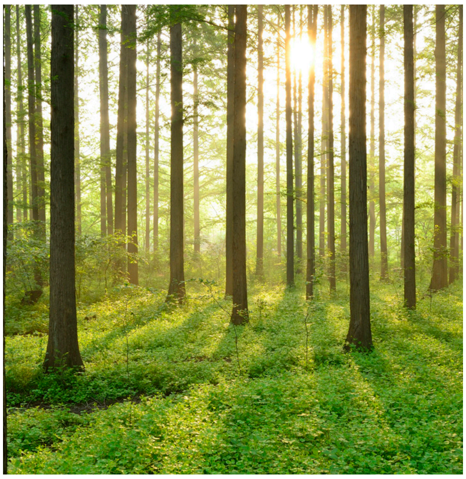
DISTRIBUTED COLD STORAGE IN DISTRICT COOLING

REPORT 2021:751



TERMISKA ENERGILAGER

Energiforsk

Distributed Cold Storage in District Cooling

Distribuerade kyllager i fjärrkylanät

SAMAN NIMALI GUNASEKARA, VIKTORIA MARTIN AND TED EDÉN

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Energiforsk AB | Telefon: 08-677 25 30 | E-post: kontakt@energiforsk.se | www.energiforsk.se

Förord

Det här projektet har genomförts för att få mer kunskap om hur kyllager kan integreras ute i näten i fjärrkylasystem, alltså distribuerat. Resultaten i projektet kan till exempel användas av någon som vill få bättre förståelse för hur olika placeringar av kyllager kan utvärderas mot varandra. I projekt har olika placeringar och egenskaper för kyllager jämförts i ett verkligt system. Den mest fördelaktiga lösningen i detta system har jämförts med alternativa investeringar för en ökad efterfrågan på kyla.

Det här är slutrapportering av projektet Distribuerade kyllager i fjärrkylanät / Distributed Cold Storage in District Cooling som har letts och genomförts av KTH genom Saman Nimali Gunasekara och Viktoria Martin tillsammans med Ted Edén på Norrenergi.

Projektet ingår i programmet Termiska Energilager vars långsiktiga mål är att visa hur, var och när termiska energilager kan utformas och användas och vilken ekonomisk och miljömässig nytta de kan ge med finansiering från Energimyndighetens TERMO-program. En fokusgrupp, tillika programmets styrgrupp, har följt och granskat projektet. Styrgruppen består av Henrik Lindståhl (ordförande) (Tekniska verken i Linköping AB), Lennart Hjalmarsson (Göteborg Energi AB), Per Haker (Hässleholm Miljö AB), Einar Port (Mälarenergi AB), Per Kallner (Vattenfall R&D AB), Lina Hoffert (Öresundskraft Kraft & Värme AB), Morgan Romvall (Halmstad Energi och Miljö AB), Ted Edén (Norrenergi AB) och Erik Holmén (ENA Energi) och Julia Kuylenstierna (adjungerade Energiforsk).

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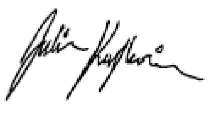

Julia Kuylenstierna Programansvarig Energiforsk

Här redovisas resultat och slutsatser från ett projekt inom ett forskningsprogram som drivs av Energiforsk. Det är rapportförfattaren/-författarna som ansvarar för innehållet.

Sammanfattning

I det här arbetspaketet (WP 2.3 inom *Termiska energilager – lösningen för ett flexibelt energisystem* projekt) har distribuerade kyllager i fjärrkylanät undersökts. Detta är gjort främst genom en litteraturstudie där olika tekniker för kylproduktion och kyllager har kartlagts och en fallstudie där implementering av kyllager i Norrenergi AB:s fjärrkylanät har analyserats genom simuleringar och utvärderingar av tekno-ekonomisk prestanda.

Litteraturstudien i detta arbetspaket visar att den svenska fjärrkylaproduktionen består av frikylning, kompressionskylare, absorptionskylare och värmepumpar, samt kyllager för att minimera investeringar i toppkapacitet. Kyllager kan användas för att möta variationer på kort sikt så som dagar, mellanlång sikt som veckor och långsiktigt mellan säsonger. Kyllager i svenska fjärrkylasystem är nästan uteslutande kallvattenlager med undantag för ett kyllager i Sundsvall sjukhuskylsystem där snö lagras säsongsvis. Undermarkslager, så kallade UTES (Underground TES), används mest för säsongslagring av både värme och kyla, t.ex. borrhålslager (Borehole Thermal Energy Storage – BTES) och akvifärlager (Aquifer Thermal Energy Storage - ATES). Bergrumslager (en till typ av UTES) använts för daglig och veckovis värme- och kyllagring. Internationella exempel av kyllager utöver kallvattenlager visar att snö och is som fasändringsmaterial (PCM) är fördelaktigt i tätbebyggda områden då de erbjuder mer kompakta lagringsvolymer än vatten. Fasändringsmaterial förutom snö och is samt termokemisk värmelagring (TCM) har låg teknisk mognadsgrad (TRL) och är knappa inom kommersiella tillämpningar i fjärrkylasystem. Ett intressant exempel är att titta på den kylanläggning som finns på Chalmers tekniska universitet i Göteborg där ett kyllager med salthydrater som lagringsmaterial har integrerats i ett lokalt energisystem. Sammanfattningsvis har kartläggningen av befintliga kyllager i fjärrkylanät visat att mer kompakta och flexibla (t.ex. PCM och TCM) tekniker för lagring av kyla komplettera de befintliga lager som finns idag. Dock teknikutveckling och kostnadsreduktion behövs för att förverkliga den potential som finns.

Resultaten från fallstudien visar att det finns potentiella kostnadsbesparingar att göra genom att implementera kyllager i fjärrkylasystemens distributionsnät. I Norrenergis system framgår att två stycken kyllager (respektive centralt och distribuerade) med en effekt på 7,5 MW vardera leder till årliga produktionskostnadsbesparingar på 5% jämfört med dagens system. Besparingarna består främst av ett minskat elbehov under topplasttimmarna. Istället kan energi från de distribuerade lagren användas under timmar med höga elpriser, dessa laddas nattetid eller under andra tider på dygnet med låga elpriser. Vidare har konkurrenskraften i denna kyllagerlösning jämförts med andra lösningar för en efterfrågan på kyla som ökar med 10 %. Den ena lösningen är att en ny ledning på ca 420 meter byggs i Frösundaområdet som har låga differenstryck och den andra är att en ny kylmaskin i Sundbyberg (6 MW kapacitet) installeras. Då driftskostnader och investeringskostnader för dessa tre

alternativ beräknades per år visade sig att lösningen med distribuerade kyllager var mest kostnadseffektiv. Denna lösning medför 3% årliga totala kostnadsbesparingar jämfört med basfallet, samtidigt som 16% och 4,5% av investerings- och driftkostnaderna (kombinerade) i en ny kylare eller en ny rörförlängning kan undvikas. Nedan (efter Engelska sammanfattningen) presenteras en omfattande svensk sammanfattning av arbetet.

Summary

District cooling (DC) is an important sector within today's energy systems, with a renewed interest in cooling as an energy service, owing to global warming. Cold storages (CSs) are an important element in DC systems, to alleviate unnecessary capacity investment costs while accommodating peak shaving and load shifting, and to lower the cold production costs as well. Through a current status mapping of DC and CS in Sweden, it is found that the DC supply is about 1 TWh/year as opposed to the estimated 2-5 TWh annual cooling demand. This also revealed that the existing CSs are almost exclusively cold water storages, and which are most likely centralized units located adjacent to cold production plants. This brings us to the question: how can expanded integration of CS allow for DC to meet an even larger share of the cooling demand, in a robust, cost effective and environmentally sound way?

To answer this, it is important to first recognize the available CS alternatives and their potential. Sundsvall seasonal snow storage system is an attractive Swedish exception to cold water CS. Cold water thermal energy storage (TES), in tanks and natural rock caverns (CTES) operate more for short-term CS whereas e.g. aquifer TES (ATES) and borehole TES (BTES) are utilized for seasonal storage (yet in building-scale). Hornsberg CTES and Arlanda ATES are Swedish UTES CS examples. Their relatively high technology readiness levels (TRLs) encourage their exploitation. CSs with snow and ice as phase change materials (PCMs) are gaining interest for being compact storages (up to 60 kWh/m^3 unlike 7 kWh/m^3 with water) with rather competitive costs for daily storage in buildings or small districts. Examples are Chitose airport, Hokkaido, and Nagoya JR station in Japan and Paris La Défense in France. CS with other PCMs or thermochemical heat storage materials (TCMs) are scarce in DC. Two PCM examples on building cooling systems are e.g. in Gothenburg, Sweden, and in Bergen, Norway, using salt-hydrates. CS with PCMs and TCS has lower TRLs and hence requires further research before reaching district level applications.

Within this background, the true benefits of CSs are evaluated herein with a special focus on distributed CS solutions. For that, the existing DC system of Norrenergi AB (catering to Solna and Sundbyberg) was chosen as a case study for a techno-economic performance evaluation and cost benefit analysis. Norrenergi AB's DC system comprises three production plants in Frösunda, Sundbyberg and Solna Strand, with one CS of 10 MW (75.7 MWh, 6500 m^3), altogether allowing a 73.1 MW peak installed capacity. Here, the expanded integration of CS capacity has been explored through the DC system (i.e., production versus demand) optimization as well as DC distribution grid dynamics optimization. Centralized and distributed CSs, considering cold water CSs (due to data limitations on other alternatives) were employed. The DC system analysis was performed as the first step using the software tool BoFit, whereas, the DC distribution grid dynamics were then evaluated using the software tool Netsim.

With BoFit, three scenarios were analyzed besides today's system- the base case (BC). In these scenarios, one additional CS of 15 MW or two CSs of 3 MW were considered at different production locations and supply combinations. Hereby, the most cost effective solution was to install one additional central CS of 15 MW in Sundbyberg. As this BoFit analysis was inconclusive on the impacts of these CSs on the distribution grid, the investigations were continued to distribution grid dynamics assessment with Netsim. In Netsim, three corresponding scenarios were analyzed using additionally: a 15 MW CS in Sundbyberg (centralized), a 15 MW CS in Frösunda (at a distributed location) and two 3 MW CSs at both Sundbyberg and Frösunda. The distributed location in Frösunda was chosen for displaying low differential pressure bottlenecks as found using Netsim. The results revealed that the optimal CS choice lies in two CSs, one located centrally in Sundbyberg and one at the distributed location in Frösunda, with a total capacity of 6-15 MW. Therein, six more scenarios (A-F) were analyzed in Netsim with two equisized CSs of 3, 4, 5, 6, 7 and 7.5 MW capacity. Here, scenario F with two CSs of 7.5 MW capacity each is found as the most optimal solution, with the lowest costs (99 SEK/MWh,cold and 589 SEK/MWh,electricicty) than the other scenarios and the BC (105 SEK/MWh,cold and 608 SEK/MWh,electricity). Although the relative difference between the operational costs savings of each consecutive scenario (A-F) is low, scenario F allows the best savings (for cold production cost per used electricity).

For a 10% demand increase, scenario F and the BC were then compared in Netsim against two other alternatives: a pipe extension (~420 m) at Frösunda low-pressure loop and a new chiller (6 MW) in Sundbyberg. Therein, scenario F followed by the new chiller had the lowest operational costs, while the new pipe extension had the lowest investment cost. Once the annual operating costs and apportioned investment costs were combined, scenario F exhibited the best cost savings, overall. It allows 3% annual cost savings than the BC, while avoids 16% and 4.5% of the costs if instead a new chiller or a new pipe extension was used. Scenario F also facilitates the largest reductions in peak electricity use (4 MW,electricity/peak hour and 35 MWh,electricity/day) and peak cold production (115 MWh,cold/day), successfully adopting power-to-cold. Sensitivity analyses on ground temperature increases and electricity price fluctuations also confirmed that scenario F outperforms the BC. Therefore, scenario F is the most optimal solution for competitively expanding DC.

In summary, this work exemplifies the benefits in implementing CSs in DC, in peak shaving, load shifting, and power-to-cold adaptations, overall leading to cost savings. Also, this work highlights the particular benefits of distributed CSs in better managing the DC distribution grid dynamics. As a whole, the work conveys the importance of DC system-level as well as distribution grid-level optimizations, which are more effective in combination to truly decide the suitability, sizing and positioning of CSs in DC. Important KPIs are also proposed herein for their general utility, i.e., the unit operating cost of cold (e.g. in SEK/MWh,cold) and unit operating cost of electricity to produce that cold (SEK/MWh,electricity), for cost as well as power-to-cold implications. Moving beyond cold water CSs is a potential future work with benefits. In future studies, CS in DC will be developed with a detailed focus on power-to-cold synergies, which emerges as a promising business area in a future electricity system with a large proportion of solar and wind.

Omfattande Sammanfattning

Fjärrkyla (FK) är en viktig sektor i dagens energisystem, där intresset för kyla som energitjänst växer på grund av den globala uppvärmningen. Kyllager är en viktig del i ett FK-system för att sänka kostnaderna för kylaproduktion genom att undvika onödig investering i kapacitet, och underlätta lastutjämning. En ny kartläggning av FK och kyllager i Sverige visar att FK-utbudet är cirka 1 TWh/år jämfört med en efterfrågan om 2-5 TWh/år. Samma kartläggning visar att befintliga kyllager till största delen utgörs av kallvattenackumulering, centralt placerad nära produktionsanläggningarna. Vi frågar oss då, hur kan en ökad integrering av kyllager verka för att FK kan expandera på ett robust, kostnadseffektivt och miljöriktigt sätt?

För att besvara frågan är det viktigt att identifiera och förstå de tillgängliga och framväxande lösningarna för att kostnadseffektivt möta de ökande kylbehoven samtidigt som klimatmålen uppfylls. Svenska FK-system producerar kylning med en kombination av frikylning, kompressionskylare, absorptionskylare och värmepumpar, medan kyllager (KL) är ett typiskt element för att minimera investeringar i toppkapacitet. Prestanda-koefficienten (COP) för dessa tekniker representerar direkt deras kostnadseffektivitet för att producera kyla. Frikylning är där det billigaste sättet att producera kyla. Frikylning är dock en begränsad resurs på grund av miljötillstånd- och lokala förutsättningar och är t.ex. av geografiska skäl inte tillgängligt för alla FK-system, då en lämplig vattenförekomst i närheten av FK-systemet krävs. KL i FK kan, förutom att underlätta lägre investeringar i FK-kapaciteten genom att möjliggöra lastutjämning av kyla, också bidra till hela energisystemet genom kraft-till-kyla-anpassningar. Med kraft-till-kyla kan KL-enheter också sänka efterfrågan från FK-systemen i elnätet vid högsta elbehov och istället fungera som en buffert för låg last som också kan komma som överskott av förnybart ursprung. Strategisk drift av KL för att utnyttja dessa fördelar är en viktig del av lösningen för att uppnå verkligt kostnadseffektiv och miljövänlig kylning.

I Sverige består KL nästan uteslutande med kallvattenlager, det enda undantaget är ett snölagringssystem i Sundsvall som förser ett sjukhus med kyla. Kallvattenlager kan vara utformade på olika sätt, exempelvis kan vattnet lagras i byggda tankar eller naturliga bergrum. Kyla kan också lagras i berggrunden i borrhålslager (Borehole Thermal Energy Storage – BTES) eller i akvifärlager (Aquifer Thermal Energy Storage - ATES). De två sistnämnda är exempel på Undermarkslager, så kallade UTES (Underground TES). UTES används ofta för säsongslagring av både värme och kyla. Hornsberg bergrums KL i Stockholm Exergi ABs FK-system fungerar för dagliga och medellånga (veckovisa) KL. Arlanda ATES är ett välkänt och det största ATES-exemplet i Sverige. Kallvatten KL såväl som UTES-system har relativt höga teknisk mognadsgrad (TRL), vilket gör deras utnyttjande mer populärt och mindre komplicerat.

I detta WP 2.3 har huvudfokus varit på kortvarig (daglig) TES, och därmed är de svenska KL-exemplen i FK-system utöver kallvattenlager sällsynta. När det gäller internationella exempel på KL utöver kallt vatten, har snö och is som fasändringsmaterial (PCM) visat sig vara värdefulla och ganska populära alternativ. PCM för snö och is erbjuder betydligt kompakta lagringsvolymer och konkurrenskraftiga kostnader, jämfört med vatten, för daglig lagringsdrift i byggnader eller små stadsdelar. Kylsystemet på Chitose flygplats i Hokkaido, Japan använder ett säsongsbetonat KL med snö. Byggnader och kylsystem för tågstationer i Nagoya JR Central är utrustade med ett kyllager där is används som PCM. På samma sätt består kylsystemet i affärsdistriktet Paris La Défense i Frankrike av ett isbaserad PCM-KL. PCM: er bortom is/snö och termokemiska värmelagringsmaterial (TCM) är knappa inom kommersiell tillämpning i fjärrkylsystem. Detta beror främst på deras relativt låga TRL. Oavsett finns flera exempel kyllager i byggnader som erbjuder värdefull erfarenhet för framtiden att utvecklas från kallt vatten till dessa mer kompakta TES-alternativ. I Göteborg i Sverige har Chalmers tekniska universitet ett kylsystem i byggnader som använder ett KL med PCM baserat på salthydrater. Även kylsystemet från University College i Bergen i Norge är kopplat till ett PCM-KL som använder salthydrater som PCM. Dessa system har en TRL på ~ 6-8 och kommer att behöva ytterligare forskning och utveckling för användning i FK-system. Termokemisk värmelagring (TCS) har de lägsta TRL-nivåerna bland termiska lager. Enerstore TCS-systemet i Berlin installerat av SaltX AB och Vattenfall är ett unikt TCS-exempel, även om det är begränsat till värmelagring och möjligen kräver ytterligare utveckling för ekonomisk konkurrenskraft. TCS är en attraktiv teknik som i grunden är en kemisk värmepump som kan användas selektivt för värme eller kyla, och därför är det klart en lovande teknik.

I rapporten diskuteras och belyses för- och nackdelar med andra tekniker än vattenbaserade för kyllagring. Parametrar för utvärdering av de olika teknikerna är deras tekniska utmaningar samt egenskaper som effekttäthet (kW/m^3) och lagringskapacitet per volymenhet (kWh/m^3), och även enhetskostnader per effekt och kapacitet (SEK/kW och SEK/MW) som relevant, med användning av tillgängliga data. Inom de begränsade uppgifterna, t.ex. PCM med is och salthydrat verkar ha mycket högre volymetrisk lagringskapaciteter upp till 14, 40, 50 och 62 kWh/m^3 än de andra kallvattenbaserade eller till och med snöbaserade KL-systemen inom 0,05-7 kWh/m^3. Deras volymetriska urladdningsegenskaper (från de tillgängliga) är också betydligt högre (vid ~ 3-7 kW/m^3) än kallt vatten eller snö KL (vid ~ 0,04-2,3 kW/m^3). I allmänhet har säsongsbetonade KL: er mycket höga investeringskostnader. Sedan har PCM (eller TCM) KL-system också höga investeringskostnader och är därför mer rekommenderade för kortvariga TES-applikationer för bättre återbetalning. Bristen på data hindrar dock en fullständig jämförelse här.

I denna rapport utvärderas de verkliga fördelarna med KL: er med särskilt fokus på distribuerade KL-lösningar. Därför har det befintliga fjärrkylsystemet från Norrenergi AB (levererar till Solna och Sundbyberg) valts som en fallstudie för en teknoekonomisk prestandautvärdering och kostnadsnyttoanalys. Norrenergi AB: s FK-system består av tre produktionsanläggningar i Frösunda, Sundbyberg och Solna Strand, med en KL på 10 MW (75,7 MWh, 6500 m^3) och installerad kapacitet på 73,1 MW (inklusive 10 MW KL). Här har den utökade integrationen av KL-kapacitet undersökts genom FK-systemoptimering samt FK-distributionsnätdynamikoptimering. Centrala såväl som distribuerade KL har övervägs. I fallstudiens första steg utfördes en systemanalys av fjärrkylanätet med programvaruverktyget BoFit. Sedan utvärderades omfattande distributionsnätets dynamik med programvaruverktyget Netsim. Dessa BoFit- och Netsim-simuleringar utfördes för en vald dag med en historiskt högsta efterfrågan i Norrenergi AB: s FK-system, dvs. 2 augusti 2018. Det antogs att genom att välja en sådan historiskt högsta efterfrågan kan resultaten däri representera resten av de dagarna som har en lägre efterfråga under året. Den här valda dagen användes data av efterfrågan för en timmeupplösning.

BoFit är ett verktyg för produktionsplanering som möjliggör produktion- mot leveransoptimering av värme eller kyla. I BoFit är produktionskostnad för kylaproduktion det viktigaste kriteriet vid optimering. Även om det är ett effektivt verktyg för att optimera produktionen för ett visst kylbehov, är BoFit emellertid inte ett termiskt nätanalysverktyg och utelämnar helt specifikationer för distributionsnätet. Ändå valdes BoFit för det första preliminära steget i den tekno-ekonomiska analysen av FK-optimering med KL i denna WP 2.3. Detta främst då en betydligt lägre arbetsinsats krävs i BoFit för att implementera en rimlig representation av ett riktigt FK-system från grunden, med förmågan att fortfarande generera representativa resultat. Med BoFit analyserades fyra framtidsscenarier som innehåller ytterligare KL: er, förutom Norrenergi AB: s FK-system idag (med en 10 MW KL i Solnaverket) - basfallet (BC). Från dessa tre scenarier ansåg scenario 1 respektive 2 ytterligare en KL på 15 MW nominell effekt i Sundbyberg (i scenario 1) eller i Frösunda (i scenario 2). Scenarierna 3 och 4 betraktade vardera två ytterligare KL: er vardera om 3 MW. I scenario 3 tilldelades dessa två 3 MW KL att endast leverera kyla till vissa utvalda kunder med högre efterfrågan. Medan i scenarierna 1, 2 och 4 tilldelades de ytterligare KL-ren för att täcka kylbehovet i hela leveranssystemet och leverera till alla kylkunder. Av dessa ytterligare KL valdes 15 MW för denna fallstudie eftersom det var en kapacitet som redan har diskuterats på Norrenergi AB för potentiella framtida utvidgningar. Sedan valdes 3 MW kapacitet som en relativt liten kapacitet för att ge en tydlig skillnad, särskilt för distribuerad implementering av KL. Resultaten i BoFit-baserad FK-systemanalys gav att 15 MW KL i Sundbyberg möjliggör de högsta kostnadsbesparingarna (23% per dag) jämfört med BC, följt av de två 3 MW KL-lösningarna som är de näst bästa valen (med 13-14 % besparingar per dag). Den mest kostnadseffektiva lösningen var således installation av ytterligare ett centralt placerat kyllager på 15 MW i Sundbyberg. BoFit-analyserna var dock inte tillräckligt detaljerade för att dra slutsatsen om placeringen av detta KL eller konsekvenserna av att implementera detta i det verkliga FK-distributionsnätet. Därför krävdes en analys av FK – nätets distributionskapacitet genom tryckfallsberäkningar.

Baserat på resultat från förenklade systemanalysen i BoFit utfördes mer detaljerade analyser av Norrenergi AB: s fjärrkylanätets dynamiska egenskaper. Detta genom tryckfallsberäkningar med ytterligare KL i Netsim. Netsim valdes främst eftersom det är ett beräkningsverktyg för termiska nät, som specifikt anger distributionsnätets flaskhalsar i termer av t.ex. differenstryck (dP) för de definierade systemen för kyla produktion och kyltillförsel. Dessutom fanns Norrenergi AB: s FK-system redan i ett nätinformationssystem (NIS) dpHeating, som var kompatibelt med Netsim. Detta möjliggjorde import av verkliga fysiska nätdata och visualisering från dpHeating till Netsim. Därmed, i Netsim analyserades fyra olika fall, BC samt tre motsvarande scenarion där ytterligare kyllager implementerats i systemet. Detta var det andra steget i den tekno-ekonomiska analysen i fallstudien på Norrenergi AB: s FK-system. Det viktigaste optimeringskriteriet var dP-nivåerna i nätet, som bör ligga mellan 100-800 kPa för att framgångsrikt leverera den kylningen som behövs utan att överskrida kundanläggningarnas fysiska kapacitet. De analyserade tre nya scenarierna här omfattar , scenario 1: ett ytterligare 15 MW KL i Sundbyberg (centraliserad), scenario 2: ett ytterligare 15 MW KL i Frösunda (på en distribuerad plats), och scenario 3: två ytterligare 3 MW KL vid både Sundbyberg och Frösunda.

Den distribuerade platsen i Frösunda identifierades baserat på beräkningar av distributionsnätets dynamik för BC utförda i Netsim. Dessa beräkningar visade på flaskhalsar och låga differenstryck i området där kyllagret placerades. Resultaten av beräkningarna (för den analyserade dagen med högst efterfrågan) i Netsim gav att scenarierna 2 och 3 hade bäst kostnadseffektivitet vilket möjliggjorde betydande besparingar jämfört med BC. Scenario 2 möjliggjorde något bättre kostnadsbesparingar än scenario 3. I scenario 2 föll dock vissa kundnoder under 100 kPa vid leverans vilket indikerar att önskad kyla inte levererades helt. Scenario 2 kräver alltså ytterligare optimering, vilket kan minska kostnadsbesparingarna. Därför ligger det optimala KL-valet totalt sett i kombinationen av scenarierna 2 och 3, dvs i två kyllager , ett som ligger centralt (i Sundbyberg) och ett på en distribuerad plats (i Frösunda-slingan), med en total kapacitet mellan 6 MW (dvs motsvarande kapacitet av två 3 MW) och 15 MW.

Som det tredje steget i denna tekno-ekonomiska analys av KL i FK i detta WP genomfördes därefter en omfattande Netsim-baserad optimering för att identifiera den ytterligare KL-lösningens optimala KL-kapacitet. Förutom BC analyserades ytterligare sex scenarier (A, B, C, D, E och F) i Netsim för konfigurationen med två utjämnade KL: er med 3, 4, 5, 6, 7 och 7,5 MW kapacitet respektive. Här gav resultaten att scenariot F med två KL med 7,5 MW kapacitet vardera, tillåter den mest optimala lösningen med de högsta kostnadsbesparingarna. Scenario F har rörliga enhetskostnader på 99 SEK/MWh,kyla och på 589 SEK/MWh,el, jämfört med BC där dessa kostnader är 105 SEK/MWh,kyla och 608 SEK/MWh,el. Här visade scenarierna med två KL i storleksintervaller 4, 5, 6 och 7 MW (dvs scenario A-E) också lägre rörliga kostnaderna än BC (100-101 SEK/MWh,kyla och 590-599 SEK/MWh,el). Även om den relativa skillnaden mellan konsekutiva scenarier (A-F) är lägre i dessa kostnadsbesparingar, ger scenario F den bästa lösningen också jämfört med de ytterligare KL-scenarierna. Resultaten i BoFit och Netsim hittills är begränsade till besparingar under ett dygn, och investeringskostnaden är exkluderad.

Det är också viktigt att undersöka konkurrenskraften hos en sådan KL-lösning, i detta fall scenario F, med andra typiska alternativ för att utöka kyltillförseln i FK och kostnaderna för både drift och investeringar. Därför utvärderades den bästa KL-lösningen som identifierats (scenario F), tillsammans med BC samt två andra alternativ: förstärkning av fjärrkylnätet till Frösundaområdet som har låga differenstryck, med en kompletterande ca 420 m lång ledning och en ny kylmaskin (6 MW kapacitet) i Sundbyberg, för en efterfrågeökning med 10%. För vart och ett av dessa alternativ och BC beräknades respektive driftskostnader samt fördelade årliga investeringskostnader. När det gäller själva driftskostnaderna hade scenario F från dessa fyra alternativ de lägsta kostnaderna (102 SEK/MWh, kyla och 591 SEK/MWh, el), följt av det nya kylmaskin i Sundbyberg (106 SEK/MWh, kyla och 608 SEK/MWh, el). Den nya fjärrkylledningen visade sig ha den lägsta investeringskostnaden (253 361 SEK/år), bland de fyra alternativen. Slutligen, när de årliga driftskostnaderna och fördelade investeringskostnaderna kombineras, framgår att scenario F ger de bästa kostnadsbesparingarna totalt sätt bland de fyra alternativen. Scenario F medför 3 % årliga kostnadsbesparingar jämfört med BC samtidigt som man undviker 16% och 4,5% av investerings- och drivskostnaderna i en ny kylare eller en ny rörförlängning. Jämfört med BC underlättar scenario F dessutom de största besparingarna i: maximal elanvändning (MW) under topplasttimme (4,4 MW El/topplasttimme), maximal elanvändning per dag (34,8 MWh el/dag) samt högsta kylproduktion per dag (115,2 MWh, kyla/dag) jämfört med BC. Detta innebär att scenario F tillåter: 39% mindre elförbrukning vid topplasttimme (kl. 13:00), 27% mindre elförbrukning under topplast timmarna per dag (mellan kl. 07:00-19:00), och 17% mindre kylproduktion under topplast timmarna per dag (mellan kl. 07:00-19:00) än i BC. Därför är scenario F en verkligt fördelaktig lösning för att uppnå en utökad FK-kapacitet.

Känslighetsanalyser på Netsim-baserade undersökningar utfördes också på BC och scenario F för variationer i marktemperaturen och elpriser. Förutom den typiska sommartemperaturen på 8° C användes två ganska höga temperaturer, dvs. 15° C och 20° C i analysen. Resultaten ger här att scenario F (med 99-100 SEK/MWh,kyla och 589 SEK/MWh,el) fortfarande överträffar BC (med 105-106 SEK/MWh,kyla och 608 SEK/MWh,el) utan signifikanta temperaturvariationer i kyltillförseln (maximal framledningstemperatur på 5,65° C - 6,32° C med Sc.F mot 5,47° C - 5,73° C med BC). I känslighetsanalysen för elpris användes tre scenarier för elprisprognoser, som överväger att öka förnybar energi och minska kärnkraften i olika grad. Trots betydande skillnader i pristopptrender och prisnivåer gav känslighetsresultaten också att scenario F överträffade BC. Denna analys belyser också förmågan hos KL i FK att fungera som buffertar av förnybar överskottsel under låglastbehov av elektricitet vilket sammanfaller med låglastbehovet för kyla, även i de olika framtida prognoserna.

Sammanfattningsvis exemplifierar detta arbete fördelarna med att implementera KL i FK vid lastutjämning och kraft-till-kyla-anpassningar, vilket totalt sett leder till kostnadsbesparingar. Detta arbete belyser också de särskilda fördelarna med distribuerade KL: er för bättre hantering av FK-distributionsnätets dynamik. Förutom de specifika slutsatser som diskuterats tidigare ger detta arbete också flera allmänna slutsatser. En viktig slutsats är vikten av att både ta hänsyn till produktionsoptimering och utformningen av fjärrkylnätet med dess tillsammans för att verkligen avgöra lämplighet, storlek och placering av KL i FK. En annan viktig slutsats i det allmänna sammanhanget ligger i den kombinerade bedömningen av nyckelindikatorerna. Särskilt rörliga enhetskostnaden för kylning (t.ex. i SEK/MWh,kyla) och elproduktion till kylningen (SEK/MWh,el) för att indikera kostnaden för kylning samt framgången med kraft- till-kyla anpassning för att producera den. Ytterligare en allmän slutsats från detta WP är den värdefulla funktionen hos specifikt distribuerade KL i FK-distributionsnät för att eliminera flaskhalsar med olika tryck och även för att återvinna överskott av kyla på distribuerade platser. Att gå bortom kallvattenlager i en riktig fallstudie med FK-system är ett potentiellt framtida arbete med mervärde. I framtida studier kommer KL i FK att utvecklas med ett detaljerat fokus på kraft-till-kyla-synergier, som framstår som ett lovande affärsområde i ett framtida elsystem med en stor andel sol och vind. Även med FK:s korta utnyttjningstid dvs huvudsakligen sommartid här i Sverige, är det troligt att drivkrafterna kommer att vara starka för kraft-till-kyla lösningar, med kyllager som absorberar överskotts el till lägre priser än på vintern.

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1 Introduction

Global warming is no longer a threat but is a reality [1], causing increasingly warmer summers in Europe, and even in Sweden [2]. Consequently, cooling demands are increasing in Sweden, owing to increasing demands on building thermal standards (and thus insulations) as well as on indoor comfort owing to increasing numbers of internal heat sources [3], besides the impacts of global warming. District cooling (DC) is a cost-efficient and a more environmentally friendly means to meet these cooling demands, instead of resolving to fossil-based alternatives, particularly in cities and close-neighborhoods. DC, by providing cooling, simultaneously acts as a waste heat sink recovering heat from the cooling consumers, which, after being upgraded via heat pumps is fed to district heating. DC supply in Sweden today is, however, limited to offices, commercial establishments as well as a share of industrial cooling [4], while excludes residential cooling. Cold thermal storage is an integral part of DC, which is primarily met with cold water storages in the current Swedish context.

Thermal energy storage (TES), be it cold or heat, reduces the capacity installation requirements of a district heating (DH) or a DC system, via peak shaving and load shifting. Thereby, a cold storage allows a smooth, efficient production that maximizes the proportion of natural cooling in the system, and increases the efficiency of existing production units. Furthermore, cold storage is expected to significantly affect the energy system as a whole in the right direction, where, the peak demand of electricity for cold production decreases during the hottest hours of the day. As the electricity production mix develops towards a larger proportion of intermittent renewable electricity, cooling can be produced when there is a surplus in the electricity system, disconnected from actual cooling needs. Therein, the cold storage adopts power-to-cold concept [5], introducing flexibility to couple the DC and electrical sectors in the energy system. Cold storage is also an attractive means to recover surplus cold (and heat) from various sources spread within the DC network.

With the increasing cooling demands, cost-effectively expanding the DC supply is crucial. Extending the DC pipe networks or adding new production units come with significant investments. The DC pipes are considerably larger, as opposed to e.g. DH, resulting in much larger investment costs. This is owing to a typically narrow design operating temperature range (of around 10 °C) in DC, which requires larger volumetric flows of cold water for a given capacity [6]. Besides, DC pipe investments' payback takes longer than DH, which has a longer utilization time than DC. Hence, finding more cost-effective means of cold supply expansion while enabling flexibility and robust supply is imperative. Here, cold storage shows a great potential.

In this context, cold storages are gaining a lot of renewed interest for DC today, in addition to the mostly centralized cold storages also and particularly distributed cold storages.

1.1 OBJECTIVES

Within this context, objectives of this work package (WP) 2.3 are as follows:

- Map the current context of distributed and centralized cold storage in DC in Sweden, to serve as the basis of a technical evaluation of distributed cold storage in DC
- Focusing on a chosen real DC system, namely the existing DC system of Norrenergi AB, perform a techno-economic performance evaluation considering cold storage alternatives (distributed and centralized, as relevant) comparison and operational strategies optimization
- By means of this performance evaluation, conduct a benefits analysis of the analyzed cold storage alternatives, and thereby quantify the benefits on both the district cooling and energy system as a whole such as electricity saving during peak load hours (in terms of e.g. the avoided MW,el max at peak cold demand, and the avoided MWh,el/day), in the possibility to absorb excess electricity in the system for cooling production disconnected from cooling needs
- Also based on this performance evaluation, conduct and present a total costs comparison of the chosen cold storage alternative with other typical cooling capacity increasing means, considering both investment and operating costs
- Evaluation of optimal operating strategies for alternative cold storages (e.g. cold water accumulator tanks, phase change materials, and underground storages) with regard to technical and economic performance in-terms of power properties (e.g. kW/m^3 storage), storage capacity (e.g. kWh/m^3 storage), cost (e.g. SEK/kWh,stored cooling and SEK/kW,cooling power from the storage), and impact on operation (e.g. temperature shift across the storage).
- Overall, bring key specific as well as general conclusions as related to DC supply optimization and extension and the role of cold storage in that

Besides these research objectives, communication of the project findings is also a key objective of the project, via appropriate channels. Here such channels are e.g. the project dissemination workshops organized by Energiforsk, International Energy Agency (IEA) - Energy Conservation through Energy Storage (ECES) Annexes with relevant scope (e.g. Annex 35 on flexible sector coupling (FSC) [7]), conference and journal publications, and master's thesis defense presentations and final reports.

1.2 SCOPE AND LIMITATIONS

The project scope is mainly bound to the current and historical context of DC and cold storage in Sweden. However, as appropriate, certain international cases of different types of cold storages are used to obtain further insights. In the techno-economic performance evaluation and benefits analysis of cold storages in DC, the existing DC network of Norrenergi AB (which caters to Solna and Sundbyberg municipalities) is used. Here, Norrenergi AB's today's DC system (as benchmark) as well as various future cases are analyzed for Norrenergi AB's today's cooling demand as well as for a projected 10% demand increase. These analyses are limited to a chosen highest demand day in the recent history of Norrenergi AB's DC operation, namely, 02 August 2018. This is chosen because, a key function of a cold storage is alleviating capacity installations for peak demand, and therefore, when one of the highest demand cases is analyzed, the obtained results can satisfactorily represent all the other lower demand cases. These results were also projected into a years' operation (and to identify the implications therein) in a rather simplified approach by projecting certain unit performance parameters into the total cold production in a year (for the total cold production in 2018). Further technical details on scope and limitations on these analyses are provided in section 2.

2 Methodology

In this WP 2.3 on distributed cold storage in district cooling, the objectives in section 1.1 are addressed through the following steps:

2.3.1 System description- a compilation of knowledge for distributed cold storage in DC systems

2.3.2 Techno-economic performance evaluation: a) comparative cold storage alternatives, b) optimization of operating strategies

2.3.3 Benefits analysis (e.g. of avoided MW electricity at peak load, avoided MWh peak load/day and the investment cost compared with the capacity increase, among others)

2.3.4 Reporting and communication – with generalizability in focus

The project begins with system description (WP2.3.1) which creates a compilation of knowledge to map the current state concerning the use of distributed (and central as relevant) cold storage in DC systems, as well as a background on DC, e.g. on the most employed cold production technologies today. On a scientific basis, experiences from the literature are compiled and analyzed, which are supplemented with a search of details of the existing installations and experiences by reaching out to e.g. the DC providers.

With this status mapping as a basis, next, a techno-economic performance evaluation is performed, which compares cold storage alternatives and examines operating strategies (WP2.3.2). The first step of this is a techno-economic comparative analysis of different cold storage alternatives besides cold water, presented by means of a literature review of many different alternatives (in sections 3.1 and 3.2). There is a significant lack of detail among these various storage types. Regardless, some key comparative highlights are drawn based on the available information. The second step of this analysis is performed in combination of WP 2.3.2 and WP 2.3.3, which is also the main step in this analysis and the key contribution in this WP 2.3. This entails comprehensive DC system and distribution grid dynamics analysis and optimization with CSs. For this, the specific DC system of Norrenergi AB is chosen, to be able to perform an analysis as close to reality as possible, and thus to obtain more practically relevant results. The tools for this modeling and simulations were determined by a combination of consultation with Norrenergi AB, insights on the tools used by other DH and DC companies like Stockholm Exergi AB and Vattenfall AB, literature screening, and eventually depending on their suitability to analyze the chosen specific system. Therein, the DH/DC system optimization tool BoFit from ProCom GmbH [8] and DH/DC distribution grid dynamics simulation tool Netsim from Vitec Software Group AB [9] were chosen and used. The key specific methodological details on the tools are further disclosed in sections 2.2 and 2.3 on BoFit and Netsim, respectively. To evaluate the sensitivity of these results, these were further analyzed against ground temperature increases (which mainly affect the cooling losses and thus temperatures of the cold supply) and electricity price fluctuations.

Concerning electricity price fluctuations, a chosen Swedish power price forecast was used for year 2040, analyzing for three different scenarios of increased share of renewables with decreasing the share of nuclear.

The third WP item (WP2.3.3) concerns the results production followed by benefits analysis, and therein, to bring forward specific as well as general conclusions. This is performed firstly by analyzing a number of scenarios (Sc.s) considering additional cold storages implementation to the current DC system of Norrenergi AB- referred to as the base case (BC), whereby a best scenario is selected, to cover today's highest demand. Thereafter, this chosen best cold storage scenario and the BC are evaluated for a 10% increased demand, as opposed to other alternative investments to accommodate such an increased demand. Therein an investment and operational cost combined comparison is performed, to identify the optimal solution overall.

Despite the fact that these analyses (on WP 2.3.2 and WP 2.3.3) are performed on this chosen case study system, the overall methodology can be applied to any DC (or DH) system, along the same objectives of evaluating the impacts and benefits of distributed and centralized additional CSs implementation. The corresponding generic methodology for any relevant DC (or DH) case study concerning implementing additional CSs (or heat storages HSs) is summarized in Figure 1. The steps A to C are explained in detailed in sections 2.1 to 2.5, as specific to Norrenergi AB's DC system. Step D here entails the overall synthesis of the results obtained within steps A-C, and therein determining the most cost-effective solution(s) to expand a DC (or DH) supply. The technical details of another corresponding DC/DH system can be easily adopted instead of Norrenergi AB's DC system (as relevant to step A and e.g. in section 2.1), for the eventual implementation into models in BoFit and Netsim (or other analogous tools), to perform a similar analysis on any other DC (or DH) system.

The last item (WP 2.3.4) focuses on reporting, discussion and dialogue about the generalizability of produced results. This is done via the following channels. The project results are presented and discussed at the bi-annual meetings organized by Energiforsk to Swedish stakeholders, as well as at Annex 35 on Flexible Sector Coupling (FSC) within International Energy Agency (IEA) – Energy Conservation through Energy Storage (ECES) technology collaboration program, to an international audience. Within this WP 2.3 two master's thesis projects with two public defenses and open access reports published in KTH DiVA [10], [11]. In addition, within the WP 2.3 work, one conference article was published [12], with two more conference presentations coming up in 2021 for one extended abstract [13] and one abstract [14] submitted. One final journal publication is also planned to be submitted by summer 2021. Moreover, the bi-annual progress summaries and this final WP 2.3 report will also serve as key communication channels.

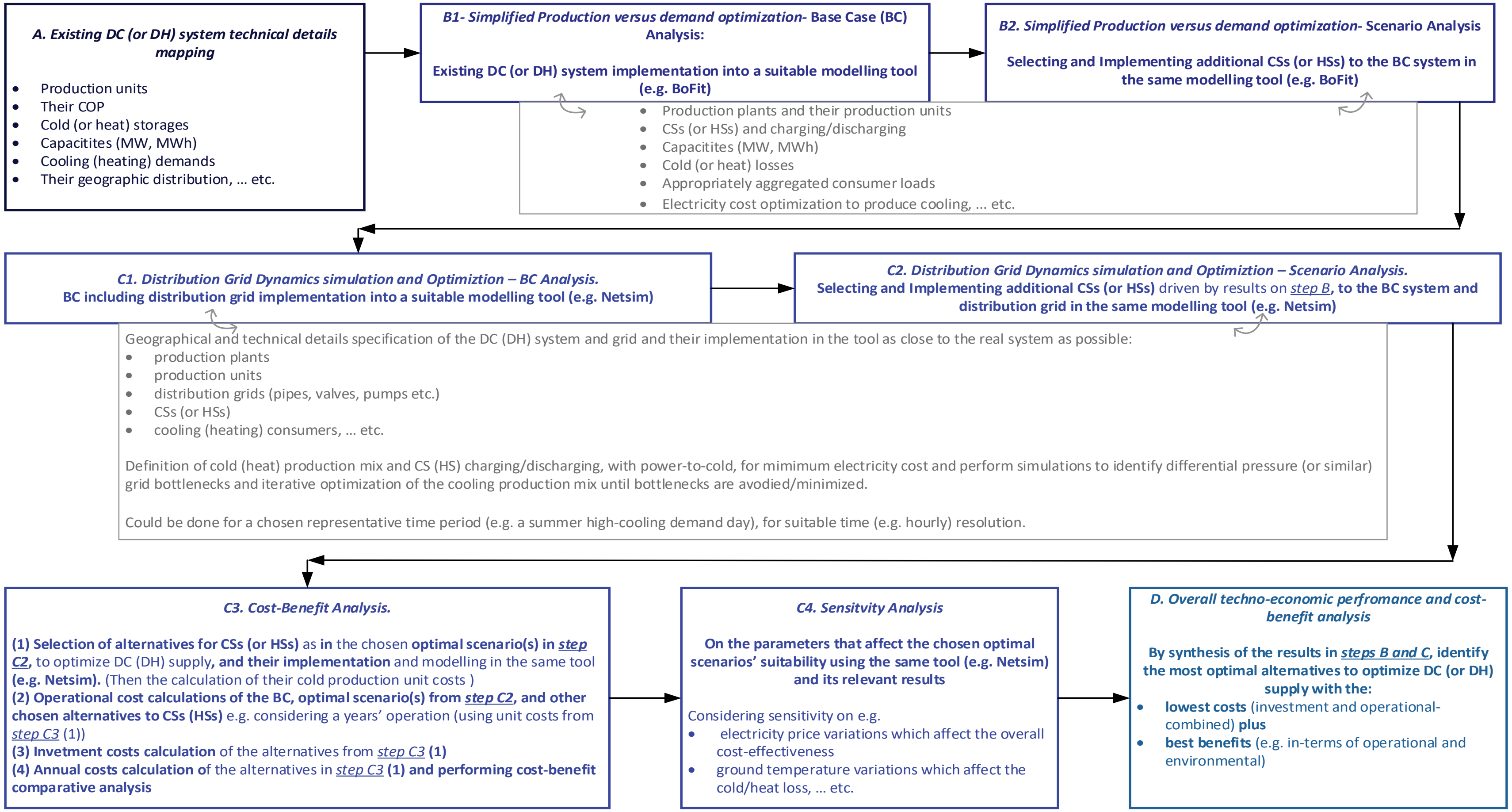

Figure 1. Generic methodology of techno-economic performance evaluation and cost-benefit analysis of a DC (DH) system optimization with CSs (HSs)

2.1 NORRENERGI AB'S DC SYSTEM AND COLD STORAGE

Here, the main technical details of Norrenergi AB's DC system that are used in the calculations are explained, as relevant to step A in Figure 1. Norrenergi AB's today's DC system (referred to as the base case- BC) consists of three main production plants situated at Sundbyberg (Sundbybergsverket -SBG), Frösunda (Frösundaverket- Frö) and Solna Strand (Solnaverket- Solna). Their DC production mix involves free cooling (FC), a number of compression chillers (CCs) and also heat pumps (HPs) which are used for producing cold during summer when heat from the HPs have a limited or very limited value[1]. A cold storage (CS) of 6500 m^3, 10 MW maximum charging/discharging and 75.7 MWh storage capacity is also located in Solnaverket, employed for demand balancing today. These units' technical specifications are summarized in Table 1, including the installed capacity and coefficient of performance (COP). Thus Norrenergi AB's today's DC system has an installed maximum cold production capacity of 73.1 MW (including the maximum cold charging/discharging capacity of the CS). The real physical spread of today's DC system of Norrenergi AB, connecting the three production plants with the customers is shown in Figure 2.

Table 1. The installed capacity of 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***	

In the ensuing techno-economic analyses performed on Norrenergi AB's DC system (for production versus supply optimization as well as grid dynamics optimization) concerning a single day (24 hours) operation. Here, one of their highest historical cold demands per day, i.e., 02 August 2018 (with a 58.97 MW= 59 MW maximum hourly demand) was used to represent the BC as well as the additional cold storages-integrated scenarios. This used cooling demand profile is shown in ***Figure*** 3, and the detailed data are given in Appendix Table 12. By accounting such a highest historical demand date, it is assumed that the results therein can sufficiently represent any eventual demand case (which will be lower than the highest demand) for today's demand profile.

[1] During winter, DC is a waste product that is used to cool down the purified wastewater when it is used in the heat pumps to recover heat. In summer, the heat demand is less and one to two heat pumps are used primarily for DC production where the heat has a limited or very limited value.

Figure 2. Norrenergi AB's DC system today, with the three cold production plants Sundbybergsverket, Frösundaverket and Solnaverket (also including the existing CS)

The operational costs were calculated based on the use of electricity to produce the required cold, combined with the hourly electrical cost data for 02 August 2018 that were obtained from Nord Pool for the region SE3 [15]. The region SE3 encompasses Stockholm county and hence both Solna and Sundbyberg municipalities [15]. These hourly prices data are depicted in Figure 4 with the tabulated data given in Appendix Table 14. Overall, it is assumed that the cost of electricity predominantly represents the operational costs of all the cold production units, while the other operational and maintenance costs remain similar (and thus excluded here).

When assigning operational strategies to these analyzed cases, cold production technologies with higher COPs were prioritized over low COP technologies, in an order of merit based on their COP. This means that the used order of merit for the cold production is free cooling, compression chillers, and lastly the heat pumps. In deciding the operating strategy for the cold storage charging and discharging, power-to-cold concept was adopted. Figure 4 shows that the electricity cost peaks occur during the day, with lower costs at nighttime. Thus, to charge the cold storages, both high-COP technologies as well as the use of nighttime cheaper electricity were prioritized simultaneously. To discharge the cold storage to cover cooling peaks during the day, peak shaving and load shifting were combined. The specific details and data for the charging and discharging of the cold storages are explained further in the following sections.

For the investment costs analyses, certain historical values and rules of thumb were combined with available data from e.g. Holgersson et al., 2019 [16] and

DACE price booklet, 2020 [17]. These steps are also further detailed in the following sections.

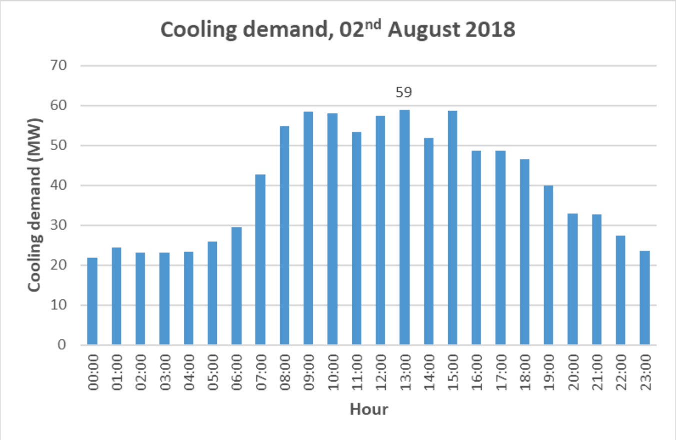

Figure 3. Norrenergi AB's DC demand profile for 02nd August 2018, used as the representative high historical demand day, in the numerical modelling

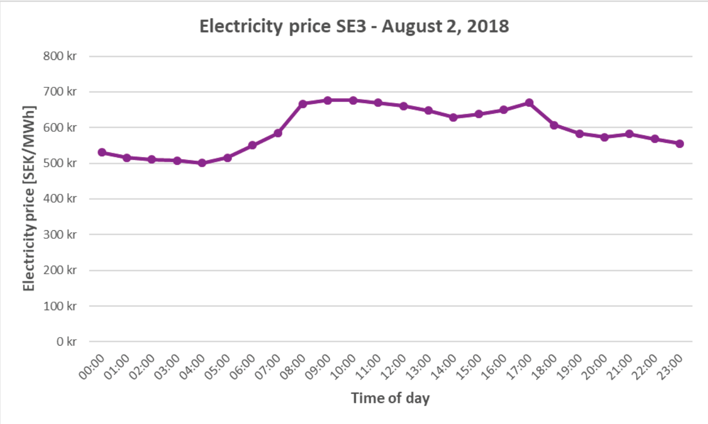

Figure 4. The price of the electricity used in the calculations, from Nord Pool [15] for SE3 region, 02 August 2018

2.2 BOFIT FOR DC SYSTEM OPTIMIZATION

In this section, the DC production versus supply optimization method as relevant to the case study of Norrenergi AB's DC system is explained. This corresponds to steps B1 and B2 in Figure 1[2].

BoFit [8] is an optimization software tool used mainly for planning the production in the energy sector [18]. In this WP 2.3, BoFit was used to optimize the DC system of Norrenergi AB, considering the optimization of cold production for the demand (i.e., consumers) of cold, without any consideration on the distribution network requirements and limitations. Therefore, this BoFit optimization excludes the implications of these loads on the distribution grid. Even if this was a considerable

[2] Choosing the capacities, number and placement of additional cold storages into a DC system is specific to each individual DC system and should be done considering many factors such as, their total DC installed capacity, peak demands that are expected to be shaven and shifted, as well as economic and geographical restrictions, among others.

simplification, it was used as a preliminary assessment to obtain reasonable estimates of the optimal sizing of the additional cold storages as well as their potential placement in Norrenergi AB's DC system. The advantage of using BoFit here was the reasonable simplicity to implement Norrenergi AB's DC system there from scratch, without requiring the intricate technical and geographical details of their real distribution grid as well as the customer demand profiles, among others.

In BoFit, Norrenergi AB's three production plants were aggregated to the three so-called 'containers'. Inside each respective container, the corresponding cold production units (c.f. Table 1) of each were assigned, along with their technical data. These three production plant containers were then linked to customers, also aggregated into several regions, based on their demands as well as geographical location. This simplification was essential to save effort and time in this first step of optimization. However, the aggregation was decided in consultation with Norrenergi AB, to ensure that they still represent the overall production and supply aspects of their DC system today as realistically as possible.

The BoFit model of Norrenergi AB's DC system today (BC) is shown in Figure 5 and Figure 6, showing the entire DC system, and e.g. the container of Solnaverket, respectively. Besides the production plant containers, free cooling was also assigned to a separate container (FC source, Figure 5), to allow its' cold production to be common for the entire grid, for being the most cost-effective cold production technology used.

The cold loss in the system was also defined as a 'demand' to maintain energy balance in the model. Here, cooling loss of 1.6 MW was used based on historical data from Norrenergi AB. The chosen customer regions comprise of cooling demands from the regions (as shown in Figure 5), Huvudsta, Solna-Sundbyberg, Central Solna, Hallonberg, Arenastaden and Frösunda, respectively. The detailed designation of demand (MW) of the real customers in Norrenergi DC system to each of these aggregated regions are specified in **Appendix** Table 15. Based on the historical data from Norrenergi AB for 2018, the forecasted demand for each customer (c.f. Table 15) accounted for a total of 50.1 MW maximum demand. Then again, the total real maximum production of cold was 58.97 MW at 13:00 on 02 August 2018. Thus, to calculate the real supplied cold amount for each of these customers, the respective forecast for each customer was divided by the total forecasted amount (50.1 MW) then multiplied by the total real consumption which is 57.4 MW (i.e., obtained by deducting 1.6 MW of losses from the total maximum production of 58.97 MW).

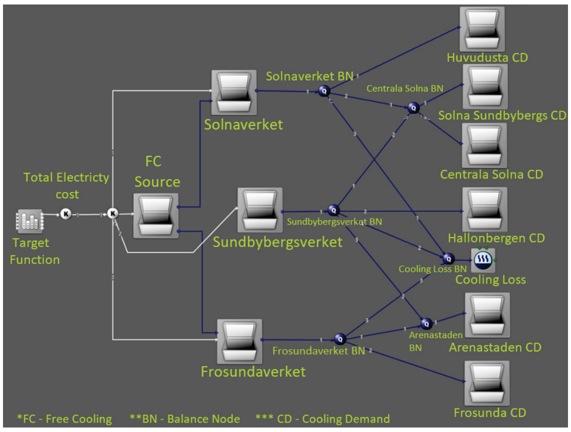

Figure 5. BoFit model of Norrenergi AB's today's DC system and the existing cold storage, supplying cold to regionalized customers (to simplify the supply mix) [10].

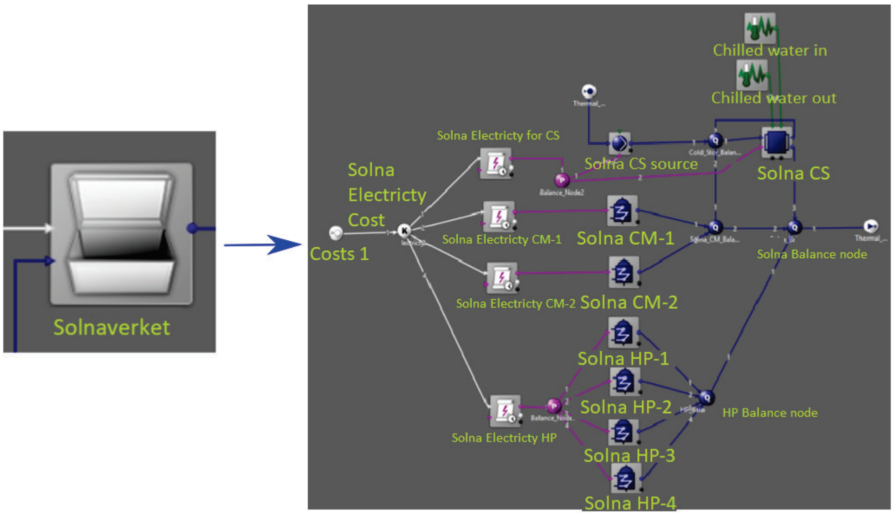

Figure 6. Solnaverket Container in BoFit. On left: the container as seen at the main model level, on right: all the production units and the existing cold storage (10 MW) assigned inside this Solna container [10].

The free cooling source is the lake Lilla Värtan. The amount of free cooling that can be extracted from this is limited by a maximum flow rate of water (360 l/s [19]). Therein, the maximum available free cooling capacity was calculated for return and supply temperatures 14 °C and 4 °C (i.e., 10 °C difference), considering the sensible heat storage capacity in water (using specific heat capacity of water c_p of 4.19 kJ/(kg·K) and the density of water ρ of 1000 kg/m^3. This maximum free cooling capacity was found to be 15 MW, which was used in the BoFit model calculations.

With BoFit, today's DC system, i.e., the BC (with 10 MW CS in Solnaverket) as well as four scenarios with additional cold storages, to further optimize the DC supply, were modelled. These scenarios comprise: one 15 MW at Sundbyberg (Sc. 1), one 15 MW at Frösunda (Sc. 2), and two 3 MW CS at Sundbyberg and Frösunda (in both Sc.3 and Sc.4). The capacities of these new CSs were determined by consultations with Norrenergi AB. Their visualization in BoFit are depicted in Figure 7.

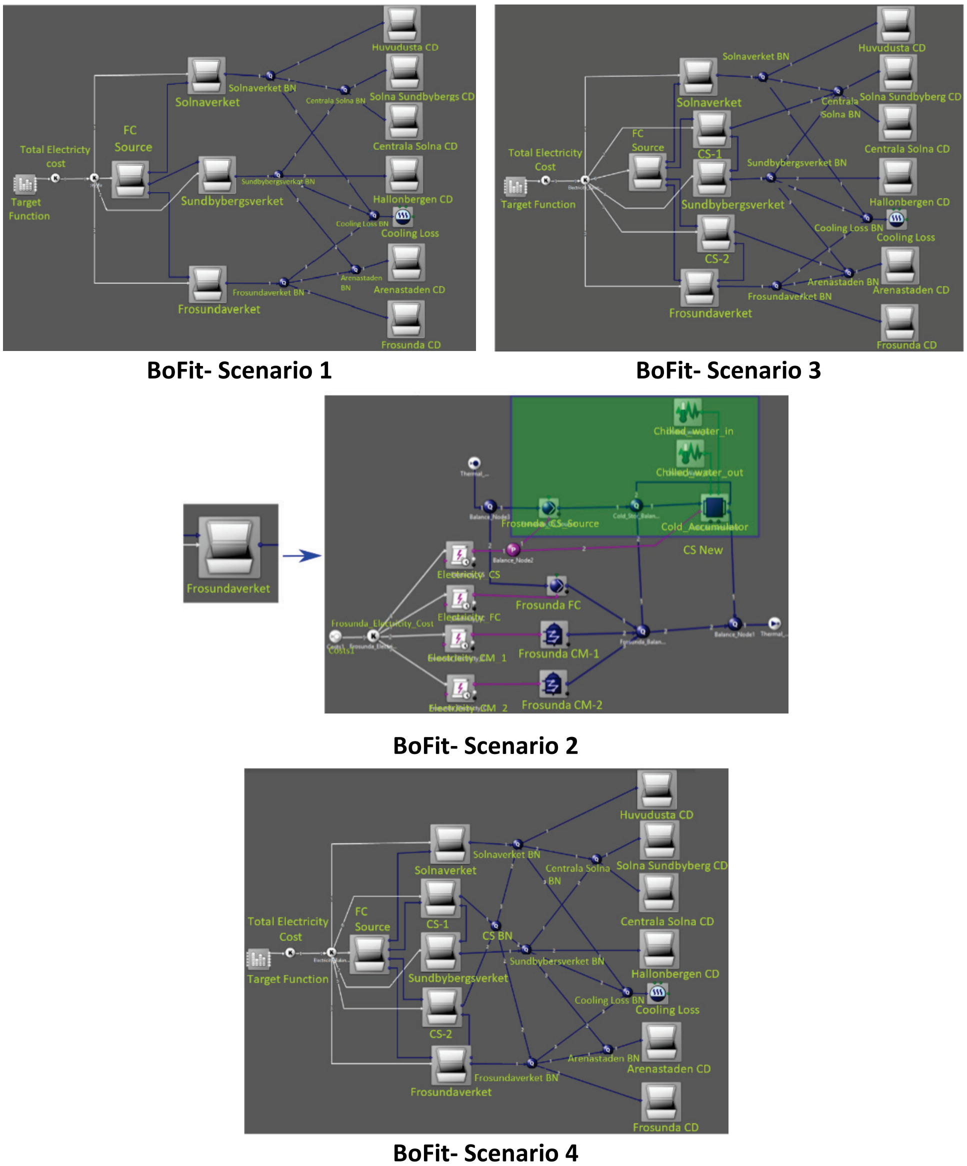

Figure 7. The BoFit models of the 4 chosen scenarios with additional CSs (one 15 MW at Sundbyberg (Sc. 1), one 15 MW at Frösunda (Sc. 2), and two 3 MW CS at Sundbyberg and Frösunda (in both Sc.3 and Sc.4)., with various supply configurations) [10].

For these additional CSs, the 15 MW capacity was chosen, for being an already identified capacity of interest based on certain pre-calculations performed by Norrenergi AB. Then, to compare such a rather large storage, to have contrast, it was decided to choose another small CS capacity as well. Thus, a 3 MW capacity was chosen arbitrarily, to be small enough yet not too small to have an impact. In scenarios 1, 2 and 4, the additional CSs supply cold to all cold consumers, whereas, in scenario 3, the additional CSs supply cold to only certain chosen high-demand customers. This was done to investigate at least some attributes of a distributed CS, even though BoFit cannot evaluate the dynamics of the DC distribution grid and therefore the impact of the placement of units on the grid.

An energy balance was performed on each case, BC as well as each scenario, to ensure that the calculations are correct.

This optimization work was done mainly via the master's thesis work of Yifru Woldemarium Biramo in 2019 [10], to which the readers are directed for further details. Based on the results from this preliminary optimization study of the simplified supply-demand aspects of Norrenergi AB's DC system with the additional CS cases, it was then decided that a detailed network dynamics analysis is essential as the next and the main step. Therefore, in this report, the pursuing network dynamics analysis is explained and discussed in more detail.

2.3 NETSIM FOR DC DISTRIBUTION GRID DYNAMICS-BASED PRODUCTION OPTIMIZATION

In this section, the DC distribution grid dynamics optimization method, illustrated in Figure 1[3] along steps C1 and C2, applied specifically to the case study of Norrenergi AB's DC system is explained.

Netsim [9] is an interactive thermal network simulation software, which calculates the DH and DC distribution grid dynamics in terms of e.g. pressure differences, flow rates and temperatures of hot or cold water. With Netsim simulations, evaluating network expansions, identifying grid bottlenecks (in-terms of pipe sizing and of differential pressure) as well as energy demands assessment of components (e.g. pumps) can be done. As the next step in WP 2.3, Norrenergi AB's today's DC system as well as several cold storage scenarios were modelled in Netsim.

Norrenergi AB have their DC system visualized in a network information system (NIS) called dpHeating, from Digpro Technologies AB [20]. dpHeating contains DC network and components' dimensioning information (e.g. on pipes, valves, pumps etc.) and is useful for documentation purposes but has no calculation module. It was, however, possible to import Norrenergi AB's DC network from dpHeating into Netsim. Therefore, this import was done by Bilek, 2020 [11], therein implementing this DC system in Netsim to perform grid dynamics calculations.

In these Netsim optimizations, the grid bottlenecks in terms of differential pressure (dP) was considered as the main optimization criteria (to be maintained within 100-800 kPa), for which, the cold production and CSs charging/discharging profiles were iteratively optimized. If the dP falls below 100 kPa, the agreed quality for DC is not met and there might be a limited supply. Whereas, the DC distribution grid and its components are physically capable of handling only dP below 800 kPa. While maintaining these dP criteria, the production mix was then iteratively optimized, by assigning the highest COP production mix (i.e., the lowest production cost mix) as possible, following the order of merit on COP. The order of merit on COP suggests the priority on free cooling (COP: 10), then chillers in Sundbyberg, Solna and Frösunda (COP: 5) and followed by the heat pumps in Solna (COP: 3), to fulfill each hourly total demand. Their installed capacities as listed in Table 1 were used here as each type of unit's maximum production limit. This first assigned production mix purely based on the order of merit on COPs was then iteratively adjusted following several Netsim calculations for each model (BS

[3] In this case too, the capacities, the number, and positioning of the additional cold storages should be chosen based on each specific DC system conditions.

and each and every scenario) to bring the dP for each hour on the entire distribution grid to be well within 100-800 kPa.

Once such a truly optimized cold production mix was identified per modelled case (BC or a scenario), by using the definition of COP, the amount of electricity required to produce the cold of each type of unit per hour was calculated. Therein, the cost of cold production is then calculated, using the hourly electricity costs from Nord Pool [15] (c.f. Appendix, Table 14) for 02 August 2018.

The required production capacity (in MW) per hour is defined in Netsim as a power factor, in relation to the total maximum contracted demand of the system which is 66.706 MW (in this work concerning for summer 2018). The hourly demand profile used in determining these power factors for 02 August 2018 is shown in ***Figure 8*** with tabulated data in **Appendix** Table 12.

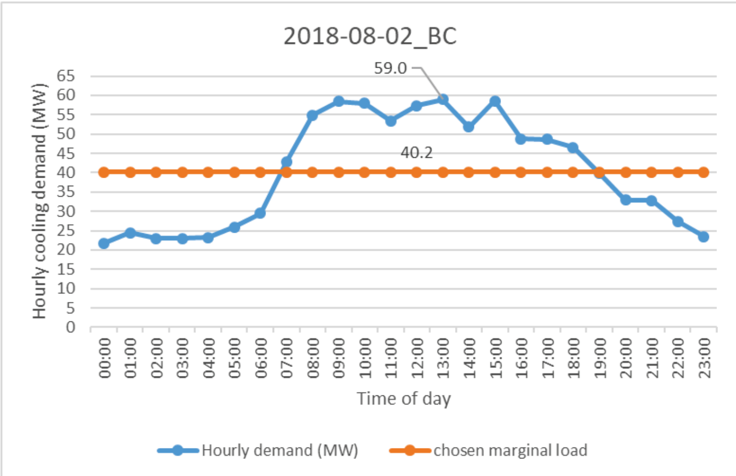

Figure 8. The demand profile on 02 August 2018, and the cutoff demand chosen at the mean demand 40.22 (also showing the maximum peak demand of 59 MW at 13:00)

An ambient temperature of 26 °C (which dictates the proportion of real cold supply required out of the contracted maximum supply in MW[4]) and a ground temperature of 8 °C (which influences e.g. cold losses) were used. The supply and return temperature limits were defined to be 5 °C and 15 °C, within the entire DC system, including to and from each CSs. The temperature variations in the DC network is mainly governed by the ground temperature, which however has slow changes as compared to ambient temperatures [21]. Therefore, in the main Netsim calculations, the temperature variations are not discussed. However, a sensitivity analysis is performed (discussed later in sections 2.5 and 3.4.4) specifically on ground temperature to and its impacts on the DC supply.

CS charging and discharging was assigned as following. The existing CS in today's system in Solna has a 10 MW maximum charging/discharging capacity for 6500 m^3 volume. The maximum cold storage capacity of this CS, i.e., E_{CS} can be calculated

[4] This is defined for a power factor on production (of assigned production per contracted maximum cooling) as a function of ambient temperature (ranging 2-36 °C ambient temperatures with 0.076 to 1 production power factors), based on Norrenergi AB's historical data. For ambient temperatures at or above 26 °C, this power factor is 1, meaning, up to a maximum of 100% of the contracted cooling power should be supplied, while specifically following the hourly production power factor each day.

using Eqn. 1 [11], considering its volume (V), density of water ρ, c_p of water and the temperature difference ΔT of 10 °C (between the supply and return temperatures of 5 °C and 15 °C). Thereby, the cold storage capacity of this 10 MW CS is found to be 75.7 MWh.

$$E_{CS} = \frac{V}{3600}\frac{\rho c_p \Delta T}{1000} \quad \textbf{Eqn. 1}$$

The mean demand (40.22 MW) within the 02 August 2018 hourly demands was chosen as a cutoff (marginal) load for the BC, as shown in Figure 8. This was done to even-out the cold production while shaving the peak demand, by adjusting the CS charging/discharging. Then, considering the difference (C_{dif}, *in MWh*) between this defined cutoff factor (C_{cutoff}, *in MWh*) and each hourly demand (Ct, *in MWh*), the available 'additional' cold available for storage (C_{NW}, *in MWh*) was determined, as explained in Eqn. 2 [11]. This (C_{NW}) equals to a total of 155.2 MWh of cold (for the entire 24 hours).

$$C_{NW} = \sum_{t=1}^{24} C_{cutoff} - C_t = \sum_{t=1}^{24} C_{dif} \quad \textbf{Eqn. 2}$$

To adjust this available cold per hour to match the real capacity of the CS (e.g. a maximum of 10 MW for the existing CS in Solna), a storage ratio (r_{CS}) was defined, based on Eqn. 3 [11]. This storage ratio for the existing 10 MW CS is found to be 0.49.

$$r_{CS} = \frac{E_{CS}}{C_{NW}} \quad \textbf{Eqn. 3}$$

$$C_{CS} = \sum_{t=1}^{24} (C_{dif} \times r_{CS}) = E_{CS} \quad \textbf{Eqn. 4}$$

Afterwards, the realistic amount of cold for charging the CS (C_{CS}) was calculated by using Eqn. 4 [11] (which equals the total storage capacity of the CS considering the entire 24 hours). In this manner, the realistic charging capacity for each CS was determined. In a similar way, also for discharging the stored cold in the CS up to consuming its total capacity (E_{CS}), the hourly cold discharging amounts were calculated. The resultant charging and discharging profiles of the existing 10 MW CS (in Solnaverket) is shown in Figure 9, with detailed tabulated data in Appendix Table 16.

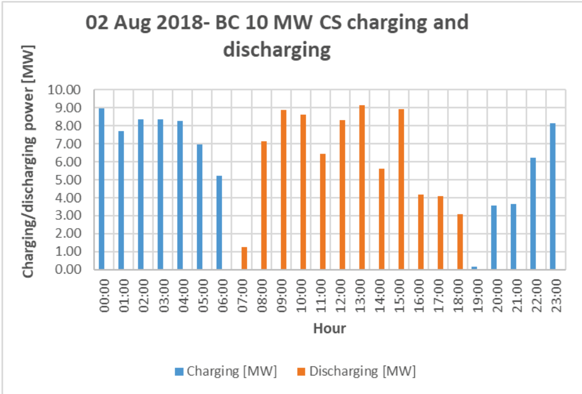

Figure 9. The cold charging and discharging profiles of the 10 MW CS in Solnaverket.

Building upon the findings from Biramo, 2019 [10] (explained later in section 3.3), the first part of the distribution grid dynamics analysis was thus conducted through the master's thesis of Zinar Bilek, 2020 [11]. Besides the BC, three scenarios were modelled, in his work. In scenario 1 and 2, an additional 15 MW[5] CS (15000 m^3) was considered, respectively, at Sundbyberg and at a distributed location in Frösunda. In scenario 3, two additional CSs of 3 MW (and 3000 m^3 volume) each, at Sundbyberg and at the distributed location in Frösunda were considered. This distributed location in Frösunda was chosen also based on Netsim calculations first performed on the BC, which indicated low dP conditions around this network region. For the scope of this master's thesis, the models used simplified pipe details in the grid with e.g. somewhat overestimated surface roughness details (to avoid underestimation of dP levels) and a larger volume of the additional CSs (sized allowing 1000 m^3/MW).

To assign the hourly charging and discharging of the additional CSs in these scenarios, the available cold to charge these was recalculated. As an example, considering the 15 MW additional CS with a 15000 m^3 volume, using Eqn. 1, thus its energy storage capacity becomes 174.6 MWh. Then, e.g. for scenario 1 or 2 in Bilek, 2020 [11], the total energy capacity required to charge the two CSs in the DC system (the existing 10 MW CS and new 15 MW CS) is the sum of their respective capacities, i.e., 250.3 MWh. As the mean demand from the BC is now insufficient as a cutoff to cover this total CS charging capacity requirement, it needs to be increased. Therefore, the mean demand was increased iteratively (e.g. using 0.1 MW increments) to find the suitable cutoff demand, until the sum of the available energy per hour became equal to the total CS charging requirement (for this e.g., which is 250.3 MWh). For the 15 MW additional CS scenarios, this cutoff demand is found to be 47.6 MW. Accordingly, the new storage ratio (r_{CS}) as well as the new realistic amount of cold for charging the CS (C_{CS}) were calculated for these scenarios, following Eqn. 3 and Eqn. 4. Thereby, the hourly charging and discharging capacities for each CS were determined. These determined hourly capacities were eventually averaged and evenly distributed within the respective

[5] These charging/discharging powers of the CSs stated within this techno-economic evaluation, are nominal powers of the CSs, unless otherwise specified.

charging and discharging durations by Bilek, 2020 [11] to approach this first step of the Netsim study more systematically.

The charging and discharging hourly time series used by Bilek, 2020 [11], for the existing 10 MW (6500 m^3, 75.7 MWh) CS, 15 MW (15000 m^3, 174.6 MWh) and 3 MW (3000 m^3, 34.9 MWh) CSs are given in Appendix, Table 17, Table 18 and Table 19 respectively. The CS charging duration of these CSs was 07:00-18:00 and discharging during 00:00-06:00 and then 19:00-23:00[6], thus accommodating peak shaving of electrical and cooling load to cheaper nighttime production.

In the physical interpretation of the CSs in Netsim, the charging and discharging of each CS should be defined at a respective node. However, the Netsim version that was used here had only in total 10 such nodes available (for production units and CSs altogether). Therefore, when two additional CSs were considered (e.g. in scenario 3 by Bilek, 2020 [11], Solna chillers and heat pumps were aggregated into one single node of total installed nominal power of 28 MW (i.e., the sum of the capacities of chillers: 10 MW and heat pumps: 18 MW in Solnaverket). Once the Netsim calculation results were obtained, the production from Solna was then separated out again into Solna chillers and heat pumps by assigning up to 10 MW to chillers and the remainder to the heat pumps (following the order of merit on COP). Thereby the overall results are ensured to be still valid and comparable.

In Netsim, one node location must be defined with a set pressure[7], and one production plant which should be allowed to produce theoretically unlimited amount of cold. In all the Netsim analyses in this WP 2.3, the plant allowing unlimited production was chosen to be Solna chillers (or the combined Solna production in scenarios with two additional CSs). That is, the real calculated cold production results (per hour) in Netsim are for this specified plant unit, while the rest of the production mix follows the defined power factors. In the BC and scenarios of Bilek, 2020 [11], a set pressure of 250 kPa was used at a point in the grid at western Solna (node 124495). This type of set pressure definition is also done in the physical DC systems' real operation. That is, distribution pumps from one chosen production plant are used (in conjunction with the control of the DC supply from the rest of the network) to ensure that the network dP levels remain within desired limits while effectively producing the required cooling. In all the Netsim models in this work, even if such an unlimited production was allowed in e.g. Solna, through the iterative optimizations of production mix and dP, it was ensured that Solna production did not exceed its real physical limit of 28 MW.

Building upon the results from Bilek, 2020 [11], the main and the second step of the Netsim-based analysis was conducted then. There, the network pipe data of the BC Netsim model from Bilek, 2020 [11], were upgraded to better represent the real data[8]. Thereafter, to determine the optimal CS sizes, the BC was compared with six

[6] For the 15 MW CS, as it requires quite a large total storage capacity (MWh), at the hours 07:00 and 18:00 both charging and discharging had to be assigned to occur simultaneously.
[7] Choosing the suitable set pressure node is done also by performing Netsim calculations. That is, the dynamic calculations are first performed for an initial set node, and therein, a consistently low-pressure node is chosen as the set pressure node for the calculations thereafter
[8] This was done by identifying the years/periods of construction and expansion of Norrenergi AB's Dc network and accordingly assigning the pipe types, dimensions and insulation types corresponding to these different construction/expansion periods. Here, certain pipes had to be approximated to a certain

scenarios (A-F) each developed using two equisized CSs (of 3, 4, 5, 6, 7 and 7.5 MW nominal power respectively), one at Sundbybergsverket (i.e., centralized) and the other at Frösunda low-pressure loop (i.e., distributed). The volumes of these additional CSs in Scenarios A-F were determined by linearly downscaling to the required power (MW), considering today's CS of 6500 m³ that can deliver 10 MW[9]. The volume (m³), charging/discharging nominal power (MW) and the cold storage capacity (MWh) of these respective CSs of the BC and scenarios A-F are summarized Table 2.

The hourly charging of these additional CSs were decided based on the approach explained earlier, along Eqn. 3 and Eqn. 4. These obtained hourly values were used in these extended Netsim calculations (without averaging out like was done in Bilek, 2020 [11]) to analyze a more realistic DC operation. The discharging of the additional CSs were assigned manually to discharge the most amount of cold at the highest peak hours, and the rest distributed in a rather declining order around the maximum peak hours, to match the remaining CS capacity. During either charging or discharging of a CS, the maximum allowable power was the nominal power of the respective CS (e.g. 10 MW of the existing CS), while ensuring that the total storage capacity was fully charged/discharged (e.g. 75.6 MWh of the existing CS in Solna). The charging/discharging hourly time series used on each of these CSs are presented in Appendix Table 20-Table 25. These CSs also allow charging duration between 07:00-18:00 and discharging during 00:00-06:00 and then 19:00-23:00, accommodating peak electricity as well as cold shaving and shifting to cheaper nighttime production.

Table 2. The charging/discharging nominal power, volume, storage capacity, as well as the volumetric power and capacities of the CSs used in the BC and scenarios A-F. (Here, scenarios A-F also contain the 10 MW CS as in BC, while they additionally contain two identical CSs each with the characteristics listed)

Case/Scenario	CS nominal power [MW]	CS volume [m³]	CS storage capacity [MWh]	CS nominal volumetric power [kW/m³]	CS volumetric storage capacity [kWh/m³]
BC	10	6500	75.7	1.5	11.6
Sc.A (3 MW*2)	3	2000	23.3	1.5	11.7
Sc.B (4 MW*2)	4	2600	30.3	1.5	11.7
Sc.C (5 MW*2)	5	3300	38.4	1.5	11.6
Sc.D (6 MW*2)	6	4000	46.6	1.5	11.7
Sc.E (7 MW*2)	7	4600	53.5	1.5	11.6
Sc.F (7.5 MW*2)	7.5	5000	58.2	1.5	11.6

In this extensive Netsim analysis work, all the scenarios and the BC were simulated using the set differential pressure at a node in western Solna (node 62799, still also close to node 124495 used by Bilek, 2020 [11]) in the grid to be 250 kPa (which is required by Netsim). The Netsim model visualization of the BC, the two cold storages in Sundbyberg and Frösunda, a pipe extension at Frösunda loop and a new chiller in Sundbyberg respectively are shown in Figure 10 a)-d).

period, based on the limited availability of precise data. This was nevertheless assumed sufficiently accurate for the purpose of this WP 2.3.

[9] That is, using the factor 650 m³/MW to calculate the required exact volume, and then rounding that up to the nearest 100 m³ to allow a practical volume considering the physical construction of a tank.

Succeeding the Netsim-based production optimization calculations for scenarios A-F, for a 10% future demand increase, the chosen optimal scenario (with the additional cold storages) and the BC were analyzed against two more alternatives. These alternatives are, connecting the Frösunda loop experiencing low-pressure with the main grid coming from Sundbyberg, and adding a new chiller to Sundbyberg to cover the additional peak cold demand (e.g. Figure 10 (c) and (d)).

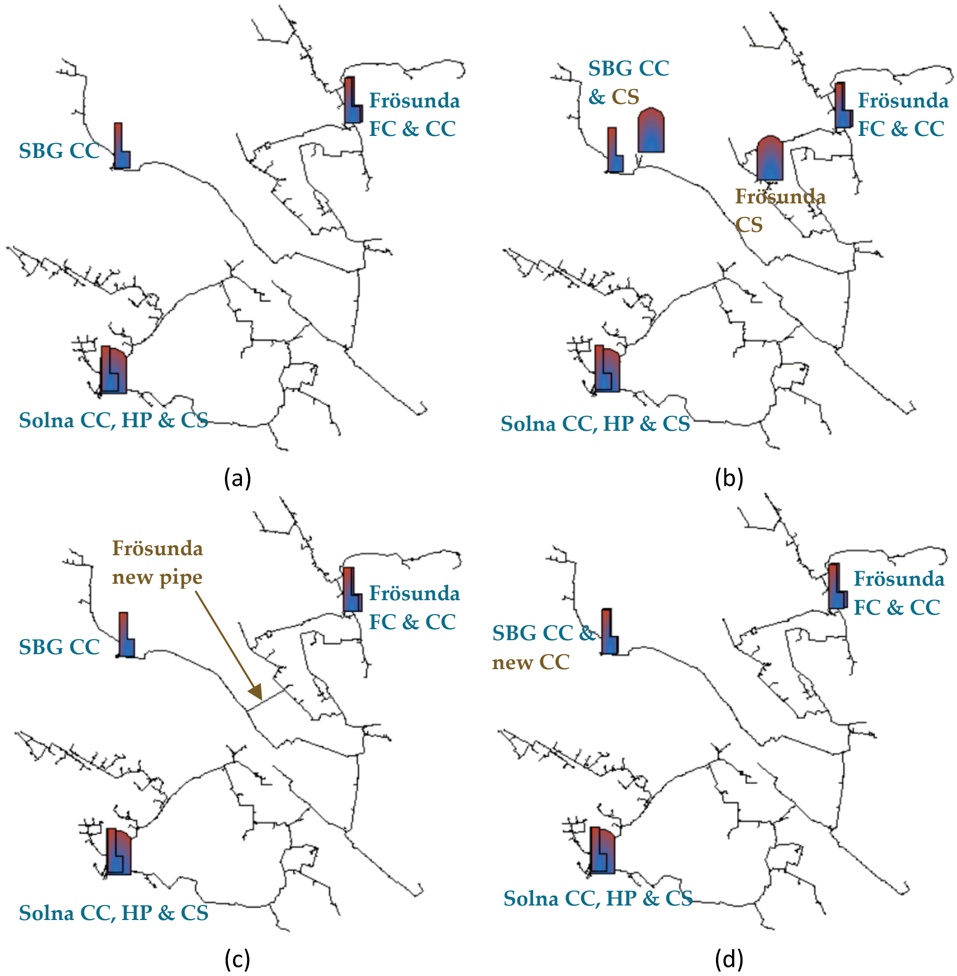

Figure 10. Netsim models of Norrenergi AB's DC network concerning: (a) the BC, (b) a scenario with two additional CSs in Sundbyberg and Frösunda loop, (c) a new pipe extension between Frösunda and Sundbyberg grid, and (d) a new chiller at Sundbyberg. (BC- base case, SBG- Sundbyberg, CC- chiller, HP- heat pump, CS- cold storage)

The 10% higher demand was calculated by increasing each hourly demand also by 10%, thus with the maximum hourly peak demand of 64.9 MW (see Appendix Table 13). For this 10% higher demand situation, the set pressure in each Netsim model was to 250 kPa (for the same specific node 62799) in the initial calculation of each. This first calculation yielded at certain grid sections: critically lower dP levels (on BC), or critically higher dP levels (on the optimal CS scenario and the Sundbyberg new chiller). Therefore, the set pressure in these alternatives were then adjusted to be sufficiently higher and lower than 250 kPa (yet well within 100-800 kPa full range), and new calculations were performed to balance the grid at lowest possible costs. Therein, the final set pressures used were: 300 kPa for BC, 150 kPa for the optimal cold storages scenario and the new chiller in Sundbyberg, and 250 kPa for the new pipe in Frösunda loop, respectively. Even if they are not calculated for the same set pressures, the obtained results are still valid, practically possible, and hence are comparable.

An optimal scenario or an alternative was chosen by comparing them with BC on several key performance indicators (KPIs) defined such as (here these unit costs refer to operating costs only):

- 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).
- KPI,5- the avoided peak electricity (MW) use at the maximum peak load hour (MW,electricity/peak hour),
- KPI,6- the avoided peak electricity use per day (MWh,electricity/day)
- KPI,7- the avoided peak cooling production per day (MWh,cold/day), which is the amount of peak shaving)

The calculation of the KPI,1- KPI,4 are rather self-explanatory, and will be discussed more along the corresponding results in section 3.4. The peak electricity use at the maximum peak demand hour was calculated (by summing up the electricity used by each plant) for the hour 13:00. This hour has the highest peak cooling demand on the chosen day (02 August 2018)[10]. Per day, the respective peak electricity use and the peak cold production were calculated by summing up the amount of electricity used or the cold produced within the peak demand hours: 07:00-19:00. KPI,5 - KPI,7 were thus obtained as the difference between BC and each scenario (100% demand case) or alternative (110% demand case). That is, for KPI,5, KPI,6 and KPI,7, the difference of BC versus scenario or alternative was calculated respectively concerning the peak electricity use (MW,electricity), peak cold production per day (MWh,cold/day) and peak electricity use per day (MWh, electricity/day). These KPIs were defined considering the results that can be obtained via this type of analysis using network dynamics optimization with e.g. Netsim. The main motive behind defining KPI,1- KPI,4 was to find comparative indicators that can emphasize the costs of cold production concerning the produced cold but also the used electricity in producing that. The motive behind defining KPI,5 - KPI,7 was to specifically characterize the power-to-cold adaptation in-terms of the amount of cold that is decoupled from the peak cold demand and therein the avoidance of peak electricity use in MW and MWh which instead can be absorbed when in surplus.

2.4 COST BENEFIT ANALYSIS

This section details the employed cost-benefit analysis methodology in this WP as related to step C3 in Figure 1, as specific to Norrenergi AB's DC system study.

[10] Typically the peak cold demand hour lies at around 17:00, however, for this chosen day it has shifted to 13:00, possibly due to the exceptional summer weather in 2018 and/or some other changes.

In 2018, Norrenergi AB has produced in total 81 GWh cold. For the 10% higher demand case, this total production was also assumed to have increased by a 10% (i.e., to 89.1 GWh). By multiplying this projected total production with KPI,1 (unit cost of cold produced in SEK/MWh,cold), the total operating costs for this 10% higher demand was calculated for all the four alternatives: BC, the optimal scenario with two new CSs, new pipe in Frösunda, and new chiller in Sundbyberg, respectively.

Investment costs were also estimated for each of these four alternatives, for this 10% higher cold demand situation. The sizing that was used for the new cold storages (volume, m^3), the new pipe (length, m) and the new chiller (nominal power capacity, MW) depended on the Netsim simulation results, and are therefore explained more in section 3.4.2. The unit costs and their typical payback periods that were considered are summarized in Table 3, with table footnotes further explaining the final cost figures that were used. By dividing the total investment cost for each new investment alternative by the respective payback period, the apportioned annual investment cost was calculated. Here, the impact of inflation and depreciation was assumed similar for all the three new investments cases, and thus was not further considered.

Table 3. The investment cost data and payback periods used in the cost calculations

Component	*Specifications (if relevant)*	*Unit investment cost*	*Typical payback period (years)*
Cold water storage	*-*	*1700 SEK/m³ [16]* [a]	*30* [c]
	Vertical storage tank, Carbon steel, cone roof model	*1173 SEK/m³ [17]* [b]	
DC pipes	*DN 300*	*18 000 SEK/m* [c]	*30* [c]
	DN 400	*20 000 SEK/m* [c]	
Chillers	*-*	*5000 to 7000 SEK/kW* [c,d]	*20* [c]

[a] *as this is an average investment cost for several existing heat storage establishments, from 2002-2018 (including the costs of the storage tank, design, complete equipment, insulation and outer casing with or without considering the pipe connections to the DC grid* [16]*), a 10% more cost was considered to account e.g. extra costs in insulation for CSs).*
[b] *this is an interpolated value, for 5000 m³ size, using the costs for storage sizes 1000, 1800, 6000 and 13500 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.*
[c] *data from Norrenergi, and* [d] *the average of this range, i.e., 6000 SEK/kW was used.*

Finally, the apportioned annual investment cost and the annual cold production cost (for the 10% higher demand case) were summed up, to obtain the total annual cost per alternative. For BC, the investment cost is zero. By comparing the total annual cost of the three alternatives: optimal scenario with two new CSs, a new pipe, and a new chiller, to that of the BC, the avoided/additional cost are thus calculated.

Albeit this performed cost analysis being a quite simplified approach to describe the annual costs of an investment, it is still considered as sufficiently representative of the key cost aspects of these alternatives. That is because, this analysis only aims to give examples of how the "total production cost" of these different alternatives can look like for local conditions and standard investments. Therefore, the results therein are considered as valuable inputs for the techno-economic analysis in this WP 2.3.

2.5 SENSITIVITY ANALYSIS

In this section, the employed sensitivity analysis methodology, corresponding to step C4 in Figure 1, is explained specifically for Norrenergi AB's DC system study.

To identify the sensitivities of the results that governed the final choice of optimal scenario/alternative, temperature and electricity price are chosen as two main variables. Here, the identified optimal scenario/alternative and the BC, based on Netsim results, were analyzed using several temperature and electricity price variations, as explained below. The results of these sensitivities are discussed in detail in section 3.4.4.

The DC grid which is always positioned underground is only affected by the ground temperature (in this case, soil temperature is more relevant, however, it will be referred to as ground in this report). The ground temperature used in the main calculations is 8 °C, for an ambient temperature 26 °C (which is the highest ambient temperature for the considered day). Typically, the changes in ground (soil) temperature are very slow and therefore large variations in ground (soil) temperatures even during the summer are probably unlikely. Specifically, Backman, 2014 [21] comparing the ground and air temperature variations in Uppsala shows that on average the ground temperature does not vary above around 15 °C even in warmest summer months, July-August. Stockholm county (including Solna and Sundbyberg) therefore can be approximated to have similar temperature behaviors. Regardless, to analyze the temperature sensitivity (mainly owing to cold losses) of the DC network and system, the ground temperatures of 15 °C and 20 °C (the latter as a very extreme case), respectively, for e.g. ambient temperatures (i.e., the highest per day) of 32 °C and 36 °C. This choice on ambient temperature does not affect the temperature behavior in the grid. The ambient temperature specification in Netsim only governs the production power factor, which is set to 1 for ambient temperatures above 26 °C (see section 2.3), and therefore also is unaffected with this assumption. Respective Netsim simulations-based optimizations were conducted on each temperature for the BC and the chosen most optimal CS scenario (explained further in sections 3.4.1 - 3.4.4).

To analyze the impact of electricity price fluctuations on this final optimal solution versus BC, another sensitivity analysis was performed. A proportional increase/decrease in the electricity prices only proportionally increases/decreases the production costs of all scenarios. Besides, for the objectives of this WP 2.3 it is more relevant to see the impact on the electricity price when the share of renewables increase while e.g. nuclear decreases (along the plans to decommission nuclear plants in Sweden). Therefore, an electricity price forecast study by Sridhar and Baskar, 2020 [22] considering three different scenarios for increased exploitation of renewables and decreasing the share of nuclear power[11] was chosen. From this study [22], the year 2040 (and there, a summer day with ambient

[11] Here, today's real electricity demand in Sweden has been chosen as basis for 2020, while assigning demand increase projections in the three price forecast scenarios up to 2040 [22].

temperature 26 °C) as a representative case for the sensitivity analysis of this DC system optimization work. The specific hourly price forecasts data for a representative day in summer 2040 were acquired via personal communication with Thakur, Sridhar and Baskar, 2021 [23]. The forecasts were done without considering inflation, and therefore, here an annual inflation rate of 2% was assumed, and therefore the prices were adjusted for the year 2040 (2% inflation for 20 years resulting in a price increase by a factor of 1.49). The three Swedish electricity price scenarios used are as follows, in short, and the readers are encouraged to refer to Sridhar and Baskar, 2020 [22] for further explanations on these scenarios. In all the three scenarios, the electricity demand and the total production for a given year are kept constant. Whereas, to fulfill the demand increases as well as to cover the consequent gap from reducing nuclear power share, electricity from wind, solar power and combined heat and power (CHP) plants is used [22].

- **El_Scenario 1**- This considers electricity production for business as usual (to reach 100% renewable by 2040), with complete phasing out of nuclear power in the electricity mix by 2040.
- **El_Scenario 2**- This considers a decreasing trend of nuclear power production in the electricity mix, however, without completely phasing out nuclear power plants (i.e., have two nuclear plants remaining) by 2040.
- **El_Scenario 3**- This considers that the installed nuclear capacity in 2020 to remain unchanged until 2040, and therefore the increase in the share of renewables is rather low, besides from hydropower.

The corresponding hourly electricity prices for each of these three scenarios for year 2040 used in the sensitivity analysis in this work, are given in Appendix Table 26 (for both without and including inflation, respectively). By employing the Netsim results (production mix and electricity use) for the BC and the most optimal scenario chosen (c.f. sections 3.4.1 - 3.4.4, and for ground and ambient temperatures of 8 °C and 26 °C), the production cost variations are calculated using these forecasted electricity prices for 2040.

3 Results and Discussion

In this section, the results of the WP 2.3 are discussed. This includes the highlights of the current Swedish context of DC and cold storage coupled with inspirations on cold storage beyond cold water. In addition, the key results from the techno-economic performance evaluation and benefits analysis of the chosen DC system of Norrenergi AB and the developed scenarios are discussed in-terms of specific as well as general perspectives.

3.1 CURRENT STATE OF COLD STORAGE IN DISTRICT COOLING IN SWEDEN

When analyzing the state of CS in DC, it is imperative to also map what specific technologies comprise the production mix, as they are used to charge the CS. DC supply in Sweden today is mainly made of free cooling, compression cooling, absorption cooling, as well as heat pumps co-producing cold (besides heat) [6], [24], [25] (c.f. Figure 11). Free cooling, where natural cold extracted from sea/lake water is used [6], [25], is the most cost-effective method of cold production today, with the highest COP (at or above 10). Compression cooling (COP: 3-7) and absorption cooling (COP: 0.7-1.2) are electrically-driven and heat-driven refrigeration systems respectively [24], [26]. Heat pumps (COP: 2-4) have COPs lower than e.g. free cooling and compression chillers. However, heat pumps bring added value with their dual heat and cold production ability, serving both DH and DC, and by recovering heat from the DC return lines. Heat pumps are operated in summer prioritizing the cold production over heat, thus referred to as 'refrigeration' heat pumps [26].

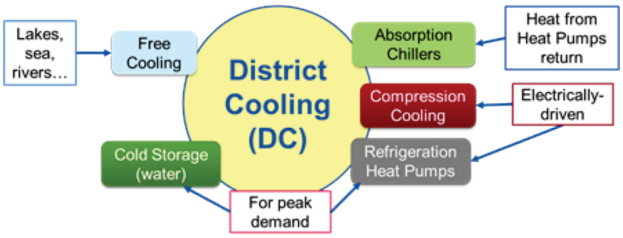

Figure 11. Swedish district cooling production mix and the state of cold storage

In Sweden by 2019, the proportion of the use of each of these technologies indicates (see Figure 12 [27]) that absorption- and compression-cooling is used the most, followed by free cooling and cold from heat pumps. Even though free cooling is the most cost-effective choice, environmental limitations (on the flow rates allowed from the natural water bodies), as well as geographical limitations (of unavailability of suitable water bodies) restrict its exploitation. This can be a reason for a lower percentage of free cooling employed in the mix. Heat pumps are not employed for base demand production for their higher operating cost; however, inherently cover a certain share of DC, to optimize their co-produced cold.

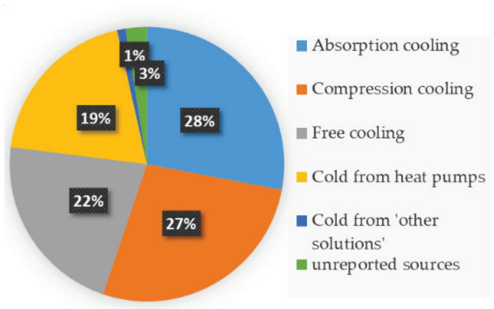

Figure 12. The proportion of cold production technologies used in Sweden, by 2019 (based on [27])

Cold storages are an integral part of the DC systems also in Sweden, for an effective management of the cold produced via these technologies [6]. CSs primarily shave peak demands and shift that cold production to more cost-effective off-peak (often night) time. Thereby, the key contribution of a CS to a DC system is avoiding the investments on an oversized overall capacity (and thus related costs), while still meeting the highest peak loads, occurring especially in summer [6]. The details available on the CSs in the Swedish DC systems is limited. However, the findings indicate that they are almost exclusively limited to cold water storage. The majority of these are constructed tanks, with the exception of a rock cavern CS in Hornsberg (50 000 m^3, 55 MW, 0.4 GWh) in use by Stockholm Exergi AB [28]. Mapping the positioning of the CSs in the Swedish DC networks was also not possible for the lack of specific information. However, the most common practice today possibly is to construct them centrally, adjacent to cold production plants. Whereas, distributed CSs appear as a future possibility to introduce, develop and expand competitive DC systems.

The total DC production in Sweden today on average is around 1 TWh (with the highest so far being 1.16 TWh in 2018) [27]. However, literature suggests that the demand is far more, i.e., is 2-5 TWh as of 2016 [29]. Therefore, there is a clear deficit in the cold supply in Sweden, despite an 8% annual growth rate since 2000 [6]. According to status-mapping done by Energiföretagen, it is seen that the 2019's installed capacity of the Swedish DC supply is expected to increase by 50% by 2030 [30]. Certain Swedish cities like Hässleholm [31], and others [32], which currently do not have DC are also considering to invest in DC, while some of the existing DC networks are planning for expansions (e.g. Göteborg and Linköping) [30]. In this context, the role of CSs to minimize capacity investments while accommodating a better production cost of cold is undeniable.

3.2 MOVING BEYOND COLD WATER STORAGE

Besides cold water, other potential cold storage alternatives include such as phase change materials (PCMs), thermochemical heat storage materials (TCMs), while an alternative to aboveground water storage could be underground water storage.

When considering underground TES (UTES) as potential alternatives to typical aboveground water storages, the main types are aquifer TES (ATES), borehole TES (BTES), and (rock) cavern TES (CTES) [33]. UTESs are typically used for long-term (i.e., seasonal) storage of heat and cold, while some instances also exist which use these also for medium-term (i.e., weekly) and or short-term (daily) storage [33].

BTES are considered as one of the most promising UTES types, both technically and economically, for seasonal TES [3]. In this WP 2.3, the cold water storages were investigated for short-term (daily) storage only, and thus these UTES were also excluded in the techno-economic analysis.

Considering PCMs and TCMs as cold storage alternatives instead of water in a detailed techno-economic analysis was initially anticipated in this WP 2.3. However, through the project it was discovered that the available technical data in real thermal energy systems today are scarce, at the required level of technical detail (e.g. at hourly resolution) and at the reasonable capacities comparable with real DC systems' requirements. This lack in technical data include parameters such as the charging/discharging power (W) and storage capacity (Wh) characteristics of sufficiently large-enough storages also in-relation to their real storage volumes (m^3), coupled with actual state-of-charge and cost data. This is specifically lacking at the considered scales of capacities (in the range of 3-15 MW e.g.) in this WP, e.g. in-relation to the real DC system of Norrenergi AB.

Water, as a TES material, has a straightforward state-of-charge variation based on the sensible heat change governed by temperature difference and flow rate only. TES with water is at technology readiness level (TRL) 9, at fully commercial scale. Whereas, TES with PCMs or TCMs give rise to transient state-of-charge behaviors that are far from being straightforward, being a combination of both sensible and phase change or chemical reaction heats. That is, the rate of phase change (in PCMs) or a chemical reaction (in TCMs) is much more complicated than the temperature- and flow- dependent rate of sensible heat change in cold water storages. TES with PCMs or TCMs are today still at TRLs lower than 9, particularly concerning operational scales as required by DC or DH. In addition, TES with water are simple containers (tanks), and can be scaled-up linearly for power (W) and capacity (Wh) requirements by volume. In-contrast, TES with PCMs or TCMs require more intricate heat exchanger configurations within the storage container itself, due to their inherently poor thermal conductivity otherwise resulting in very low charging/discharging powers. Therefore, TES with PCMs or TCMs result in very case-specific volumes (m^3) per charging power (W) and capacity (Wh) for each specific configuration, and cannot be linearly scaled-up, unlike water TES. Therefore, in this WP 2.3, for these limitations on CSs other than with cold water, the techno-economic analysis was eventually chosen to be limited to cold water.

Regardless, to provide a sound comparison of these technologies, in this section, a techno-economic comparison of these cold storage alternatives that could eventually function as alternatives to cold water storages is discussed. This is driven by a literature assessment, and also moving beyond Swedish examples.

Although the current 'norm' of cold storage in Sweden is using cold water, there is in-fact one attractive exception in Sundsvall. There, snow is stored in winter (70 000 m^3 by 2011) and used to cover a considerable share of cooling (480 MWh) for Sundsvall county hospital in summer. The operating temperature range of this CS is 2-8 °C (i.e., supply to return), and the nominal discharging power is 3 MW. The capital cost of the system per capacity is 3.3 euro/kWh (~33 SEK/kWh) [34], [35]. Sweden also has some very interesting UTES examples. The rock cavern CS in Hornsberg CTES employed in Stockholm Exergi AB's DC system, is one such example, having a 55 000 m^3 volume with 55 MW (and up to 80 MW [36]) and 0.4 GWh capacities [28]. The BTES system in Xylem AB, Emmaboda is one of the largest BTES systems in the world, for industrial surplus heat recovery for seasonal heat storage [37]. This BTES consists of an array of 140 boreholes (at a depth of 150m) with a 330 000 m^3 effective CS volume. Its highest charging and discharging heat capacity obtained so far in 7 years are 2200 MWh and 400 MWh respectively. This is however optimized and operated for heating purposes only [37]. BTES can be operated solely for seasonal cold storage and cooling, however, combined storage of heat and cold (from summer to winter) is gaining more interest [3]. For an efficient operation of a BTES, Reuss, 2015 [3] explains that it requires to be at least 1000 m^3 volume. BTES with combined heat and cold storage, i.e., low-temperature operation (0-90 °C) are anticipated to gain much more interest in future for large buildings' space heating and cooling demands [3]. BTES for seasonal cold storage can be coupled with solar thermal power production, as e.g. a numerical simulation design of a 10 MW BTES for a case study in China exemplifies [38].

ATES are an attractive seasonal TES alternative for both heat and cold storage, for large-scale heating and cooling, such as in buildings (commercial and public), industries as well as DHC systems [39]. ATES is however possible only if a suitable aquifer exists close to the application and the necessary hydrogeological conditions are met [39]. ATES systems allow energy savings of 40-70% and have costs between 0.2-2 Million Euros for small to large systems. By 2018, more than 2800 ATES were operating globally, with 2.5 TWh annual heat and cold supply. Around 99% of the ATES today operate below 25 °C and are therefore low-temperature systems. Netherlands has the largest global share of ATES installations (85%), while Sweden, Denmark and Belgium account for another 10%. The most well-known ATES in Sweden is in Arlanda, providing cooling and heating to Arlanda airport, and is one of the largest systems in the world [39], [40]. The Arlanda ATES is 200 000 000 m^3 by volume and provides around 9 GWh cooling within temperatures 3-6 °C [40], with a power capacity of 10 MW [39]. The capital cost of this system is 5 million Euro [39].

Among the many examples from the Netherlands, two ATES that cater to DHC in Amsterdam, have respectively 7 and 4 wells, 20 MW and 8.3 MW capacity, and the capital cost of the larger system was 25 million Euro [39]. An ATES system has been catering for cooling of the German Parliament Buildings in Berlin for many years, with two separate ATES for heat and cold storage respectively [41]. From these, the cold storage ATES comprises 10 wells of 30-60 m depth. It has an annual cooling capacity of 3950 MWh, with the respective cold well inlet and outlet temperatures 5 and 6-10 °C [41]. Another ATES e.g. from Germany catering to a DHC system is at Neubrandenburg, comprising 2 wells, with a power capacity of 3.3 MW [39]. In New Jersey, USA, an ATES solely working as CS is supplementing a university cooling system, with 6 wells at a power capacity of 2 MW at a capital cost of 2.6 million Euro [39]. The TRL of these ATES system can be considered to be 6-9, based on the TRL mapping done by Fleuchaus et al., 2018 [39]. These examples highlight the popularity of ATES for seasonal TES, however also the gaps in the techno-economic data of these systems in literature.

Numerous other international CS examples also exist, which use CS beyond the conventional framework of cold water. Two such examples are summarized in Figure 13 along with some of their technical specifications.

Nagoya JR Station DHC

- Ice (phase change materials- PCMs) storage of 49 MWh
- Ice macro-encapsulated in plastic balls, 1226 m^3
- 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 m^3 (from a tri-generation plant), 35 MW cooling
- Less requirements of insulation

Figure 13. International inspirations on moving beyond cold water storage and typical storage designs, for DC (based on [42], [43], [44], and [45]. PtC: Power-to-Cold)

One example is Nagoya JR central station DC system in Japan, which employs ice (as a PCM) instead of cold water, charged adopting power-to-cold, to cater to their DC system [42]. Designed by Nagoya Netsukyokyu Co. Ltd., this is in fact a combined DHC system, producing ice using nighttime cheaper electricity adopting power-to-cold, and natural gas-based co-generation of heat [42]. This CS system is made of encapsulated ice (PCM), with a capacity of 1226 m^3 and 49 MWh [42]. The power-to-cold operation of this CS has enabled electricity load leveling (used to provide the cooling) towards 3-4 MW. The cold discharging average power is around 4.1 MW (i.e., with storage discharging over ~12 hours). The system caters to cooling and heating demands of Nagoya JR Central towers (commercial building), as well as Nagoya subway and commuter train (JR Central) [42]. The energy compactness of the ice in-contrast to cold water is very attractive for densely populated areas like Nagoya.

Climaespaço DC system in Lisbon, Portugal [43], [44] has a CS storing stratified cold water in partially-underground tank of 15 000 m^3 volume [43] and 35 MW cooling power [46]. This CS is charged by nighttime cheaper electricity adopting to power-to-cold, enabling operational cost savings [43]. With its partially-underground construction (with 6 m underground out of the full height of 17 m), heat losses as well as insulation requirements are minimized, thanks to the rather constant ground temperature [47]. Such a partially-underground CS is an attractive CS solution allowing a larger storage volume within a restricted space and when access to large water bodies is limited, while also benefitting from heat loss reduction.

PCMs beyond ice for CS applications at district scales are almost non-existent, whereas certain building applications are found at research and development level. A recent Swedish example encompasses a multistory office building cooling system in Gothenburg coupled with a PCM CS using a commercial salt hydrate PCM SP 11 for daily (short-term) storage [48]. This PCM CS is a rectangular tank embedded with a tube-bundle heat exchanger, containing 9380 kg of the PCM SP11 and 7 m^3 total volume. This CS of has a 99 kWh actual cooling capacity, which however is only 36% of the installed cooling capacity (i.e., 275 kWh). The average charging and discharging powers respectively were found to be 7.1–5.5 kW and 19.8 kW, respectively. The overall cold charging power of the CS was 60-75% lesser than the designed power, and this was found to be the main reason behind experiencing such a reduced cooling capacity in operation [48]. Despite these limitations, this CS is operating adopting power-to-cold, charging using absorption chillers using night-time cheaper electricity and then discharging to shave the daily peak cooling demands thus reducing the load on the heat pumps with more expensive cold production during peak hours. The total investment cost for the system was 546 452 SEK. For a 5 year payback time (i.e., the guaranteed lifetime for stable operation by the suppliers), the economic analysis yielded that the cost of the CS should be below 9804 SEK per year [48]. This system is at a TRL of ~7-8 [49]. Unlike in a cold water TES, charging/discharging powers in a PCM CS vary non-linearly with state-of-charge/-discharge of the CS, starting at a higher power then significantly slowing at the end of the cycle. That is because their power is dictated by the available amount of PCM for the intended phase change at a given time (with some flexibility allowed from the embedded heat exchanger). Therefore, in a PCM CS the possibility to adjust its charging/discharging power to match the hourly cooling load variations is significantly limited.

This PCM SP 11 (a mixture of ammonium chloride, sodium acetate and sodium formate) used in the Gothenburg system has exhibited supercooling and phase separation during laboratory thermal cycling experiments (using 168 kg of PCM) at different heating cooling rates [50]. Therefore, to avoid/minimize phase separation in the real application system, the manufacturer has added a thickening agent (by 3 w/w%) to the PCM [50]. Generally, when choosing PCMs from blends, incongruently melting compositions, including peritectics like sodium acetate trihydrate (SAT) or Glauber salt ($Na_2SO_4.10H_2O$), are recommended to be avoided despite their abundance and affordability in large-scale. This is because, these incongruently melting blends inherently phase separate, while such like peritectics undergo both supercooling and phase separation. Regardless of the available techniques today (to minimize phase separation and supercooling) like with additives, nucleating agents and thickeners, the possibility to achieve truly successful large-scale TES operation with such incongruently melting blends is very low. Therefore, choosing an inherently suitable material (be it a pure material or a mixture) as a PCM is of utmost importance for the success of the TES system. Pure materials are suitable and simpler as PCMs, however purity comes at a significant cost. Blends often are more cost-effective PCM options, yet should be chosen carefully and correctly. Blends that are perfect as PCMs are those that melt congruently (forming compounds or solid solutions), as well as eutectic blends that do not supercool, and those will lead to successful TES systems also allowing large-scale application [51], [52].

A numerical analysis of a passive building cooling system for Stockholm with a PCM CS presented a multi-objective optimization of system cost and cold supply for several CS operational strategies [53]. The cooling solution here with a CS considering a commercial salt-based PCM was compared to a conventional air conditioning (AC) solution as a reference [53]. The peak cooling demand of the building was at 3.6 kW during the day and no cooling demand during night. Therefore, the PCM-CS charging was assigned to nighttime with free cooling using cold air. This cooling system was optimized to cover the largest share of cooling demand using free cooling at the lowest cost. From a Pareto front from the multi-objective optimization, 4 representative cases were then considered. Case 1 and 4 represent respectively: low cost yet lower comfort level (only 25% of cooling met at 20% cost[12]) and a higher share of cooling met at a higher cost similar to the AC operation (80% of cooling met at 100% cost). Whereas, case 2 (65% of cooling met at 25% cost) and case 3 (75% of cooling met at 55% cost) are chosen as two optimal points between best cost and comfort-level solutions. Therein, it was decided that cases 2 and 3 are better than cases 1 and 2, meeting more than 75% of the peak cooling demand at a cost 50-66% less than that with an AC. A sensitivity analysis on the system's cost for the variations in PCM cost and electricity tariff indicated that case 3 is the most optimal strategy, with lowest dependence on price increase of PCM and electricity, thus with the best economic feasibility [53]. This study emphasizes the value in trade-offs between the cost and the comfort-level (dictated by the discharging power) when employing these PCM-CS systems. That is, this type of a PCM-CS system can result in a considerably higher electricity demand than a conventional air conditioning system, if high cooling powers are desired (i.e., to reach the full comfort level) [53].

Examples of cooling systems with PCM-CS at non-residential building applications are also found internationally. In Paris, France, the cooling system catering to the business district: Paris La Défense comprises an ice-based PCM-CS. This CS, with a storage capacity of 240 MWh, is charged at -7 °C using three refrigeration units of 8 MW capacity each, and discharged at 4.5 °C at 60 MW (nominal) power. The heat transfer fluid used is water-glycol solution (for discharging) and water (for charging). Its storage efficiency is very high, at 95%, and is at TRL 9 [49]. Chitose Airport in Hokkaido, Japan has a seasonal CS using snow of 120 000 m^3 with 5-10 GWh storage capacity. This snow CS is a retrofit-solution implemented by replacing an adsorption chiller of 351 kW nominal power. The operating temperature range of the CS is 2-12 °C with a nominal discharging power of 3.5-7 MW. This is at a TRL 8-9 [49]. In Norway, the cooling system of the building premises of University College of Bergen is coupled with a PCM- CS. This CS is made of four tanks of 57 m^3 volume, containing an encapsulated commercial PCM based on a salt-hydrate. It is operated to cover the peak cooling demand (maximum at 3 MW) supplementing the 1.4 MW installed capacity of the chiller-heat pump system, by up to 1.6 MW (discharging). The heat transfer fluid used is water, and the system is at TRL 6-7. The storage capacity of the system is 11.24 MWh with 1.4 MW charging power, and an operating temperature range of 4-18 °C [49].

CS with TCMs has the lowest TRL in these considered technologies, and no known cases operated within district cooling systems were available to the authors of this report. TCMs are among the TES materials with the highest energy storage densities (as compared to PCMs and sensible TES materials), and have the attractive feature of temperature tailoring to applications, by adjusting the reaction pressures. That is, a Thermochemical heat storage (TCS) system can basically function as a chemical heat pump, selectively operating in heat storage and cold storage modes, respectively. This attractive feature, however, also brings a trade-

[12] The costs in these four cases are normalized system cost [53].

off by requiring a more complex system design for TCS than for PCM or sensible TES. One example of TCS installations for district thermal systems is the pilot-scale TCS system EnerStore, installed through collaborations between Vattenfall AB and SaltX AB. This employs the reversible reaction between CaO and water (forming $Ca(OH)_2$), and has an installed capacity of 10 MWh with 1 MW charging and 3 MW discharging nominal powers [45]. Even if this TCS CS was eventually designed for heat storage only and has room for improving its techno-economic performance, it is nevertheless a one of a kind example.

To further exemplify the dual (heating/cooling) mode of TCS systems, another example is brought here. This is of a lab-scale TCS system designed for low-temperature (below 100 °C) industrial process applications, installed at CNR-ITAE in Italy, for waste heat and cold storage. This system uses adsorption reaction of water to an adsorbent. It is charged at 70-90 °C while is discharged at 5-15 °C and uses water as the heat transfer fluid. In this TCS system (which is basically a chemical heat pump system), the energy storage capacity is 220 Wh/kg for desorption at 90°C, condensation/adsorption at 34°C and evaporation at 10 °C. The nominal power is 500 W and the storage efficiency is 38% (also for the same conditions of desorption, condensation and evaporation) [49]. The TRL of the system is at 4 [49], and therefore clearly there are room for improvement of the technology. Analyses and details of numerous other lab-scale and small pilot-scale TCS systems are available in literature. However, those will not be discussed further in this report, as they are not directly relevant (i.e., not scalable) to the scales considered in district cooling systems.

A summary of techno-economic parameters of these discussed alternatives to cold water CS is shown in Table 4, which also indicates the data gaps in their specifications. Due to their limited techno-economic data, making reasonable comparisons is challenging. Nevertheless, within this limited set of information, it appears that e.g. PCMs TES allow significant storage capacity per volume, despite the volume compromises made to e.g. improve heat transfer (i.e., charging/discharging power), than e.g. water CS systems. There, snow storage as well as ice storage systems seem to have a clear advantage, with water/snow being a cheap/free PCM alternative. From the available limited cost data, it seems the PCM-CS systems have very high costs per MWh and MW cooling provided. These capital-intensive TES alternatives (like with PCMs or TCMs) are more likely to pay-off for short-term TES operation with many cycles per year, rather than with seasonal TES with only one or two cycles per year. The seasonal ATES systems (using water) also appear to have high costs per MW, yet better costs per storage capacity (MWh) than e.g. snow-based CS systems. Generally, water-based CS are popular solutions. The possible reasons for their popularity could be their higher TRLs, and relative simplicity in CS design and operation, and the ability to allow significant cost savings in operation.

Table 4. Techno-economic parameters of the different alternative CS technologies discussed (NA: not available, *the found ranges are given in their average)

CS system	Volume	Storage capacity	Nominal Discharging power	Charging power	Volumetric capacity		Cost		TRL
	m^3	MWh	MW,discharging	MW,charging	kWh/m^3	$kW,disch/m^3$	SEK/MWh	SEK/MW	
Sundsvall snow CS, Sweden	70 000	480	3	NA	6.9	0.04	33 297	5 327 520	9
Chitose Airport Snow CS, Hokkaido, Japan	120 000	7 500*	5.25*	NA	62.5	0.04	NA	NA	8-9
Hornsberg rock cavern CS, Sweden	55 000	400	55	NA	7.3	1.00	NA	NA	9
BTES, Emmaboda, Sweden (heating only)	330 000	2 200	NA	NA	6.7	NA	5 733	NA	9
Arlanda ATES, Sweden	200 000 000	9 000	10	NA	0.05	0.0001	5 606	5 045 000	6-9
Amsterdam ATES,1, Netherlands	NA	NA	20	NA	NA	NA	NA	12 612 500	6-9
Amsterdam ATES,2, Netherlands	NA	NA	8.3	NA	NA	NA	NA	NA	6-9
Parliament Buildings ATES, Germany	NA	3 950	NA	NA	NA	NA	NA	NA	6-9
Neubrandenburg ATES, Germany	NA	NA	NA	3.3	NA	NA	NA	NA	6-9
New Jersey university ATES, USA	NA	NA	2	NA	NA	NA	NA	13 117 000	6-9
Climaespaço CS, Lisbon, Portugal	15 000	NA	35	NA	NA	2.3	NA	NA	9
Nagoya, Japan- ice PCM CS for DHC	1 226	49	4.1	NA	40.0	3.3	NA	NA	9
Ice CS, Paris La Défense, France	NA	240	60	24	NA	NA	NA	NA	9
Gothenburg PCM CS	7	99 kWh	19.8 kW	7.1–5.5 kW	14.1	2.8	5 519 717	27 598 586	7-8
University College of Bergen PCM CS, Norway	228	11.24	1.6	1.4	49.3	7.0	NA	NA	6-7
Enerstore TCS, SaltX-Vattenfall, Germany (Heating only)	NA	10	3	1	NA	NA	NA	NA	~6
Lab TCS-CS CNR-ITAE, Italy	NA	220 Wh/kg	0.5 kW	NA	NA	NA	NA	NA	4

3.3 NORRENERGI AB'S DC SYSTEM OPTIMIZATION WITH ADDITIONAL COLD STORAGES (USING BOFIT)

The first step of the techno-economic analysis of DC with CSs was done with BoFit. Here, the existing DC system of Norrenergi AB (BC) and several scenarios containing additional CSs were modelled in BoFit to optimize purely the cooling production versus the demand, as was explained in section 2.2. The key results from this analysis are discussed concisely here, while more details are found in Biramo, 2019 [10].

Firstly, the energy balances performed on these BoFit models of the BC and each scenario verified that the calculations are correct fundamentally. The key results out of this analysis using BoFit optimization of Norrenergi AB's DC *system* are summarized in Table 5. Here, BC is today's DC system which has one existing CS of 10 MW nominal capacity. Whereas, scenario 1 comprises one additional 15 MW CS in Sundbyberg. Scenario 2 considers one additional 15 MW CS in Frösunda. Scenarios 3 and 4 consider two additional 3 MW CSs, one in Sundbyberg and the other in Frösunda. In scenarios 1, 2 and 4 these additional CSs supply cold to all cold consumers, whereas, in scenario 3, the additional CSs supply cold to only certain chosen high-demand customers.

Table 5. Key results summary of BoFit optimization of BC and Scenarios 1-4 (CS: cold storage, BC- base case).

Scenario #	*Cold storage at:*	*# of CSs*	*CS nominal capacity (MW)*	*CS is supplying cold to:*	*% Production cost reduction, as compared to BC*
1	*Sundbybergsverket*	*1*	*15*	*Whole grid*	*23%*
2	*Frösundaverket*	*1*	*15*	*Whole grid*	*4%*
3	*Placed between the three DC production plants*	*2*	*3*	*Chosen (larger) loads*	*13%*
4		*2*	*3*	*Whole grid*	*14%*

As Table 5 indicates, to simply minimize the cost of electricity to produce the considered cold demand (for the considered historically highest cold demand day: 02 August 2018), the four analyzed scenarios with additional (new) CSs, all allow cost savings than the BC. Therefore, these results imply that additional CSs have the capability to reduce the operating cost of today's DC system of Norrenergi AB.

The results further indicate that scenario 1 is the optimal choice here. Scenario 1 employs an additional CS of 15 MW maximum capacity in Sundbyberg discharged to supply cooling to the all customers within the DC system. Scenario 1 allows 23% cost savings than the BC, which is the highest cost saving from the studied scenarios. Scenarios 4 and 3, with two additional CSs of 3 MW capacity each, have respectively 14% and 13% lesser costs than the BC, thus being the ´second best' choices. Here, scenario 4, which is assigned to provide cooling to the demands in the entire DC system, apparently has a bit better cost saving than scenario 3 which was limiting the CSs to supply cold to only chosen larger demands. Then, scenario 2 with one additional CS of 15 MW capacity in Frösunda has the lowest cost savings of only 4% than the BC. As the costs savings of 4% in scenario 2, with an additional CS in Frösunda, are much lower than the rest of the scenarios, this scenario can be considered the least suitable investment.

Overall, the BoFit analysis of the purely the DC system simplified into demand versus production of cold implies the following, concerning operational costs based on electricity use to produce cold. Installing a new CS of 15 MW in Sundbyberg (scenario 1) to supply cold to cover the cooling demands in the entire DC system is the most optimal solution, allowing the best operational cost savings (as compared to BC). Whereas, e.g. employing two 3 MW CSs in the system have lesser cost savings than with scenario 1, however, still are more attractive solutions that e.g. installing a 15 MW CS in Frösunda.

A significant limitation in this study is the inability to include the impacts of these CSs in the real distribution grid of the DC system and the bottlenecks therein. Therefore, these results exclude the implications of operating these CSs in the distributed grid, altogether. Nevertheless, these are valuable preliminary results that can be used as a basis for the next step of the techno-economic assessment: the detailed distribution grid dynamics analysis.

3.4 NORRENERGI AB'S DC NETWORK OPTIMIZATION WITH ADDITIONAL COLD STORAGES USING NETSIM

The results of the DC distribution grid *dynamics* simulations of Norrenergi AB's system are discussed herein. This discussion concerns: determining the optimal storage combination and placements; optimal sizing of the chosen combination; the comparison of such an optimal cold storage solution versus other alternatives without additional CS; and the avoided costs in investments as well as in the operation of these chosen additional CSs as compared to other alternatives to meet increased cooling demands.

3.4.1 The optimal cold storage combination and sizing

Netsim simulations produce dP data (as well as production data for each production unit, heat balance, flow balance, pressure and temperature data, all for each hour, for hourly data input). This collection of data is also visualized for each time step, e.g. as shown in Figure 14 for dP, concerning the BC system at the hour 13:00, showing the grid is well within the desired dP range of 100-800 kPa.

The first part of the DC distribution grid dynamics optimization was performed within the work by Bilek, 2020 [11]. The final cold production mix used in each scenario (BC and Scenarios 1-3) and the Netsim results therein of Solna plant in Bilek, 2020 [11] are summarized in Appendix Table 27 to Table 30. The final operating costs and related analysis of the Netsim simulations of the BC and Scenarios 1-3 by Bilek, 2020 [11] is presented in Table 6. Here, the BC has the existing CS of 10 MW (6500 m^3, 75.7 MWh) CS at Solnaverket. Scenarios 1 and 2 comprise an additional 15 MW (15000 m^3, 174.6 MWh) CS respectively at Sundbyberg and at the Frösunda low-dP loop, whereas scenario 3 consists of two additional CSs of 3 MW (3000 m^3, 34.9 MWh) each, at Sundbyberg and Frösunda low-dP loop.

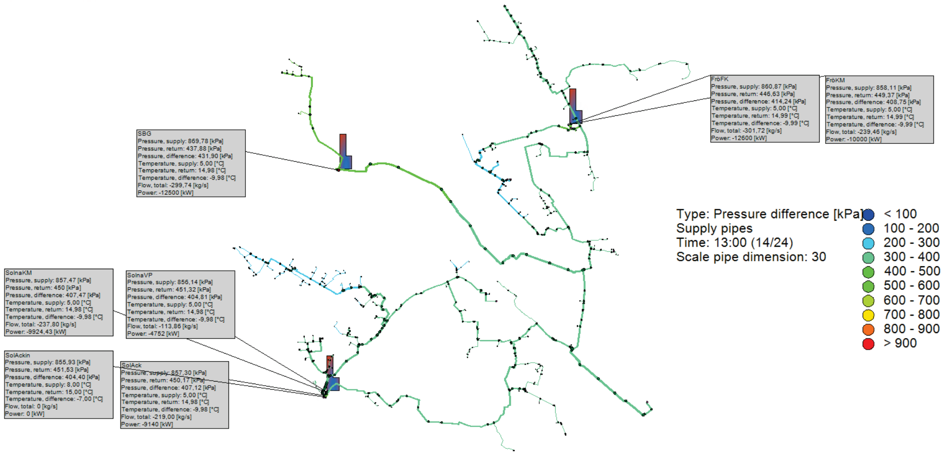

Figure 14. Netsim simulation result of BC (Norrenergi AB's today's DC system) at 13:00

Table 6. The Netsim results summary of Bilek, 2020 [11] for the BC and scenarios 1-3

Case/ 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,1 (SEK/MWh, cold)	115.2	112.1	110.0	110.3

With the Netsim cost calculations alone, it appears that scenario 2 (15 MW new CS in Frösunda) has the lowest operating cost, and allowing the highest cost savings of 4.8%. Although scenario 3 allows a bit lower cost savings (4.3%) than scenario 2 (two 3 MW CSs), per KPI,1 on the unit cost of cold (SEK/MWh) both scenario 2 and scenario 3 are very similar. Scenario 1 (15 MW CS at Sundbyberg) has the lowest cost savings. These results are rather comparable with those of the preliminary DC system study in BoFit by Biramo [10], on the cost savings for the chosen CS capacity (i.e., 15 MW CS having the lowest costs), although their positioning is in contrast. Besides, in the BoFit analysis, the considerable simplification of the DC system and completely excluding the distribution grid dynamics appear to have resulted in significant overestimation of the cost savings. Nevertheless, both BoFit and the preliminary Netsim analyses indicate that a 15 MW CS is the most cost-effective choice. Whereas, it's approximate positioning with BoFit identified as best in Sundbyberg, was then identified to be better in the Frösunda loop with a more accurate dynamics analysis in Netsim. The 15 MW CS in Sundbyberg in Netsim, although delivers the expected cold satisfactorily, it is at a higher cost, to balance the distribution grid dynamics.

To conclude on these three scenarios analyzed in Netsim, however, it is imperative to also consider the resultant dP levels in the grid, which correspond to the operational costs in Table 6. As examples, in Figure 15, Figure 16 and Figure 17 the corresponding dP levels of some representative nodes in the DC distribution grid are summarized, for scenarios 1, 2 and 3 respectively.

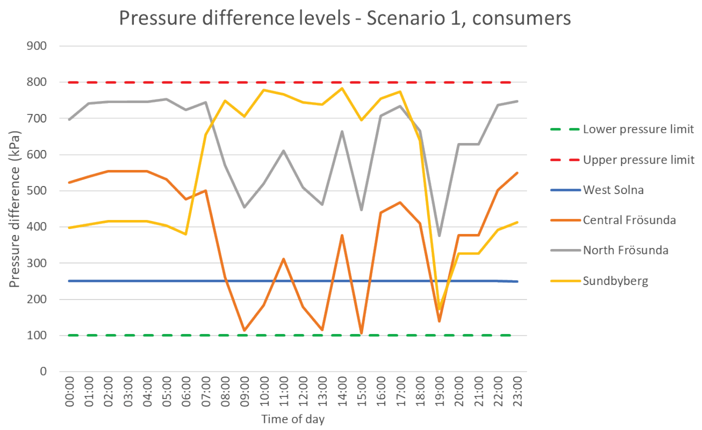

Figure 15. Differential pressure levels at chosen customer (demand) nodes in the DC distribution grid in Scenario 1 [11]

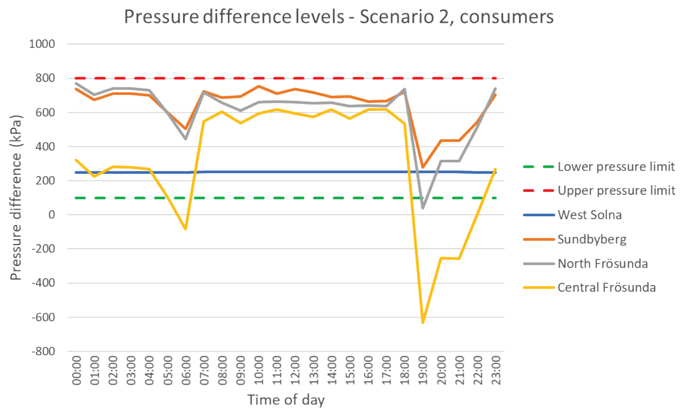

Figure 16. Differential pressure levels at chosen customer (demand) nodes in the DC distribution grid in Scenario 2 [11]

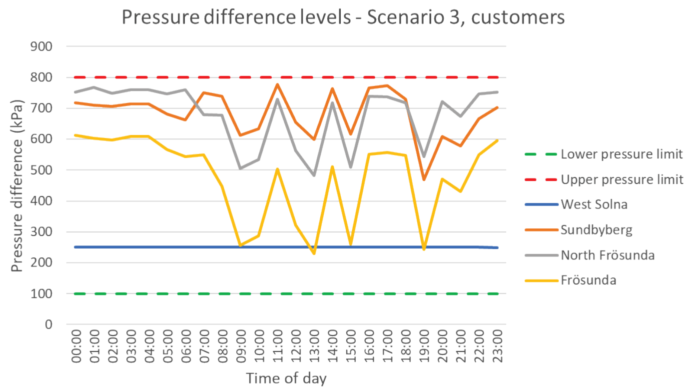

Figure 17. Differential pressure levels at chosen customer (demand) nodes in the DC distribution grid in Scenario 2 [11]

By comparing Figure 15, Figure 16 and Figure 17, it is clear that e.g. scenarios 1 and 3 meet the dP criteria well, thus were able to deliver the total amount of desired cold to the cooling customers. However, scenario 2 falls below 100 kPa margin at certain customer nodes, thus failing to deliver some of the required cold. These dP levels can indeed be improved to ensure the cold supply is fully met via further iterations in Netsim, with further adjustments on the cold production mix. As Bilek, 2020 [11] has been the first preliminary study of the Netsim-based optimization, such refinements were excluded. Nevertheless, these dP results, when combined with the cost data in Table 6, it is clear that the most optimal CS solution lies in a combination of scenarios 2 and 3. That is, the optimal CS solution should comprise two CSs each with nominal powers between 3 MW and 7.5 MW (totaling to a 15 MW, with two CSs), one at Sundbyberg (central location nearby the existing production plant) and the other located within the low dP loop in Frösunda (as a distributed CS). This verdict was the basis for the ensuing extensive Netsim-based DC distribution grid optimization, to identify the most optimal CS capacities.

The key results of the subsequent extensive DC distribution grid analysis using Netsim and the corresponding operational costs and KPIs considering two additional CSs in Sundbyberg and Frösunda loop are summarized in Table 7. Here, scenarios A-F comprise two additional equisized CSs of the capacity 3, 4, 5, 6, 7, and 7.5 MW (c.f. ***Table*** 2 for details). The final Netsim results on the optimal production mix and the resultant use of electricity and therein the production costs of this refined BC and the scenarios A-F are presented in Appendix Table 31 to Table 37.

Table 7. The results summary of Netsim-based optimization of the two CS sizing in scenarios A-F, using two equisized additional CSs (of capacity 3, 4, 5, 6, 7 and 7.5 MW each) in Sundbyberg and Frösunda loop (Sc.- scenario, El.- electricity)

Key parameter or KPI (below)\Case (right)	***BC***	***Sc.A (3*2)***	***Sc.B (4*2)***	***Sc.C (5*2)***	***Sc.D (6*2)***	***Sc.E (7*2)***	***Sc.F (7.5*2)***
Total cold produced (MWh,cold)	*964*	*965*	*965*	*966*	*965*	*965*	*966*
Total El. consumed to produce that cold (MWh,El.)	*167*	*163*	*163*	*163*	*163*	*163*	*163*
Total cold production cost (SEK)	*101397*	*97604*	*97270*	*96889*	*96480*	*96160*	***96026***
KPI,1. Unit Cost of cold produced (SEK/MWh,cold)	*105.1*	*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*	*0.961*	*0.958*	*0.954*	*0.950*	*0.947*	***0.946***
KPI,3. Unit Cost of El. to produce cold (SEK/MWh,El.)	*608*	*599*	*597*	*595*	*592*	*590*	***589***
KPI,4, unit cold supplied per used El. (MWh,El/MWh,cold)	*5.78*	*5.93*	*5.93*	*5.93*	*5.93*	*5.93*	***5.93***
KPI,5, avoided peak electricity use at maximum peak hour (MW,El/peak hour)	*-*	*1.9*	*2.3*	*2.7*	*3.1*	*3.5*	***3.7***
KPI,6, avoided peak electricity per day (MWh,El/ day)	*-*	*13.1*	*15.9*	*19.2*	*22.3*	*24.9*	***26.6***
KPI,7, avoided peak cold production per day (MWh,cold/day)	*-*	*46.0*	*59.9*	*76.2*	*91.8*	*105.1*	***113.2***
Maximum dP observed (kPa)	*705*	*662*	*680*	*694*	*709*	*763*	*742*
Minimum dP observed (kPa)	*250*	*250*	*250*	*250*	*250*	*250*	*250*
Cooling loss (kW)	*48*	*49*	*49*	*49*	*49*	*49*	*48*
Residual error (kW)	*-7*	*-7*	*-7*	*-8*	*-8*	*-9*	*-9*

The uncertainty of these calculated results in Netsim can be analyzed by considering the cooling losses encountered and residual error[13]. The average cooling loss in all the cases appear to be 48-49 kW. A remark here is that this is lower than the historical cold loss 1.6 MW from Norrenergi AB's DC system in e.g. 2018. Therefore, it is an indication that the physical details of the DC distribution network in Netsim, with the approximations on the years of constructions and therein the pipe and insulation types, require further refinements to obtain a more precise heat loss calculation. Nevertheless, as this calculated heat loss is very similar (48-49 kW) for all the evaluated cases, the impact of this underestimated heat loss is the same for all the analyzed cases (BC and scenarios). Therefore, the overall conclusions on the comparison of BC and each of the scenarios are still valid. The residual error is the key uncertainty indicator. This is obtained by deducting supplied cold and cooling losses from the total produced cooling. The residual error is also relatively small and in the same range for all the considered cases, varying between -7 kW to -9 kW. This confirms that the calculations have quite satisfactory accuracy, in particular for the total amounts of cold produced (in MW) versus the relative levels of these uncertainties (in a few kW).

The results in Table 7 reveal that the minimum-most and the maximum-most dP levels observed are well-within the desired 100-800 kPa margins in the BC as well as all the scenarios. Therefore, the grid dynamics are well-balanced in all the cases. As a whole, all the scenarios A-F have more promising performance than the BC, concerning all the KPIs considered. Sc.F has the most optimal performance as compared to BC as well as all the other scenarios. Concerning only the cold production costs, Scenario F allows 5.4% cost savings than with the BC, when considering the unit cost of cold production over the whole year's production (for the total production of e.g. 81 GWh in 2018). The difference between each consecutive scenario is rather small on certain KPIs (i.e., KPI,1-KPI,4), which is mainly because the nominal power of the CSs between each consecutive scenario is also small (i.e., 1 MW between scenarios Sc.A-Sc.E consecutively, or 0.5 MW between Sc.F and Sc.E).

According to the unit cost of the cold produced as in KPI,1, scenario F has the lowest unit cost of cold (99 SEK/MWh,cold), closely followed by the rest of the scenarios A-E (100-101 SEK/MWh,cold), as compared to the BC (105 SEK/MWh,cold). Thus, concerning KPI,1 alone, there is not much difference in adopting to any of the new cold storage scenarios, all of which offer (4-6 SEK/MWh) savings over the base case. However, their impact is more evident when considering the savings per year, which accounts for on average 395 847 SEK in cold production considering the year 2018 production.

When considering KPI,3 which is a direct cost implication of how successful the scenarios are in peak shaving adopting power-to-cold concept, scenario F (with two respective 7.5 MW CSs in Sundbyberg and Frösunda loop) shows a more prominent advantage, with 589 SEK/MWh, electricity. Therein, scenario F shows the best peak shaving ability, requiring 1-10 SEK/MWh,electricity less than the rest

[13] In the Netsim calculations performed in this work, the cooling losses, cooling loss per cold production% and residual errors were calculated respectively for reach model, using static calculations for three representative hours: 01:00, 13:00 and 21:00, and then averaged out.

of the scenarios, and most interestingly 18 SEK/MWh,electricity less than with the BC.

KPI,2 and KPI,4 are relative KPIs comparing a scenario with the BC, respectively for the unit cost of cold and unit cost of electricity to produce that cold. These two KPIs are valuable indicators for comparing the relative improvements without requiring to know the actual absolute costs.

Sc.F (from the analyzed scenarios) also has the best performance also concerning KPI,5, KPI,6 and KPI,7, allowing the largest savings in: peak electricity use (MW) during the peak hour (3.7 MW,El/peak hour), peak electricity use per day (26.6 MWh,electricity/day) as well as peak cold production per day (113.2 MWh,cold/day) than with the BC (for details on KPIs 5-7 calculations, see Appendix Table 38). This means that Sc.F allows: 39% less peak electricity use at peak hour (13:00) as well as 25% less peak electricity use per day, and 19% less peak cold production per day (for the period 07:00-19:00), than with the BC. These peak electricity shaving and peak cold shaving parameters altogether characterize the success in power-to-cold adaptations. That is, it is an indication of how successful a scenario is for absorbing surplus electricity in the system to produce cooling decoupled from the cooling demand. In that, scenario F (as compared to BC) 19% more of the peak cold production and therefore 40 % and 25 % of the peak electricity (in MW /peak hour and MWh/day) are shifted towards lower cooling demand durations where also there is more surplus electricity in the grid. This is a clear success in power-to-cold adaptation.

Therefore, scenario F is chosen as the most optimal additional CSs choice, overall, to have an optimized cold supply, while enabling a well-balanced Dc distribution grid and accommodating power-to-cold operation.

3.4.2 Alternatives to facilitate an increased cooling demand

Based on the results of the CS scenarios assessment discussed in section 3.4.1, Sc.F was then chosen for the analysis against several other alternatives to cold storage, that can be used to expand the cold supply in a DC system. This comparative analysis was performed for a 10% higher demand than today's actual demand. For this 110% demand situation, the BC, scenario F, a new pipe extension at Frösunda loop and installing a new chiller at Sundbyberg were the chosen alternatives. Their Netsim-based optimizations yielded the results as summarized in Table 8. Here, the capacity of the additional chiller in Sundbyberg was found to be 6 MW. This was determined as the difference between the adjusted peak demand[14] in the system between the 10% increased demand case versus today's case. The pipe dimensioning calculations in Netsim yielded that the optimal pipe dimensions for the new pipe in Frösunda loop to be DN 300 (diameter), for the extension length of 422 m. The final Netsim results concerning these alternatives for the 110% demand case, on the optimal production mix, the resultant use of electricity and the production costs are presented in Appendix Table 39 to Table 42.

[14] i.e., the remaining share of the peak demand that should be supplied by cold production units after the peak shaving amount coming from the cold storage

Table 8. Results summary for a 10% increased cooling demand, comparing BC, Scenario F (Sc.F), a new pipe in Frösunda (NppFrö) and a new chiller in Sundbyberg (SBGnCC). (Sc.- scenario, El.- electricity)

Key parameter or KPI (below)\ Case (right)	***BC***	***Sc.F (7.5*2)***	***NppFrö***	***SBGnCC***
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)	*119478*	***108395***	*118010*	*112694*
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 supplied per used El. (MWh,cold/MWh,El)	*5.41*	***5.79***	*5.49*	*5.73*
Maximum dP observed (kPa)	*710*	*786*	*782*	*701*
Minimum dP observed (kPa)	*150*	*150*	*190*	*150*
Cooling loss (kW)	*48*	*48*	*49*	*48*
Residual error (kW)	*-7*	*-5*	*-7*	*-8*

Table 8 indicates that, primarily, the scenario F has the best cost minimization, followed by e.g. the new chiller in Sundbyberg as the second best choice. From these alternatives as well, Sc.F also has the best performance concerning KPI,5, KPI,6 and KPI,7. That is, Sc.F allows the largest savings in: peak electricity use (MW) during the peak hour (4.4 MW,electricity/peak hour, at 13:00), peak electricity use per day (34.8 MWh,electricity/day considering 07:00-19:00) as well as peak cold production per day (115.2 MWh,cold/day) than with the BC. KPI,5-7 indicate the success in absorbing surplus electricity in the system to produce cooling decoupled from the cooling demand. In this context, with Sc.F, an additional 17% of the cold production is decoupled from peak cooling demand, thus enabling the surplus nighttime electricity absorption by 39 % and 27 % more (considering the reduction in peak electricity use in MW/peak hour and MWh/day) than with the BC. Thus, even for a 10% higher demand case, scenario F exhibits a consistent success in power-to-cold adaptation than with BC. In-contrast, the new chiller and the new pipe in Frösunda have extremely low/no savings than with the BC, per KPIs 5 to 7 (see details in Appendix Table 43).

Concerning the uncertainty of these alternatives' Netsim results, the average cold loss is very similar (48-49 kW), with residual error -5 to -8 kW. Regarding cooling loss, the same remark as in section 3.4.2 is valid, which implies the physical data of the system can be improve, whereas, the overall results are still valid (for BC and all the alternatives). For the total amounts of cold produced and used, the errors are very small and therefore the results have a satisfactory accuracy.

As a whole, the results altogether unanimously point to the fact that scenario F with two equisized CSs at Sundbyberg (i.e., centrally located) and located in the Frösunda lop-dP loop (i.e., distributed) is the most optimal scenario and alternative to expand the DC supply of Norrenergi AB.

3.4.3 Cost benefit analysis- operational, investment and total costs and benefits

By multiplying a 110% of the total cold production in 2018 (i.e., 89.1 GWh) with the unit cost of cold (i.e., KPI,1) of each alternative in Table 8, their annual operating costs were determined. Besides operating costs, the investment costs play a significant role in eventually dictating which capacity provision alternative is the best. Thus, the investment costs of the four alternatives in Table 8 were then evaluated using the unit costs and payback periods, as explained in section 2.4. The optimal volume of a cold storage to supply 7.5 MW is found to be 5000 m^3 (by considering the size and capacity of the existing CS of 6500 m^3 for 10 MW). As was mentioned (section 3.4.2), the optimal pipe dimensions for the extension in Frösunda loop were DN 300 (diameter), for the extension length of 422 m. The capacity of the new chiller for Sundbyberg was found to be 6 MW. Combining these dimensions with the unit costs in Table 3, the final total investment costs as well as the annual apportioned investment costs of these three alternatives were calculated. To calculate the investment cost of a CS, from the two unit costs of CS that were found (c.f. Table 3): 110% of 1700 SEK/m^3 [16] (i.e., 1870 SEK/m^3) and 160% of 1173 SEK/m^3 [17] (i.e., 1877 SEK/m^3) the highest of the two (i.e., 1877 SEK/m^3) was finally used. The final costs of these alternatives considering total investment, apportioned annual investment and the production per year are summarized in Table 9.

Table 9. Total costs summary of the BC, Scenario F (Sc.F), new pipe extension in Frösunda loop (NppFrö) and new chiller in Sundbyberg (SBGnCC), for 10% higher cooling demand

Cost category\ Alternative	*BC*	*Sc.F (2*7.5 MW)*	*NppFrö*	*SBGnCC*
Total investment cost (SEK)	*0*	*18,773,120*	*7,600,824*	*36,000,000*
Annually apportioned Investment cost (SEK/year)	*0*	*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)	*10,034,694*	*9,729,866*	*10,164,187*	*11,265,711*
Total cost compared to BC (%)		*3.0 % less*	*1.3 % more*	*12.3 % more*
Avoided cost in-relation to installing TES instead of a new chiller (%)		*15.8 %*	*-*	*-*
Avoided costs in-relation to installing TES instead of a new pipe (%)		*4.5 %*	*-*	*-*

As seen, scenario F (with two 7.5 MW cold storages in Sundbyberg and Frösunda) clearly is the best alternative out of all these four alternatives. Scenario F allows 3 % annual cost savings as compared to the BC, which has much higher operating costs. In addition, by adopting scenario F, respectively 15.8 % and 4.5 % of total costs/year are avoided, as compared to instead investing in (and operating) a 6 MW new chiller in Sundbyberg or a new pipe extension of 422 m in Frösunda loop. In other words, this new chiller in Sundbyberg and the new pipe in Frösunda loop causes respectively, 12.3% and 1.3% higher annual total costs than the BC, making scenario F the best alternative, which instead allows 3% cost savings.

3.4.4 Sensitivity analysis- implications of ground temperature and electricity price variations

The sensitivity analysis results on the ground (soil) temperature and electricity price variations concerning the BC and the identified optimal scenario Sc.F with two CSs of 7.5 MW capacity each are discussed here.

The Netsim-based optimization results of temperature sensitivity analysis on the BC and Sc.F are summarized in Table 10. Here the respective ground temperatures: 8 °C, 15 °C and 20 °C for the ambient temperatures 26 °C, 32 °C and 36 °C were considered. The corresponding details on the cold production mix, electricity use and the resultant costs per hour and for the day for BC and Sc.F are given in Appendix, Table 31, Table 37 (for 8 °C/26 °C conditions) and Table 44 to Table 47 (for 15 °C/32 °C and 20 °C/36°C conditions).

Table 10. Netsim-based temperature sensitivity analysis results summary on BC and Scenario F (for ground temperatures 8 °C, 15 °C and 20 °C)

Key parameter or KPI (below) **Case (right)**	**BC 8°C**	**Sc.F 8°C**	**BC 15°C**	**Sc.F 15°C**	**BC 20°C**	**Sc.F 20°C**
Total cold produced (MWh)	964	966	968	970	971	974
Total El consumed to produce that cold (MWh)	167	163	168	164	169	164
Total cold production cost (SEK)	101397	96026	102004	96567	102625	96957
KPI,1. Unit Cost of cold produced (SEK/MWh,cold)	105	99	105	100	106	100
KPI,2. The ratio of unit cost of cold of a Sc. as compared to BC	1	0.946	1	0.945	1	0.942
KPI,3. Unit Cost of El to produce cold (SEK/MWh,El)	608	589	608	589	608	589
Minimum temperature (°C)	5.00	5.00	5.00	5.00	5.00	5.00
Maximum temperature (°C)	5.47	5.65	5.60	5.95	5.74	6.32
Cost reduction Sc.F vs BC (SEK)		5371		5437		5668
Cost reduction Sc.F vs BC (%)		5%		5%		6%
Difference in KPI,1 Sc.F vs BC (SEK/MWh,cold)		6		6		6
Unit cost of cold reduction on KPI,1, Sc.F vs BC (%)		5%		6%		6%
Unit cost of electricity reduction on KPI,3 Sc.F vs BC (SEK/MWh,El)		18		18		18
Unit cost of electricity reduction on KPI,3 Sc.F vs BC (%)		3%		3%		3%
Maximum dP observed (kPa)	705	742	699	774	694	768
Minimum dP observed (kPa)	250	250	250	250	248	250
Cooling loss (kW)	48	48	-121	-122	-242	-244
Residual error (kW)	-7	-9	-18	-23	-24	-34

Table 10 indicates that even for the considered very- to- extremely- high ground temperatures (i.e., the highest likely temperature of 15 °C, and the extreme case of 20 °C which may not be likely unless climate change impacts will be very severe, for Stockholm), the main conclusion that scenario F is a better choice than BC holds. That is, scenario F, albeit the increased ground temperatures, and therefore, more cooling losses as well as an increasing trend in the costs, still is a more economical choice than the BC. Interestingly, Sc.F allows 5% to 6% cost savings than the BC, even for such warmer conditions, while supplying all the desired cold (maintaining dP levels well-within the desired 100-800 kPa levels).

Concerning the temperature distribution in the DC network, the supply temperature variations (which is more relevant to verify the desired cooling supply is met) are also shown in Table 10. The shown maximum temperature for each case is the maximum considering several hundreds of nodes, which have a real flow. There are a number of pipes which have no flow (e.g. previous customer nodes now not included in the supply), which therefore results in these redundant nodes to resolve to the ground temperature. These are however excluded here, as they are not relevant for this discussion.

There were also three isolated nodes (i.e., 61726, 60087 and 60890) resulting in somewhat higher supply temperatures consistently in each model, regardless of being BC or Sc.F. These nodes had temperatures up to ~2 °C, 5.4 °C and 5.4-5.9 °C higher than the maximum shown in table for the 8 °C, 15 °C and 20 °C ground temperature conditions, respectively. These are very likely causes of over-dimensioned pipe properties in the model but not in the actual DC system[15]. As these are also isolated incidents, these are also considered as irrelevant to the main temperature sensitivity analysis discussion here. This can be rectified by running pipe-dimensioning calculations over the pipes in these nodes to determine the optimal sizes.

The cooling loss is increasing with the ground temperature increase, with respectively 48 kW, 121-122 kW and 242-244 kW absolute values for the three temperature cases. Despite the underestimation for today's case (historical heat loss of 1.6 MW versus 48 kW here), for the same reasons explained in section 3.4.1, the main results and therein the overall conclusions from the results are still valid here as well. The increase in the heat losses for the higher ground temperature cases also verify that the calculations are going in the correct direction. The residual error also exhibits an increasing trend with the ground temperature increase, from -7 kW to -34 kW, plus has a higher residual error for the Sc.F than for the BC (still with 2-10 kW difference). This is very likely due to the somewhat higher amount of cold production in the Sc.F than with BC, on each temperature case. Despite the increasing trend in the residual error, it is still very small compared to the total produced cold in BC and Sc.F. Therefore, overall it can be concluded that the calculated results here as well have quite good accuracy.

The next part of the sensitivity analysis was on the electricity price fluctuations especially when more renewables are exploited while e.g. gradually decommissioning nuclear. Here as well, the BC is compared with Sc.F, for Sc.F being the most optimal choice for effectively expanding the DC supply and adopting power-to-cold successfully. The electricity prices used in the cold

[15] During the pipe details refinement, as exact pipe properties are not always available in a real DC system which has been developed over a long time period, certain pipes were assumed to belong to a certain expansion time period. Therein, the dimensions and pipe properties were assigned considering the typical pipe and insulation types used during that certain expansion period.

production costs calculation for the BC and Sc.F (for a representative summer day) for today's case (using 2018 data) from Nordpool [15] and the year 2040 forecasted prices from El-Scenario 1 to El-Scenario 3 from Thakur, Sridhar and Baskar, 2021 [23] are summarized in Figure 17.

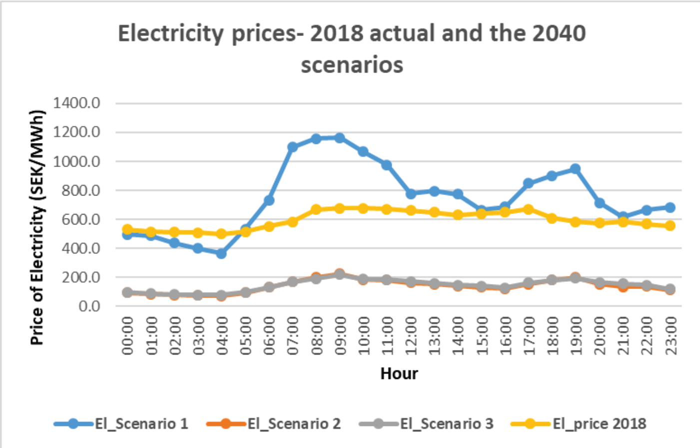

Figure 18. The hourly electricity prices on today's case (2018)) (from [15]) and from the considered three scenarios in 2040 (from [23])

The electricity prices of today's case (2018) and the El-Scenarios 2 and 3 have comparable peak/off peak trends, although the prices in these two future scenarios are around five times lower than in 2018. Whereas, the business-as-usual (for Swedish climate targets) price forecast, i.e., El_Scenario 1 has considerable fluctuations with prominent two peaks during the day and early evening hours respectively. This type of a variety of electricity prices with different price peak trends and very different price levels can show the sensitivity of the chosen CS cases better.

It is only the electricity price that is varying in this part of the sensitivity analysis. Therefore, the same Netsim results of the BC and Sc.F (for 8 °C ground and 26 °C ambient temperatures), from section 3.4.1, Table 7 (and in Appendix, Table 31, Table 37) are used here, to calculate only their production cost variations for each electricity price scenario. These cost results corresponding to El-Scenario 1- EL-Scenario 3 for BC and Sc.F are summarized in Table 11 (while their detailed hourly costs are given in Appendix Table 48 and Table 49 respectively)

The results concerning the electricity price fluctuations comparing scenario F with BC indicates the following. The higher the electricity price becomes, the higher the cost saving proportions allowed with Sc.F. El_Scenario 1 having the largest prices, allows the largest cost savings of 8% from the daily cost of cold production, accounting for 12 SEK/MWh,cold. Then again, for this El_Scenario 1, the success in adopting to power-to-cold is 6% better than with the BC, at 48 SEK/MWh,electricity lower than with the BC.

Table 11. The sensitivity analysis results summary on electricity price fluctuations on BC and Scenario F (Sc.F), considering electricity price forecasts for 2040, from El_Scenario 1 (El_S1), El-scenario 2 (El_S2) and El-scenario 3 (El_S3) respectively

Key parameter or KPI (below) Case (right)	BC El_S1	Sc.F El_S1	BC El_S2	Sc.F El_S2	BC El_S3	Sc.F El_S3
Total cold produced (MWh)	964	966	964	966	964	966
Total El consumed to produce that cold (MWh)	167	163	167	163	167	163
Total cold production cost (SEK)	131545	120582	24596	22520	25234	23181
KPI,1. Unit Cost of cold produced (SEK/MWh,cold)	136.4	124.8	25.5	23.3	26.2	24.0
KPI,2. The ratio of unit cost of cold of a Sc. as compared to BC	1	0.915	1	0.914	1.000	0.917
KPI,3. Unit Cost of electricity to produce cold (SEK/MWh,El)	788	740	147	138	151	142
Reduction in total cost with Sc.F vs BC (SEK)		10963		2077		2053
Reduction in total cost with Sc.F vs BC (%)		8%		8%		8%
Difference in KPI,1 Sc.F vs BC (SEK/MWh,cold)		12		2		2
Unit cost of cold reduction on KPI,1, Sc.F vs BC (%)		8%		9%		8%
Unit cost of electricity reduction on KPI,3 Sc.F vs BC (SEK/MWh,El)		48		9		9
Unit cost of electricity reduction on KPI,3 Sc.F vs BC (%)		6%		6%		6%

In these electricity price sensitivity calculations, the same CS charging/discharging profile used in 2018's price trends (c.f. Appendix, Table 16 and Table 25) were employed. However, the price fluctuations of El_Scenario 1 has two price peaks during the day and early evening, unlike with more subtle peaks in 2018 prices. Therefore, for this El_Scenario 1, adjusting the CS discharging profile to also coincide with these electricity price peaks (i.e., to further shift the cooling production out from the peak electricity price durations) as much as possible while catering peak shaving of cooling is suitable and will be done in practice. Likewise, the CS charging should be re-adjusted to be within the lower electricity price hours e.g. 00:00-04:00, 12:00-16:00 and again 21:00-23:00. These adjustments will improve the cost savings in both BC and Sc.F, while Sc.F will allow an even more cost-effective DC supply.

The cost results employing El_Scenario 2 and El_Scenario 3 for respectively SC.F and BC are very similar, because the two price forecasts also have very similar price trends and price levels. Main highlight here is that, despite the very low price levels, still Sc.F allows cost savings of 8-9% considering the total cost as well as unit cost of cold, and 6% savings considering the success of adopting power-to-cold.

Overall, all three electricity price scenarios consider an increased exploitation of renewables (including solar and wind, besides hydro) and at least to a certain degree of reduction in nuclear power. The cooling demand peaks appear during the day (due to warmer daytimes in summer), while the electricity prices also appear to peak mostly within the day, for any of the three scenarios. Renewable electricity is assigned very low costs in these price forecast models [22], and therefore, the low price durations are very likely to represent a larger share of renewables in all the three price models. As the CS charging will also be configured to these low electricity price durations, the CSs add a nice complement in absorbing these renewable electrical supplies from the electricity grid. Sc.F with additional CSs has an expanded capacity to absorb such renewable electricity influxes even than the BC, again outperforming the BC, even during such future electricity price fluctuations.

Therefore, all in all, it appears that implementing scenario F with two CSs each of 7.5 MW capacity in Sundbyberg and Frösunda loop is a promising solution to effectively and economically expand the DC supply of today’s system of Norrenergi AB.

3.4.5 DC system and distribution grid dynamics- BoFit and Netsim combined analysis

In summary, the BoFit analyses in this WP 2.3 indicated that installing a 15 MW additional CS in Sundbyberg (centrally located) is the best choice from those analyzed, to optimize Norrenergi AB’s DC supply. Driven by limitations in BoFit, which cannot investigate distribution grid dynamics, then the assessment was continued to Netsim. The first part of the Netsim analyses therein indicated that the optimal CS choice is a combination of the minimum of 6 MW and a maximum of 15 MW total capacity, which however, should be in two CSs in Sundbyberg (central) and Frösunda (distributed). Interestingly, in both BoFit and preliminary Netsim analyses, implementing an additional 15 MW CS was identified to offer the best cost savings. However, it’s positioning, initially found suitable in Sundbyberg based on the approximate indications from BoFit, turned out to be better in Frösunda at a distributed location as shown in Netsim with distribution grid dynamics analysis. The second step of the Netsim analyses indicated that, two CSs of 7.5 MW capacity each give the optimal capacity, from a range of 3, 4, 5, 6, and 7.5 MW. Thus far, the results were based on the cold production costs only (for a chosen highest demand day), but did not consider their investment costs. In the third step of the Netsim analyses, the chosen optimal scenario with two 7.5 MW CSs was compared with other typical DC expansion investments for a 10% higher demand case: a new chiller (in Sundbyberg, 6 MW) or a new pipe extension (in Frösunda, 422 m). Results here indicated that installing two such 7.5 MW capacity CSs in Norrenergi AB’s DC grid is the most cost-optimal solution from those analyzed, even when considering the total cost by combining operating and investment costs. Sensitivity analyses on the electricity price fluctuations (with increased renewables and decreased nuclear) and ground temperature variations further maintained that this scenario with two 7.5 MW CSs is the most economically profitable from all analyzed options, to optimize the DC supply.

BoFit’s strength is the ability to perform cost optimization of cold production versus cooling demand (based on the electricity use), without having to implement any elements of the distribution network (like pipes, valves and pumps) into the model. Implementing the physical DC distribution in its entirety is a very tedious process needing a lot of effort to reach a realistic result. Therefore, in this WP 2.3, employing BoFit modelling has been a rather simple and time-effective first step to identify the potentially 'better' CS choices for Norrenergi AB's DC system. However, a simplified evaluation from e.g. BoFit cannot confirm the ultimate suitability regarding the sizing and positioning of those CS choices (or other installations). That is because, the BoFit models completely lack details at grid level to indicate the consequences of these installations on the physical distribution grid. For this task, Netsim proves to be the correct tool.

The strength of Netsim is its ability to indicate what practical bottlenecks and limitations arise when executing the chosen installation choices in the real DC network. Netsim can also indicate the most appropriate sizing and positioning of the new capacity installations such as CSs, new pipe extensions and new chillers, as well as the most optimal production mix for cost-optimization. However, it is not Netsim's strength to allow an easy implementation of a reasonable representation of a real existing DC system for purely a production versus demand optimization. That is, e.g. to preliminarily identify the optimal CS sizes and their likely function, using this kind of a detailed distribution network analysis like with Netsim as the first step may not be as effective as starting off with BoFit. This is mainly for the level of detail and therein the time and effort required by distribution grid calculation tools like Netsim to reach a reasonably realistic result.

Therefore, as a whole, in this WP 2.3, the combined use of a BoFit-based simplified optimization as the first step, and the detailed distribution grid dynamic analysis-based optimization with Netsim as the second step, have proven the best approach for a more time-effective and comprehensive assessment.

4 Concluding Remarks

In Sweden, only 1 TWh/year DC is supplied today, in-contrast to an estimated 2-5 TWh demand. Therefore, significant DC expansions are to be anticipated, accelerated further by the effects of global warming. In this context, the findings of this WP 2.3 overall indicate significant potential in CS for robust, cost-effective and environmentally sound operation as well as expansion of DC. The role of distributed CSs in this is also undeniable. DC systems benefit from CSs, which minimize the installation costs for peak capacity via peak shaving and load shifting and power-to-cold adaptation. The findings in this work package specifically highlights an additional key benefit, particularly of distributed CSs, in enabling better distribution grid dynamics to e.g. avoid differential pressure bottlenecks in DC networks.

The cold supply in a DC system is achieved by mean of a combination of technologies like free cooling, absorption and compression chillers and heat pumps. CSs in DC alleviate DC system investments on peak capacity through shaving peak cooling demands and shifting that load to off-peak more cost effective production. Usually this cost-effective cold production and hence CS charging coincides at night when the cooling demand as well as the electricity prices are low (i.e., when electricity surpluses exist). Thereby, CSs enable power-to-cold adaptation, providing a buffer for cheap and/or surplus renewable electricity.

CS in Swedish DC is mainly achieved using cold water, in built tanks or occasionally rock caverns for short-term storage, while UTES types like BTES and ATES are also quite popular for seasonal storage (predominantly in thermal systems at buildings-scale) and often of both heat and cold. Among many examples, Arlanda ATES is the largest ATES in Sweden. Netherlands employs the largest global share of ATES systems in DHC. Snow storage in Sundsvall is an exceptional example for seasonal CS as a cost effective and rather compact alternative to cold water. Here, snow is used as a convenient source of free cooling. Snow and ice storage in place of cold water CSs are quite popular around the world, with commercial applications on rather small district-scale DC systems, e.g. in Hokkaido and Nagoya, Japan and France, Paris. PCMs beyond ice/snow are still emerging into cooling systems beyond building-level, awaiting further developments to become competitive at district scales. TCMs need even further research and developments than PCMs to reach district energy systems. The ability of TCS systems to function as reversible chemical heat pumps, which can selectively store heat or cold, is a catchy feature and a great selling point, when their TRL will improve. Overall, the significantly high volumetric storage capacities of PCMs (also including snow and ice) and TCMs make them a valuable next step in realizing alternatives to CS beyond cold water.

Sizing and positioning cold storages into a DC system (for expanding an existing system or designing an entirely new system) require specific evaluations of the system as a whole (i.e., production versus demand), as well as of the distribution grid dynamics (i.e., concerning distribution limitations). On the one hand, the system-level evaluations, like with BoFit, which, purely optimize cooling production versus demand (yet excludes the distribution grid aspects altogether) facilitate preliminary choices on the potential sizing and arrangement of the CSs in a DC. These are simpler to implement into a model because they exclude the implementation of a real physical grid and the meticulous details therein and thus are more time-effective. However, these DC system-level analyses such as with BoFit alone are not conclusive enough, for their inability to indicate the impact of implementing these CSs on the actual DC distribution grid. Therefore, the DC system optimizations that exclude the grid dynamics are not conclusive enough to indicate the practical suitability of these CS choices.

The distribution grid-level evaluations, on the other hand, are very much into details, and hence require more time and effort to implement the intended system into a model that can provide representative results. Therefore, distribution grid evaluations, with e.g. tools like Netsim, are better suited as the second step of an overall assessment when starting from scratch. That is, tools like Netsim are more effective when used to proceed to an in-depth analysis, starting from the preliminary results obtained from a simpler and faster system analysis such as with BoFit. With the distribution grid dynamics, the real technical feasibility of the preliminary CS choices found from a DC system analysis can be investigated, allowing fine-tuning and more accurate cost analyses on both operation and investments. Either of the two approaches alone will not be as effective as applying their combination, in particular to analyze new solutions into an existing real DC system, which is not yet implemented in a distribution grid calculation tool to sufficient detail. In-contrast, if an existing DC system is already implemented in a suitable distribution grid dynamics calculation tool to sufficient detail, the additional CS implementation can be analyzed solely using that tool, without requiring the use of an additional tool. For choosing the optimal alternative to be installed in the real DC establishment, applying several iterative steps adjusted based on previous results will be the most appropriate method. This kind of a combined optimization approach will be equally beneficial in planning expansions of existing DC systems as well as entirely new DC networks.

In addition to these system-level and network-level technical aspects, a number of practical criteria should also be accounted before dimensioning and positioning distributed CSs in the real physical DC systems. These include design and space requirements and the eventual practical feasibilities at the chosen locations when they are placed out in the DC network. As an overall conclusion, when choosing the suitable complements to expand the DC supply, it is important to thoroughly evaluate the need for investment and the capacity cost, as DC normally has a short utilization duration per year.

The specific results on the techno-economic performance evaluation and cost-benefit analyses conducted on the case study DC system of Norrenergi AB include the following. With the DC system analysis in BoFit (on production versus demand), it was found that installing a 15 MW CS in Sundbyberg (potentially centralized) is the most cost-optimal solution, than the BC, a 15 MW CS in Frösunda or two CSs of 3 MW capacity in Sundbyberg and Frösunda. These results were then carried on to Netsim-based distribution grid dynamics modelling. There, it was found that e.g. a low differential pressure grid loop that exists in Frösunda is a suitable location for a distributed CS. Therefore, the Frösunda CS was placed in Netsim models in this low-dP loop. Further Netsim-based optimizations revealed that the best cost-saving scenarios are the 15 MW CS in Frösunda (distributed low-pressure loop location), closely followed by the two 3 MW CSs use in Sundbyberg and Frösunda. Interestingly, the common results from BoFit and Netsim analyses up to this point included that 15 MW CS has the highest cost savings. Whereas, it's positioning showed contrasting results in BoFit indicating best positioning of this in Sundbyberg, versus in Netsim implying it's best positioning in Frösunda distributed location. The reason for this contrast is that BoFit excludes the distribution grid dynamics, which, however are essential to know the real impacts of these CSs in the DC system, as exemplified by Netsim. Nevertheless, the scenario with the 15 MW CS in Frösunda, in Netsim analysis, failed to deliver the desired total amount of cold at certain instances. Therefore, the most optimal scenario was then considered to be a combination of scenarios 2 and 3 in Netsim, i.e., two CSs in Sundbyberg (central) and Frösunda (distributed), with a total capacity between 6 MW (i.e., 2 times 3 MW) and 15 MW. Continued Netsim evaluations considering two CSs in Sundbyberg and Frösunda loop indicated that the most optimal size for these CSs is 7.5 MW (each). Moreover, operational cost calculations for a 10% higher demand indicated that, this optimal CSs solution and e.g. a 6 MW new chiller in Sundbyberg are more cost-effective than the BC or a new pipe extension of 422 m in Frösunda. Investment costs of the BC, the optimal CSs solution (scenario F), the new pipe in Frösunda and the new chiller in Sundbyberg revealed that the new pipe has the lowest investment cost. Final cost analyses combining annual operational and investment costs unveiled that this optimal CS solution (with two 7.5 MW CSs in Sundbyberg and Frösunda loop) is the best alternative, of all the scenarios and alternatives evaluated.

This optimal CSs solution: scenario F, has lower unit costs (99 SEK / MWh,cold, and 589 SEK / MWh,electricicty) and allows 3% annual total cost savings than the BC (105 SEK / MWh,cold and 608 SEK / MWh,electricity in BC), while avoiding 16% and 4.5% of the investment costs if a chiller or a new pipe was installed. This optimal CS solution also accommodates the most savings in peak electricity use (4.4 MW, electricity/peak hour and 34.8 MWh,electricity/day) as well as in peak cold production (115.2 MWh,cold/day) than with the BC. This means that scenario F allows: 39% less peak electricity use at peak hour (at 13:00), 27% less peak electricity use and 17% less peak cold production per day (between 07:00-19:00), than with the BC. In other words, scenario F, as compared to the BC, is able to decouple the cooling production from the peak cold demand by 17% more, while accommodating 39% and 27% more of the absorption of electricity at nighttime when it is in surplus (than during the day). Therefore, scenario F is a truly beneficial solution for competitively expanding DC capacity.

The sensitivity of this scenario F as compared to the BC for ground temperature increases from 8 °C to 15 °C and 20 °C still maintains that scenario F brings cost savings than the BC. The temperature variations in the DC supply are a little more influenced (concerning maximum supply temperatures) in the case of scenario F than with BC. Scenario F is nonetheless within the range 5.65 °C-6.32 °C as compared to 5.47 °C-5.73 °C for BC, considering the expected supply temperature of 5 °C. The typical ground temperature variations are not so significant; however, here the sensitivity analysis exemplifies that even for extreme ground temperature variations the overall conclusions (that scenario F still outperforms the BC) still hold. The calculated heat losses in Netsim have been lower than the actual data, indicating that the thermo-physical characteristics of the real DC grid elements should be refined in Netsim. Nevertheless, the ground temperature sensitivity analysis results can be considered as still valid. This is because, the calculated heat losses will be affected to a similar/comparable extent (in any of the temperature cases) by the distribution grid elements' thermo-physical property improvements in the model. The sensitivity on electricity price fluctuations for three scenarios considering varying degrees of increased renewables and decreased nuclear also shows that scenario F still outperforms BC. Indeed, for the extreme cases of very low electricity prices the absolute cost savings are lower. However, the share of the savings still show considerable advantages of resolving to scenario F for expanded DC supply. The electricity sensitivity analysis also highlights the potential in these additional CSs in a DC system to act as buffers for absorbing cheap electricity as well as surpluses of renewable electricity. Therefore, CSs are true enablers of renewable electricity storage via power-to-cold in the right type of electricity mix.

In these investigations, the largest additional CS total capacity was maintained to be 15 MW (i.e., two of 7.5 MW). This was governed by the initial choice of 15 MW CS also based on Norrenergi's own previous estimations, which was then confirmed as the optimal capacity from those evaluated in BoFit and Netsim. Nevertheless, to find the most optimal CS size, a valuable future work will be to further evaluate CSs of capacitates above 7.5 MW (e.g. 8 MW, 9 MW and 10 MW, or more). However, this result depends on many factors, with one main being the grid's physical ability to handle the exchange of large cooling loads during charging and discharging of the CSs. In the 10% higher demand case, already the 7.5 MW CSs had a considerable stress on the grids ending in dP levels marginally lower than 800 kPa (i.e., 786 kPa). Then again, the investment costs (which increase with CS capacity increase) and the cost savings per year (which may decrease if there are more dP bottlenecks due to larger CS loads) must be also compared. Overall, it is likely that a marginally larger CS capacity (than 7.5 MW) could become the most cost-optimal CS choice.

The techno-economic analysis on the case study of Norrenergi AB's DC system also brings some important general conclusions valuable for DC sector as a whole. One such general conclusion is in the KPIs identified in this work, which specifically exemplifies the benefits of CSs in DC with power-to-cold adaptations, which are not accounted for, by default. Namely, the combined assessment of the KPIs on the unit costs of produced cold (e.g. SEK/MWh,cold) and the unit cost of electricity used to produce that cold (SEK/MWh,electricity) exemplifies the true benefits of CSs in DC. While the KPI on unit cost of cold indicates the cost-effectiveness of the DC operation, the KPI on the unit cost of electricity is a direct measure of the degree of success in realizing power-to-cold. Additional KPIs of general interest are e.g. the avoided amount of electricity to produce the hourly maximum peak demand (MW,electricity) and the increase in peak shaving (from the additional CSs) or the total peak shaving (by introducing CSs) (in both

MWh,cold/day and MWh,electricity/day) concerning the peak demand hours. These KPIs can be used to characterize the capability of CSs within a DC system to absorb surplus/renewable electricity while producing cooling decoupled from the cooling demand, achieving power-to-cold.

These WP 2.3 findings on the whole emphasize the utility of integrating distributed CSs into DC systems, in addition to the common practice of centralized CSs. This brings another key conclusion of general interest. That is, for a DC network with limited distribution capacity through several production facilities with different marginal production costs and a distribution network with areas having concentrated demand, using distributed CSs provides great opportunities to become more competitive. The cost savings identified in this WP 2.3 concerning the case study of Norrenergi AB's system (e.g. 3% annual savings to invest on and operate two 7.5 MW CSs instead of business-as-usual) may not be as significant as one may expect. Nevertheless, the qualitative benefits these CSs offer e.g. in absorbing surplus renewable electricity, in an electricity mix already evolving towards an increased share of intermittent renewables, are also drivers to encourage their deployment. Here, distributed CSs are promising solutions for both existing DC networks to increase capacity, as well for entirely new DC systems for an optimized supply. Based on the techno-economic analysis, therefore, another general conclusion is that for any DC system, the distribution network sections that have high-density consumer loops are likely segments to succumb to low differential pressure 'bottlenecks' and are therefore also potential locations for a distributed CS. If there are distributed surplus cold sources (from e.g. industrial and commercial establishments) also within certain parts of the DC distribution grid, these could also be points of interest for distributed CSs. In this WP, the possibility of recovering surplus cold via distributed CSs was not explored, however, is a worth future investigation.

The power-to-cold adaptation in this work was considered more as by-default, via charging the CS with cold produced with nighttime cheaper electricity, i.e., for peak shaving and load shifting. The sensitivity analysis for three different electricity price forecasts for increased renewables and decreasing nuclear provided a valuable complement here. Therein, the potential in CSs to absorb cheap and or renewable surcharges of electricity with power-to-cold is further exemplified. However, here the operational benefits of power-to-cold, specifically for renewable surplus electricity storage while guaranteeing robustness to the DC system when catering to commercial establishments such as data centers and laboratories (with cooling demands throughout the year) have not been analyzed. Norrenergi AB's electricity mix is already 100% renewable, and hence the surplus renewable electricity storage was also achieved by default. Further detailed evaluations on power-to-cold with CS to identify business cases within the energy sector will also be a valuable future work. This will be an especially worthwhile study despite the short Swedish summer periods where DC operates for the most, if the summer electricity prices will be lower than in winter (which is a likely situation if Sweden meets its climate targets for 2040).

In this WP, it was anticipated at the outset to also evaluate various CS options in the techno-economic analysis. However, due to lack of example cases and data in the required level of detail for the district-level application, the techno-economic performance and benefits analyses were eventually restricted to cold water CSs only. Nevertheless, backed by a literature review-based critical assessment, the key features as well as challenges in these CS alternatives to cold water are brought forward herein. Overall, these compact TES technologies are expected to play a significant role as CSs in future DC systems. Evaluating CS options out of these compact CS alternatives in detailed techno-economic assessments as relevant to a DC system operation will hence be another valuable future work.

Sökord

District cooling (DC); Cold storage (CS); Power-to-cold; DC system; DC distribution grid; Differential pressure (dP); Peak demand; Peak Shaving; Load shifting; Free cooling; Chiller; Heat pump; BoFit; Netsim; System analysis; Distribution grid dynamics analysis; Optimization; Key performance indicator (KPI); Cost; Investment; Avoided cost

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7 Appendix

The Appendix here presents further details and detailed data that were used in the techno-economic assessment of Norrenergi AB's DC system for today's case (BC) and various scenarios during BoFit and Netsim modelling work. The relevant sections in the main report cross-refer to these elements in the Appendix, to explain their use better.

Table 12. The hourly cooling demand on 02 August 2018 in Norrenergi AB's DC system- today's case, also showing the average and the maximum demands of this data series

Time	Demand (MW)
00:00	21.8
01:00	24.4
02:00	23.0
03:00	23.0
04:00	23.2
05:00	25.9
06:00	29.5
07:00	42.8
08:00	54.9
09:00	58.4
10:00	58.0
11:00	53.4
12:00	57.3
13:00	**59.0**
14:00	51.8
15:00	58.6
16:00	48.7
17:00	48.6
18:00	46.5
19:00	39.9
20:00	32.9
21:00	32.7
22:00	27.4
23:00	23.5
Mean demand (MW)	**40.22**
Maximum (MW)	59.0

Table 13. The hourly cooling demand on 02 August 2018 in Norrenergi AB's DC system- a 10% increase of today's case, also showing the average and the maximum demands of this data series

Time	Demand (MW)
00:00	24.0
01:00	26.9
02:00	25.3

03:00	25.3
04:00	25.6
05:00	28.5
06:00	32.5
07:00	47.0
08:00	60.4
09:00	64.3
10:00	63.7
11:00	58.7
12:00	63.0
13:00	**64.9**
14:00	56.9
15:00	64.4
16:00	53.6
17:00	53.5
18:00	51.2
19:00	43.9
20:00	36.2
21:00	36.0
22:00	30.2
23:00	25.8
Mean demand (MW)	**44.25**
Maximum (MW)	64.9

Table 14. The hourly electricity (spot) prices from Nord Pool for SE3 on 02 August 2018

Time	Elspot prices (SEK/MWh)
00:00	530.06 kr
01:00	515.43 kr
02:00	510.69 kr
03:00	507.40 kr
04:00	500.29 kr
05:00	515.84 kr
06:00	550.76 kr
07:00	583.72 kr
08:00	666.02 kr
09:00	676.74 kr
10:00	676.74 kr
11:00	669.42 kr
12:00	660.77 kr
13:00	647.38 kr
14:00	629.15 kr
15:00	638.01 kr
16:00	649.65 kr
17:00	669.11 kr

Time	Elspot prices (SEK/MWh)
18:00	607.31 kr
19:00	583.41 kr
20:00	573.22 kr
21:00	581.97 kr
22:00	567.96 kr
23:00	555.50 kr

Table 15. The historical demand data from Norrenergi AB, that was converted into the real demand data (and six demand regions in BoFit) based on the maximum production of 58.97 MW of cold on 02 August 2018, with 1.6 MW cold losses (thus real supply being 57.4 MW cold)

Network- and Customer Areas	Forecasted demand (MW, 2018)	Aggregated total demand per region (MW, 2018)	Total production estimate per aggregated region (MW, for 2018)
Solna-Sundbyberg		**13.9**	**15.9**
Solna Business Park	3.0		3.4
Solna strand	6.9		7.9
Centrala Sundbyberg	4.0		4.6
Huvudsta		**2.4**	**2.7**
Huvudsta V	0.7		0.8
Huvudsta Ö	1.7		1.9
Centrala Solna		**3.9**	**4.5**
Skytteholm	1.7		1.9
Solna Centrum	1.6		1.8
Råsunda	0.6		0.7
Frösunda		**28.4**	**32.5**
Frösunda	4.1		4.7
Nya Ulriksdal	1.1		1.3
Hagalund Ö	1.1		1.3
Hagalund V	0.1		0.1
Hagastaden	5.0		5.7
Bergshamra	1.1		1.3
Arenastaden	15.8	**15.8**	**18.1**
Sundbyberg		**1.4**	**1.6**
Hallonbergen	1.4		1.6
Total	50.1	**50.1**	**57.4**

Table 16. The 10 MW, 6500 m³ CS (Solna) charging and discharging per hour, also showing the available total energy for storage, the crude discharging and the final used adjusted realistic charging and discharging (in MW). (Adjusted charging/discharging represent the real CS of up to 10 MW nominal capacity and thus are used in the calculations)

Time [hour]	Available energy for charging the CS [MW]	**Adjusted charging [MW]**	Crude discharging [MW]	**Adjusted discharging [MW]**
00:00	18.4	8.98	0	0
01:00	15.8	7.69	0	0
02:00	17.2	8.38	0	0
03:00	17.2	8.37	0	0
04:00	17.0	8.27	0	0
05:00	14.3	6.97	0	0
06:00	10.7	5.21	0	0
07:00	0.0	0	2.53	1.23
08:00	0.0	0	14.65	7.14
09:00	0.0	0	18.21	8.87
10:00	0.0	0	17.73	8.64
11:00	0.0	0	13.17	6.42
12:00	0.0	0	17.09	8.33
13:00	0.0	0	18.75	9.14
14:00	0.0	0	11.54	5.62
15:00	0.0	0	18.35	8.94
16:00	0.0	0	8.53	4.15
17:00	0.0	0	8.42	4.10
18:00	0.0	0	6.29	3.06
19:00	0.3	0.17	0	0
20:00	7.3	3.58	0	0
21:00	7.5	3.65	0	0
22:00	12.8	6.24	0	0
23:00	16.7	8.15	0	0
Total [MWh]	155.2	**75.65**	155.2	**75.65**

Table 17. The 10 MW, 6500 m³ CS (Solna) charging and discharging per hour as used by Bilek, 2020 [11], also showing the available total energy for storage, the adjusted charging, the final used averaged charging, the crude discharging, the adjusted discharging and the final used averaged discharging (in MW).

Time [hour]	Available energy for charging the CS [MW]	Adjusted charging [MW]	**Averaged charging [MW]**	Crude discharging [MW]	Adjusted discharging [MW]	**Averaged discharging [MW]**
00:00	18.4	8.98	6.30	0	0	0
01:00	15.8	7.69	6.30	0	0	0
02:00	17.2	8.38	6.30	0	0	0
03:00	17.2	8.37	6.30	0	0	0
04:00	17.0	8.27	6.30	0	0	0
05:00	14.3	6.97	6.30	0	0	0
06:00	10.7	5.21	6.30	0	0	0
07:00	0.0	0	0	2.53	1.23	6.30

08:00	0.0	0	0	14.65	7.14	6.30
09:00	0.0	0	0	18.21	8.87	6.30
10:00	0.0	0	0	17.73	8.64	6.30
11:00	0.0	0	0	13.17	6.42	6.30
12:00	0.0	0	0	17.09	8.33	6.30
13:00	0.0	0	0	18.75	9.14	6.30
14:00	0.0	0	0	11.54	5.62	6.30
15:00	0.0	0	0	18.35	8.94	6.30
16:00	0.0	0	0	8.53	4.15	6.30
17:00	0.0	0	0	8.42	4.10	6.30
18:00	0.0	0	0	6.29	3.06	6.30
19:00	0.3	0.17	6.30	0	0	0
20:00	7.3	3.58	6.30	0	0	0
21:00	7.5	3.65	6.30	0	0	0
22:00	12.8	6.24	6.30	0	0	0
23:00	16.7	8.15	6.30	0	0	0
Total [MWh]	155.2	75.65	**75.65**	155.2	75.65	**75.65**

Table 18. The 15 MW, 15000 m³ CS (Sundbyberg or Frösunda) charging and discharging per hour as used by Bilek, 2020 [11], also showing the available total energy for storage, the adjusted charging, the final used averaged charging, and final used averaged discharging* (*calculated by taking the average of total CS capacity over the discharging period of 12 hours (in MW).

Time [hour]	Available energy for charging the CSs [MW]	Adjusted charging [MW]	**Averaged charging [MW]**	**Averaged discharging [MW]**
00:00	25.8	18.0	12.47	0
01:00	23.2	16.2	12.47	0
02:00	24.6	17.2	12.47	0
03:00	24.6	17.2	12.47	0
04:00	24.4	17.0	12.47	0
05:00	21.7	15.1	12.47	0
06:00	18.1	12.6	12.47	0
07:00	4.9	3.4	12.47	14.55
08:00	0	0	0	14.55
09:00	0	0	0	14.55
10:00	0	0	0	14.55
11:00	0	0	0	14.55
12:00	0	0	0	14.55
13:00	0	0	0	14.55
14:00	0	0	0	14.55
15:00	0	0	0	14.55
16:00	0	0	0	14.55
17:00	0	0	0	14.55
18:00	1.1	0.8	12.47	14.55
19:00	7.7	5.4	12.47	0

20:00	14.7	10.3	12.47	0
21:00	14.9	10.4	12.47	0
22:00	20.2	14.1	12.47	0
23:00	24.1	16.8	12.47	0
Total [MWh]	250.0	174.6	**174.6**	**174.6**

Table 19. The 3 MW, 3000 m³ CS (one each at Sundbyberg and Frösunda) charging and discharging per hour as used by Bilek, 2020 [11], also showing the available total energy for storage, the adjusted charging, the final used averaged charging and final used averaged discharging* (*calculated by taking the average of total CS capacity over the discharging period of 12 hours (in MW).

Time [hour]	Available energy for charging the CSs [MW]	Adjusted charging [MW]	**Averaged charging [MW]**	**Averaged discharging [MW]**
00:00	17.6	4.2	2.9	0
01:00	14.9	3.6	2.9	0
02:00	16.3	3.9	2.9	0
03:00	16.3	3.9	2.9	0
04:00	16.1	3.9	2.9	0
05:00	13.4	3.2	2.9	0
06:00	9.8	2.4	2.9	0
07:00	0	0	0	2.9
08:00	0	0	0	2.9
09:00	0	0	0	2.9
10:00	0	0	0	2.9
11:00	0	0	0	2.9
12:00	0	0	0	2.9
13:00	0	0	0	2.9
14:00	0	0	0	2.9
15:00	0	0	0	2.9
16:00	0	0	0	2.9
17:00	0	0	0	2.9
18:00	0	0	0	2.9
19:00	0	0	2.9	0
20:00	6.5	1.6	2.9	0
21:00	6.6	1.6	2.9	0
22:00	11.9	2.9	2.9	0
23:00	15.9	3.8	2.9	0
Total [MWh]	**145.6**	34.9	**34.92**	**34.9**

Table 20. The charging and discharging time series of the 3 MW, 2000 m³ and 23.3 MWh CS in scenario A (one each at Sundbyberg and Frösunda) also showing the available total energy for storage (in MW).

Time [hour]	Available energy for charging the CSs [MW]	**Adjusted charging [MW]**	**Manually assigned discharging [MW]**
00:00	15.5	2.94	0

01:00	12.8	2.44	0
02:00	14.2	2.71	0
03:00	14.2	2.71	0
04:00	14.0	2.67	0
05:00	11.3	2.16	0
06:00	7.7	1.47	0
07:00	0.0	0	0.34
08:00	0.0	0	1.50
09:00	0.0	0	2.50
10:00	0.0	0	2.50
11:00	0.0	0	2.50
12:00	0.0	0	2.80
13:00	0.0	0	3.00
14:00	0.0	0	1.50
15:00	0.0	0	2.50
16:00	0.0	0	1.50
17:00	0.0	0	1.30
18:00	0.0	0	1.00
19:00	0.0	0	0.34
20:00	4.4	0.83	0
21:00	4.5	0.86	0
22:00	9.8	1.87	0
23:00	13.8	2.62	0
Total [MWh]	**122.2**	**23.3**	**23.3**

Table 21. The charging and discharging time series of the 4 MW, 2600 m³ and 30.3 MWh CS in scenario B (one each at Sundbyberg and Frösunda) also showing the available total energy for storage (in MW).

Time [hour]	Available energy for charging the CSs [MW]	**Adjusted charging [MW]**	**Manually assigned discharging [MW]**
00:00	16.7	3.7	0
01:00	14.1	3.1	0
02:00	15.5	3.4	0
03:00	15.5	3.4	0
04:00	15.3	3.4	0
05:00	12.6	2.8	0
06:00	9.0	2.0	0
07:00	0	0	0.331
08:00	0	0	1.50
09:00	0	0	3.80
10:00	0	0	2.50
11:00	0	0	3.00
12:00	0	0	3.80
13:00	0	0	**4.00**

14:00	0	0	2.00
15:00	0	0	3.00
16:00	0	0	2.50
17:00	0	0	2.00
18:00	0	0	1.50
19:00	0	0	0.331
20:00	5.6	1.3	0
21:00	5.8	1.3	0
22:00	11.1	2.5	0
23:00	15.0	3.3	0
Total [MWh]	136.2	**30.3**	30.3

Table 22. The charging and discharging time series of the 5 MW, 3300 m³ and 38.4 MWh CS in scenario B (one each at Sundbyberg and Frösunda) also showing the available total energy for storage (in MW).

Time [hour]	Available energy for charging the CSs [MW]	**Adjusted charging [MW]**	**Manually assigned discharging [MW]**
00:00	18.2	4.58	0
01:00	15.5	3.92	0
02:00	17.0	4.27	0
03:00	17.0	4.27	0
04:00	16.7	4.22	0
05:00	14.1	3.54	0
06:00	10.5	2.64	0
07:00	0.0	0	0.7
08:00	0.0	0	2.0
09:00	0.0	0	3.0
10:00	0.0	0	4.0
11:00	0.0	0	4.5
12:00	0.0	0	5.0
13:00	0.0	0	5.0
14:00	0.0	0	4.5
15:00	0.0	0	4.0
16:00	0.0	0	3.0
17:00	0.0	0	2.0
18:00	0.0	0	0.7
19:00	0.1	0.03	0
20:00	7.1	1.79	0
21:00	7.3	1.83	0
22:00	12.6	3.17	0
23:00	16.5	4.16	0
Total [MWh]	152.5	**38.4**	**38.4**

Table 23. The charging and discharging time series of the 6 MW, 4000 m³ and 46.6 MWh CS in scenario B (one each at Sundbyberg and Frösunda) also showing the available total energy for storage (in MW).

Time [hour]	Available energy for charging the CSs [MW]	**Adjusted charging [MW]**	**Manually assigned discharging [MW]**
00:00	19.6	5.40	0
01:00	16.9	4.66	0
02:00	18.3	5.05	0
03:00	18.3	5.05	0
04:00	18.1	4.99	0
05:00	15.4	4.25	0
06:00	11.8	3.26	0
07:00	0.0	0	0.78
08:00	0.0	0	3.00
09:00	0.0	0	4.00
10:00	0.0	0	4.50
11:00	0.0	0	5.00
12:00	0.0	0	6.00
13:00	0.0	0	6.00
14:00	0.0	0	5.00
15:00	0.0	0	4.50
16:00	0.0	0	4.00
17:00	0.0	0	3.00
18:00	0.0	0	0.78
19:00	1.5	0.40	0
20:00	8.5	2.34	0
21:00	8.6	2.37	0
22:00	13.9	3.84	0
23:00	17.9	4.93	0
Total [MWh]	168.8	**46.6**	**46.6**

Table 24. The charging and discharging time series of the 7 MW, 4600 m³ and 53.5 MWh CS in scenario B (one each at Sundbyberg and Frösunda) also showing the available total energy for storage (in MW).

Time [hour]	Available energy for charging the CSs [MW]	**Adjusted charging [MW]**	**Manually assigned discharging [MW]**
00:00	20.7	6.07	0
01:00	18.1	5.29	0
02:00	19.5	5.71	0
03:00	19.5	5.71	0
04:00	19.3	5.64	0
05:00	16.6	4.86	0
06:00	13.0	3.81	0
07:00	0.0	0	0.77

08:00	0.0	0	3.0
09:00	0.0	0	4.0
10:00	0.0	0	5.5
11:00	0.0	0	6.5
12:00	0.0	0	7.0
13:00	0.0	0	7.0
14:00	0.0	0	6.5
15:00	0.0	0	5.5
16:00	0.0	0	4.0
17:00	0.0	0	3.0
18:00	0.0	0	0.77
19:00	2.6	0.77	0
20:00	9.6	2.82	0
21:00	9.8	2.86	0
22:00	15.1	4.42	0
23:00	19.0	5.57	0
Total [MWh]	182.7	**53.5**	**53.5**

Table 25. The charging and discharging time series of the 7.5 MW, 5000 m³ and 58.2 MWh CS in scenario B (one each at Sundbyberg and Frösunda) also showing the available total energy for storage (in MW).

Time [hour]	Available energy for charging the CSs [MW]	**Adjusted charging [MW]**	**Manually assigned discharging [MW]**
00:00	21.5	6.50	0
01:00	18.8	5.70	0
02:00	20.2	6.13	0
03:00	20.2	6.12	0
04:00	20.0	6.06	0
05:00	17.3	5.25	0
06:00	13.7	4.16	0
07:00	0.5	0.15	0
08:00	0.0	0	3.0
09:00	0.0	0	4.0
10:00	0.0	0	5.0
11:00	0.0	0	6.0
12:00	0.0	0	7.3
13:00	0.0	0	7.5
14:00	0.0	0	7.3
15:00	0.0	0	6.0
16:00	0.0	0	5.0
17:00	0.0	0	4.0
18:00	0.0	0	3.0
19:00	3.4	1.02	0
20:00	10.4	3.14	0

21:00	10.5	3.18	0
22:00	15.8	4.79	0
23:00	19.8	5.99	0
Total [MWh]	192.0	**58.2**	**58.2**

Table 26. The forecasted electricity prices for a summer day in 2040 [23] used in the sensitivity analysis of DC network optimization with CSs, for the 3 considered scenarios (here an inflation of 2% per year was assumed, to include inflation in 2040)

	2040 prices, excluding inflation			**2040 prices, including inflation**		
Hour	**El_Sceanrio 1**	**El_Sceanrio 2**	**El_Sceanrio 3**	**El_Sceanrio 1**	**El_Sceanrio 2**	**El_Sceanrio 3**
00:00	333.2	62.4	64.4	495.1	92.8	95.7
01:00	328.2	57.3	59.2	487.7	85.2	88.0
02:00	292.9	51.8	54.1	435.3	76.9	80.4
03:00	267.6	49.2	51.5	397.6	73.1	76.6
04:00	245.8	47.7	51.3	365.2	70.9	76.3
05:00	359.4	63.0	64.9	534.1	93.6	96.4
06:00	492.3	88.3	89.0	731.6	131.2	132.2
07:00	738.6	113.5	112.4	1097.6	168.6	167.1
08:00	779.8	133.9	128.2	1158.7	199.0	190.4
09:00	784.1	151.9	146.6	1165.2	225.7	217.9
10:00	717.4	124.5	125.7	1066.0	185.0	186.8
11:00	656.2	121.8	123.2	975.0	181.0	183.1
12:00	521.9	110.0	114.6	775.5	163.4	170.3
13:00	535.3	102.8	107.5	795.4	152.7	159.7
14:00	521.0	94.3	97.8	774.2	140.2	145.3
15:00	446.4	88.4	94.6	663.3	131.4	140.5
16:00	462.0	81.0	86.3	686.6	120.4	128.2
17:00	570.5	102.6	108.9	847.7	152.4	161.8
18:00	606.6	122.0	120.7	901.4	181.3	179.3
19:00	637.3	133.5	130.3	947.0	198.3	193.6
20:00	480.9	102.6	111.9	714.7	152.5	166.3
21:00	416.1	90.2	104.7	618.3	134.0	155.6
22:00	447.9	92.5	99.5	665.5	137.4	147.9
23:00	459.6	76.1	80.6	682.9	113.1	119.8

Table 27. Netsim calculated results on BC by Bilek, 2020 [11] for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant						Electricity use by MW (per hour) by each plant to produce cold						Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	Solna CC	Solna HP	SBG	FröFC	FröCC		Solna CC	Solna HP	SBG	FröFC	FröCC		Solna CC	Solna HP	SBG	FröFC	FröCC	Sum (SEK)
00:00	9.60	0	8.75	12.60	0.00		1.92	0.00	1.75	1.26	0.00		1,018	0	928	668	0	2,613
01:00	9.99	0	11.00	12.60	0.00		2.00	0.00	2.20	1.26	0.00		1,030	0	1,134	649	0	2,814
02:00	9.69	0	10.00	12.60	0.00		1.94	0.00	2.00	1.26	0.00		989	0	1,021	643	0	2,654
03:00	9.56	0	10.13	12.60	0.00		1.91	0.00	2.03	1.26	0.00		970	0	1,027	639	0	2,637
04:00	9.31	0	10.38	12.60	0.00		1.86	0.00	2.08	1.26	0.00		932	0	1,038	630	0	2,600
05:00	9.31	0.9	10.75	12.60	1.50		1.86	0.30	2.15	1.26	0.30		960	155	1,109	650	155	3,028
06:00	10.00	2.7	12.00	12.60	2.30		2.00	0.90	2.40	1.26	0.46		1,101	496	1,322	694	253	3,866
07:00	8.71	0	12.50	12.60	8.50		1.74	0.00	2.50	1.26	1.70		1,017	0	1,459	735	992	4,204
08:00	9.93	10.62	12.50	12.60	10.00		1.99	3.54	2.50	1.26	2.00		1,322	2,358	1,665	839	1,332	7,516
09:00	10.00	14.58	12.50	12.60	10.00		2.00	4.86	2.50	1.26	2.00		1,353	3,289	1,692	853	1,353	8,540
10:00	9.88	14.04	12.50	12.60	10.00		1.98	4.68	2.50	1.26	2.00		1,337	3,167	1,692	853	1,353	8,402
11:00	9.90	9.36	12.50	12.60	10.00		1.98	3.12	2.50	1.26	2.00		1,325	2,089	1,674	843	1,339	7,269
12:00	9.93	13.32	12.50	12.60	10.00		1.99	4.44	2.50	1.26	2.00		1,313	2,934	1,652	833	1,322	8,052
13:00	9.95	15.3	12.50	12.60	10.00		1.99	5.10	2.50	1.26	2.00		1,289	3,302	1,618	816	1,295	8,319
14:00	9.88	7.38	12.50	12.60	10.00		1.98	2.46	2.50	1.26	2.00		1,243	1,548	1,573	793	1,258	6,415
15:00	10.00	14.58	12.50	12.60	10.00		2.00	4.86	2.50	1.26	2.00		1,276	3,101	1,595	804	1,276	8,052
16:00	9.97	3.96	12.50	12.60	10.00		1.99	1.32	2.50	1.26	2.00		1,295	858	1,624	819	1,299	5,895
17:00	10.00	3.24	12.50	12.60	10.00		2.00	1.08	2.50	1.26	2.00		1,338	723	1,673	843	1,338	5,915
18:00	9.09	1.26	12.50	12.60	10.00		1.82	0.42	2.50	1.26	2.00		1,104	255	1,518	765	1,215	4,858
19:00	9.98	8.82	12.50	12.60	7.70		2.00	2.94	2.50	1.26	1.54		1,165	1,715	1,459	735	898	5,972
20:00	10.00	4.5	12.50	12.60	4.00		2.00	1.50	2.50	1.26	0.80		1,146	860	1,433	722	459	4,620
21:00	9.83	4.68	12.50	12.60	4.00		1.97	1.56	2.50	1.26	0.80		1,144	908	1,455	733	466	4,705
22:00	9.96	1.62	11.63	12.60	1.80		1.99	0.54	2.33	1.26	0.36		1,132	307	1,321	716	204	3,679
23:00	9.23	0	11.13	12.60	0.00		1.85	0.00	2.23	1.26	0.00		1,025	0	1,236	700	0	2,961
TOT (MWh)	**233.69**	**130.86**	**283.25**	**302.40**	**139.80**	**1090.00**	**46.74**	**43.62**	**56.65**	**30.24**	**27.96**	**205.21**	**27,824**	**28,062**	**33,917**	**17,976**	**17,808**	**(SEK) 125,587**

Table 28. Netsim calculated results on Scenario 1 (15 MW CS in SBG) by Bilek, 2020 [11] for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant						Electricity use by MW (per hour) by each plant to produce cold						Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	Solna CC	Solna HP	SBG	FröFC	FröCC		Solna CC	Solna HP	SBG	FröFC	FröCC		Solna CC	Solna HP	SBG	FröFC	FröCC	Sum (SEK)
00:00	9.94	2.34	12.50	12.60	6.00		1.99	0.78	2.50	1.26	1.20		1,053	413	1,325	668	636	4,096
01:00	9.85	3.6	12.50	12.60	7.50		1.97	1.20	2.50	1.26	1.50		1,015	619	1,289	649	773	4,345
02:00	9.92	2.7	12.50	12.60	7.00		1.98	0.90	2.50	1.26	1.40		1,013	460	1,277	643	715	4,108
03:00	9.92	2.7	12.50	12.60	7.00		1.98	0.90	2.50	1.26	1.40		1,006	457	1,269	639	710	4,081
04:00	9.92	2.7	12.50	12.60	7.00		1.98	0.90	2.50	1.26	1.40		992	450	1,251	630	700	4,024
05:00	9.87	4.68	12.50	12.60	8.40		1.97	1.56	2.50	1.26	1.68		1,018	805	1,290	650	867	4,629
06:00	9.87	7.38	12.50	12.60	9.60		1.97	2.46	2.50	1.26	1.92		1,087	1,355	1,377	694	1,057	5,570
07:00	8.83	0	8.75	12.60	10.00		1.77	0.00	1.75	1.26	2.00		1,031	0	1,022	735	1,167	3,955
08:00	9.94	6.3	2.25	12.60	10.00		1.99	2.10	0.45	1.26	2.00		1,324	1,399	300	839	1,332	5,193
09:00	9.87	9.54	3.13	12.60	10.00		1.97	3.18	0.63	1.26	2.00		1,335	2,152	423	853	1,353	6,116
10:00	9.84	8.28	3.75	12.60	10.00		1.97	2.76	0.75	1.26	2.00		1,332	1,868	508	853	1,353	5,914
11:00	9.99	5.22	2.00	12.60	10.00		2.00	1.74	0.40	1.26	2.00		1,337	1,165	268	843	1,339	4,952
12:00	9.98	8.1	3.13	12.60	10.00		2.00	2.70	0.63	1.26	2.00		1,319	1,784	413	833	1,322	5,670
13:00	9.91	9.54	3.75	12.60	10.00		1.98	3.18	0.75	1.26	2.00		1,284	2,059	486	816	1,295	5,938
14:00	9.93	3.78	1.50	12.60	10.00		1.99	1.26	0.30	1.26	2.00		1,249	793	189	793	1,258	4,282
15:00	9.99	9.54	3.00	12.60	10.00		2.00	3.18	0.60	1.26	2.00		1,275	2,029	383	804	1,276	5,767
16:00	9.90	1.98	0.00	12.60	10.00		1.98	0.66	0.00	1.26	2.00		1,286	429	0	819	1,299	3,832
17:00	9.94	1.26	0.00	12.60	10.00		1.99	0.42	0.00	1.26	2.00		1,331	281	0	843	1,338	3,793
18:00	9.99	1.62	10.00	12.60	10.00		2.00	0.54	2.00	1.26	2.00		1,213	328	1,215	765	1,215	4,736
19:00	10.94	18	12.50	12.60	10.00		2.19	6.00	2.50	1.26	2.00		1,277	3,500	1,459	735	1,167	8,137
20:00	9.99	10.98	12.50	12.60	10.00		2.00	3.66	2.50	1.26	2.00		1,145	2,098	1,433	722	1,146	6,545
21:00	9.98	10.98	12.50	12.60	10.00		2.00	3.66	2.50	1.26	2.00		1,162	2,130	1,455	733	1,164	6,644
22:00	9.85	6.12	12.50	12.60	9.00		1.97	2.04	2.50	1.26	1.80		1,118	1,159	1,420	716	1,022	5,435
23:00	9.94	3.06	12.50	12.60	7.30		1.99	1.02	2.50	1.26	1.46		1,104	567	1,389	700	811	4,570
TOT (MWh)	**238.06**	**140.40**	**191.25**	**302.40**	**218.80**	**1090.91**	**47.61**	**46.80**	**38.25**	**30.24**	**43.76**	**206.66**	**28,306**	**28,297**	**21,436**	**17,976**	**26,318**	**(SEK) 122,332**

Table 29. Netsim calculated results on Scenario 2 (15 MW CS in Frösunda loop) by Bilek, 2020 [11] for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant						Electricity use by MW (per hour) by each plant to produce cold						Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	Solna CC	Solna HP	SBG	FröFC	FröCC		Solna CC	Solna HP	SBG	FröFC	FröCC		Solna CC	Solna HP	SBG	FröFC	FröCC	Sum (SEK)
00:00	8.98	0	12.50	12.60	9.30		1.80	0.00	2.50	1.26	1.86		951	0	1,325	668	986	3,930
01:00	10.00	0.9	12.50	12.60	10.00		2.00	0.30	2.50	1.26	2.00		1,031	155	1,289	649	1,031	4,154
02:00	9.92	0	12.50	12.60	9.70		1.98	0.00	2.50	1.26	1.94		1,013	0	1,277	643	991	3,924
03:00	9.92	0	12.50	12.60	9.70		1.98	0.00	2.50	1.26	1.94		1,006	0	1,269	639	984	3,898
04:00	10.00	0	12.50	12.60	9.60		2.00	0.00	2.50	1.26	1.92		1,001	0	1,251	630	961	3,842
05:00	9.87	3.06	12.50	12.60	10.00		1.97	1.02	2.50	1.26	2.00		1,018	526	1,290	650	1,032	4,515
06:00	9.93	7.02	12.50	12.60	10.00		1.99	2.34	2.50	1.26	2.00		1,093	1,289	1,377	694	1,102	5,555
07:00	8.10	0	12.50	12.60	7.00		1.62	0.00	2.50	1.26	1.40		946	0	1,459	735	817	3,958
08:00	9.86	5.4	10.25	12.60	3.00		1.97	1.80	2.05	1.26	0.60		1,313	1,199	1,365	839	400	5,116
09:00	9.91	7.74	11.88	12.60	3.00		1.98	2.58	2.38	1.26	0.60		1,341	1,746	1,607	853	406	5,953
10:00	9.91	6.66	12.50	12.60	2.80		1.98	2.22	2.50	1.26	0.56		1,341	1,502	1,692	853	379	5,767
11:00	10.00	4.32	10.75	12.60	2.10		2.00	1.44	2.15	1.26	0.42		1,339	964	1,439	843	281	4,867
12:00	10.00	6.3	11.88	12.60	3.00		2.00	2.10	2.38	1.26	0.60		1,322	1,388	1,569	833	396	5,508
13:00	10.00	7.56	11.63	12.60	4.00		2.00	2.52	2.33	1.26	0.80		1,295	1,631	1,505	816	518	5,765
14:00	10.00	3.42	10.25	12.60	1.50		2.00	1.14	2.05	1.26	0.30		1,258	717	1,290	793	189	4,247
15:00	9.92	7.56	11.25	12.60	3.80		1.98	2.52	2.25	1.26	0.76		1,266	1,608	1,436	804	485	5,598
16:00	9.99	1.98	9.50	12.60	0.40		2.00	0.66	1.90	1.26	0.08		1,299	429	1,234	819	52	3,832
17:00	9.96	1.62	9.63	12.60	0.00		1.99	0.54	1.93	1.26	0.00		1,333	361	1,288	843	0	3,825
18:00	9.97	0.36	12.50	12.60	8.80		1.99	0.12	2.50	1.26	1.76		1,211	73	1,518	765	1,069	4,637
19:00	10.90	18	12.50	12.60	10.00		2.18	6.00	2.50	1.26	2.00		1,272	3,500	1,459	735	1,167	8,133
20:00	9.98	10.98	12.50	12.60	10.00		2.00	3.66	2.50	1.26	2.00		1,145	2,098	1,433	722	1,146	6,544
21:00	9.98	10.98	12.50	12.60	10.00		2.00	3.66	2.50	1.26	2.00		1,162	2,130	1,455	733	1,164	6,644
22:00	9.93	5.04	12.50	12.60	10.00		1.99	1.68	2.50	1.26	2.00		1,128	954	1,420	716	1,136	5,354
23:00	9.93	0.36	12.50	12.60	10.00		1.99	0.12	2.50	1.26	2.00		1,104	67	1,389	700	1,111	4,370
TOT (MWh)	**236.96**	**109.26**	**284.50**	**302.40**	**157.70**	**1090.82**	**47.39**	**36.42**	**56.90**	**30.24**	**31.54**	**202.49**	**28,187**	**22,337**	**33,635**	**17,976**	**17,802**	**(SEK) 119,936**

Energiforsk

Table 30. Netsim calculated results on Scenario 3 (two 3 MW CSs in SBG and Frösunda loop) by Bilek, 2020 [11] for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant						Electricity use by MW (per hour) by each plant to produce cold						Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	Solna CC	Solna HP	SBG	FröFC	FröCC		Solna CC	Solna HP	SBG	FröFC	FröCC		Solna CC	Solna HP	SBG	FröFC	FröCC	Sum (SEK)
00:00	8.65	0.00	12.50	12.60	3.00		1.73	0.00	2.50	1.26	0.60		917	0	1,325	668	318	3,228
01:00	10.00	0.00	12.50	12.60	4.40		2.00	0.00	2.50	1.26	0.88		1,031	0	1,289	649	454	3,422
02:00	9.37	0.00	12.50	12.60	3.60		1.87	0.00	2.50	1.26	0.72		957	0	1,277	643	368	3,245
03:00	9.24	0.00	12.50	12.60	3.70		1.85	0.00	2.50	1.26	0.74		937	0	1,269	639	375	3,221
04:00	9.24	0.00	12.50	12.60	3.70		1.85	0.00	2.50	1.26	0.74		925	0	1,251	630	370	3,176
05:00	10.00	1.33	12.50	12.60	5.20		2.00	0.44	2.50	1.26	1.04		1,032	229	1,290	650	536	3,737
06:00	10.00	3.45	12.50	12.60	7.20		2.00	1.15	2.50	1.26	1.44		1,102	633	1,377	694	793	4,598
07:00	6.83	0.00	11.25	12.60	5.00		1.37	0.00	2.25	1.26	1.00		798	0	1,313	735	584	3,430
08:00	10.00	5.98	12.50	12.60	10.00		2.00	1.99	2.50	1.26	2.00		1,332	1,326	1,665	839	1,332	6,495
09:00	10.00	9.96	12.50	12.60	10.00		2.00	3.32	2.50	1.26	2.00		1,353	2,248	1,692	853	1,353	7,499
10:00	10.00	8.46	12.50	12.60	10.00		2.00	2.82	2.50	1.26	2.00		1,353	1,908	1,692	853	1,353	7,159
11:00	10.00	2.87	12.50	12.60	10.00		2.00	0.96	2.50	1.26	2.00		1,339	639	1,674	843	1,339	5,834
12:00	10.00	7.83	12.50	12.60	10.00		2.00	2.61	2.50	1.26	2.00		1,322	1,725	1,652	833	1,322	6,853
13:00	10.00	9.79	12.50	12.60	10.00		2.00	3.26	2.50	1.26	2.00		1,295	2,113	1,618	816	1,295	7,137
14:00	10.00	1.67	12.13	12.60	9.30		2.00	0.56	2.43	1.26	1.86		1,258	350	1,526	793	1,170	5,097
15:00	10.00	9.33	12.50	12.60	10.00		2.00	3.11	2.50	1.26	2.00		1,276	1,984	1,595	804	1,276	6,935
16:00	9.66	0.00	11.50	12.60	8.50		1.93	0.00	2.30	1.26	1.70		1,256	0	1,494	819	1,104	4,673
17:00	9.79	0.00	11.63	12.60	8.10		1.96	0.00	2.33	1.26	1.62		1,309	0	1,556	843	1,084	4,792
18:00	9.36	0.00	10.63	12.60	7.70		1.87	0.00	2.13	1.26	1.54		1,137	0	1,291	765	935	4,128
19:00	10.00	14.21	12.50	12.60	10.00		2.00	4.74	2.50	1.26	2.00		1,167	2,764	1,459	735	1,167	7,291
20:00	10.00	5.11	12.50	12.60	8.70		2.00	1.70	2.50	1.26	1.74		1,146	977	1,433	722	997	5,276
21:00	10.00	5.74	12.50	12.60	8.30		2.00	1.91	2.50	1.26	1.66		1,164	1,114	1,455	733	966	5,432
22:00	10.00	1.37	12.50	12.60	6.20		2.00	0.46	2.50	1.26	1.24		1,136	259	1,420	716	704	4,235
23:00	8.99	0.00	12.50	12.60	4.00		1.80	0.00	2.50	1.26	0.80		999	0	1,389	700	444	3,532
TOT (MWh)	**231.12**	**87.10**	**294.63**	**302.40**	**176.60**	**1091.85**	**46.22**	**29.03**	**58.93**	**30.24**	**35.32**	**199.74**	**27,539**	**18,270**	**34,998**	**17,976**	**21,641**	**(SEK) 120,424**

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Table 31. Netsim calculated results on the refined model on BC for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	0.00	8.75	9.37	0.0	30.72	1.26	0.00	1.75	1.87	0.00	4.88	668	0	928	993	0	2589
01:00	12.60	0.00	11.00	8.47	0.0	32.07	1.26	0.00	2.20	1.69	0.00	5.15	649	0	1134	873	0	2656
02:00	12.60	0.00	10.00	8.75	0.0	31.35	1.26	0.00	2.00	1.75	0.00	5.01	643	0	1021	893	0	2558
03:00	12.60	0.00	10.13	8.61	0.0	31.34	1.26	0.00	2.03	1.72	0.00	5.01	639	0	1027	874	0	2541
04:00	12.60	0.00	10.38	8.54	0.0	31.52	1.26	0.00	2.08	1.71	0.00	5.04	630	0	1038	855	0	2523
05:00	12.60	0.50	10.75	9.04	0.0	32.89	1.26	0.10	2.15	1.81	0.00	5.32	650	52	1109	932	0	2743
06:00	12.60	1.00	12.00	9.10	0.0	34.70	1.26	0.20	2.40	1.82	0.00	5.68	694	110	1322	1003	0	3129
07:00	12.47	8.00	12.50	8.49	0.0	41.46	1.25	1.60	2.50	1.70	0.00	7.05	728	934	1459	991	0	4112
08:00	12.60	10.00	12.50	9.92	2.6	47.67	1.26	2.00	2.50	1.98	0.88	8.63	839	1332	1665	1322	587	5745
09:00	12.60	10.00	12.50	9.94	4.5	49.50	1.26	2.00	2.50	1.99	1.49	9.24	853	1353	1692	1345	1007	6250
10:00	12.60	10.00	12.50	9.95	4.2	49.28	1.26	2.00	2.50	1.99	1.41	9.16	853	1353	1692	1346	954	6198
11:00	12.60	10.00	12.50	9.91	1.9	46.90	1.26	2.00	2.50	1.98	0.63	8.37	843	1339	1674	1327	422	5605
12:00	12.60	10.00	12.50	9.91	3.9	48.92	1.26	2.00	2.50	1.98	1.30	9.04	833	1322	1652	1310	860	5976
13:00	12.60	10.00	12.50	9.92	4.8	49.78	1.26	2.00	2.50	1.98	1.58	9.33	816	1295	1618	1285	1025	6039
14:00	12.60	10.00	12.50	9.96	1.0	46.11	1.26	2.00	2.50	1.99	0.35	8.10	793	1258	1573	1254	219	5097
15:00	12.60	10.00	12.50	9.93	4.5	49.57	1.26	2.00	2.50	1.99	1.51	9.26	804	1276	1595	1268	965	5907
16:00	12.60	9.00	12.50	9.97	0.5	44.57	1.26	1.80	2.50	1.99	0.17	7.72	819	1169	1624	1295	109	5017
17:00	12.60	9.00	12.50	9.93	0.5	44.48	1.26	1.80	2.50	1.99	0.15	7.70	843	1204	1673	1329	100	5150
18:00	12.60	7.50	12.50	9.93	0.9	43.39	1.26	1.50	2.50	1.99	0.29	7.53	765	911	1518	1206	175	4575
19:00	12.60	6.00	12.50	8.99	0.0	40.09	1.26	1.20	2.50	1.80	0.00	6.76	735	700	1459	1048	0	3942
20:00	11.34	4.00	12.50	8.60	0.0	36.44	1.13	0.80	2.50	1.72	0.00	6.15	650	459	1433	985	0	3527
21:00	11.72	4.00	12.50	8.15	0.0	36.37	1.17	0.80	2.50	1.63	0.00	6.10	682	466	1455	949	0	3551
22:00	11.97	1.80	11.63	8.23	0.0	33.63	1.20	0.36	2.33	1.65	0.00	5.53	680	204	1321	935	0	3140
23:00	12.35	0.00	11.13	8.13	0.0	31.60	1.23	0.00	2.23	1.63	0.00	5.09	686	0	1236	903	0	2825
TOT (MWh)	**299.25**	**130.80**	**283.25**	**221.75**	**29.29**	**964.34**	**29.93**	**26.16**	**56.65**	**44.35**	**9.76**	**166.85**	**17795**	**16738**	**33917**	**26523**	**6424**	(SEK) **101397**

Table 32. Netsim calculated results on Scenario A (two 3 MW CSs in SBG and Frösunda loop), for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	1.90	12.50	9.84	0.0	36.84	1.26	0.38	2.50	1.97	0.00	6.11	668	201	1325	1043	0	3237
01:00	12.60	2.20	12.50	9.91	0.0	37.21	1.26	0.44	2.50	1.98	0.00	6.18	649	227	1289	1022	0	3187
02:00	12.60	2.10	12.50	9.92	0.0	37.12	1.26	0.42	2.50	1.98	0.00	6.16	643	214	1277	1013	0	3147
03:00	12.60	2.10	12.50	9.92	0.0	37.12	1.26	0.42	2.50	1.98	0.00	6.16	639	213	1269	1006	0	3127
04:00	12.60	2.10	12.50	9.74	0.0	36.94	1.26	0.42	2.50	1.95	0.00	6.13	630	210	1251	974	0	3066
05:00	12.60	2.40	12.50	9.78	0.0	37.28	1.26	0.48	2.50	1.96	0.00	6.20	650	248	1290	1009	0	3196
06:00	12.60	2.90	12.50	9.44	0.0	37.44	1.26	0.58	2.50	1.89	0.00	6.23	694	319	1377	1040	0	3431
07:00	12.60	6.00	12.50	9.47	0.0	40.57	1.26	1.20	2.50	1.89	0.00	6.85	735	700	1459	1106	0	4001
08:00	12.60	10.00	12.50	9.46	0.0	44.56	1.26	2.00	2.50	1.89	0.00	7.65	839	1332	1665	1260	0	5096
09:00	12.60	9.90	12.50	9.75	0.0	44.75	1.26	1.98	2.50	1.95	0.00	7.69	853	1340	1692	1320	0	5205
10:00	12.60	9.60	12.50	9.69	0.0	44.39	1.26	1.92	2.50	1.94	0.00	7.62	853	1299	1692	1311	0	5155
11:00	12.60	7.20	12.50	9.62	0.0	41.92	1.26	1.44	2.50	1.92	0.00	7.12	843	964	1674	1288	0	4769
12:00	12.60	8.60	12.50	9.71	0.0	43.41	1.26	1.72	2.50	1.94	0.00	7.42	833	1137	1652	1284	0	4905
13:00	12.60	9.00	12.50	9.45	0.0	43.55	1.26	1.80	2.50	1.89	0.00	7.45	816	1165	1618	1224	0	4823
14:00	12.60	8.40	12.50	9.89	0.0	43.39	1.26	1.68	2.50	1.98	0.00	7.42	793	1057	1573	1245	0	4667
15:00	12.60	9.80	12.50	9.84	0.0	44.74	1.26	1.96	2.50	1.97	0.00	7.69	804	1250	1595	1256	0	4905
16:00	12.60	6.90	12.50	9.46	0.0	41.46	1.26	1.38	2.50	1.89	0.00	7.03	819	897	1624	1229	0	4568
17:00	12.60	7.20	12.50	9.65	0.0	41.95	1.26	1.44	2.50	1.93	0.00	7.13	843	964	1673	1291	0	4770
18:00	12.60	6.60	12.50	9.85	0.0	41.55	1.26	1.32	2.50	1.97	0.00	7.05	765	802	1518	1196	0	4281
19:00	12.60	4.60	12.50	9.78	0.0	39.48	1.26	0.92	2.50	1.96	0.00	6.64	735	537	1459	1142	0	3872
20:00	12.60	3.30	12.50	9.44	0.0	37.84	1.26	0.66	2.50	1.89	0.00	6.31	722	378	1433	1082	0	3616
21:00	12.60	3.30	12.50	9.53	0.0	37.93	1.26	0.66	2.50	1.91	0.00	6.33	733	384	1455	1110	0	3682
22:00	12.60	2.60	12.50	9.54	0.0	37.24	1.26	0.52	2.50	1.91	0.00	6.19	716	295	1420	1084	0	3515
23:00	12.60	2.10	12.50	9.55	0.0	36.75	1.26	0.42	2.50	1.91	0.00	6.09	700	233	1389	1061	0	3383
TOT (MWh)	**302.40**	**130.80**	**300.00**	**232.23**	**0.00**	**965.43**	**30.24**	**26.16**	**60.00**	**46.45**	**0.00**	**162.85**	**17976**	**16368**	**35666**	**27594**	**0**	**(SEK) 97604**

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Table 33. Netsim calculated results on Scenario B (two 4 MW CSs in SBG and Frösunda loop), for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	3.50	12.50	9.78	0.0	38.4	1.26	0.70	2.50	1.96	0.00	6.42	668	371	1325	1037	0	3401
01:00	12.60	3.70	12.50	9.79	0.0	38.6	1.26	0.74	2.50	1.96	0.00	6.46	649	381	1289	1010	0	3329
02:00	12.60	3.60	12.50	9.89	0.0	38.6	1.26	0.72	2.50	1.98	0.00	6.46	643	368	1277	1010	0	3298
03:00	12.60	3.60	12.50	9.89	0.0	38.6	1.26	0.72	2.50	1.98	0.00	6.46	639	365	1269	1003	0	3276
04:00	12.60	3.60	12.50	9.69	0.0	38.4	1.26	0.72	2.50	1.94	0.00	6.42	630	360	1251	970	0	3211
05:00	12.60	3.80	12.50	9.66	0.0	38.6	1.26	0.76	2.50	1.93	0.00	6.45	650	392	1290	997	0	3329
06:00	12.60	4.00	12.50	9.40	0.0	38.5	1.26	0.80	2.50	1.88	0.00	6.44	694	441	1377	1035	0	3547
07:00	12.60	6.20	12.50	9.28	0.0	40.6	1.26	1.24	2.50	1.86	0.00	6.86	735	724	1459	1084	0	4003
08:00	12.60	10.00	12.50	9.46	0.0	44.6	1.26	2.00	2.50	1.89	0.00	7.65	839	1332	1665	1260	0	5096
09:00	12.60	7.30	12.50	9.76	0.0	42.2	1.26	1.46	2.50	1.95	0.00	7.17	853	988	1692	1321	0	4853
10:00	12.60	9.60	12.50	9.69	0.0	44.4	1.26	1.92	2.50	1.94	0.00	7.62	853	1299	1692	1312	0	5155
11:00	12.60	6.30	12.50	9.53	0.0	40.9	1.26	1.26	2.50	1.91	0.00	6.93	843	843	1674	1275	0	4636
12:00	12.60	6.70	12.50	9.62	0.0	41.4	1.26	1.34	2.50	1.92	0.00	7.02	833	885	1652	1271	0	4641
13:00	12.60	7.10	12.50	9.35	0.0	41.5	1.26	1.42	2.50	1.87	0.00	7.05	816	919	1618	1211	0	4564
14:00	12.60	7.40	12.50	9.89	0.0	42.4	1.26	1.48	2.50	1.98	0.00	7.22	793	931	1573	1245	0	4541
15:00	12.60	8.90	12.50	9.75	0.0	43.7	1.26	1.78	2.50	1.95	0.00	7.49	804	1136	1595	1244	0	4778
16:00	12.60	4.90	12.50	9.46	0.0	39.5	1.26	0.98	2.50	1.89	0.00	6.63	819	637	1624	1229	0	4308
17:00	12.60	5.80	12.50	9.65	0.0	40.6	1.26	1.16	2.50	1.93	0.00	6.85	843	776	1673	1291	0	4583
18:00	12.60	5.70	12.50	9.75	0.0	40.6	1.26	1.14	2.50	1.95	0.00	6.85	765	692	1518	1184	0	4160
19:00	12.60	4.70	12.50	9.70	0.0	39.5	1.26	0.94	2.50	1.94	0.00	6.64	735	548	1459	1132	0	3874
20:00	12.60	4.30	12.50	9.28	0.0	38.7	1.26	0.86	2.50	1.86	0.00	6.48	722	493	1433	1064	0	3713
21:00	12.60	4.30	12.50	9.39	0.0	38.8	1.26	0.86	2.50	1.88	0.00	6.50	733	500	1455	1093	0	3781
22:00	12.60	3.90	12.50	9.44	0.0	38.4	1.26	0.78	2.50	1.89	0.00	6.43	716	443	1420	1072	0	3651
23:00	12.60	3.60	12.50	9.48	0.0	38.2	1.26	0.72	2.50	1.90	0.00	6.38	700	400	1389	1053	0	3542
TOT (MWh)	302.40	132.50	300.00	230.57	0.00	965.47	30.24	26.50	60.00	46.11	0.00	162.85	17976	16227	35666	27401	0	(SEK) 97270

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Table 34. Netsim calculated results on Scenario C (two 5 MW CSs in SBG and Frösunda loop), for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	5.20	12.50	9.82	0.0	40.1	1.26	1.04	2.50	1.96	0.00	6.76	668	551	1325	1041	0	3585
01:00	12.60	5.30	12.50	9.77	0.0	40.2	1.26	1.06	2.50	1.95	0.00	6.77	649	546	1289	1007	0	3492
02:00	12.60	5.30	12.50	9.85	0.0	40.2	1.26	1.06	2.50	1.97	0.00	6.79	643	541	1277	1006	0	3467
03:00	12.60	5.30	12.50	9.85	0.0	40.2	1.26	1.06	2.50	1.97	0.00	6.79	639	538	1269	999	0	3445
04:00	12.60	5.30	12.50	9.64	0.0	40.0	1.26	1.06	2.50	1.93	0.00	6.75	630	530	1251	964	0	3376
05:00	12.60	5.30	12.50	9.65	0.0	40.1	1.26	1.06	2.50	1.93	0.00	6.75	650	547	1290	996	0	3482
06:00	12.60	5.30	12.50	9.38	0.0	39.8	1.26	1.06	2.50	1.88	0.00	6.70	694	584	1377	1033	0	3688
07:00	12.60	5.40	12.50	9.34	0.0	39.8	1.26	1.08	2.50	1.87	0.00	6.71	735	630	1459	1090	0	3915
08:00	12.60	9.00	12.50	9.46	0.0	43.6	1.26	1.80	2.50	1.89	0.00	7.45	839	1199	1665	1260	0	4963
09:00	12.60	8.90	12.50	9.76	0.0	43.8	1.26	1.78	2.50	1.95	0.00	7.49	853	1205	1692	1321	0	5070
10:00	12.60	6.60	12.50	9.69	0.0	41.4	1.26	1.32	2.50	1.94	0.00	7.02	853	893	1692	1312	0	4749
11:00	12.60	3.30	12.50	9.53	0.0	37.9	1.26	0.66	2.50	1.91	0.00	6.33	843	442	1674	1275	0	4234
12:00	12.60	4.30	12.50	9.62	0.0	39.0	1.26	0.86	2.50	1.92	0.00	6.54	833	568	1652	1271	0	4324
13:00	12.60	5.10	12.50	9.35	0.0	39.6	1.26	1.02	2.50	1.87	0.00	6.65	816	660	1618	1211	0	4305
14:00	12.60	2.40	12.50	9.89	0.0	37.4	1.26	0.48	2.50	1.98	0.00	6.22	793	302	1573	1245	0	3912
15:00	12.60	6.90	12.50	9.75	0.0	41.7	1.26	1.38	2.50	1.95	0.00	7.09	804	880	1595	1244	0	4523
16:00	12.60	3.90	12.50	9.46	0.0	38.5	1.26	0.78	2.50	1.89	0.00	6.43	819	507	1624	1229	0	4178
17:00	12.60	5.80	12.50	9.65	0.0	40.6	1.26	1.16	2.50	1.93	0.00	6.85	843	776	1673	1291	0	4583
18:00	12.60	7.30	12.50	9.74	0.0	42.1	1.26	1.46	2.50	1.95	0.00	7.17	765	887	1518	1183	0	4353
19:00	12.60	5.40	12.50	9.70	0.0	40.2	1.26	1.08	2.50	1.94	0.00	6.78	735	630	1459	1132	0	3955
20:00	12.60	5.30	12.50	9.42	0.0	39.8	1.26	1.06	2.50	1.88	0.00	6.70	722	608	1433	1080	0	3843
21:00	12.60	5.30	12.50	9.50	0.0	39.9	1.26	1.06	2.50	1.90	0.00	6.72	733	617	1455	1105	0	3910
22:00	12.60	5.30	12.50	9.44	0.0	39.8	1.26	1.06	2.50	1.89	0.00	6.71	716	602	1420	1073	0	3810
23:00	12.60	5.30	12.50	9.42	0.0	39.8	1.26	1.06	2.50	1.88	0.00	6.70	700	589	1389	1047	0	3724
TOT (MWh)	**302.40**	**132.50**	**300.00**	**230.66**	**0.00**	**965.56**	**30.24**	**26.50**	**60.00**	**46.13**	**0.00**	**162.87**	**17976**	**15833**	**35666**	**27414**	**0**	**(SEK) 96889**

Table 35. Netsim calculated results on Scenario D (two 6 MW CSs in SBG and Frösunda loop), for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	6.90	12.50	9.73	0.0	41.7	1.26	1.38	2.50	1.95	0.00	7.09	668	731	1325	1032	0	3756
01:00	12.60	6.80	12.50	9.77	0.0	41.7	1.26	1.36	2.50	1.95	0.00	7.07	649	701	1289	1007	0	3646
02:00	12.60	6.80	12.50	9.91	0.0	41.8	1.26	1.36	2.50	1.98	0.00	7.10	643	695	1277	1013	0	3627
03:00	12.60	6.80	12.50	9.90	0.0	41.8	1.26	1.36	2.50	1.98	0.00	7.10	639	690	1269	1005	0	3603
04:00	12.60	6.80	12.50	9.69	0.0	41.6	1.26	1.36	2.50	1.94	0.00	7.06	630	680	1251	970	0	3531
05:00	12.60	6.90	12.50	9.48	0.0	41.5	1.26	1.38	2.50	1.90	0.00	7.04	650	712	1290	978	0	3630
06:00	12.60	6.60	12.50	9.33	0.0	41.0	1.26	1.32	2.50	1.87	0.00	6.95	694	727	1377	1027	0	3825
07:00	12.60	5.30	12.50	9.29	0.0	39.7	1.26	1.06	2.50	1.86	0.00	6.68	735	619	1459	1084	0	3898
08:00	12.60	7.00	12.50	9.46	0.0	41.6	1.26	1.40	2.50	1.89	0.00	7.05	839	932	1665	1260	0	4696
09:00	12.60	6.90	12.50	9.75	0.0	41.8	1.26	1.38	2.50	1.95	0.00	7.09	853	934	1692	1320	0	4799
10:00	12.60	5.60	12.50	9.69	0.0	40.4	1.26	1.12	2.50	1.94	0.00	6.82	853	758	1692	1312	0	4614
11:00	12.60	2.30	12.50	9.52	0.0	36.9	1.26	0.46	2.50	1.90	0.00	6.12	843	308	1674	1274	0	4099
12:00	12.60	2.30	12.50	9.62	0.0	37.0	1.26	0.46	2.50	1.92	0.00	6.14	833	304	1652	1271	0	4059
13:00	12.60	3.10	12.50	9.35	0.0	37.5	1.26	0.62	2.50	1.87	0.00	6.25	816	401	1618	1211	0	4046
14:00	12.60	1.40	12.50	9.88	0.0	36.4	1.26	0.28	2.50	1.98	0.00	6.02	793	176	1573	1244	0	3785
15:00	12.60	5.90	12.50	9.75	0.0	40.7	1.26	1.18	2.50	1.95	0.00	6.89	804	753	1595	1244	0	4395
16:00	12.60	1.90	12.50	9.45	0.0	36.5	1.26	0.38	2.50	1.89	0.00	6.03	819	247	1624	1228	0	3918
17:00	12.60	3.80	12.50	9.65	0.0	38.6	1.26	0.76	2.50	1.93	0.00	6.45	843	509	1673	1291	0	4316
18:00	12.60	7.20	12.50	9.69	0.0	42.0	1.26	1.44	2.50	1.94	0.00	7.14	765	875	1518	1177	0	4335
19:00	12.60	6.20	12.50	9.61	0.0	40.9	1.26	1.24	2.50	1.92	0.00	6.92	735	723	1459	1121	0	4038
20:00	12.60	6.40	12.50	9.40	0.0	40.9	1.26	1.28	2.50	1.88	0.00	6.92	722	734	1433	1077	0	3966
21:00	12.60	6.40	12.50	9.49	0.0	41.0	1.26	1.28	2.50	1.90	0.00	6.94	733	745	1455	1104	0	4037
22:00	12.60	6.60	12.50	9.49	0.0	41.2	1.26	1.32	2.50	1.90	0.00	6.98	716	750	1420	1078	0	3964
23:00	12.60	6.80	12.50	9.45	0.0	41.4	1.26	1.36	2.50	1.89	0.00	7.01	700	755	1389	1050	0	3894
TOT (MWh)	**302.40**	**132.70**	**300.00**	**230.36**	**0.00**	**965.46**	**30.24**	**26.54**	**60.00**	**46.07**	**0.00**	**162.85**	**17976**	**15459**	**35666**	**27379**	**0**	**(SEK) 96480**

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Table 36. Netsim calculated results on Scenario E (two 7 MW CSs in SBG and Frösunda loop), for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	8.10	12.50	9.91	0.0	43.1	1.26	1.62	2.50	1.98	0.00	7.36	668	859	1325	1050	0	3902
01:00	12.60	7.90	12.50	9.93	0.0	42.9	1.26	1.58	2.50	1.99	0.00	7.33	649	814	1289	1024	0	3776
02:00	12.60	8.10	12.50	9.92	0.0	43.1	1.26	1.62	2.50	1.98	0.00	7.36	643	827	1277	1013	0	3761
03:00	12.60	8.10	12.50	9.92	0.0	43.1	1.26	1.62	2.50	1.98	0.00	7.36	639	822	1269	1007	0	3737
04:00	12.60	8.00	12.50	9.80	0.0	42.9	1.26	1.60	2.50	1.96	0.00	7.32	630	800	1251	980	0	3662
05:00	12.60	7.80	12.50	9.79	0.0	42.7	1.26	1.56	2.50	1.96	0.00	7.28	650	805	1290	1010	0	3755
06:00	12.60	7.60	12.50	9.41	0.0	42.1	1.26	1.52	2.50	1.88	0.00	7.16	694	837	1377	1037	0	3945
07:00	12.60	5.20	12.50	9.41	0.0	39.7	1.26	1.04	2.50	1.88	0.00	6.68	735	607	1459	1098	0	3900
08:00	12.60	9.40	12.25	7.30	0.0	41.5	1.26	1.88	2.45	1.46	0.00	7.05	839	1252	1632	972	0	4695
09:00	12.60	6.80	12.50	9.85	0.0	41.7	1.26	1.36	2.50	1.97	0.00	7.09	853	920	1692	1333	0	4798
10:00	12.60	3.50	12.50	9.79	0.0	38.4	1.26	0.70	2.50	1.96	0.00	6.42	853	474	1692	1324	0	4343
11:00	12.60	0.00	12.50	8.82	0.0	33.9	1.26	0.00	2.50	1.76	0.00	5.52	843	0	1674	1181	0	3698
12:00	12.60	0.20	12.50	9.72	0.0	35.0	1.26	0.04	2.50	1.94	0.00	5.74	833	26	1652	1284	0	3795
13:00	12.60	1.00	12.50	9.45	0.0	35.6	1.26	0.20	2.50	1.89	0.00	5.85	816	129	1618	1224	0	3787
14:00	12.60	0.00	12.25	8.54	0.0	33.4	1.26	0.00	2.45	1.71	0.00	5.42	793	0	1541	1074	0	3408
15:00	12.60	3.80	12.50	9.84	0.0	38.7	1.26	0.76	2.50	1.97	0.00	6.49	804	485	1595	1255	0	4139
16:00	12.60	1.80	12.50	9.55	0.0	36.4	1.26	0.36	2.50	1.91	0.00	6.03	819	234	1624	1241	0	3917
17:00	12.60	3.70	12.50	9.74	0.0	38.5	1.26	0.74	2.50	1.95	0.00	6.45	843	495	1673	1304	0	4315
18:00	12.60	7.10	12.50	9.81	0.0	42.0	1.26	1.42	2.50	1.96	0.00	7.14	765	862	1518	1192	0	4338
19:00	12.60	6.80	12.50	9.75	0.0	41.6	1.26	1.36	2.50	1.95	0.00	7.07	735	793	1459	1137	0	4124
20:00	12.60	7.30	12.50	9.47	0.0	41.9	1.26	1.46	2.50	1.89	0.00	7.11	722	837	1433	1086	0	4078
21:00	12.60	7.30	12.50	9.57	0.0	42.0	1.26	1.46	2.50	1.91	0.00	7.13	733	850	1455	1114	0	4152
22:00	12.60	7.70	12.50	9.55	0.0	42.3	1.26	1.54	2.50	1.91	0.00	7.21	716	875	1420	1085	0	4095
23:00	12.60	8.00	12.50	9.56	0.0	42.7	1.26	1.60	2.50	1.91	0.00	7.27	700	889	1389	1062	0	4040
TOT (MWh)	**302.40**	**135.20**	**299.50**	**228.40**	**0.00**	**965.50**	**30.24**	**27.04**	**59.90**	**45.68**	**0.00**	**162.86**	**17976**	**15494**	**35602**	**27089**	**0**	**(SEK) 96160**

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Table 37. Netsim calculated results on Scenario F (two 7.5 MW CSs in SBG and Frösunda loop), for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	9.00	12.50	9.86	0.0	44.0	1.26	1.80	2.50	1.97	0.00	7.53	668	954	1325	1045	0	3992
01:00	12.60	8.70	12.50	9.93	0.0	43.7	1.26	1.74	2.50	1.99	0.00	7.49	649	897	1289	1024	0	3859
02:00	12.60	8.90	12.50	9.95	0.0	44.0	1.26	1.78	2.50	1.99	0.00	7.53	643	909	1277	1017	0	3846
03:00	12.60	8.90	12.50	9.95	0.0	44.0	1.26	1.78	2.50	1.99	0.00	7.53	639	903	1269	1010	0	3821
04:00	12.60	8.80	12.50	9.83	0.0	43.7	1.26	1.76	2.50	1.97	0.00	7.49	630	881	1251	984	0	3746
05:00	12.60	8.60	12.50	9.77	0.0	43.5	1.26	1.72	2.50	1.95	0.00	7.43	650	887	1290	1007	0	3834
06:00	12.60	8.30	12.50	9.42	0.0	42.8	1.26	1.66	2.50	1.88	0.00	7.30	694	914	1377	1038	0	4023
07:00	12.60	7.00	12.50	9.61	0.0	41.7	1.26	1.40	2.50	1.92	0.00	7.08	735	817	1459	1122	0	4134
08:00	12.60	6.90	12.50	9.39	0.0	41.4	1.26	1.38	2.50	1.88	0.00	7.02	839	919	1665	1250	0	4673
09:00	12.60	6.80	12.50	9.85	0.0	41.8	1.26	1.36	2.50	1.97	0.00	7.09	853	920	1692	1334	0	4799
10:00	12.60	4.50	12.50	9.79	0.0	39.4	1.26	0.90	2.50	1.96	0.00	6.62	853	609	1692	1325	0	4479
11:00	12.60	0.20	12.50	9.63	0.0	34.9	1.26	0.04	2.50	1.93	0.00	5.73	843	27	1674	1289	0	3833
12:00	12.60	0.00	12.50	9.22	0.0	34.3	1.26	0.00	2.50	1.84	0.00	5.60	833	0	1652	1218	0	3703
13:00	12.60	0.00	12.50	9.45	0.0	34.6	1.26	0.00	2.50	1.89	0.00	5.65	816	0	1618	1224	0	3658
14:00	12.60	0.00	10.00	9.10	0.0	31.7	1.26	0.00	2.00	1.82	0.00	5.08	793	0	1258	1144	0	3195
15:00	12.60	2.80	12.50	9.85	0.0	37.7	1.26	0.56	2.50	1.97	0.00	6.29	804	357	1595	1256	0	4013
16:00	12.60	0.00	12.50	9.35	0.0	34.5	1.26	0.00	2.50	1.87	0.00	5.63	819	0	1624	1215	0	3658
17:00	12.60	1.70	12.50	9.74	0.0	36.5	1.26	0.34	2.50	1.95	0.00	6.05	843	227	1673	1303	0	4047
18:00	12.60	2.60	12.50	9.85	0.0	37.6	1.26	0.52	2.50	1.97	0.00	6.25	765	316	1518	1197	0	3796
19:00	12.60	7.30	12.50	10.00	0.1	42.5	1.26	1.46	2.50	2.00	0.02	7.24	735	852	1459	1167	14	4226
20:00	12.60	7.90	12.50	9.53	0.0	42.5	1.26	1.58	2.50	1.91	0.00	7.25	722	906	1433	1092	0	4153
21:00	12.60	8.00	12.50	9.51	0.0	42.6	1.26	1.60	2.50	1.90	0.00	7.26	733	931	1455	1107	0	4227
22:00	12.60	8.50	12.50	9.50	0.0	43.1	1.26	1.70	2.50	1.90	0.00	7.36	716	966	1420	1079	0	4181
23:00	12.60	8.80	12.50	9.59	0.0	43.5	1.26	1.76	2.50	1.92	0.00	7.44	700	978	1389	1065	0	4132
TOT (MWh)	**302.40**	**134.20**	**297.50**	**231.68**	**0.07**	**965.85**	**30.24**	**26.84**	**59.50**	**46.34**	**0.02**	**162.94**	**17976**	**15170**	**35352**	**27514**	**14**	**(SEK) 96026**

Table 38. The calculation steps and results on BC and scenarios A-F (100% demand case) of KPI,5, KPI,6 and KPI,7, based on Netsim analyses.

Time period	**Parameter /KPI**	**BC**	ScA	ScB	ScC	ScD	ScE	**SC.F**	Unit
13:00	peak el use (MWEl)	**9.33**	7.45	7.05	6.65	6.25	5.85	**5.65**	MW,El/hr,peak
07:00-19:00	total peak el used per day (MWh,El/day)	107.88	94.76	91.98	88.72	85.60	82.95	81.33	MWh,El/day
07:00-19:00	total peak cold produced per day (MWh/day)	**601.72**	555.72	541.78	525.52	509.91	496.65	**488.50**	MWh,cold/day
13:00	**KPI,5 The avoided peak electricity (MW) use at the maximum peak load hour (MW,electricity/peak hour)**	**-**	**1.88**	**2.28**	**2.68**	**3.08**	**3.48**	**3.68**	**MW,El/hr,peak**
07:00-19:00	**KPI,6 The avoided peak electricity use per day (MWh,electricity/day)**	**-**	**13.12**	**15.91**	**19.16**	**22.28**	**24.93**	**26.55**	**MWh,El/day**
07:00-19:00	**KPI,7 The avoided peak cooling production per day (MWh,cold/day)**	**-**	**46.00**	**59.95**	**76.20**	**91.82**	**105.07**	**113.23**	**MWh,cold/day**
13:00	The avoided peak electricity (MW) use at the maximum peak load hour (Sc comp. to BC) %		20%	24%	29%	33%	37%	39%	%
07:00-19:00	The avoided peak electricity use per day (Sc comp. to BC) %		12%	15%	18%	21%	23%	25%	%
07:00-19:00	The avoided peak cooling production per day (Sc comp. to BC) %		8%	10%	13%	15%	17%	19%	%

Table 39. Netsim calculated results on 110% demand case- BC, for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	0.00	8.75	9.90	1.62	32.9	1.26	0.00	1.75	1.98	0.54	5.53	668	0	928	1050	286	2931
01:00	12.60	0.00	11.00	9.95	0.99	34.5	1.26	0.00	2.20	1.99	0.33	5.78	649	0	1134	1025	170	2979
02:00	12.60	0.00	10.00	9.96	1.13	33.7	1.26	0.00	2.00	1.99	0.38	5.63	643	0	1021	1018	193	2876
03:00	12.60	0.00	10.13	9.94	1.03	33.7	1.26	0.00	2.03	1.99	0.34	5.61	639	0	1027	1008	174	2849
04:00	12.60	0.00	10.38	9.91	0.90	33.8	1.26	0.00	2.08	1.98	0.30	5.62	630	0	1038	992	150	2810
05:00	12.60	0.50	10.75	9.96	1.66	35.5	1.26	0.10	2.15	1.99	0.55	6.05	650	52	1109	1028	285	3123
06:00	12.60	1.00	12.00	9.93	2.11	37.6	1.26	0.20	2.40	1.99	0.70	6.55	694	110	1322	1094	387	3607
07:00	12.47	8.00	12.50	9.90	2.84	45.7	1.25	1.60	2.50	1.98	0.95	8.27	728	934	1459	1156	553	4830
08:00	12.60	10.00	12.50	9.91	8.15	53.2	1.26	2.00	2.50	1.98	2.72	10.46	839	1332	1665	1320	1810	6966
09:00	12.60	10.00	12.50	9.94	10.33	55.4	1.26	2.00	2.50	1.99	3.44	11.19	853	1353	1692	1346	2331	7574
10:00	12.60	10.00	12.50	9.94	10.04	55.1	1.26	2.00	2.50	1.99	3.35	11.10	853	1353	1692	1345	2266	7508
11:00	12.60	10.00	12.50	9.97	7.24	52.3	1.26	2.00	2.50	1.99	2.41	10.17	843	1339	1674	1335	1615	6805
12:00	12.60	10.00	12.50	9.91	9.65	54.7	1.26	2.00	2.50	1.98	3.22	10.96	833	1322	1652	1309	2125	7240
13:00	12.60	10.00	12.50	9.89	10.66	55.6	1.26	2.00	2.50	1.98	3.55	11.29	816	1295	1618	1281	2299	7309
14:00	12.60	10.00	12.50	9.96	6.25	51.3	1.26	2.00	2.50	1.99	2.08	9.83	793	1258	1573	1254	1310	6188
15:00	12.60	10.00	12.50	9.94	10.40	55.4	1.26	2.00	2.50	1.99	3.47	11.22	804	1276	1595	1268	2213	7156
16:00	12.60	10.00	12.50	9.96	4.39	49.4	1.26	2.00	2.50	1.99	1.46	9.22	819	1299	1624	1294	951	5987
17:00	12.60	10.00	12.50	9.93	4.32	49.4	1.26	2.00	2.50	1.99	1.44	9.19	843	1338	1673	1329	964	6147
18:00	12.60	10.00	12.50	9.94	3.02	48.1	1.26	2.00	2.50	1.99	1.01	8.76	765	1215	1518	1207	612	5317
19:00	12.60	8.00	12.50	9.96	0.95	44.0	1.26	1.60	2.50	1.99	0.32	7.67	735	933	1459	1163	186	4475
20:00	10.08	8.00	10.00	9.94	1.69	39.7	1.01	1.60	2.00	1.99	0.56	7.16	578	917	1146	1139	323	4104
21:00	11.72	4.00	12.50	9.93	1.48	39.6	1.17	0.80	2.50	1.99	0.49	6.95	682	466	1455	1156	286	4044
22:00	11.97	1.80	11.63	9.91	1.04	36.3	1.20	0.36	2.33	1.98	0.35	6.21	680	204	1321	1125	198	3528
23:00	12.35	0.00	11.13	9.92	0.54	33.9	1.23	0.00	2.23	1.98	0.18	5.62	686	0	1236	1102	100	3124
TOT (MWh)	**297.99**	**141.30**	**280.75**	**238.39**	**102.44**	**1060.87**	**29.80**	**28.26**	**56.15**	**47.68**	**34.15**	**196.03**	**17723**	**17997**	**33631**	**28342**	**21786**	**(SEK) 119478**

Table 40. Netsim calculated results on 110% demand case- Scenario F (two 7.5 MW CSs in SBG and Frösunda loop), for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	10.00	12.50	10.00	1.16	46.26	1.26	2.00	2.50	2.00	0.39	8.15	668	1060	1325	1060	205	4318
01:00	12.60	10.00	12.50	10.00	1.03	46.13	1.26	2.00	2.50	2.00	0.34	8.10	649	1031	1289	1031	176	4176
02:00	12.60	10.00	12.50	10.00	1.14	46.24	1.26	2.00	2.50	2.00	0.38	8.14	643	1021	1277	1021	194	4157
03:00	12.60	10.00	12.50	10.00	1.14	46.24	1.26	2.00	2.50	2.00	0.38	8.14	639	1015	1269	1015	193	4130
04:00	12.60	10.00	12.50	10.00	1.10	46.20	1.26	2.00	2.50	2.00	0.37	8.13	630	1001	1251	1001	184	4066
05:00	12.60	10.00	12.50	10.00	1.00	46.10	1.26	2.00	2.50	2.00	0.33	8.09	650	1032	1290	1032	173	4176
06:00	12.60	10.00	12.50	10.00	0.75	45.85	1.26	2.00	2.50	2.00	0.25	8.01	694	1102	1377	1102	138	4412
07:00	12.60	9.90	12.50	9.38	0.00	44.38	1.26	1.98	2.50	1.88	0.00	7.62	735	1156	1459	1095	0	4446
08:00	12.60	8.50	12.50	9.62	0.00	43.22	1.26	1.70	2.50	1.92	0.00	7.38	839	1132	1665	1281	0	4918
09:00	12.60	8.70	12.50	9.56	0.00	43.36	1.26	1.74	2.50	1.91	0.00	7.41	853	1178	1692	1294	0	5016
10:00	12.60	8.40	12.50	9.63	0.00	43.13	1.26	1.68	2.50	1.93	0.00	7.37	853	1137	1692	1303	0	4985
11:00	12.60	4.60	12.50	9.62	0.00	39.32	1.26	0.92	2.50	1.92	0.00	6.60	843	616	1674	1288	0	4421
12:00	12.60	9.00	12.50	9.58	0.00	43.68	1.26	1.80	2.50	1.92	0.00	7.48	833	1189	1652	1266	0	4939
13:00	12.60	6.30	12.25	9.54	0.00	40.69	1.26	1.26	2.45	1.91	0.00	6.88	816	816	1586	1235	0	4452
14:00	12.60	6.60	12.50	9.62	0.00	41.32	1.26	1.32	2.50	1.92	0.00	7.00	793	830	1573	1210	0	4406
15:00	12.60	8.80	12.50	9.58	0.00	43.48	1.26	1.76	2.50	1.92	0.00	7.44	804	1123	1595	1223	0	4745
16:00	12.60	6.80	12.50	9.48	0.00	41.38	1.26	1.36	2.50	1.90	0.00	7.02	819	884	1624	1232	0	4558
17:00	12.60	7.70	12.50	9.54	0.00	42.34	1.26	1.54	2.50	1.91	0.00	7.21	843	1030	1673	1277	0	4824
18:00	12.60	8.20	12.50	9.51	0.00	42.81	1.26	1.64	2.50	1.90	0.00	7.30	765	996	1518	1155	0	4435
19:00	12.60	10.00	12.50	10.00	0.16	45.26	1.26	2.00	2.50	2.00	0.05	7.81	735	1167	1459	1167	32	4559
20:00	12.60	10.00	12.50	10.00	0.56	45.66	1.26	2.00	2.50	2.00	0.19	7.95	722	1146	1433	1146	106	4555
21:00	12.60	10.00	12.50	10.00	0.55	45.65	1.26	2.00	2.50	2.00	0.18	7.94	733	1164	1455	1164	106	4622
22:00	12.60	10.00	12.50	10.00	0.82	45.92	1.26	2.00	2.50	2.00	0.27	8.03	716	1136	1420	1136	155	4563
23:00	12.60	10.00	12.50	10.00	1.11	46.21	1.26	2.00	2.50	2.00	0.37	8.13	700	1111	1389	1111	206	4516
TOT (MWh)	**302.40**	**213.50**	**299.75**	**234.67**	**10.52**	**1060.84**	**30.24**	**42.70**	**59.95**	**46.93**	**3.51**	**183.33**	**17976**	**25072**	**35634**	**27845**	**1868**	**(SEK) 108395**

Table 41. Netsim calculated results on 110% demand case-A new 6 MW chiller at Sundbyberg (nCC SBG), for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant						Sum	Electricity use by MW (per hour) by each plant to produce cold						Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total						
Time	FröFC	FröCC	SBG	nCC SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	nCC SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	nCC SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	0.00	11.25	0.00	8.99	0.00	32.84	1.26	0.00	2.25	0.00	1.80	0.00	5.31	668	0	1193	0	953	0	2814
01:00	12.60	0.00	12.50	0.00	9.44	0.00	34.54	1.26	0.00	2.50	0.00	1.89	0.00	5.65	649	0	1289	0	973	0	2911
02:00	12.60	0.00	12.50	0.00	8.60	0.00	33.70	1.26	0.00	2.50	0.00	1.72	0.00	5.48	643	0	1277	0	878	0	2798
03:00	12.60	0.00	12.50	0.00	8.59	0.00	33.69	1.26	0.00	2.50	0.00	1.72	0.00	5.48	639	0	1269	0	871	0	2779
04:00	12.60	0.00	12.50	0.00	8.69	0.00	33.79	1.26	0.00	2.50	0.00	1.74	0.00	5.50	630	0	1251	0	869	0	2750
05:00	12.60	0.50	12.50	0.00	9.87	0.00	35.47	1.26	0.10	2.50	0.00	1.97	0.00	5.83	650	52	1290	0	1018	0	3009
06:00	12.60	0.50	12.50	2.40	9.63	0.00	37.63	1.26	0.10	2.50	0.48	1.93	0.00	6.27	694	55	1377	264	1061	0	3451
07:00	12.60	6.70	12.50	4.20	9.71	0.00	45.71	1.26	1.34	2.50	0.84	1.94	0.00	7.88	735	782	1459	490	1133	0	4601
08:00	12.60	10.00	12.50	6.00	9.88	2.16	53.14	1.26	2.00	2.50	1.20	1.98	0.72	9.66	839	1332	1665	799	1316	480	6431
09:00	12.60	10.00	12.50	6.00	9.96	4.32	55.38	1.26	2.00	2.50	1.20	1.99	1.44	10.39	853	1353	1692	812	1348	975	7032
10:00	12.60	10.00	12.50	6.00	9.93	4.05	55.08	1.26	2.00	2.50	1.20	1.99	1.35	10.30	853	1353	1692	812	1344	914	6968
11:00	12.60	10.00	12.50	6.00	9.95	1.26	52.31	1.26	2.00	2.50	1.20	1.99	0.42	9.37	843	1339	1674	803	1332	281	6272
12:00	12.60	10.00	12.50	6.00	9.92	3.64	54.65	1.26	2.00	2.50	1.20	1.98	1.21	10.16	833	1322	1652	793	1311	801	6710
13:00	12.60	10.00	12.50	6.00	9.88	4.66	55.64	1.26	2.00	2.50	1.20	1.98	1.55	10.49	816	1295	1618	777	1280	1006	6791
14:00	12.60	10.00	12.50	5.82	9.98	0.41	51.31	1.26	2.00	2.50	1.16	2.00	0.14	9.06	793	1258	1573	732	1255	87	5698
15:00	12.60	10.00	12.50	6.00	9.91	4.43	55.44	1.26	2.00	2.50	1.20	1.98	1.48	10.42	804	1276	1595	766	1265	942	6647
16:00	12.60	9.50	12.50	5.10	9.74	0.00	49.44	1.26	1.90	2.50	1.02	1.95	0.00	8.63	819	1234	1624	663	1266	0	5605
17:00	12.60	9.50	12.50	4.80	9.95	0.00	49.35	1.26	1.90	2.50	0.96	1.99	0.00	8.61	843	1271	1673	642	1332	0	5761
18:00	12.60	8.50	12.50	4.68	9.78	0.00	48.06	1.26	1.70	2.50	0.94	1.96	0.00	8.35	765	1032	1518	568	1187	0	5072
19:00	12.60	6.00	12.50	3.60	9.30	0.00	44.00	1.26	1.20	2.50	0.72	1.86	0.00	7.54	735	700	1459	420	1085	0	4399
20:00	12.60	5.00	12.50	0.00	9.61	0.00	39.71	1.26	1.00	2.50	0.00	1.92	0.00	6.68	722	573	1433	0	1101	0	3830
21:00	12.60	3.50	12.50	1.80	9.21	0.00	39.61	1.26	0.70	2.50	0.36	1.84	0.00	6.66	733	407	1455	210	1073	0	3878
22:00	12.60	1.50	12.50	0.00	9.76	0.00	36.36	1.26	0.30	2.50	0.00	1.95	0.00	6.01	716	170	1420	0	1109	0	3415
23:00	12.60	0.00	12.50	0.00	8.84	0.00	33.94	1.26	0.00	2.50	0.00	1.77	0.00	5.53	700	0	1389	0	982	0	3070
TOT (MWh)	**302.40**	**131.20**	**298.75**	**74.40**	**229.10**	**24.93**	**1060.78**	**30.24**	**26.24**	**59.75**	**14.88**	**45.82**	**8.31**	**185.24**	**17976**	**16806**	**35534**	**9552**	**27342**	**5484**	**(SEK) 112694**

Table 42. Netsim calculated results on 110% demand case- A new pipe of 422 m extension on Frösunda loop, for cold production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	11.84	0.00	11.75	9.28	0.00	32.87	1.18	0.00	2.35	1.86	0.00	5.4	628	0	1246	983	0	2857
01:00	12.60	0.00	12.50	9.44	0.00	34.54	1.26	0.00	2.50	1.89	0.00	5.6	649	0	1289	973	0	2911
02:00	12.60	0.00	12.50	8.60	0.00	33.70	1.26	0.00	2.50	1.72	0.00	5.5	643	0	1277	878	0	2798
03:00	12.60	0.00	12.50	8.59	0.00	33.69	1.26	0.00	2.50	1.72	0.00	5.5	639	0	1269	871	0	2779
04:00	12.60	0.00	12.50	8.69	0.00	33.79	1.26	0.00	2.50	1.74	0.00	5.5	630	0	1251	869	0	2750
05:00	12.60	2.00	12.50	8.39	0.00	35.49	1.26	0.40	2.50	1.68	0.00	5.8	650	206	1290	865	0	3011
06:00	12.60	3.00	12.50	9.56	0.00	37.66	1.26	0.60	2.50	1.91	0.00	6.3	694	330	1377	1053	0	3454
07:00	12.60	10.00	12.50	9.90	0.72	45.72	1.26	2.00	2.50	1.98	0.24	8.0	735	1167	1459	1155	140	4658
08:00	12.60	10.00	12.50	9.91	8.15	53.16	1.26	2.00	2.50	1.98	2.72	10.5	839	1332	1665	1320	1810	6966
09:00	12.60	10.00	12.50	9.94	10.33	55.37	1.26	2.00	2.50	1.99	3.44	11.2	853	1353	1692	1345	2331	7574
10:00	12.60	10.00	12.50	9.95	10.03	55.08	1.26	2.00	2.50	1.99	3.34	11.1	853	1353	1692	1347	2262	7507
11:00	12.60	10.00	12.50	9.97	7.24	52.31	1.26	2.00	2.50	1.99	2.41	10.2	843	1339	1674	1335	1615	6805
12:00	12.60	10.00	12.50	9.91	9.65	54.65	1.26	2.00	2.50	1.98	3.22	11.0	833	1322	1652	1309	2125	7240
13:00	12.60	10.00	12.50	9.89	10.66	55.65	1.26	2.00	2.50	1.98	3.55	11.3	816	1295	1618	1281	2299	7309
14:00	12.60	10.00	12.50	9.96	6.25	51.31	1.26	2.00	2.50	1.99	2.08	9.8	793	1258	1573	1254	1310	6187
15:00	12.60	10.00	12.50	9.94	10.40	55.44	1.26	2.00	2.50	1.99	3.47	11.2	804	1276	1595	1268	2213	7156
16:00	12.60	10.00	12.50	9.96	4.39	49.45	1.26	2.00	2.50	1.99	1.46	9.2	819	1299	1624	1294	951	5987
17:00	12.60	10.00	12.50	9.93	4.32	49.35	1.26	2.00	2.50	1.99	1.44	9.2	843	1338	1673	1329	964	6147
18:00	12.60	10.00	12.50	9.94	3.02	48.06	1.26	2.00	2.50	1.99	1.01	8.8	765	1215	1518	1207	612	5317
19:00	12.60	9.10	12.50	9.82	0.00	44.02	1.26	1.82	2.50	1.96	0.00	7.5	735	1062	1459	1146	0	4402
20:00	12.60	5.00	12.50	9.61	0.00	39.71	1.26	1.00	2.50	1.92	0.00	6.7	722	573	1433	1101	0	3830
21:00	12.60	4.64	12.50	9.90	0.00	39.64	1.26	0.93	2.50	1.98	0.00	6.7	733	540	1455	1152	0	3880
22:00	12.60	2.00	12.50	9.26	0.00	36.36	1.26	0.40	2.50	1.85	0.00	6.0	716	227	1420	1052	0	3415
23:00	12.60	0.00	12.50	8.84	0.00	33.94	1.26	0.00	2.50	1.77	0.00	5.5	700	0	1389	982	0	3070
TOT (MWh)	**301.64**	**145.74**	**299.25**	**229.14**	**85.16**	**1060.93**	**30.16**	**29.15**	**59.85**	**45.83**	**28.39**	**193.38**	**17936**	**18487**	**35587**	**27369**	**18631**	**(SEK) 118010**

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Table 43. The calculation steps and results on BC (BC_110p), scenarios F (Sc.F_110p, new chiller in Sundbyberg (nKMSBG) and new pipe in Frösunda loop (nPPFrö) for the 110% demand case, of KPI,5, KPI,6 and KPI,7, based on Netsim analyses.

Time period	Parameter /KPI	BC_110p	SC.F_110p	nKMSBG	nPPFrö	Unit
13:00	peak el use (MWEl)	11.29	6.88	10.49	11.29	
07:00-19:00	total peak el used per day (MWh,El/day)	129.31	94.52	120.85	128.89	
07:00-19:00	total peak cold produced per day (MWh/day)	669.57	554.38	669.51	669.57	
13:00	**KPI,5 The avoided peak electricity (MW) use at the maximum peak load hour (MW,electricity/peak hour)**	-	**4.4**	**0.8**	**0.0**	MW,El
07:00-19:00	**KPI,6 The avoided peak electricity use per day (MWh,electricity/day)**	-	**34.8**	**8.5**	**0.4**	MWh,El/day
07:00-19:00	**KPI,7 The avoided peak cooling production per day (MWh,cold/day)**	-	**115.19**	**0.06**	**0.01**	MWh,Cold/day
13:00	The avoided peak electricity (MW) use at the maximum peak load hour (alternative comp. to BC) %	-	39%	7%	0%	%
07:00-19:00	The avoided peak electricity use per day (alternative comp. to BC) %	-	27%	7%	0%	%
07:00-19:00	The avoided peak cooling production per day (alternative comp. to BC) %	-	17%	0.009%	0%	%

Table 44. Netsim results on temperature sensitivity analysis on BC, for 15 °C ground and 32 °C ambient temperatures, of the production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	0.00	8.75	9.56	0.0	30.91	1.26	0.00	1.75	1.91	0.00	4.92	668	0	928	1014	0	2609
01:00	12.60	0.00	11.00	8.63	0.0	32.23	1.26	0.00	2.20	1.73	0.00	5.19	649	0	1134	890	0	2673
02:00	12.60	0.00	10.00	8.92	0.0	31.52	1.26	0.00	2.00	1.78	0.00	5.04	643	0	1021	911	0	2575
03:00	12.60	0.00	10.13	8.78	0.0	31.50	1.26	0.00	2.03	1.76	0.00	5.04	639	0	1027	891	0	2558
04:00	12.60	0.00	10.38	8.70	0.0	31.67	1.26	0.00	2.08	1.74	0.00	5.07	630	0	1038	870	0	2538
05:00	12.60	0.50	10.75	9.19	0.0	33.04	1.26	0.10	2.15	1.84	0.00	5.35	650	52	1109	948	0	2759
06:00	12.60	1.00	12.00	9.29	0.0	34.89	1.26	0.20	2.40	1.86	0.00	5.72	694	110	1322	1024	0	3149
07:00	12.47	8.00	12.50	8.70	0.0	41.67	1.25	1.60	2.50	1.74	0.00	7.09	728	934	1459	1015	0	4137
08:00	12.60	10.00	12.50	9.98	2.8	47.90	1.26	2.00	2.50	2.00	0.94	8.70	839	1332	1665	1329	627	5793
09:00	12.60	10.00	12.50	9.99	4.6	49.70	1.26	2.00	2.50	2.00	1.54	9.29	853	1353	1692	1352	1039	6290
10:00	12.60	10.00	12.50	9.98	4.4	49.45	1.26	2.00	2.50	2.00	1.46	9.21	853	1353	1692	1351	987	6236
11:00	12.60	10.00	12.50	9.99	2.0	47.07	1.26	2.00	2.50	2.00	0.66	8.42	843	1339	1674	1337	442	5635
12:00	12.60	10.00	12.50	9.98	4.0	49.09	1.26	2.00	2.50	2.00	1.34	9.09	833	1322	1652	1319	884	6009
13:00	12.60	10.00	12.50	9.99	4.9	49.95	1.26	2.00	2.50	2.00	1.62	9.38	816	1295	1618	1293	1049	6071
14:00	12.60	10.00	12.50	9.98	1.2	46.27	1.26	2.00	2.50	2.00	0.40	8.15	793	1258	1573	1256	249	5129
15:00	12.60	10.00	12.50	9.99	4.7	49.75	1.26	2.00	2.50	2.00	1.55	9.31	804	1276	1595	1275	991	5941
16:00	12.60	9.00	12.50	9.98	0.6	44.73	1.26	1.80	2.50	2.00	0.22	7.77	819	1169	1624	1297	140	5049
17:00	12.60	9.00	12.50	9.99	0.6	44.64	1.26	1.80	2.50	2.00	0.19	7.74	843	1204	1673	1336	124	5181
18:00	12.60	7.50	12.50	9.98	1.0	43.55	1.26	1.50	2.50	2.00	0.32	7.58	765	911	1518	1212	197	4603
19:00	12.60	6.00	12.50	9.13	0.0	40.23	1.26	1.20	2.50	1.83	0.00	6.79	735	700	1459	1065	0	3959
20:00	11.34	4.00	12.50	8.74	0.0	36.58	1.13	0.80	2.50	1.75	0.00	6.18	650	459	1433	1002	0	3544
21:00	11.72	4.00	12.50	8.30	0.0	36.52	1.17	0.80	2.50	1.66	0.00	6.13	682	466	1455	967	0	3569
22:00	11.97	1.80	11.63	8.38	0.0	33.77	1.20	0.36	2.33	1.68	0.00	5.56	680	204	1321	951	0	3156
23:00	12.35	0.00	11.13	8.27	0.0	31.74	1.23	0.00	2.23	1.65	0.00	5.11	686	0	1236	919	0	2841
TOT (MWh)	**299.25**	**130.80**	**283.25**	**224.41**	**30.69**	**968.40**	**29.93**	**26.16**	**56.65**	**44.88**	**10.23**	**167.85**	**17795**	**16738**	**33917**	**26824**	**6730**	**(SEK) 102004**

Table 45. Netsim results on temperature sensitivity analysis on Sc.F, for 15 °C ground and 32 °C ambient temperatures, of the production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	9.60	12.50	9.44	0.0	44.14	1.26	1.92	2.50	1.89	0.00	7.57	668	1018	1325	1000	0	4011
01:00	12.60	9.20	12.50	9.61	0.0	43.91	1.26	1.84	2.50	1.92	0.00	7.52	649	948	1289	990	0	3877
02:00	12.60	9.50	12.50	9.52	0.0	44.12	1.26	1.90	2.50	1.90	0.00	7.56	643	970	1277	973	0	3863
03:00	12.60	9.50	12.50	9.52	0.0	44.12	1.26	1.90	2.50	1.90	0.00	7.56	639	964	1269	966	0	3838
04:00	12.60	9.20	12.50	9.60	0.0	43.90	1.26	1.84	2.50	1.92	0.00	7.52	630	921	1251	961	0	3763
05:00	12.60	8.60	12.50	9.94	0.0	43.64	1.26	1.72	2.50	1.99	0.00	7.47	650	887	1290	1026	0	3852
06:00	12.60	8.30	12.50	9.60	0.0	43.00	1.26	1.66	2.50	1.92	0.00	7.34	694	914	1377	1058	0	4043
07:00	12.60	7.00	12.50	9.84	0.0	41.94	1.26	1.40	2.50	1.97	0.00	7.13	735	817	1459	1149	0	4161
08:00	12.60	6.90	12.50	9.88	0.0	41.88	1.26	1.38	2.50	1.98	0.00	7.12	839	919	1665	1316	0	4739
09:00	12.60	7.30	12.50	9.59	0.0	41.99	1.26	1.46	2.50	1.92	0.00	7.14	853	988	1692	1298	0	4830
10:00	12.60	4.90	12.50	9.60	0.0	39.60	1.26	0.98	2.50	1.92	0.00	6.66	853	663	1692	1299	0	4507
11:00	12.60	0.20	12.50	9.81	0.0	35.11	1.26	0.04	2.50	1.96	0.00	5.76	843	27	1674	1313	0	3857
12:00	12.60	0.00	12.50	9.40	0.0	34.50	1.26	0.00	2.50	1.88	0.00	5.64	833	0	1652	1242	0	3726
13:00	12.60	0.00	12.50	9.63	0.0	34.73	1.26	0.00	2.50	1.93	0.00	5.69	816	0	1618	1247	0	3681
14:00	12.60	0.00	10.00	9.26	0.0	31.86	1.26	0.00	2.00	1.85	0.00	5.11	793	0	1258	1165	0	3216
15:00	12.60	3.30	12.50	9.52	0.0	37.92	1.26	0.66	2.50	1.90	0.00	6.32	804	421	1595	1215	0	4035
16:00	12.60	0.00	12.50	9.51	0.0	34.61	1.26	0.00	2.50	1.90	0.00	5.66	819	0	1624	1236	0	3678
17:00	12.60	1.70	12.50	9.90	0.0	36.70	1.26	0.34	2.50	1.98	0.00	6.08	843	227	1673	1325	0	4068
18:00	12.60	3.10	12.50	9.52	0.0	37.72	1.26	0.62	2.50	1.90	0.00	6.28	765	377	1518	1156	0	3816
19:00	12.60	8.00	12.50	9.53	0.0	42.63	1.26	1.60	2.50	1.91	0.00	7.27	735	933	1459	1112	0	4240
20:00	12.60	7.90	12.50	9.69	0.0	42.69	1.26	1.58	2.50	1.94	0.00	7.28	722	906	1433	1111	0	4172
21:00	12.60	8.00	12.50	9.68	0.0	42.78	1.26	1.60	2.50	1.94	0.00	7.30	733	931	1455	1127	0	4246
22:00	12.60	8.50	12.50	9.66	0.0	43.26	1.26	1.70	2.50	1.93	0.00	7.39	716	966	1420	1098	0	4199
23:00	12.60	8.80	12.50	9.74	0.0	43.64	1.26	1.76	2.50	1.95	0.00	7.47	700	978	1389	1083	0	4149
TOT (MWh)	**302.40**	**139.50**	**297.50**	**230.99**	**0.00**	**970.39**	**30.24**	**27.90**	**59.50**	**46.20**	**0.00**	**163.84**	**17976**	**15775**	**35352**	**27464**	**0**	**(SEK) 96567**

Table 46. Netsim results on temperature sensitivity analysis on BC, for 20 °C ground and 36 °C ambient temperatures, of the production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	0.00	8.75	9.64	0.0	30.99	1.26	0.00	1.75	1.93	0.00	4.94	668	0	928	1022	0	2617
01:00	12.60	0.00	11.00	8.75	0.0	32.35	1.26	0.00	2.20	1.75	0.00	5.21	649	0	1134	902	0	2685
02:00	12.60	0.00	10.00	9.04	0.0	31.64	1.26	0.00	2.00	1.81	0.00	5.07	643	0	1021	923	0	2588
03:00	12.60	0.00	10.13	8.90	0.0	31.62	1.26	0.00	2.03	1.78	0.00	5.06	639	0	1027	903	0	2570
04:00	12.60	0.00	10.38	8.80	0.0	31.78	1.26	0.00	2.08	1.76	0.00	5.10	630	0	1038	881	0	2549
05:00	12.60	0.50	10.75	9.31	0.0	33.16	1.26	0.10	2.15	1.86	0.00	5.37	650	52	1109	960	0	2771
06:00	12.60	1.00	12.00	9.42	0.0	35.02	1.26	0.20	2.40	1.88	0.00	5.74	694	110	1322	1038	0	3164
07:00	12.47	8.00	12.50	8.84	0.0	41.82	1.25	1.60	2.50	1.77	0.00	7.12	728	934	1459	1033	0	4154
08:00	12.60	10.00	12.50	9.73	3.2	48.07	1.26	2.00	2.50	1.95	1.08	8.79	839	1332	1665	1296	719	5852
09:00	12.60	10.00	12.50	9.73	5.0	49.84	1.26	2.00	2.50	1.95	1.67	9.37	853	1353	1692	1317	1129	6344
10:00	12.60	10.00	12.50	9.69	4.8	49.58	1.26	2.00	2.50	1.94	1.60	9.29	853	1353	1692	1312	1080	6290
11:00	12.60	10.00	12.50	9.96	2.1	47.18	1.26	2.00	2.50	1.99	0.71	8.46	843	1339	1674	1334	474	5663
12:00	12.60	10.00	12.50	9.98	4.1	49.22	1.26	2.00	2.50	2.00	1.38	9.14	833	1322	1652	1319	912	6037
13:00	12.60	10.00	12.50	9.99	5.0	50.07	1.26	2.00	2.50	2.00	1.66	9.42	816	1295	1618	1293	1076	6098
14:00	12.60	10.00	12.50	9.73	1.5	46.38	1.26	2.00	2.50	1.95	0.52	8.22	793	1258	1573	1224	325	5173
15:00	12.60	10.00	12.50	9.72	5.1	49.88	1.26	2.00	2.50	1.94	1.69	9.39	804	1276	1595	1241	1076	5991
16:00	12.60	9.00	12.50	9.73	1.0	44.84	1.26	1.80	2.50	1.95	0.34	7.84	819	1169	1624	1265	218	5095
17:00	12.60	9.00	12.50	9.97	0.7	44.76	1.26	1.80	2.50	1.99	0.23	7.78	843	1204	1673	1335	153	5208
18:00	12.60	7.50	12.50	9.73	1.3	43.67	1.26	1.50	2.50	1.95	0.44	7.65	765	911	1518	1182	270	4646
19:00	12.60	6.00	12.50	9.24	0.0	40.34	1.26	1.20	2.50	1.85	0.00	6.81	735	700	1459	1078	0	3972
20:00	11.34	4.00	12.50	8.86	0.0	36.70	1.13	0.80	2.50	1.77	0.00	6.21	650	459	1433	1016	0	3557
21:00	11.72	4.00	12.50	8.41	0.0	36.63	1.17	0.80	2.50	1.68	0.00	6.15	682	466	1455	979	0	3582
22:00	11.97	1.80	11.63	8.48	0.0	33.87	1.20	0.36	2.33	1.70	0.00	5.58	680	204	1321	963	0	3168
23:00	12.35	0.00	11.13	8.37	0.0	31.84	1.23	0.00	2.23	1.67	0.00	5.13	686	0	1236	930	0	2852
TOT (MWh)	299.25	130.80	283.25	224.04	33.91	971.25	29.93	26.16	56.65	44.81	11.30	168.85	17795	16738	33917	26745	7431	(SEK) 102625

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Table 47. Netsim results on temperature sensitivity analysis on Sc.F, for 20 °C ground and 36 °C ambient temperatures, of the production mix and electricity use (in MW per hour and MWh per day), and the production costs (SEK). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Cold output in MW (per hour) by each plant					Sum	Electricity use by MW (per hour) by each plant to produce cold					Sum	Cost (of electricity) to produce cold in SEK (per hour) by each plant and total					
Time	FröFC	FröCC	SBG	Solna CC	Solna HP	Cold, MW	FröFC	FröCC	SBG	Solna CC	Solna HP	El., MW	FröFC	FröCC	SBG	Solna CC	Solna HP	Sum (SEK)
00:00	12.60	9.60	12.50	9.56	0.0	44.26	1.26	1.92	2.50	1.91	0.00	7.59	668	1018	1325	1013	0	4024
01:00	12.60	9.20	12.50	9.73	0.0	44.03	1.26	1.84	2.50	1.95	0.00	7.55	649	948	1289	1003	0	3890
02:00	12.60	9.50	12.50	9.64	0.0	44.24	1.26	1.90	2.50	1.93	0.00	7.59	643	970	1277	985	0	3876
03:00	12.60	9.50	12.50	9.64	0.0	44.24	1.26	1.90	2.50	1.93	0.00	7.59	639	964	1269	979	0	3851
04:00	12.60	9.20	12.50	9.73	0.0	44.03	1.26	1.84	2.50	1.95	0.00	7.55	630	921	1251	973	0	3775
05:00	12.60	8.80	12.50	9.87	0.0	43.77	1.26	1.76	2.50	1.97	0.00	7.49	650	908	1290	1018	0	3865
06:00	12.60	8.30	12.50	9.73	0.0	43.13	1.26	1.66	2.50	1.95	0.00	7.37	694	914	1377	1072	0	4057
07:00	12.60	7.20	12.50	9.81	0.0	42.11	1.26	1.44	2.50	1.96	0.00	7.16	735	841	1459	1145	0	4180
08:00	12.60	7.20	12.50	9.93	0.0	42.23	1.26	1.44	2.50	1.99	0.00	7.19	839	959	1665	1323	0	4786
09:00	12.60	7.30	12.50	9.76	0.0	42.16	1.26	1.46	2.50	1.95	0.00	7.17	853	988	1692	1321	0	4853
10:00	12.60	4.90	12.50	9.74	0.0	39.74	1.26	0.98	2.50	1.95	0.00	6.69	853	663	1692	1319	0	4526
11:00	12.60	0.20	12.50	9.94	0.0	35.24	1.26	0.04	2.50	1.99	0.00	5.79	843	27	1674	1331	0	3874
12:00	12.60	0.00	12.50	9.52	0.0	34.62	1.26	0.00	2.50	1.90	0.00	5.66	833	0	1652	1258	0	3743
13:00	12.60	0.00	12.50	9.75	0.0	34.85	1.26	0.00	2.50	1.95	0.00	5.71	816	0	1618	1263	0	3697
14:00	12.60	0.00	10.00	9.37	0.0	31.97	1.26	0.00	2.00	1.87	0.00	5.13	793	0	1258	1179	0	3230
15:00	12.60	3.30	12.50	9.65	0.0	38.05	1.26	0.66	2.50	1.93	0.00	6.35	804	421	1595	1232	0	4052
16:00	12.60	0.00	12.50	9.62	0.0	34.72	1.26	0.00	2.50	1.92	0.00	5.68	819	0	1624	1250	0	3693
17:00	12.60	1.90	12.50	9.82	0.0	36.82	1.26	0.38	2.50	1.96	0.00	6.10	843	254	1673	1314	0	4084
18:00	12.60	3.10	12.50	9.63	0.0	37.83	1.26	0.62	2.50	1.93	0.00	6.31	765	377	1518	1170	0	3830
19:00	12.60	8.00	12.50	9.65	0.0	42.75	1.26	1.60	2.50	1.93	0.00	7.29	735	933	1459	1126	0	4253
20:00	12.60	7.90	12.50	9.80	0.0	42.80	1.26	1.58	2.50	1.96	0.00	7.30	722	906	1433	1124	0	4185
21:00	12.60	8.00	12.50	9.80	0.0	42.90	1.26	1.60	2.50	1.96	0.00	7.32	733	931	1455	1141	0	4260
22:00	12.60	8.50	12.50	9.78	0.0	43.38	1.26	1.70	2.50	1.96	0.00	7.42	716	966	1420	1111	0	4212
23:00	12.60	8.80	12.50	9.86	0.0	43.76	1.26	1.76	2.50	1.97	0.00	7.49	700	978	1389	1095	0	4161
TOT (MWh)	**302.40**	**140.40**	**297.50**	**233.34**	**0.00**	**973.64**	**30.24**	**28.08**	**59.50**	**46.67**	**0.00**	**164.49**	**17976**	**15886**	**35352**	**27743**	**0**	**(SEK) 96957**

Table 48. Sensitivity analysis of the Netsim results on BC on electricity price fluctuations, for the price forecasts in 2040 (summer day) [23], concerning El_Scenario 1 (El_S1), El-scenario 2 (El_S2) and El-scenario 3 (El_S3). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	BC, El_Scenario 1					Sum	BC, El_Scenario 2					Sum	BC, El_Scenario 3					Sum
Time	FröFC	FröCC	SBG	SEK	Solna HP	SEK	FröFC	FröCC	SBG	Solna CC	Solna HP	SEK	FröFC	FröCC	SBG	Solna CC	Solna HP	SEK
00:00	624	0	866	928	0	2418	117	0	162	174	0	453	121	0	167	179	0	467
01:00	614	0	1073	826	0	2513	107	0	187	144	0	439	111	0	194	149	0	453
02:00	548	0	871	761	0	2180	97	0	154	135	0	385	101	0	161	141	0	403
03:00	501	0	805	685	0	1991	92	0	148	126	0	366	96	0	155	132	0	383
04:00	460	0	758	624	0	1842	89	0	147	121	0	358	96	0	158	130	0	385
05:00	673	53	1148	965	0	2840	118	9	201	169	0	498	121	10	207	174	0	513
06:00	922	146	1756	1332	0	4156	165	26	315	239	0	745	167	26	317	241	0	751
07:00	1369	1756	2744	1864	0	7733	210	270	422	286	0	1188	208	267	418	284	0	1177
08:00	1460	2317	2897	2300	1022	9996	251	398	498	395	176	1717	240	381	476	378	168	1643
09:00	1468	2330	2913	2316	1734	10762	284	451	564	449	336	2084	275	436	545	433	324	2012
10:00	1343	2132	2665	2121	1503	9764	233	370	462	368	261	1694	235	374	467	372	263	1711
11:00	1229	1950	2438	1933	614	8164	228	362	452	359	114	1515	231	366	458	363	115	1533
12:00	977	1551	1939	1537	1010	7014	206	327	409	324	213	1478	215	341	426	338	222	1540
13:00	1002	1591	1989	1579	1260	7420	192	305	382	303	242	1424	201	319	399	317	253	1490
14:00	976	1548	1936	1543	269	6272	177	280	350	279	49	1135	183	291	363	290	51	1177
15:00	836	1327	1658	1318	1003	6141	166	263	329	261	199	1217	177	281	351	279	212	1301
16:00	865	1236	1716	1369	115	5302	152	217	301	240	20	930	162	231	321	256	22	990
17:00	1068	1526	2119	1684	127	6525	192	274	381	303	23	1173	204	291	404	321	24	1245
18:00	1136	1352	2253	1790	260	6790	228	272	453	360	52	1366	226	269	448	356	52	1351
19:00	1193	1136	2368	1702	0	6399	250	238	496	356	0	1340	244	232	484	348	0	1308
20:00	810	572	1787	1229	0	4397	173	122	381	262	0	938	189	133	416	286	0	1023
21:00	725	495	1546	1008	0	3773	157	107	335	218	0	817	182	125	389	254	0	950
22:00	797	240	1547	1096	0	3679	165	49	320	226	0	760	177	53	344	243	0	818
23:00	843	0	1519	1110	0	3473	140	0	252	184	0	575	148	0	267	195	0	609
TOT (SEK)	**22439**	**23259**	**43310**	**33619**	**8917**	**131545**	**4189**	**4341**	**8101**	**6282**	**1684**	**24596**	**4310**	**4426**	**8335**	**6458**	**1706**	**25234**

Table 49. Sensitivity analysis of the Netsim results on Sc.F on electricity price fluctuations, for the price forecasts in 2040 (summer day) [23] , concerning El_Scenario 1 (El_S1), El-scenario 2 (El_S2) and El-scenario 3 (El_S3). (CC- chillers, HP- heat pumps, FC- Free cooling, SBG- Sundbyberg, Frö- Frösunda)

	Sc.F, El_Scenario 1					Sum	Sc.F, El_Scenario 2					Sum	Sc.F, El_Scenario 3					Sum
Time	FröFC	FröCC	SBG	SEK	Solna HP	SEK	FröFC	FröCC	SBG	Solna CC	Solna HP	SEK	FröFC	FröCC	SBG	Solna CC	Solna HP	SEK
00:00	624	891	1238	976	0	3729	117	167	232	183	0	699	121	172	239	189	0	721
01:00	614	849	1219	969	0	3651	107	148	213	169	0	638	111	153	220	175	0	659
02:00	548	775	1088	867	0	3278	97	137	192	153	0	579	101	143	201	160	0	605
03:00	501	708	994	792	0	2994	92	130	183	146	0	551	96	136	191	152	0	577
04:00	460	643	913	718	0	2735	89	125	177	140	0	531	96	134	191	150	0	571
05:00	673	919	1335	1043	0	3970	118	161	234	183	0	696	121	166	241	188	0	717
06:00	922	1214	1829	1379	0	5344	165	218	328	247	0	958	167	220	331	249	0	966
07:00	1383	1537	2744	2110	0	7773	212	236	422	324	0	1194	211	234	418	321	0	1183
08:00	1460	1599	2897	2175	0	8131	251	275	498	374	0	1396	240	263	476	357	0	1336
09:00	1468	1585	2913	2296	0	8262	284	307	564	445	0	1600	275	296	545	429	0	1545
10:00	1343	959	2665	2087	0	7055	233	166	462	362	0	1224	235	168	467	366	0	1236
11:00	1229	39	2438	1877	0	5583	228	7	452	348	0	1036	231	7	458	353	0	1048
12:00	977	0	1939	1430	0	4346	206	0	409	301	0	916	215	0	426	314	0	954
13:00	1002	0	1989	1503	0	4494	192	0	382	289	0	863	201	0	399	302	0	902
14:00	976	0	1548	1408	0	3932	177	0	280	255	0	712	183	0	291	264	0	738
15:00	836	371	1658	1306	0	4171	166	74	329	259	0	826	177	79	351	277	0	884
16:00	865	0	1716	1284	0	3866	152	0	301	225	0	678	162	0	321	240	0	722
17:00	1068	288	2119	1651	0	5127	192	52	381	297	0	922	204	55	404	315	0	978
18:00	1136	469	2253	1776	0	5634	228	94	453	357	0	1133	226	93	448	353	0	1121
19:00	1193	1383	2368	1894	23	6861	250	290	496	397	5	1437	244	283	484	387	5	1403
20:00	900	1129	1787	1362	0	5178	192	241	381	290	0	1105	210	263	416	317	0	1205
21:00	779	989	1546	1176	0	4491	169	214	335	255	0	973	196	249	389	296	0	1130
22:00	839	1131	1664	1265	0	4898	173	234	344	261	0	1012	186	251	370	281	0	1089
23:00	860	1202	1707	1309	0	5079	143	199	283	217	0	841	151	211	300	230	0	891
TOT (SEK)	**22657**	**18680**	**44567**	**34655**	**23**	**120582**	**4234**	**3475**	**8330**	**6477**	**5**	**22520**	**4359**	**3576**	**8575**	**6666**	**5**	**23181**

DISTRIBUTED COLD STORAGE IN DISTRICT COOLING

Mycket tyder på att efterfrågan på kyla kommer att öka med ett varmare klimat och ett ökat krav på komfort. Till exempel finns det studier som visar att utbudet av fjärrkyla i Sverige idag är cirka 1 TWh per år samtidigt som efterfrågan ligger på mellan 2 och 5 TWh per år.

Kyllager kan sänkta kostnaderna för produktion av kyla genom att man undviker onödig investering i kapacitet och underlättar lastutjämning. Befintliga kyllager är till största delen centralt placerade kallvattenackumulatorer. Här har man frågat sig hur en ökad integration av kyllager kan bidra till att expandera fjärrkyla på ett robust, kostnadseffektivt och miljöriktigt sätt.

Rapporten beskriver distribuerade kyllager i fjärrkylanät och jämför kyllager med olika placeringar i ett befintligt system. Den bästa kyllagerlösningen i systemet jämförs därefter med alternativa investeringar för ett ökat kylbehov. Resultatet visar att distribuerade kyllager innebär årliga kostnadsbesparingar jämfört med att investeringar görs i en ny kylmaskin eller en ny rörledning.

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