunda loop
- (c) **A new pipe (422 m) extension** between Frösunda and Sundbyberg network
- (d) **A new chiller (6 MW)** at Sundbyberg

KPI,5: avoided MW electricity at peak load

KPI,6: avoided MWh peak load/day (i.e., peak shaving)

Results: Norrenergi AB's DC network dynamics optimization

110% Demand- Alternatives' Benefits Analysis

Sc.F scenario F, NppFrö: new pipe in Frösunda, SBGnKM: new chiller in Sundbyberg

case	BC	ScF (7.5*2)	NppFrö	nKMSBG
Total cold produced (MWh)	1061	1061	1061	1061
Total El consumed to produce that cold (MWh)	196	183	193	185
Total cold production cost (SEK)	119 478	108 395	118 010	112 694
KPI,1. Unit Cost of cold produced (SEK/MWh,Cold)	112.6	102.2	111.2	106.2
KPI,2. The ratio of unit cost of cold of a Sc. as compared to BC	1	0.91	0.99	0.94
KPI,3. Unit Cost of El to produce cold (SEK/MWh,El)	609	591	610	608
KPI 4, unit cold produced per used el (MWh,Cold/MWh,El)	5.41	5.79	5.49	5.73
Max diff. pressure observed (kPa)	710	786	782	701
Min diff. pressure observed (kPa)	150	150	190	150

Results: Norrenergi AB's DC network dynamics optimization

110% Demand- Alternatives' Cost Analysis

Component	Specifications (if relevant)	Unit investment cost	Typical payback period (years)
Cold water storage	-	1700 SEK/m ³ [14] ^a	30 ^c
	Vertical storage tank, Carbon steel, cone roof model	1173 SEK/m ³ [15] ^b	
DC pipes	DN 300	18 000 SEK/m ^c	30 ^c
	DN 400	20 000 SEK/m ^c	
Chillers	-	5000- 7000 SEK/kW ^{c,d}	20 ^c

^aas this is an average for several existing heat storage establishments, from 2002-2018, a 10% more cost was used to account e.g. extra costs in insulation.

^bthis is an interpolated value, for 5000 m³ size, using the costs for storage sizes 1000, 1800, 6000 and 13 500 m³, which produce a linear cost function. To account costs on internals, civil work, painting and insulation, 160% of this unit cost was used as the final unit cost.

^cdata from Norrenergi, and

^dthe average of this range, i.e., 6000 SEK/kW was used.

Total annual cost = apportioned investment cost + annual operating cost
(Netsim results → electricity costs for cold production)

Results: Norrenergi AB's DC network dynamics optimization

Final Cost Benefits Analysis

Sc.F scenario F, NppFrö: new pipe in Frösunda, SBGnKM: new chiller in Sundbyberg

	BC	ScF	NewPPFrö	SBGnKM
Total investment cost SEK	0	18,773,120	7,600,824	36,000,000
Annually apportioned Investment cost (SEK/year)		625,771	253,361	1,800,000
Total cold production cost per year (SEK/Year)	10,034,694	9,104,095	9,910,826	9,465,711
Total costs (Investment cost/year + operating cost/year), SEK/Year	10,034,694	9,729,866	10,164,187	11,265,711
Avoided costs by installing TES instead of a new chiller		16%		
Avoided costs by installing TES instead of a new pipe		4.5%		
Total cost as compared to BC		3 % less	4 % more	12 % more

KPI,5 Avoided MW electricity at peak load

Sc.F (vs. BC) →

avoiding additional **4 MW,electricity** at peak hour (KPI,5) and **115 MWh,cold/day** (KPI,6)

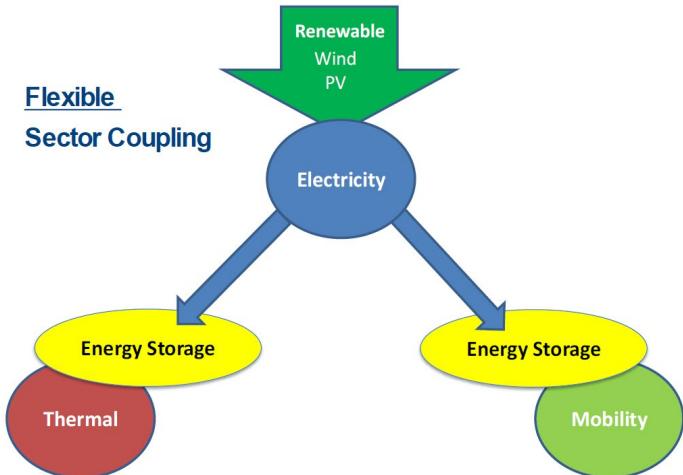
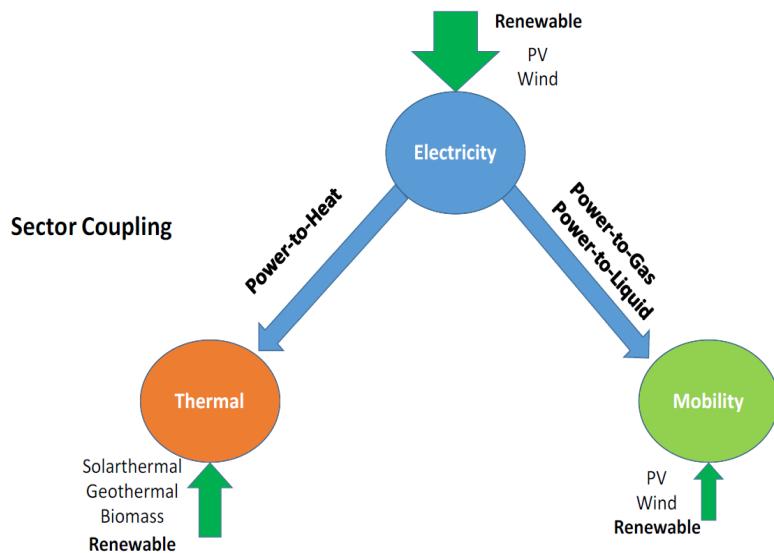
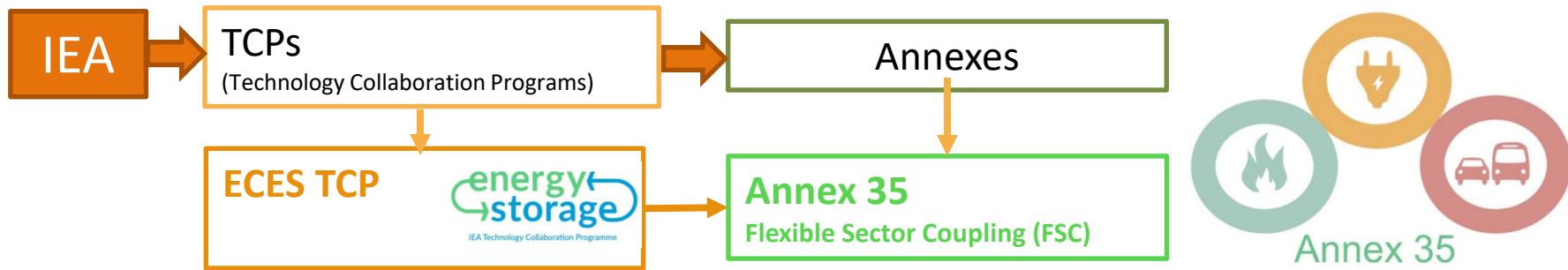
39% less electricity use at the peak hour (13:00), **17% peak shaving** of cold **per day** (during 07:00-19:00)

KPI,6 Avoided MWh peak load/day

Publications and Dissemination

- **02 master's theses** (published) on preliminary studies of DC system and network optimization with distributed cold storages
 - Yifru Biramo ([KTH DiVA](#))
 - Zinar Bilek ([KTH DiVA](#))
- **01 conference article** (published) and **02 conference abstracts** (submitted for oral presentation)
 - Eurotherm seminar # 112, Spain (Y129) - Current state of DC and CS in Sweden
 - Enerstock 2021, Slovenia - DC system prel. optimization with distributed CS
 - DHC 2021 conference, UK- DC network prel. optimization with distributed CS
- **01 journal manuscript** on the CSs optimal capacity and cost benefits analysis (by Summer 2021)
- **Final project reporting** to Energiforsk → Swedish Energy Agency
- **Dissemination and collaboration** at **IEA ECES** (Energy Conservation through Energy Storage) **Annex 35** on **Flexible Sector Coupling (FSC)**

Collaboration @ IEA ECES Annex 35 Flexible Sector Coupling (FSC)



Sources: Annex 35 draft work plan &
<https://iea-eces.org/events/kick-off-meeting-annex-35-flexible-sector-coupling-by-energy-storage-implementation/>

Collaboration @ IEA ECES Annex 35 Flexible Sector Coupling (FSC)...

Subtask 1: FSC Concept Development

- Basic Concept of Flexible Sector Coupling (FSC)
- Put FSC in context of overall energy system transformation
- Distinction from Demand side management and other flexibility measures to emphasize focus on energy storage
- Identify bottlenecks in the legal framework hindering the deployment of energy storage in FSC
- Deliver white paper as living document reporting the progress of FSC concept development

ST1 leader- Coordination

Through WP 2.3 work

Subtask 2: Configuration related storage technology specifications

- Collect existing and future storage applications in the context of sector coupling
- Characterize FSC storage configurations
- Identify promising applications for scenario analysis

Subtask 3: Local Energy System Design and Operation

- Energy system analysis on a local level (cities, districts/quartiers, buildings).
- Design and operational optimization of storages.
- Evaluation of the potential of flexible sector coupling on a local system level.

Subtask 4: National scale energy system analyses of FSC potential

- National energy system analysis of different scenarios
- Elaborating on the findings for the local level studies (ST 3) to scale up the use and consider a mix of such solutions
- Quantify potential of large scale FSC



Annex 35

Sources:
Annex 35 draft work plan &
<https://iea-eces.org/events/kick-off-meeting-annex-35-flexible-sector-coupling-by-energy-storage-implementation/>

Concluding Remarks:

Current State of DC and CS in Sweden

- **1 TWh supply vs 2-5 TWh estimated demand**
- **Compact TES** (ice, snow, thermochemical heat storage, etc.) **vs. cold water?**
- **Cold storage- distributed vs centralized?** (lack of detail)
 - General practice of centralized large/medium capacity CSs (?)

Concluding Remarks:

DC system and network optimization with distributed (and central) cold storages

A combined analysis!

- **System study: 1st step** → simple, quick preliminary indication of the expected solutions
- **Network dynamics study- 2nd step** → detailed technical feasibility of the choices (as in their influence on the real distribution network). More time and resource intensive.

Norrenergi AB system case study:

- BoFit preliminary system study: **15 MW CS at Sundbyberg** supplying cold to entire gird
- Netsim preliminary study: **two CSs in Sundbyberg** (central) **and Frösunda** (distributed) in **3-7.5 MW capacity** range
- Netsim detailed study- **two 7.5 MW CSs in Sundbyberg** (Central) **and Frösunda** (distributed) **is the best choice**, than using the BC, a new pipe extension or a new chiller, considering **technical combined with cost analysis**.

KPIs on the true benefits of CSs in DC with power-to-cold:

- unit cost of produced cold (e.g. **SEK/MWh,cold**)
- unit cost of electricity used to produce that cold (**SEK/MWh,electricity**)

Distributed and central CS combinations, tailored to each system, also based on distribution network requirements

Future work

- **Power-to-cold business cases** analyses
 - Used here only as by-default using nighttime cheap electricity (i.e., based on the price differences in electricity) to charge the CSs
 - Sensitivity analyses on electricity price variations
 - On benefits to electrical and thermal systems in synergy
- **Cold storage beyond cold water- particularly compact TES**
 - Phase change materials- **PCMs** (ice, snow, and other)
 - Thermochemical heat storage -**TCS**
- More specific analysis of **renewable vs. non-renewable electricity use**
 - By-default, the studied system is 100% renewable electricity-based

Questions for Discussion

- Comments/questions?
- Suggestions for improvements?
- Specific discussion on the choice of cold storages
 - Experience/details on **distributed cold storage**?
 - More experience **beyond cold water storages**?
 - PCMs, ice/other?
 - Thermochemical storages?
- Other...?

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Appendix: Norrenergi AB's DC network dynamics optimization- Uncertainty analysis

- Residual error (kW) and heat loss/production% of Netsim calculations:

Category	BC	ScA	ScB	ScC	ScD	ScE	ScF	Average
Residual error (kW)	-9.5	-5.3	-5.6	-5.8	-11	-6	-6.1	-7 kW
Heat loss/heat prod %	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.1 %

Residual error= Produced power –Consumed power- Losses

Category	110% BC	110% ScF	110% nPP_Frö	110% nKMSBG	Average
Residual error (kW)	-9.4	-6.2	-9.4	-9.3	-9 kW
Heat loss/heat prod %	0.07	0.07	0.07	0.07	0.1 %