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Energimyndighetens titel på projektet – engelska District cooling vs. local solutions for space cooling	
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Förord

Författarna vill tacka alla forskare inom IEA EBC Annex 80 - Resilient Cooling of Buildings för ett gott samarbete samt för att ha gett möjlighet att öka kunskapen om motståndskraftiga strategier for komfortkyla med hänsyn till framtida klimatprognoser och värmeböljor.

Finansieringen av studien av Energimyndigheten, inom Termo-programmet, uppskattas mycket (Fjärrkyla kontra lokala lösningar för kylning av utrymmen, projektnummer 48296–1, Dnr: 2019–003410).

Innehållsförteckning

Sammanfattning

Projektet tar ett övergripande perspektiv och inkluderar primärenergianvändning, klimatpåverkan och ekonomiska aspekter. Målet med projektet är att undersöka olika kyltekniker för den planerade stadsdelen Näringen i Gävle, som förväntas vara helt utbyggd före 2050. Fokus ligger på att jämföra fjärrkyla med lokala lösningar för bostadshus, eftersom stadsdelen huvudsakligen kommer att bestå av bostäder. Det är också viktigt att notera att bostadshus i Sverige generellt sett inte är utrustade med kylsystem, vilket gör det intressant att utvärdera dessas prestanda med tanke på framtiden.

Med de pågående klimatförändringarna och dess påverkan på byggnaders energianvändning och termiska komfort, har kraven på byggnads utformning blivit mer strikta. Eftersom byggnader konstrueras för att stå emot tidens tand, krävs en mer detaljerad analys av deras prestanda i förhållande till det framtida klimatet. Syftet är att ge en översikt över de genomförda studierna för att belysa byggnaders energibehov under de aktuella omständigheterna. Rapporten inkluderar även en översikt av det framtida arbete som planeras.

De utförda studierna har inriktat sig på tre centrala forskningsfrågor. För det första, hur påverkar en representativ meteorologisk klimatfil (TMY) resultaten av simuleringar under nuvarande och framtida klimatscenario? Den andra frågan undersöker på vilket sätt termiska komforten inomhus kan förbättras och hur detta påverkar kylbehovet samt primärenergin (PE) i en prototypbyggnad. Slutligen, vilka alternativ för komfortkyla är mest ekonomiskt gynnsamma för både fastighetsägare och energileverantörer?

Den första forskningsfrågan upptäcktes att den fritt tillgängliga typiska klimatfilen inte täcker förändringarna i klimatet och dess konsekvenser för byggnaden. Kylbehovet ökade upp till 5 gånger mot om den nuvarande klimatfilen för typisk år (baserad på 1991-2010 väderdata), när man använder den projicerade klimatfilen och de extrema klimatfilerna.

För att besvara den andra forskningsfrågan utvärderades olika parametrar relaterade till byggnaders termiska förhållanden för att studera och förbättra energianvändningen och inomhusklimatet. En undersökning genomfördes för att undvika aktiv kylning, dvs hur man kan minska kylbehovet med passiva åtgärder genom solavskärmning och nyttja omgivande luft för kylning. När dessa två åtgärder inte räcker måste aktiv kylning av t ex tilluften ske, trots att automatiska solskydd minskar kylbehovet med upp till 70%. Dessutom minskade även PE och CO_2e-utsläpp för de undersökta kylmetoderna, klimat och väderförhållanden.

Tre kyltekniker (fjärrkyla, kylmaskin kopplade/urkopplade med solceller (PV)-system och absorptionskyla) utvärderades för att svara den tredje forskningsfrågan. Baserat på resultaten från primärt energianvändning och livscykelkostnad verkade kylmaskin med PV-system vara fördelaktig, eftersom denna teknologi visade det lägsta värdet för primärenergianvändning och livscykelkostnad. Jämfört med kylmaskin utan PV minskade primärenergiantalet och livscykelkostnaden med 13 % i genomsnitt. Dessutom visade sig fjärrkyla systemet vara ett ekonomiskt fördelaktigt val för byggnader med stora golvytor.

Summary

The project takes a comprehensive perspective and includes primary energy use, climate impact, and economic aspects. The goal of the project is to examine various cooling alternatives for the planned district Näringen in Gävle, which is expected to be fully developed before 2050. The focus is on comparing district cooling with local cooling solutions for residential buildings, as the district will mainly consist of residences. It is also important to note that residential buildings in Sweden are generally not equipped with cooling systems, making it interesting to evaluate their performance with future considerations.

With the ongoing climate change and its impact on the energy use of buildings and the thermal comfort of occupants, the requirements for building design have become more severe. As buildings are constructed to last longer, it necessitates a more detailed analysis of their performance in relation to future climates. The purpose is to provide an overview of the studies conducted to shed light on buildings' energy needs under current circumstances. The report also includes an overview of the future work that is planned.

The conducted studies have focused on three central research questions. Firstly, how does a representative meteorological climate file (TMY) impact the results of simulations under current and future climate scenarios? The second question explores how indoor thermal comfort can be improved and how this affects the cooling demand and primary energy (PE) in a prototype building. Lastly, what alternatives for comfort cooling are most economically advantageous for both property owners and energy providers?

In response to the first research question, it was discovered that the freely available typical climate file does not cover the induced changes in climate and its extreme consequences for the building. The required cooling energy usage increased up to 5 times the currently available climate file (typical climate file based on 1991-2010 data), in some cases, when using the projected climate file and the extreme climate files.

To address the second research question, various parameters related to the thermal conditions of buildings were evaluated to study and improve energy use and indoor building conditions. Investigation was conducted to avoid the use of active cooling, i.e., how to reduce cooling demand with passive measures through sun shading and ambient air for cooling. When these two measures are insufficient, active cooling with ventilative cooling must be used. It was discovered that the use of automatic shading systems as an energy-saving measure helps reduce energy use by up to 70% in some cases. Additionally, PE and CO_2 emissions also decreased for the studied cooling methods, climate, and weather files.

Three cooling technologies (district cooling, compression chillers connected/disconnected with photovoltaic (PV) systems, and absorption chillers)

were evaluated to address the third research question. Based on the results from primary energy use and life cycle cost, the compression chillers with a PV system appeared advantageous, as this technology demonstrated the lowest values for primary energy use and life cycle cost. Compared to compression chillers without PV, primary energy use and life cycle cost decreased by an average of 13%. Additionally, the district cooling system proved to be an economically advantageous choice for buildings with large floor areas.

Inledning/Bakgrund

Idag leverera 36 aktörer drygt 1 TWh fjärrkyla till ca 40 urbana orter. Mellan 2000 och 2017 ökade leveranserna med 5,5% per år samtidigt som löpsträckan rör ökat med 11 % per år. I en undersökning från 2016 framgick att ungefär hälften av fjärrkylan användes som komfortkyla och resten för övriga kylprocesser. Ungefär 17 % av offentliga sektorns byggnader kyls aktivt med fjärrkyla. Drygt 40 % av fjärrkylan används av kontorsfastigheter och kommersiella lokaler. Enligt Palm och Gustafsson (2018) är alla överens om att kylbehovet kommer att öka, men få har detta på agenda, till exempel har få politiker och kommuner långtidsplaner kring fjärrkyla. Energibolagen har ansvarat för fjärrkylans kostnader, implementering och utveckling. Men den allmänna kunskapen om kyla är begränsad ur många perspektiv, och det finns en misstro när energiföretagen presenterar information/fakta om fjärrkyla eftersom dessa inte har undersökts eller bekräftats av tredje part (Palm et al., 2018).

Nya hållbara stadsdelar, vilka kommer byggas eller utökas, ska bestå länge och dessas infrastruktur implementeras genom beslut baserade på korrekta underlag. Byggnaderna ska förses med el, värme och komfortkyla, där kylbehovet förväntas öka eftersom byggnaderna dimensioneras som nära nollenergibyggnader (NNEB), eventuellt där byggnaders interna värmegenerering ökar. Komfortkyla kan genereras lokalt i en byggnad med eldriven kylmaskin, fjärrvärmedriven sorptiv kyla eller absorptionsvärmepump alternativt med fjärrkyla, vilken kan bestå av frikyla med eldriven kylmaskin eller fjärrvärmedriven adsorptionsvärmepump som spets. Dessa lösningar medför olika resursanvändning (energislag och primärenergi), miljöeffekter (växthusgasutsläpp) och livscykelkostnader. Det finns intressanta aspekter som påverkar jämförelsens utfall:

- Kylbehovet och därmed kylans elbehov sker på sommaren, när nationella elbehovet är lägre och flödande energikällor finns tillgängliga (vind, sol, vatten), samtidigt som vissa kärnkraftsanläggningar underhålls. Detta kan medföra skillnader i säsongsvisa primärenergital och utsläpp för elproduktion.
- Fjärrvärme måste sommartid leverera energi för bl a för värmeberedning av tappvarmvatten – vad som eldas inverkar på fjärrvärmens primärenergianvändning och utsläpp. Möjlighet ges till att använda fjärrvärmedrivna absorptionsvärmepumpar. Dessa kräver höga fram- och skapar höga returtemperaturer för att vara effektiva, vilket inverkar negativt ur elproduktionssynpunkt. Placering av lokal absorptionsvärmepump kan medföra högre distributionsförluster. Central placering (vid kraftanläggningen) medför att fjärrkylarör måste dras från centralanläggningen till stadsdelen, vilket medför höga investeringskostnader.
- Graden av frikyla har inverkan, men finns inte alltid tillgängligt och varierar under kylsäsongen.
- Användning av lokala eldrivna kylmaskiner kan vara attraktiva utifrån att elpriset är lägre under sommaren. Priserna kan komma att ändras i framtiden och ha andra säsongsvisa profiler.

Idag kan nya kontorsbyggnader ha mer kyl- än värmebehov, främst i södra Sverige (Carlander et al., 2020). Men det byggs sällan bostäder som förses med kyla. I och med klimatförändringarna behöver, när nya stadsdelar ska byggas, analyseras om dagens och framtida nybyggnader är i behov av kyla och hur det lämpligen kan tillgodoses. Omfattande studier utfördes för befintliga byggnader (bostäder och lokaler) av Nordman et al. (2010), men klimatförändringarnas takt har ökat mot det som projicerades tidigare.

Genomförande

Genomförandet har utförts genom två huvudsakliga spår. Det ena har varit en fallstudie som har fokuserat på omvandling av stadsdelen Näringen i Gävle, där ca. 6000 lägenheter inklusive samhällsservice ska byggas. Det andra har varit deltagande i IEA EBC Annex 80 – Resilient Cooling of Buildings. Medan Annex 80 har huvudsakligen haft byggnaden som systemgräns, har fallstudie Näringen även omfattat fjärrkyla och svenska elförsörjningssystemet som systemgräns. Inom byggnadens systemgräns är kriterierna för termisk komfort avgörande för behovet av aktivt tillförd kyla, vilket blir utgångspunkten om och hur kyla ska levereras till nya stadsdelen.

Fallstudie Näringen, Gävle

Näringen är en stadsdel som utvalts att delta i EU:s Cities Mission där 100 europeiska städer ska nå klimatneutralitet tills året 2030 (EU Kommissionen, u.å.). Ett industri- och verksamhetsområde omvandlas till ett bostadsområde med arbetsplatser och serviceinrättningar, dvs en stadsdel med 6000 nya bostäder och 450 000 kvadratmeter lokalyta i etapper mellan 2025–2040 (Gävle kommun, u.å.). Dessa byggnader kommer att resas enligt dagens byggnadsregler som ska ha en energiprestanda omfattande ”nära noll energibyggnader” (NNEB) och helst med bättre energiprestanda än som krävs idag. Fokus ligger på flerbostadshus eftersom småhus inte ingår i planbestämmelserna; detta utifrån områdets detaljplan och från en pilotstudie om uppvärmning av den nya stadsdelen (Gustafsson et al., 2021). Sex typhus valdes för att representera blivande bostadsbeståndet. Dessa är tämligen lika i utformningen som nyligen rests i Gävles nya stadsdelar - Gävle Strand Etapp 1 (färdigbyggt) och Etapp 2 samt 3 som idag byggs mot havet, se Figur 1.

Figur 1. Vy av Gävle från havet. Rödmarkerade området omfattar Gävle strand Etapp 1 (färdigbyggt), och Etapp 2 och 3 som byggs idag. Gulmarkerade området inringar området Näringen.

Deltagande i IEA EBC Annex 80

Projektet har även omfattat deltagande i Annex 80. Annex 80 *Resilient Cooling of Buildings* syftar till att (IEA EBC Annex 80, u.å.):

a. Minska extern energi från att nå inomhusmiljöer;
b. Förbättra personlig komfort förutom att kyla hela utrymmen;
c. Avlägsna värme från inomhusmiljöer;
d. Kontrollera latent värme (fukt) i inomhusmiljöer.

Annex 80's arbete har pågått sedan 2018 och avslutas i slutet av 2023. Medverkan har varit genom att bidra med arbete kring följande punkter:

Annex 80 utförde en litteraturundersökning för fastställande av kunskapsläget för kylning av byggnader; vårt bidrag är fjärrkyla och sorptiv kylning. Samt perspektiv om resiliens tillämpat på kylsystem, byggnader, människor och samhället. En översyn av indikatorer (Key Performance Indicies, KPI) för byggnader inklusive dessas system och miljöer har genomförts.

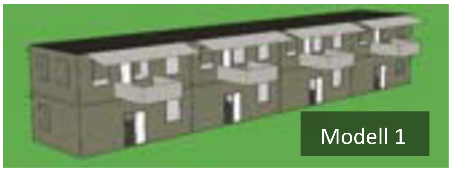
Medverkan i två av Annex 80's arbetsgrupper omfattade delaktighet i klimatdatagruppen och byggnadssimuleringsgruppen. Klimatdatagruppen framställde projicerade klimatfiler (typiska år inklusive värmeböljor) samt simulerade framtida byggnader som utsätts för projicerade klimatet för att utvärdera olika tekniker med hjälp av indikatorer (KPI).

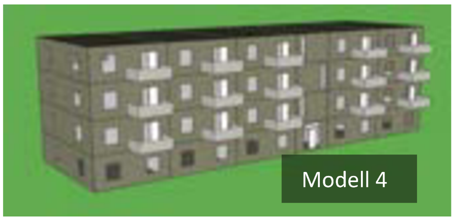
Vissa etapper av Annex 80 är vid föreliggande rapports skrivande inte färdiga i sin helhet. Dock informeras om kommande publikationer.

Tillämpning av indikatorerna har utförts på ett verkligt studieobjekt (Rådhuset i Gävle) för att utvärdera indikatorernas tillämpbarhet i anknytning till kylning av byggnaden.

Genomförande

Kylbehovet kartlades för blivande bostadsstadsdelen på Näringen i Gävle. Visst förarbete gjordes enligt (Gustafsson et al., 2021) med bland annat 6 modeller av representativa flerbostadshus. Dessa visas i Figur 2. IDA-ICE användes för att studera förekomsten av övertemperaturer, dels för nutida typiska år, dels för framtida projicerade typiska meteorologiska år (TMY) vilka framställdes med den metod som utvecklats inom IEA EBC Annex 80, se t ex (Machard et al., 2022); (Sayadi et al., 2021). Indata för normaliserad brukande har till beräkningar hämtats från BEN3 och SVEBY (2012), med underlag av minskat hushållsel i flerbostadshus med 30 %, hämtat från en undersökning av Westin (2019).





Modell	A_{temp} (m^2)	Antal lägenheter
1	400	4
2	945	12
3	1500	18
4	1700	20
5	2144	39
6	4000	53

Figur 2. Sex representativa byggnader för blivande stadsdelen. Gaveln på Modell 6 omfattar en mindre lokal (kontorsverksamhet).

Studier omfattade att anpassa byggnaderna för minimering av kylbehovet genom passiva metoder, t ex genom minskad fönsterarea i relation to golvarea, att nyttja reglering av ventilationens tilluftstemp för frikyla och rörlig solavskärmning, dvs att studera hur utformning och i viss mån passiva metoder inverkar på kylbehovet. Av stor vikt är vilka gränsvärden (innetemperaturer, framförallt med avseende på luft- och operativa temperaturer) som sätts, vilka kan uppfattas som någorlunda diffusa i svensk bygglagstiftning och rekommendationer eftersom dessa mer ställs som funktionskrav. Av denna anledning, parallellt med Annex 80's arbete om att ta fram indikatorer, har en översyn om hur andra EU-länder hanterar definitioner, gränsvärden, beräkningsmetoder och standarder.

Största kylbehovet uppstår under sommarhalvåret, vilket eventuellt skapar ett ökat elbehov. Nationella elbehovet är under sommarhalvåret lägre med en högre andel elproduktion baserat på flödande källor (sol och vatten). Primärenergifaktorer och växthusgasutsläpp, vilka oftast baseras på årliga medelvärden (mix), marginal vid elbrist (extremkyla utomhus) osv är möjligen inte representativa för sommarhalvåret. Dessa undersöktes utifrån nuläget och hur energisystemets sommarproduktion kan se ut år 2030. Arbetet har påbörjats genom att analysera historisk produktionsstatistik. I merparten av studier kring Näringen har Boverkets primärenergital med viktingsfaktorer enligt BBR29 använts. Framtagande av primärenergital skulle kunna utföras enligt metod föreslagen Karlsson et al. (2016).

Föregående etapper användes för att studera vilka lösningsalternativ för komfortkyla till nya stadsdelen (lokala respektive fjärrkyla) ger lägst resursanvändning (primärenergi), miljöeffekt (växthusgasutsläpp) och livcykelkostnadsanalys (LCC-analys) ur fastighetsägar- och energileverantörperspektiv.

Idag finns ett fjärrkylanät där kylmaskiner finns belägna i närheten av området där kylmaskinerna kyls med vatten från Gavleån, med möjlighet till frikyla därifrån. Jämförelser utförs med lokala kylmaskiner med och utan solceller samt lokala absorptionsvärmepumpar som drivs med fjärrvärme. Fokus ligger på hur flerbostadshusen ska kylas, eftersom nybyggda lokaler i regel har kylbehov som kan överstiga värmebehovet. Eftersom flerbostadshus förses med mekaniska ventilationssystem har undersökningarna förutsatt att dessa kan kylas genom kyld tilluft.

LCC-analyserna har baserats på en jämförelse mellan teknikerna. En kostnadspost som inte är medtaget, är distributionssystemen inom byggnaderna samt värmeväxlare som krävs för kylning av tilluften (vilka antas vara lika för teknikerna). I fallet där inverkan/behovet av VAV-system har studerats, dvs att ökade luftflöden behövs utifrån kylbehovet i förhållande till hygienisk ventilation, har dessa merkostnader i jämförelse med CAV-system inte medtagits eftersom de kan behövas oavsett kylteknik.

Resultatspridning bl a genom deltagande i IEA EBC Annex 80 *Resilient Cooling of Buildings*. Ett antal vetenskapliga publikationer har tillkommit i form av granskade artiklar i vetenskapliga tidskrifter och två konferenser med granskningsförfarande.

Resultat

I denna del presenteras en kombination av resultat från Annex 80 och för området Näringen. I viss mån sammanfattas även metoder som leder fram till resultaten.

Termiska innemiljön och gränsvärden

Komfortkylbehovet hos en byggnad uppstår när gränsvärden hos mätbara indikatorer inom innemiljön överskrids och för att undvika känslan av obehag/ohälsa hos personer som vistas i eller delar av byggnaden. Kylbehovet är därmed beroende av vilka kriterier som ställs. Byggreglerna har sin utgångspunkt utifrån Boverkets och andra myndigheters bestämmelser. Folkmyndighetens författningssamling (2014) anger att bedömning av olägenhet för människors hälsa i bostäder bör ske om lufttemperaturen är över 26 °C samt om operativa temperaturen varaktigt är över 26 °C under sommaren och kortvarigt över 28 °C. I R1 (EMTF, 2013) specificeras två klasser, TQ1 och TQ2 baserade på operativ temperatur enligt SS-EN ISO 7730, att rumstemperaturer (operativa temperaturer) över 26 °C accepteras under kortare perioder (sommarens varmaste dagar) respektive maximalt över 28 °C (sommarens varmaste dagar). Motsvarande värden för lokaler är att inom klassen TQ1 dimensionera för att hålla rumstemperaturen ca 3 °C lägre än utomhustemperaturen. I arbetslokaler föreslås att det kan vara rimligt att tillåta högre temperaturer under 80 arbetstimmar per år om inte andra projektspecifika krav ställs. Därutöver finns målvärden för golvtemperatur, begränsning av vertikal temperaturgradient och strålningstemperaturasymmetri samt dragrisk, vilka inte ingår i föreliggande studier.

Inom IEA EBC Annex 80 har en undersökning (Attia et al., 2023) utförts för att skapa en bild om vilka metoder och standarder, gränsvärden och nationella bestämmelser används för bostäder i olika medlemsstater inom EU, med avseende på övertemperaturer och kylbehov. Resultaten är spretiga. Härmed nämns några kriterier för hur överhettning definieras i grannländer: I Norge anges att när indikatorn operativ temperatur överskridit 26 °C i totalt 50 timmar, fås överhettning; i Danmark, när operativa temperaturen 27 °C överskrids maximalt över 100 timmar och är över 28 °C i 25 timmar per år; i Finland, när lufttemperaturen 27 °C överskrids med 150 °Ch (med adaptiv termisk komfortmodell) i flerfamiljsbostäder med mer än två våningar – i övrigt är gränsvärdet 32 °C.

I ett led att harmonisera beräkningsmetoder och analyser av termisk komfort och kylbehov, har ett konceptuellt ramverk tagits fram (Attia et al., 2021; Rahif et al., 2022). Här ges en kort översikt: Annex 80 föreslår att gränsvärden och beräkningsmetoder åtskiljs beroende om ventilationssystemet är mekaniskt eller naturligt. Det finns två komfortmodeller i ISO 17772-1 (ISO, 2017a). Den ena är en PMV-PPD baserad modell (statisk) som är tillämpbar för byggnader med mekanisk ventilation (med begränsad möjlighet att öppna fönster) och den andra en adaptiv modell för byggnader med naturlig ventilation (Attia et al., 2021); (Zhang et al., 2021); (Zhang et al., 2023). När byggnader utsätts för värmeböljor utan och eventuellt med strömavbrott, bör Standard effective temperature, SET enligt ASHRAE 55-2017, tillämpas för temperaturer över gränsvärdet 30 °C där PMV-PPD-modeller inte är tillämpbara. SET tar hänsyn till människors tolerans för höga lufttemperaturer bland annat med hänsyn till luftfuktighet, i form av termisk stress där hälsan kan äventyras.

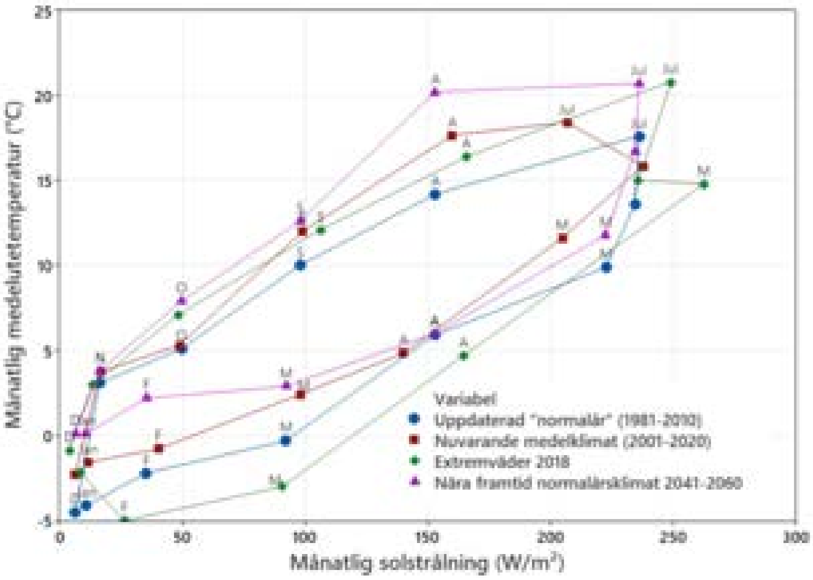
Annex 80 har även framstället en lista över indikatorer (Key Performance Indicators, KPI's) för kvantifiering av kylbehovet, energianvändning, termiska inneklimatet och byggnadens resiliens, dessa sammanfattas i en tabell, se Bilagor. För att kvantifiera resiliens, kan man använda följande KPI:er. Några fler som är relaterade till termisk komfortmätning har också använts. Dessa är Indoor Overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*), and Overheating Escalation Factor (*αIOD*). *IOD* kvantifierar och viktar lokala övertemperaturer över tid i förhållande till brukarnas närvaro. *AWD* indikerar hur allvarligt utetemperaturen överskrider en definierad referensutetemperatur, schablonmässigt satt till 18°C. α_{IOD} är ett mått på byggnadens möjlighet att minska värmestressen som utomhusluften medför över längre tid och därmed ett mått på byggnadens och dess systems resiliens. Annual Exceedance Hours (Unmet hours) är ett mått på antalet timmar som temperaturen överskrider ett målvärde, baserat på PMV/PPD. Därutöver anges kylbehovet i form av energistorheter (specifikt behov, primärenergi) såsom kWh/m², år och W/m². Köld- och värmefaktor samt koldioxidekvivalent $kgCO_2e/m^2$ utsläpp, med mera. (Attia et al., 2021; Rahif et al., 2022).

Framtida klimatet

För att undersöka en byggnads dynamiska energiprestanda krävs väderdata per timme eftersom det betraktas som det yttre randvillkoret inom byggnadssimulering. Ett typiskt meteorologiskt år (TMY) innehåller 8760 timmar baserade på fleråriga data sammanställda för att projicera det framtida klimatet. I Annex 80 har en teknik för projicering utgått från en metod som beskrivits av Machard et al. (2022). European Coordinated Regional Downscaling Experiment (EURO-CORDEX) används för att framställa projicerande klimatfiler. Data laddas ner från Earth System Grid Federation (ESGF, u.å.). Klimatvariabler för den europeiska domänen med Representative Concentration Pathway (RCP) 8.5 valdes som socioekonomiskt scenario. Data extraherades och bias-korrigerades mot 20 års timobservationsdata. Bias korrigeringsmetoden baseras på multivariate bias correction algorithm (MBCn), en metod introducerad av Cannon (2016; 2015). Metoden hjälper till att länka klimatet simulerat av Regional Climate Model (RCM).

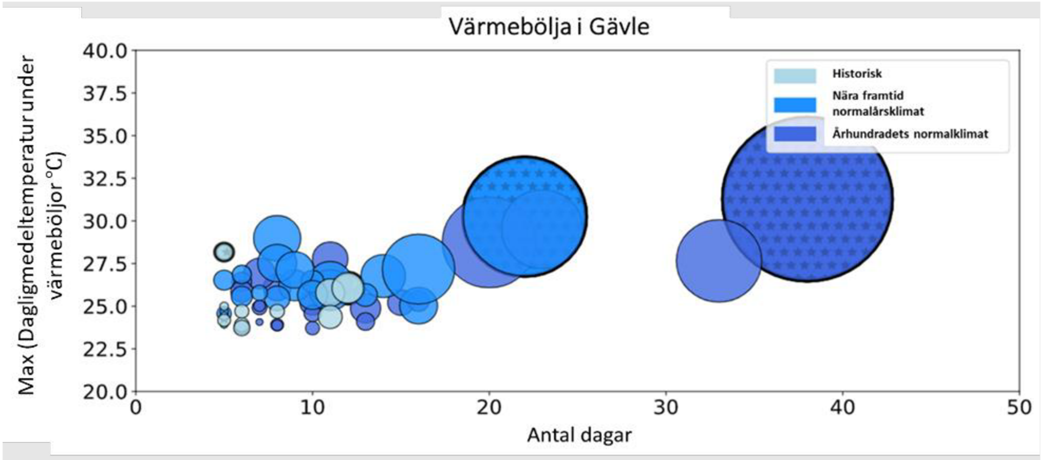
I Figur 3 visas resultat (Sayadi et al., 2022a; 2022b) om förändringarna av utelufttemperatur kontra solstrålning för olika typiska år: ”extremt” klimat med värmebölja i 2018 och Sveby's typiska år baserat på historiska data från 1981–

2010 i Gävle. Månatliga medelvärden indikerar att förändringarna hos solstrålningen försumbara; dock har temperaturer ökat. Man kan dra slutsatsen att byggnaders kylbehov framförallt kommer att påverkas av ändringar hos omgivningstemperaturen. Klimatförändringarna är kraftigare under sommaren (maj-augusti). Årsmedeltemperaturen är för nuvarande typiska året (baserat på 1981–2010) 5,8 °C medan medeltemperaturen för Nuvarande medelklimatet (baserat på 2001–2020) och Nära framtid typiskt klimat (2041–2060) är 6,9 respektive 8,8 °C. Observera att dessa data inte innehåller värmeböljor.



Figur 3. Månatliga medelvärden för utetemperaturer och solstrålning mot horisontell yta för tre olika perioder (TMY) och för året 2018 i Gävle. Diagram från (Sayadi et al., 2022a).

Projicerade värmeböljor för Gävle stad har också studerats, och i Figur 4 presenteras temperaturomfång och varaktighet för dessa värmeböljor under tre olika tidsperioder. Dessa perioder omfattar det historiska spannet (2000–2020), det närmaste normalåret (2041–2060) och i slutet av århundradet (2081–2100). Dessa värmeböljor identifierades genom användning av specifika tröskelvärden, såsom när omgivningstemperaturen översteg 25 °C under en period längre än fyra på varandra följande dagar. Man kan jämföra de ljusblåa bubblorna (de som representerar de senaste gångna åren) med de framtida, mörkare blå färgtonerna. Extremvädret från sommaren 2018 återfinns bland de ljusblåa färgtonerna. Vid seklets slut är de mörkblå cirklarna större och representerar högre temperaturer samt fler dagar för värmeböljornas varaktighet. Detta understryker vikten av att ta hänsyn till framtida klimatdata, särskilt i sammanhang som rör beslutsfattande och utformning av byggnaders resiliens.

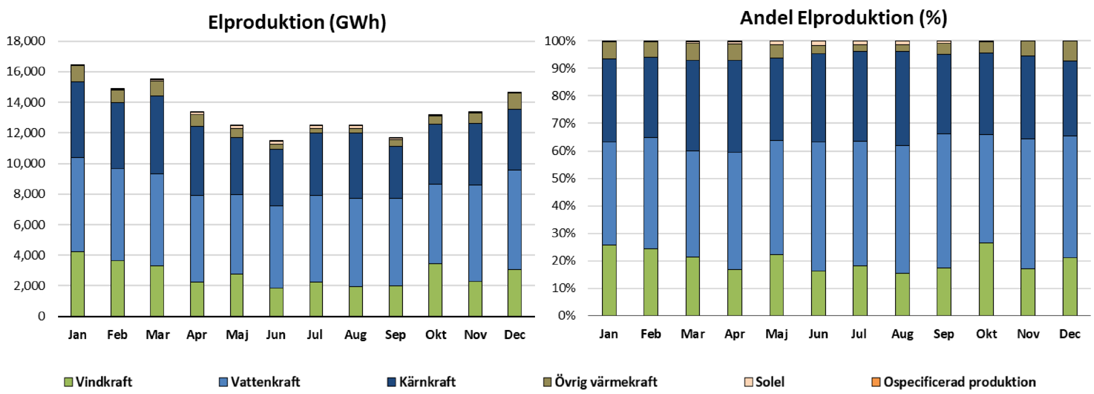


Figur 4. Bubbeldiagrammet som visar antalet värmeböljor och dessas intensitet och varaktighet under tre klimatperioder.

Primärenergi faktorer

Elektricitet

Under 2017–2020 togs fyra kärnkraftreaktorer ur bruk, varvid 4 kvarstår och avses vara i drift till 2040. Detta innebär stora förändringar i Sveriges energisystem. Men elbehovet är nationellt sett lägre när behovet av aktiv kyla är störst. I figur 5 visas statistik för 2022 som ett exempel. Data har hämtats från Svenska kraftnäts "kontrollrummet" (Svenska Kraftnät, u.å). Enligt figuren delas produktionen upp i olika kraftslag såsom vind-, vatten-, sol-, och kärnkraft. Övrig värmekraft innebär produktion från värmekraftverk exkluderat kärnkraft eller reservkraft oavsett bränsleslag (kol, olja, träbränslen, sopor, etc.). Ospecificerad produktion inkluderar produktion/inmatning av el från anläggningar som har fler än ett produktionsslag, återmatningsenergi från järnvägsdrift, nettoberäknad produktion där inte mätning finns på generatorn (inom icke koncessionspliktigt nät) etc. Gasturbin och dieselkraft (reservkraft) är försumbart och har exkluderats från diagram. Enligt figuren är den totala elproduktion lägst under sommaren, med lägre produktion av vindkraft och i viss mån kärnkraft.



Figur 5. Elproduktion, 2022 delad per olika kraftslag, presenterat både per mängd TWh och procentuell andel på månatlig basis.

Baserat på detaljerade energiproduktionsdata från (Energiföretagen, u.å.) och (Svenska Kraftnät, u.å.) och med primärenergifaktorer enligt Boverkets *Konsekvensutredning BFS 2020:4* (Boverket, 2020) metodik, fås för svensk elmix under året 2022 primärenergifaktorn (PEF) 1,61. Jämförelsevis gav Boverkets konsekvensutredning för referensfallet 2021 värdet 1,66 på årsbasis. Utförs beräkningen för en säsongsvis PEF, fås för sommaren 2022 (juni, juli och augusti) värdet 1,65. Som framgår av resultatet, är PEF aningen högre under sommaren på grund av mer solkraftproduktion samtidigt som andelen hos värmekraft och framförallt vindkraft är lägre. I princip ser månatliga andelsfördelningen för åren 2020–2022 likartade, vilket pekar mot en svag ökning av PEF under sommarsäsongen.

Inför 2030 kommer varken kärn- eller vattenkraftens andel öka med hänsyn till utbyggnadstakt. Utifrån att nya vindkraftsparker och solkraftsanläggningar byggs upp och tas i drift torde andelen vatten- och kärnkraft minska, vilket marginellt påverkar sommarsäsongens PEF (primärenergifaktorerna för vind-, vatten- och solkraft är 1,05, 1,10 respektive 1,25). Slutsatsen blir att sommarsäsongens PEF kan för svensk elmix approximeras vara försumbart högre än årsmedelvärdets PEF nu och fram till 2030.

Med hänsyn taget till Östersjöregionens elproduktion vari Sverige är nettoexportör men importerar el, har Boverket satt viktningsfaktorn på el till 1,8 som kan sjunka till 1,7 tills året 2030. Värdet 1,8 har använts i våra studier.

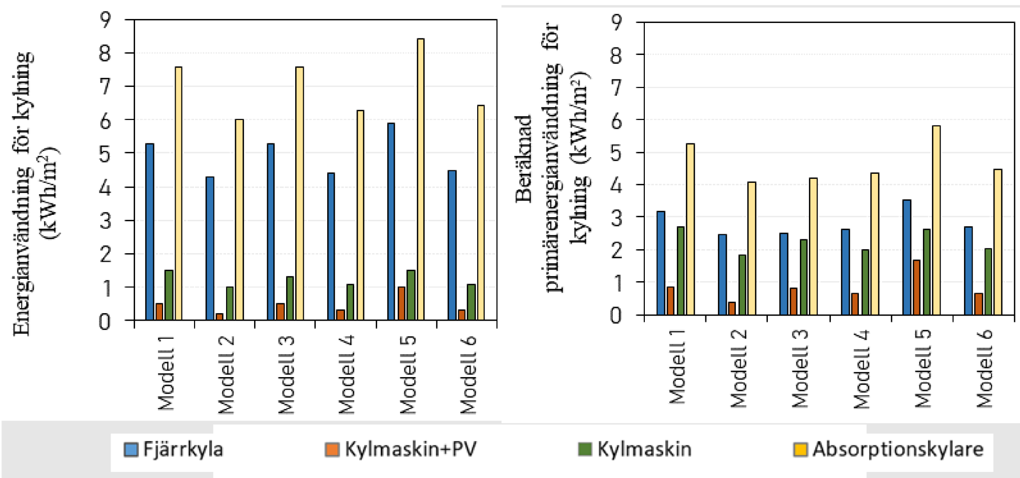
Primärenergianvändning för de olika kylteknikerna

Resultat för använd energi för kyla respektive beräknad primärenergianvändning under juni–augusti visas i Figur 6 för var och en av prototypbyggnaderna som presenterades i Figur 2 för projicerade typiskt klimat ("nära framtid" 2040-2060). Graferna har hämtats ur Sayadi et al. (2023). Figur 6 (till höger) visar den beräknade primärenergianvändningen under kyl perioden (juni–augusti) för varje byggnadsmodell och de implementerade kylteknikerna. Den totala energianvändningen (uppvärmning och komfortkyla) för varje teknik samt byggnadsmodell per uppvärmd golvarea visas i Tabell 1. Figur 7 visar den totala beräknade primärenergianvändningen för hela året för varje modell och de implementerade kylteknikerna. För att beakta den beräknade primärenergianvändningen för kylsäsongen, har primärenergifaktorer använts från Boverkets (2020) sätt att beräkna primärenergins viktningsfaktorer.

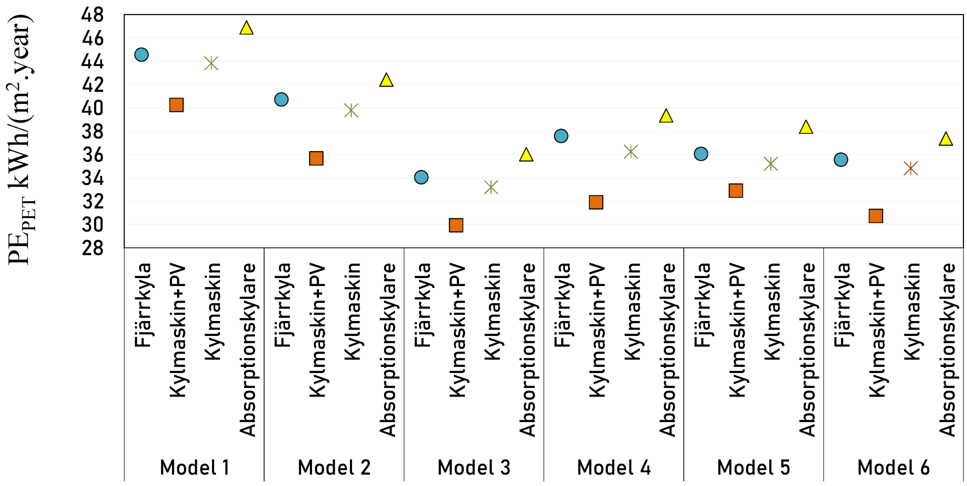
Tabell 1: Totala energianvändning för varje teknik samt byggnads modell (kWh/m²)

Modell	Fjärrkyla	Kylmaskin+PV	Kylmaskin	Absorptionsvärmepump
1	60,2	54,4	54,6	62,5
2	53,7	47,8	50,8	55,4
3	45,3	39,6	41,4	47,5
4	48,9	43,4	45,6	50,8
5	46,1	40,7	41,7	48,6
6	46,0	40,4	42,6	47,9

Som framgår i Figur 6 är både energianvändning och primärenergianvändning för kylsäsongen höst för absorptionskylaren och lägst för kylmaskin + PV för varje byggnadsmodell. När det gäller kylmaskin + PV, hjälper elektriciteten som produceras av solcellsinstallationen till att minska energin som används för kylning. Från de erhållna resultaten i Figur 6 (höger) kan man dra slutsatsen att den viktningsfaktor som beaktas för fjärrkyla underskattar köldfaktorn (COP-/EER-värdet). Boverkets viktningsfaktor är 0,6 för fjärrkyla (vilken implicit indikerar en köldfaktor med beloppet 3) och en lägre i storleksordningen 0,3 skulle kunna antas för fjärrkyla systemet med tanke på möjlig tillgänglig fri kyla i fjärrkyla nät (Energiföretagen Sverige, 2018) och stordriftens fördelar som vattenkylda kylmaskiner medför. Detta innebär att de blå staplarna i Figur 6 (höger) för fjärrkyla skulle halveras och medföra lägre primärenergianvändning än kylmaskiner men högre än kombinationen av kylmaskin och solceller.



Figur 6. Använd energi för kylning (vänster) och uppskattad säsongsbunden primärenergianvändning för juni-aug (höger) för de studerade byggnadsmodellerna och kylteknikerna



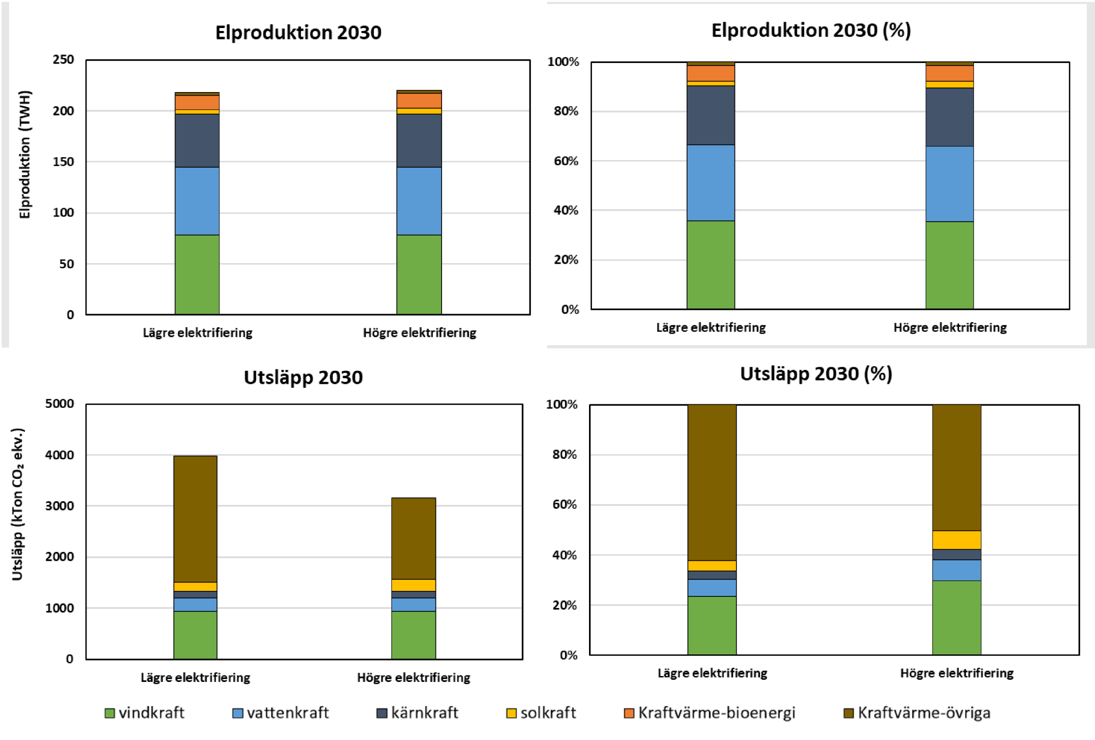
Figur 7. PE$_{PET}$ för de undersökta teknikerna, fjärrkyla, kylmaskin + PV system, kylmaskin och absorptionskylare för var och en av prototypbyggnadsmodellerna under ett helt år.

Koldioxidsekvivalentutsläpp

Vindkraft, vattenkraft och kärnkraft avger 12, 4 och 2,5 gram koldioxid per kilowattimme (Ygeman, 2021). Och mera elproduktion tillförs från fossilfria källor, till exempel, Vattenfalls elförsäljning är spårbar med ursprungsgarantier för sol- och vindkraft, vattenkraft och kärnkraft med en andel på 3, 45 respektive 51% med nästan noll CO2-utsläpp under driftstid för året 2022. Detta tack vare att fossila energikällor nästan har eliminerats (Vattenfall, u.å.). Utifrån de föreslagna energiscenarierna från Energimyndigheten (2023) har dessa källor ett annat bidrag till den totala elförsäljningen år 2030. För att få en överblick på det svenska koldioxidutsläppet baserat på de senaste rapporterna visas Figur 8. I scenario med lägre (Lägre) eller högre (Högre) elektrifieringstakt är den totala elproduktionen 218 alternativt 220 TWh år 2030. I Högre elektrifieringsscenariot sker en omfattande elektrifiering i samhället som en del av omställningen för att nå klimatmålen. I Högre elektrifiering antas utvecklingen av elektrifieringen i Norden och även i EU vara högre än i Lägre elektrifiering (Energimyndigheten, 2023). I båda fallen visar resultatet att CO2e-utsläpp varierar mellan ca 7,0 till 16,3 g/kWh utan och med fossila bränsle i kraftvärmens elproduktion. Figur 8 visar utsläpp inklusive kraftvärmeverk med ca 3,2 TWh fossila bränsle år 2030. Detta kan jämföras med Svenskproducerad el som har ett växthusgasutsläpp på runt 13 gram CO2-ekvivalenter per kWh (Vattenfall, 2020). För att beräkna utsläpp av svensk elmix i år 2030 har emissionsfaktorer använts för vind-, vatten-, kärn-, solkraft samt kraftvärme (bioenergi) och kraftvärme (övriga fossilberoendebränsle) enligt Tabell 2 (Sveriges riksdag, 2020) och (Energimyndigheten, u.å.).

Tabell 2. Elproduktionskällor och deras respektive koldioxidutsläpp (Sveriges riksdag, 2020) och (Energimyndigheten, u.å.)

Elproduktionskälla	CO_2 ekvivalent (g/kWh)
Vindkraft	12
Vattenkraft	4
Kärnkraft	2,5
Solkraft	41
Kraftvärme-bioenergi	0
Kraftvärme-övriga	850
Svensk elmix (g/kWh)	16,3



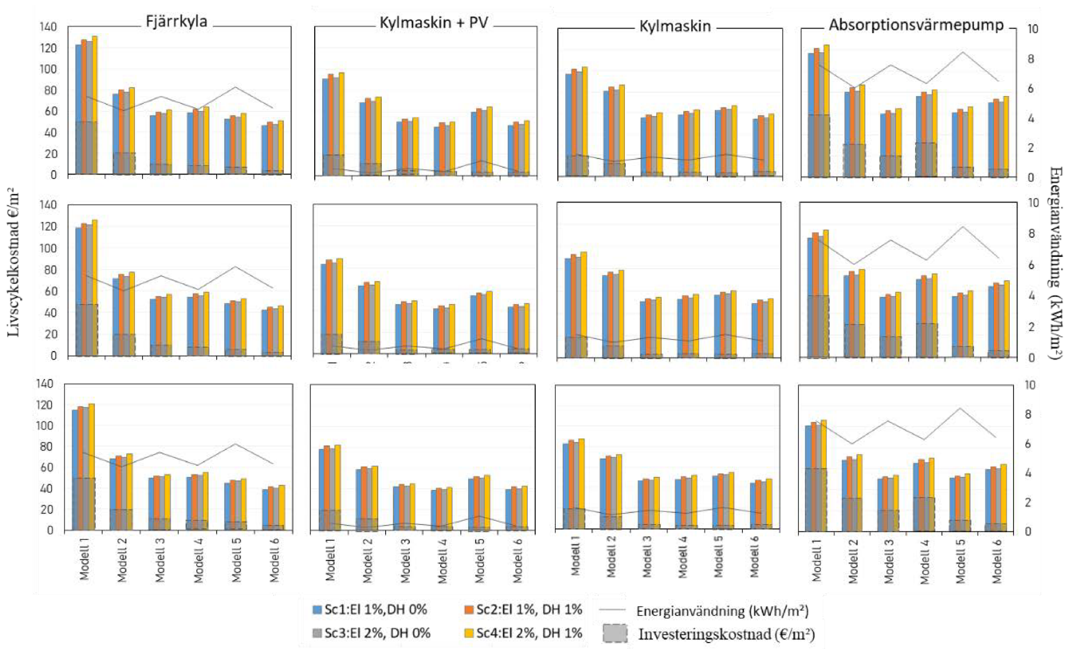
Figur 8. Översikt över elproduktion och respektive koldioxidutsläppsår 2030.

Emissionsfaktorn för fjärrvärme har lokalt visat en stor minskning under det senaste decenniet med ett värde på 37 gCO_2e/kWh året 2010 till 4 gCO_2e/kWh år 2021 för Gävle (Gävle Energi, u.å.) och den förväntas minska ytterligare. Det är dock mer komplicerat att genomföra en bedömningsanalys för ett kylsystem. Svenskt elnät är anslutet till andra länder (Norge, Finland, Danmark, Tyskland och Polen). De tillgängliga historiska utsläppsfaktorerna visar minskningen av CO_2-utsläpp från i genomsnitt 133 gCO_2e/kWh i början av 2000-talet (Eriksson et al., 2012) till 90,4 gCO_2e/kWh under 2020-talet (Sandgren et al., 2021).

Ekonomisk analys

En livcykelkostnadsanalys över en period på 25 år har tillämpats utifrån att kylmaskiner, värmeväxlare, ventilationssystem, etc. har ungefärlig sådan livslängd. I beräkningarna har reala prisökningar och reala diskonteringsräntor använts för att eliminera inverkan av inflation. Därutöver är priser baserade på nivåer som fanns innan kriget i Ukraina, vilket har bidragit till oförutsed ökning av inflation och framförallt energipriser. Kostnader beräknades i svenska kronor (SEK) för att sedan omvandlas till Euro (€) med kursen 10:1. Energibehoven baseras på projicerat typiskt år ("nära framtid").

Figur 9 visar resultatet av livscykelkostnadsanalysen från (Sayadi et al., 2023). De tre raderna med diagram avser olika reala kalkylräntor: uppifrån och ner är dessa 3, 4 respektive 5 %. Vänstra axeln visar livscykelkostnader per kvadratmeter A_{temp} för respektive byggnadsmodell som kyls med fjärrkyla, kylmaskin i kombination med solceller, enbart kylmaskin och absorptionsvärmepump. Högra axeln visar specifik energianvändning för varje system (grå linje) - observera att beloppen avser olika energislag (el- eller termisk energi). Scenarier 1 till 4 handlar om hur elens (El) respektive fjärrvärmens (DH) prisökning (procent per år) inverkar på livscykelkostnaden.



Figur 9. Livscykelkostnadsanalys för de studerade byggnadsmodellerna, reala diskonteringsräntor 3, 4 och 5 % (figurrader 1–3) samt olika reala prisökningsscenarier (El avser elektricitet, DH avser fjärrvärme), för fjärrkyla, kylmaskin med och utan solceller samt absorptionskylare.

Generellt visar resultaten på att byggnadernas storlek har inverkan på lönsamheten, oavsett teknik. Mindre byggnader är dyrare att kyla, dels med anledning att investeringskostnaden per kvm golvarea är högre, dels beroende på att mindre byggnader har relativt större transmissionsegenskaper per kvadratmeter golvarea. Fjärrkylans specifika behov avspeglar byggnadernas kylbehov, vilka grovt ligger på 4 - 6 kWh/m^2,år hos byggnader som utsätts för typiskt nära framtida klimat. Framtida värmeböljor, vilkas inverkan inte har studerats hittills, kommer naturligtvis medföra ett ökat kylbehov.

Livscykelkostnadsskillnaderna mellan fjärrkyla och kylmaskiner är små, men indikerar att kylmaskiner är lönsammare för mindre byggnader medan fjärrkyla blir lönsammare ju större byggnaden är.

En intressant aspekt är att absorptionsvärmepump har marginellt högre kostnad än fjärrkylans och lägre för den minsta modellen samt jämbördigt för modeller 2 och 3, samt i paritet med mellanstor byggnad som förses med kylmaskin. Det här gör att absorptionsvärmepumpen kan vara en konkurrenskraftig framtida teknik, förutsatt att dessas investeringskostnader (inköpskostnader) minskar och att verkningsgraden ökar. Härmed konstateras att elpriserna har ökat markant i och med geopolitiska läget (Ukrainakriget) inom EU efter att dessa resultat framställdes. Elpriserna påverkar direkt både fjärrkylans och kylmaskinernas drift- och därmed livscykelkostnad.

Diskussion

I denna del diskuteras resultaten och kopplar dessa till hur olika organisationer och aktörer kan samverka kring implementering av kyla i bostäder.

Att bestämma kylbehovet

Gränsvärden och beräkningsmetoder för att bestämma behovet av komfortkyla i bostäder och dimensionera kylsystemen är idag otydliga. Till skillnad mot värmebehovet och kriterier på minimitemperaturer samt beräkningsmetoder (t ex dimensionerande vinterutetemperatur DVUT), saknas motsvarande för kylning av byggnader. I vissa EU länder finns kvantifierbara definitioner om vad som räknas som övertemperatur samt dess intensitet och varaktighet. I anknytning till att en byggnads energiprestanda predikteras och kvantifieras enligt BBR och BEN3, utförs dynamiska timvisa simuleringar med typiska/normalår vilka baseras på historisk statistik. Här bör övervägas om det här är korrekt strategi för att värdera termisk- och energiprestanda för nya eller renoverade (ombyggnad) byggnader, vilka kommer att finnas i minst 100 år framöver, inte kan utföras för att möta framtida belastningar på ett bättre sätt. Alternativa projicerade (syntetiska) klimatdata kan därmed innehålla värmeböljor för att uppskatta både normal framtida komfortkyla och den kyleffekt som kan bli aktuellt vid värmeböljor. Både Boverket och Folkhälsomyndigheten är viktiga myndigheter vars föreskrifter kan styra hur byggnader bereds inför framtida klimatförändringarna, samt organisationer som tolkar och informerar om författningarna samt ställer skarpare nivåer än minimikraven, t ex SVEBY, BEBO, BELOK, Lågan och Passivhuscentrum. Dessa frågor ligger i linje med Annex 80 generella ställningstagande och för svenska situationen enligt Tillberg (2022) och Nik et al. (2022). Härmed sammanfattas rekommendationer för fastställande av byggnaders kylbehov:

1) Tydliga definitioner för gränsvärden med avseende på övertemperaturer, dessas intensitet och varaktighet, bör fastställas.
2) En genomarbetad strategi om vilken/vilka typer av klimatdatafiler bör/kan användas med tillhörande beräkningsmetoder bör utarbetas.
3) En uppdatering om hur internvärmen ser ut idag och hur den kan komma att förändras i framtiden bör undersökas.
4) Harmonisering om hur kylbehovet kan fastställas i ett föränderligt klimat, med hänsyn taget till beteenden, t ex vädring, samt hur begreppet resiliens kan definieras utifrån svenskt perspektiv.

Härmed påpekas att interna värmekällor avseende hushållsenergi i föreliggande arbete inte har modellerats enligt SVEBY’s (2012) brukarindata, vilka bl a baseras på användningen av belysningsglödlampor och äldre hushållsapparater. Istället användes Westins (2019) statistik, vilka ligger ca. 30 % lägre än SVEBY’s värden i och med att teknikutvecklingen medfört effektivare hushållsapparater och belysning, som i sin tur minskar kyleffektbehovet. Samtidigt har det framkommit i diskussioner inom Annex 80, att det internationellt saknas forskning kring prediktioner om hur internvärmekällorna i bostäder och lokaler kan komma att se ut i framtiden.

Hur byggnader egentligen används har stor inverkan på dess energibehov, så att en lokal används i möjligaste mån. Till exempel kan kontors- och skollokaler inrymma annan verksamhet utöver normal arbetstid, som avviker från byggnadens ”normaliserade” energibehov (Carlander et al., 2020). Olika standarder ger olika energibehov, såsom visas av Ferrari et al. (2023).

Passiva metoder

Minimering av kylbehovet ligger i att utforma byggnaden med passiva system för att minimera kyla som aktivt tillförs byggnaden. Ett exempel är att minimera solinstrålningen med yttre avskärmning såsom lämpligt placerade utkragade balkonger eller markiser, dvs fasta eller rörlig solavskärmning. Rörlig solavskärmning minskade kylbehovet med 3-5 kWh/m², år (Sayadi et al., 2022a) vilket ligger i linje med Ylmén och Schade’s undersökning (2021). Ett annat är genom att ha lägre g-värde hos fönster, men som medför att byggnadens värmebehov ökar under eldningssäsongen samt behovet av belysning. Ny teknik, såsom elektrokroma fönster, se (Andersson & Lindberg, 2021) vilka har två g-värden är intressanta att följa men tekniken kan anses vara dyr idag.

För att finna, tillämpa och utforma byggnader med passiv teknik för att minska kylbehovet krävs att aktörer inblandade i byggnadens programskede, gestaltnings- och projekteringsfaser har fokus på att minimera risken för överhettning och minska risken för ökat kylbehov redan i början av ett byggprojekt. Byggherren, arkitekten och konsulten måste ha en tydlig bild om kraven som ställs på byggnaden under sommarsäsongen, utifrån risk för övertemperaturer och behovet av aktivt tillsatt kyla. Här finns alternativet att sätt in lokal kyla där individen vistas istället för att kyla hela utrymmet/byggnaden (Zhang et al., 2021). Det kan även bli aktuellt med någon form av “plan B”, som diskuteras inom Annex 80, där det i händelse av en värmebölja i kombination med elavbrott bör finnas möjlighet för brukarna att förflyttas till delar av byggnaden där den termiska miljön kan tillfälligt säkerställas eller att det kan tillhandahålls små batteridrivna personliga/portabla fläktar. Men planerna kan även omfatta att fastighetsägaren på sikt ska kunna förse byggnaden/byggnader med kylsystem eller att befintliga kan förses med högre kylkapacitet, dvs förbereda för att ha utrymmen och rör/kanaler som kan distribuera kyla från system som installeras/uppgraderas i framtiden.

Aktiva kylmetoder

En utgångspunkt för kylning av framtida bostäder, är att dessa förses med mekaniska ventilationssystem. Därmed blir ventilation genom kylning av tilluften ett naturligt steg i byggnader med FTX-system, trots att större kyleffekter inte kan uppnås med denna teknik (Nik et al., 2022) utifrån att ventilationsflöden inte varieras i bostäder eller har tilluftsdon som minskar risken för drag. Detta insinuerar planering för att bostäder i framtiden förses med kylbatteri, teknisk isolering och VAV (variabla flöden, som bl a kräver större dimensioner på kanaler). I ett av projektets första studier (Sayadi et al., 2021) modellerades ett prototyphus för att studera inverkan av fönsterstorlek i förhållande till golvarea, rotation av byggnaden samt ventilationsstrategi. I ventilationsstrategin förvärmdes tilluftstemperaturen allt mindre genom värmeväxling med frånluft, när utetemperaturen stiger över byggnadens balanstemperatur. I det här fallet var balanstemperaturen 8 °C, varvid ökande innetemperaturer fås för högre utetemperaturer – när utetemperaturen når 16 °C. Denna strategi medför temporärt låga tilluftstemperaturer som kan medföra drag.

Solel

I anknytning till bostäder är solcellsteknik intressant och antalet installationer ökar kraftigt. En förutsättning för att en solcellsinstallation ska vara lönsam, är att egenkonsumtionen maximeras. Solcellsinstallation blir lönsammare för dem som har högre elanvändning under sommaren tack vare en större andel egenanvändning av producerad el. Utifrån fastighetsägarperspektivet är en kombination av lokal kylmaskin och solceller en attraktiv ekonomisk lösning, särskilt för mindre fastigheter. Det finns dock begränsningar om hur mycket el som en organisation kan producera för att inräknas som mikroproducent (43,5 kW).

I föreliggande arbete har ekonomiska beräkningarna omfattat egenförbrukning och ”export” där fastighetsägaren innehar kylmaskin och solceller. Men konceptet att fastighetsägare upplåter ytor för installation av energileverantörens solcellspaneler kan vara ett alternativ för fastighetsägare, oavsett att fastigheten har fjärrkyla, egen kylmaskin eller ingendera. Ett exempel på hur detta kan lösas är enligt följande: Gävle Energi AB (GEAB) är det kommunala energibolaget i Gävle och i deras produktportfölj ingår att sälja solcellsanläggningar till privatpersoner och företag i kommunen. Gavlefastigheter AB (GFAB), som är ett kommunalägt fastighetsbolag i Gävle, har under en längre tid satsat på solcellsanläggningar på sina fastigheter. En del av anläggningarna har uppförts med PPA-avtal (Power Purchase Agreement) mellan GFAB och GEAB. Det innebär att GEAB installerar solcellsanläggningar på GFABs tak. Ägandet av anläggningarna och därmed service och underhåll ligger juridiskt hos GEAB men GFAB köper den producerade elen till ett överenskommet pris. Det främsta skälet till affärslösningen är ett generellt mer problemfritt nyttjande av solcellsanläggningar för GFAB men också att svensk skattelagstiftning medför en ökad administrativ börda för ägare av solcellsanläggningar med en totalt installerad solcellseffekt överskridande 500 kW_p. GEAB som energibolag har dock redan rutiner för den ökade administrationen.

I befintlig bebyggelse finns hinder i detaljplaner för implementering av solceller, men inom framtida stadsdelar bör solceller vara en naturlig del av bebyggelsens utformning. Solcellsteknikens estetiska uttryck är i kontinuerlig utveckling. Här är det viktigt att samhällsplanerarna möjliggör installation av solceller, oavsett om paneler sätts på byggnader eller på ställningar i t ex omgivande grönområden. Hur solceller kan bidra till minskad inverkan på urbana värmeöar genom att omvandla en andel av solenergin till el istället för värme, jämfört med andra tekniker (t ex gröna tak med utökad biologisk mångfald och fasader, solreflekterande beläggningar), eller en kombination av dessa, ger uppslag för vidare forskning.

Teknik som används i detta projekt

Tre olika kyltekniker valdes för att utvärdera deras prestanda i det undersökta området: fjärrkyla, kylmaskiner med/utan solcellssystem (PV) och absorptionskylare. Utifrån resultaten av primärenergianvändning och livscykelkostnader framstod kylmaskin med ett PV-system som fördelaktig hos mindre byggnader, då denna teknik uppvisade de lägsta värdena för både primärenergianvändning och livscykelkostnad. Jämfört med kylaggregatet utan PV-system minskade primärenergianvändningen och livscykelkostnaderna i genomsnitt med 13%. Fjärrkyla är dock fördelaktigare ju större byggnaderna är.

Primärenergianvändning avgörs av viktningsfaktorn, som är 0,6 för fjärrkyla vilket kan anses vara betydlig lägre ca 0,3 med tanke på möjlig tillgänglig fri kyla i fjärrkyla nät. Att använda en högre viktfaktor innebär dessutom en sämre prestanda hos fjärrkylans centraler, där vatten med kallare temperaturer än omgivande luft används för att avlägsna värme, vilket behöver utredas i framtiden. Dessutom visades att fjärrkyla kan ha ekonomiskt fördelaktigt alternativ för byggnader med stora golvytor.

Publikationslista

Publicerade vetenskapliga artiklar

Sayadi, S., Akander, J., Hayati, A., Gustafsson, M. & Cehlin, M. (2023). Comparison of space cooling systems from energy and economic perspectives for a future city district in Sweden. *Energies*, 16(9). https://doi.org/10.3390/en16093852

Artikeln behandlar fallstudien Näringen, Gävle, och utgör en viktig del av projektet. Här studeras hur komfortkyla lämpligen kan förses till bostaden: genom fjärrkyla eller lokala kylmaskiner/lokala absorptionsvärmepump. Ur ekonomisk synvinkel är byggnadens storlek av vikt – lokala kylmaskiner är lämplig för mindre byggnader och fjärrkyla för större byggnader, dvs ungefär som läget ser ut i nutid.

Sayadi, S., Akander, J., Hayati, A. & Cehlin, M. (2022). Analyzing the climate-driven energy demand and carbon emission for a prototype residential nZEB in central Sweden. *Energy and Buildings*, 261, 111960. https://doi.org/10.1016/j.enbuild.2022.111960

Artikeln behandlar ett tilltänkt flerbostadshus i Näring, Gävle, som byggs i snar framtid enligt innevarande byggregler (BBR29). Byggnaden exponerades för ett typiskt år och två framtida projicerade klimat (TMY) samt året 2018 med en extremsommar. Trots att kylbehovet är litet så kommer det att öka i framtiden, upp till 5 gånger mer. Solavskärmning (här i form av markiser) har stor betydelse för att minska behovet samt att nyttja utelufts kylande verkan där ventilation med variabla flöden har en fördel.

Miller, W., Machard, A., Bozonnet, E., Yoon, N., Qi, D., Zhang, C., Liu, A., Sengupta, A., Akander, J., Hayati, A., Cehlin, M., Kazanci, O.B. & Levinson, R. (2021). Conceptualising a resilience cooling system: a socio-technical approach. *City and Environment Interactions*, 11, 100065. https://doi.org/10.1016/j.cacint.2021.100065

Denna artikel har sin utgångspunkt i att studera vad och hur resiliens definieras inom andra ämnesområden. Utsätts system för, i värsta fall katastrofer (långvariga värmeböljor med eller utan elavbrott), så brukar lärdomar efter återhämtningstiden implementeras för att minska risken för att liknande händelser sker i framtiden. En modell för kylsystem och dessas eventuella energiförsörjning (el) presenteras för att definiera villkoren för resiliens utifrån föränderligt klimat och andra faktorer som riskerar medföra övertemperaturer.

Zhang, C., Kazanci, O.B., Levinson, R., Heiselberg, P., Olesen, B.W., Chiesa, G., Sodagar, B., Ai, Z., Selkowitz, S., Zinzi, M., Mahdavi, A., Teufl, H., Kolokotroni, M., Salvati, A., Bozonnet, E., Chtioui, F., Salagnac, P., Rahif, R., Attia, S., Lemort, V., Elnagar, E., Breesch, H., Sendgupta, A., Wang, L.L., Qi, D., Stern, P., Yoon, N., Bogatu, D.I., Rupp, R.F., Arghand, T., Javed, S., Akander, J., Hayati, A., Cehlin, M., Sayadi, S., Forghani, S., Zhang, H., Arens, E. & Zhang, G. (2021). Resilient cooling strategies – A critical review and qualitative assessment. *Energy and Buildings*, 251, 111312. https://doi.org/10.1016/j.enbuild.2021.111312

Litteraturöversikten om olika tekniker för att minska övertemperaturer och kylbehov är indelat i fyra kategorier: att minska överhettning på grund av yttre faktorer, såsom solstrålning, solinstrålning, varm uteluft, etc.; tekniker för att avlägsna värme som finns i innemiljön, t ex ventilation med nattkyla; tekniker för att kyla personer istället för hela utrymmet; tekniker för att avlägsna fukt hos inneluften. Teknikernas möjligheter, mognadsgrad och kostnader värderads kvalitativt. Arbetet utfördes inom ramen för Annex 80.

Attia, S., Benzidane, C., Ramin, R., Amaripadath, D., Holzer, P., Koch, A., Maas, A., Petersen, S., Mavrogianni, A., Hidalgo-Betanozos, J.M., Hamdy, M., Almeida, M., Akander J., Khosravi Bakhtiari, H., Kinnane, O., Moosberger, S., Kosonen, R. & Carlucci, S. (2023). *Overview on overheating calculation methods in European regulation for residential buildings*. Inskickat till *Energy and Buildings* 2023-02-21. Accepterat 2023-05-10.

Artikeln är ett samarbete inom Annex 80; detta sammanställer indikatorer, gränsvärden, metoder och standarder som används i olika länder inom EU, utifrån hur kylning och överhettning av bostäder hanteras och projekteras. Vårt bidrag i arbetet var information som berör Sverige.

Konferenser med granskningsförfarande

Sayadi, S., Akander, J., Hayati, A. & Cehlin, M. (2022). Analysing future cooling demand for a new preschool building in central Sweden. In: *5th International Conference on Building Energy and Environment (COBEE 2022)*: Paper presented at COBEE 2022, Concordia University, Montreal, Canada, 25-29th July 2022, 1274.

En ny skolbyggnad som fått Guld av Miljöbyggnad, Indikator 3 Energianvändning, modellerades i IDA-ICE med typåret i nutid och motsvarande typår för perioden 2041-2060. Resultaten visar att denna byggnad har, beroende på önskade börtemperaturer, att kylbehovet kan öka upp till fyra gånger i framtiden samtidigt som PPD ökar från under 10 % upp till 15 %.

Khosravi Bakhtiari, H., Sayadi, S., Akander, J., Hayati, A. & Cehlin, M. (2022). How Will Mechanical Night Ventilation Affect the Electricity Use and the Electrical Peak Power Demand in 30 Years? – A Case Study of a Historic Office Building in Sweden. In: *5th International Conference on Building Energy and Environment (COBEE 2022)*: Paper presented at COBEE 2022, Concordia University, Montreal, Canada, 25-29th July 2022, 1123.

Mekaniska ventilationssystem i framför allt kontorsbyggnader möjliggör att ta tillvara på nattkyla. Men framtida kylpotentialen kommer att minska med klimatförändringarna, vilket medför att ventilationssystem använder mer el för att åstadkomma nattkyleffekt (längre drifttid) vilket avvägs mot el som dagtid levereras till kylmaskiner. Nattkylans fördel är att eleffektbehovet minskar under morgonen och förmiddagen.

Sayadi, S., Hayati, A., Akander, J. & Cehlin, M. (2021). Cooling demand reduction approaches for typical buildings in a future city district in mid-Sweden. In: *Proceedings of Building Simulation 2021: 17th International Conference of IBPSA*. Paper presented at Building Simulation 2021. International Building Performance Simulation Association (IBPSA), 30327. https://doi.org/10.26868/25222708.2021.30327

En prototyp till flerfamiljsbostadshus modellerades i IDA-ICE med nutida typiskt år och väderfilen för året 2018. En parameterstudie omfattande förhållandet mellan fönster- och golvarea, fasadorientering och två ventilationsstrategier utfördes för att minska uppkomst av övertemperaturer. Studien belyser vikten av att utforma byggnaden med passiva åtgärder innan aktiv kyla sätts in. Den betonar även att vid projektering bör extremväder (framtida somrar) beaktas.

Bokkapitel (granskat)

Sayadi, S., Akander, J., Hayati, A. & Cehlin, M. (2021). Review on District Cooling and its Application in Energy Systems. *Chapter in: Urban Transition - Perspectives on Urban Systems and Environments* / [ed] Marita Wallhagen & Mathias Cehlin, IntechOpen, 2021. https://doi.org/10.5772/intechopen.100307

Kapitlet beskriver fjärrkylans för- och nackdelar på global nivå.

Rapporter

International Energy Agency. (2023). *Resilient Cooling of Buildings – State of the Art Review (EBC Annex 80)*. Editors: Peter Holzer and Philipp Stern, Institute of Building Research & Innovation, Austria.

Litteraturöversikten om olika tekniker för att minska övertemperaturer och kylbehov är indelat i fyra kategorier: att minska överhettning av yttre faktorer, såsom solstrålning, solinstrålning, varm uteluft, etc.; att avlägsna värme som finns i innemiljön, t ex ventilation med nattkyla; att kyla personer istället för hela utrymmet; att avlägsna fukt hos inneluften. Arbetet utfördes inom ramen för Annex 80.

International Energy Agency. (2023). *Resilient cooling of buildings – Field study report*. Editors: Dahai Qi and Gerhard Hofer, Institute of Building Research & Innovation, Austria. Genomgår vid skrivande stund granskning hos IEA.

Den här rapporten är en huvudleverans från Annex 80 och sammanfattar resultaten av fallstudier som genomförts under Annex 80's arbetsfas. Den ger en översikt över implementerade kyllösningar och deras prestanda i förhållande till resiliens mot värmeböljor och strömavbrott. Exemplen illustrerar föredömliga tillämpningar och ska främja överföring av kunskap från forskning till praktik, men täcker inte alla teknologier som utvärderats under Annex 80. Vårt bidrag omfattade en studie av Gävles rådhus. Rådhusets kylssystem omfattar en äldre kylmaskin som kyler tilluften vid behov.

Examensarbeten

Talib Ali, A. (2022). *Resilient cooling technologies: Simulation study to determine the cooling capacity in old residential buildings located in mid-Sweden.* Student thesis, 15 hp. Master Programme in Energy Systems, University of Gävle.

Examensarbetet utgår från tre av byggnadsmodeller som använts för att simulera kylbehovet hos tilltänkta byggnader på Näringen, Gävle. Dock har U-värden hos konstruktioner i klimatskärmen ändrats till värden enligt minimikrav i BABS67, SBN75 och SBN80. Ventilationssystemet ändrades från FTX till F-vent. Typiskt år i nutid användes som klimatdata. Resultatet indikerar att kylbehovet avtar med ökat medel-U-värde på ett olinjärt sätt, vilket indikerar att i nutida klimat så har transmission av värme, från inne- till utemiljön, betydelse.

Andersson, M. & Lindberg, S. (2021). *Dynamisk energieffektivisering med hjälp av elektrokroma fönster i ett svenskt klimat – En fallstudie av en simulerad kontorslokal med geografisk variabilitet*. Examensarbete i byggnadsteknik, 15 hp. Högskolan i Gävle.

Att använda elektrokroma fönster blir alltmer populärt i kontorsbyggnader, trots dessas merkostnader vid inköp. Men tekniken medför en minskning av kylbehovet med 60 % i kontorsrum mot söder, enligt studien, på bekostnad av en liten ökning av uppvärmningsbehovet eftersom insläppt solenergi även minskar under delar av kallare årstider.

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Bilagor

Här bifogas ett antal artiklar som har publicerats inom ramen för projektet.

Analysing future cooling demand for a new preschool building.

Analyzing the climate-driven energy demand and carbon emissions for a prototype residential nZEB in central Sweden.

Comparison of space cooling systems from energy and economic perspectives for a future city district in Sweden.

Conceptualising a resilient cooling system: A socio-technical approach.

Cooling demand reduction approaches in a nearly zero energy building for future city district in central Sweden.

How will mechanical night ventilation affect the electricity use and the electrical peak power demand in 30 years? A case study of a historic office building in Sweden.

Overheating calculation methods, criteria and indicators in European reglulation for residential buildings.

Resilient cooling strategies – A critical review and qualitative assessment.

Review on district cooling and its application in energy systems.

Analysing future cooling demand for a new preschool building in central Sweden

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Analysing future cooling demand for a new preschool building in central Sweden

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SUMMARY

This study is framed around two research questions to 1) investigate the probable changes in future climate and 2) evaluate the changes in cooling demand of a studied building when implementing an assemble climate representing mid-term future period (2041-2060). The chosen building is a preschool in central Sweden that fulfills the Nearly-Zero Energy Building (NZEB) requirements based on today's Swedish National Building Regulations. To assess and cope with the present and future cooling energy needs of the building, a climate file representing present conditions along with a projected future typical climate file are utilized. The future climate is an assembled typical meteorological year climate file using the CORDEX data.

The present climate file underpredicts the future energy demands therefore verifying to be unsuitable for anticipated energy analysis. It was discovered that the cooling demand for assembled climate file is almost 4 times the present climate file for the studied conditions.

INTRODUCTION

The building sector is held responsible for about 36% of the global energy use [1]. Based on a report presented in [2], building and construction sector did not align with confining the global temperature rise based on the Paris Agreement. Therefore, finding new techniques to reduce the energy use in buildings, to pave the path for energy transition to sustainable energy, is of importance. Official journal of European Union has published Commission Recommendation (EU) 2016/1318, introducing guidelines for the promotion of Nearly Zero Energy Buildings (NZEB) [3]. NZEB refers to a building that uses low amount of energy (mostly renewable) with high performance. The importance of NZEB was emphasized in [4] therefore the EU member states are obliged to present a numerical indicator presenting the Primary Energy (PE) as well as their national or regional reflection on NZEB. Based on Swedish National Board of Housing, Building and Planning [5], primary energy number (EP_{PET}) should be less than 70 kWh/m^2 and year for non-residential buildings. Within this context, to estimate the use of energy in building, building performance simulation could be adopted to evaluate the proposed design. However, with the ongoing climate changes and the increase in extreme weather events, application of probable hourly weather data that aligns with the climate changes is essential. As in several studies, Sayadi et al.

[6] concluded that regions with projected rise in temperature, depicted increase in cooling demand and decline in heating demand, emphasizing the influence of weather data on evaluating the energy use and resilience of the buildings.

In order to face the induced climate changes, buildings have to be equipped with resilient ventilation and cooling technologies. Numerous resilient cooling strategies have been reviewed by Zhang et al. [7]. The cooling technologies were based on created categories within IEA EBC Annex 80: Resilient Cooling of Buildings [8]. To study the energy performance of a prototype building, or those that have to undergo deep renovation, assembled climate files representing future climate conditions have to be employed during the design stage as buildings can have long life span of 100 years and more. However, use of projected climate files is not considered during design phase or in updating Swedish building regulations. This research project aims to investigate the importance of this knowledge gap among policy makers and practitioners and the consequences of induced climate changes particularly during the cooling season. The chosen building is a constructed preschool that meets the enforced NZEB requirements by the building regulations. The study is framed based on two research questions (RQ):

RQ1: Investigating the possible changes in number of hours exceeding an exceedance temperature for the studied building in the future. Given that cooling systems are not commonly installed in preschools today.

RQ2: How will the cooling demand increase when using the projected climate file with reference to Swedish Meteorological and Hydrological Institute's (SMHI) climate file? This climate file is referred to as the Present climate file in this study.

METHODS

The building is constructed in central Sweden, Gävle, and has acquired an energy grade that matches the scope of this study, which is to evaluate energy performance of a NZEB commercial building under future climate condition. Swedish environmental certification of buildings, Miljöbyggnad version 3.1, analyzes fifteen different energy and environmental related indicators and each indicator can receive a grade of Bronze, Silver or Gold. In which Gold is a high level assigned to most ambitious buildings, often with a pronounced environmental profile. The building chosen in this study has achieved the Gold grade for energy use indicator [9]. It also fulfils the NZEB requirements enforced by Swedish National Board of Housing, Building and Planning [5].

Figure 1: Model of the building in IDA-ICE (left), first floor plan (middle) and second floor plan (right).

Figure 1 shows the building model. Original input parameters adopted from the design and specifications are depicted in Table 1. Three mechanical ventilation systems with heat recovery (HRVs) were employed to ventilate the building. A HRV was assigned to the kitchen ($HRV_{kitchen}$) and the other two (HRV1 and HRV2) for other occupied zones. Setpoint of 18.2°C for supply air temperature was defined. Metabolic rate in this study was considered 1.4 met [10]. Clothing level was defined within the range 0.75±0.25. Internal blinds that are controlled by the amount of sunlight are defined as the shading system for windows. The blinds are drawn when the amount of incident sunlight is 100 W/m^2 or more. The simulations were carried out by means of IDA-Indoor Climate and Energy (IDA-ICE) version. 4.8.

Table 1: Input parameters for the model building

Parameter	Value	Parameter	Value
Model floor area	1116m^2	U_{walls}	0.1 ($W/m^2 \cdot K$)
Heating set point	22°C	U_{roof}	0.08 ($W/m^2 \cdot K$)
Occupancy	hrs 9:00-15:00	$U_{windows}$	0.9 ($W/m^2 \cdot K$)
Internal gains*	75 W	$U_{average}$	0.2 ($W/m^2 \cdot K$)
Min-Max air supply	0.3-7.5 (L/m^2s)	Window/Envelope	6.5 %

*Total emitted sensible heat per unit in each zone.

Future climate projections

To investigate the effect of climate on energy performance of buildings by means of simulations, a typical meteorological year (TMY) file containing 8760 hours derived from multiyear data has to be assembled. Such a climate file was projected in this study to represent the future climate conditions. A methodology proposed by Machard et al. [11] was implemented to assemble the climate file for mid-term future (2041-2060). The European Coordinated Regional Downscaling Experiment (EURO-CORDEX) was used to assemble the climate file. CORDEX strives to provide high resolution climate scenarios to improve regional climate downscaling methods. Data were downloaded from the Earth System Grid Federation (ESGF) (ESGF, n.d.).

The required data to assemble the TMY file are the dry bulb temperature, relative humidity, atmospheric pressure, wind speed, total cloud cover and surface downwelling shortwave radiation. Climate variables were downloaded for the European domain with Representative Concentration Pathway (RCP) 8.5 as the socio-economic scenario. Data were extracted and bias-corrected against 20 years of hourly observational data for the following coordination 60.67°N, 17.14°E. The bias correction method was based on multivariate bias correction algorithm (MBCn) method introduced by Cannon [12].

Case studies

The simulation is first carried out as per the original building and ventilation specification for a freely available typical year climate file from SMHI, and assembled mid-term future climate files. The climate file from SMHI (Present climate file) has been generated from the 30-year series 1981-2020. This step is taken to ensure that the NZEB requirement based on the latest building regulations were fulfilled (PE_{PET} < 70 kWh/ (m^2 and year)). Equation 1 is used to calculate PE_{PET}.

$$PE_{PET} = \frac{\sum_{i=1}^{6}\left(\frac{E_{heating,i}}{F_{geo}} + E_{cooling,i} + E_{DHW,i} + E_{f,i}\right) \times WF_i}{A_{temp}} \quad (1)$$

Where PE_{PET} is primary energy number (kWh/(m^2 and year)), i is energy carriers (electricity, district heating, district cooling, biofuel, oil and/or gas) calculated from annual energy entities. $E_{heating}$ is energy for space heating (kWh), F_{geo} is geographical factor, $E_{cooling}$ is energy for space cooling (kWh), E_{DHW} is energy for domestic hot water (kWh), E_f is energy for building's real estate (kWh) and WF is the weighting factor.

Case one- evaluation of exceedance hours

As a response to RQ1, this case study was designed. The maximum acceptable operative temperature for non-air conditioned office buildings in summer has been defined to be 28°C for one percent of the total annual occupied hours [13]. The value was calculated by considering the averaged exceedance hour from all the occupied zones during the cooling season (June-August).

Number of hours the *exhaust* temperature exceeds 28°C, when no cooling technology was employed was also evaluated for the same period. The exhaust air temperature is the average of flow temperatures from all zones. This step was carried out using Present climate file and the assembled mid-term future climate.

Case two- evaluation of cooling requirement

To evaluate the cooling demand of the building, ideal coolers that are connected to the district cooling system were added to the zones. Ideal coolers are standalone devices. These are not connected to the main air handling unit. Ideal coolers were employed in this case to measure the cooling demand. This case was outlined to investigate RQ2. Different cooling setpoints were defined to evaluate the changes in cooling demand of the building when employing the Present and mid-term future climates. Cooling setpoints were chosen based on the ISO 7730 for preschools/ kindergartens from 24-26°C [14] for both the employed climate files.

RESULTS AND DISCUSSION

The increase in temperature is projected to be on average 3°C, as can be seen in the left hand side duration diagram in Figure 2. On the right hand side, mean monthly solar radiation for both the studied climate files are presented. As seen from figures, the changes in solar radiation are negligible when comparing the values from the two climate files. Therefore, from the presented result it could be concluded that implementing a shading technology would prevent relatively the same amount of heat gained due to sunlight entering the space, today or in the future.

It is noteworthy to remind that the Present climate has been assembled from the 30-year series 1981-2020 and the mid-term future is assembled from the 20-year series 2041-2060. These changes in temperature emphasize the need for a resilient cooling technique that could withstand the induced changes, especially during heatwaves. Heatwaves are characterized by higher temperatures with longer interval. These technologies should also be aligned with the Paris Agreement.

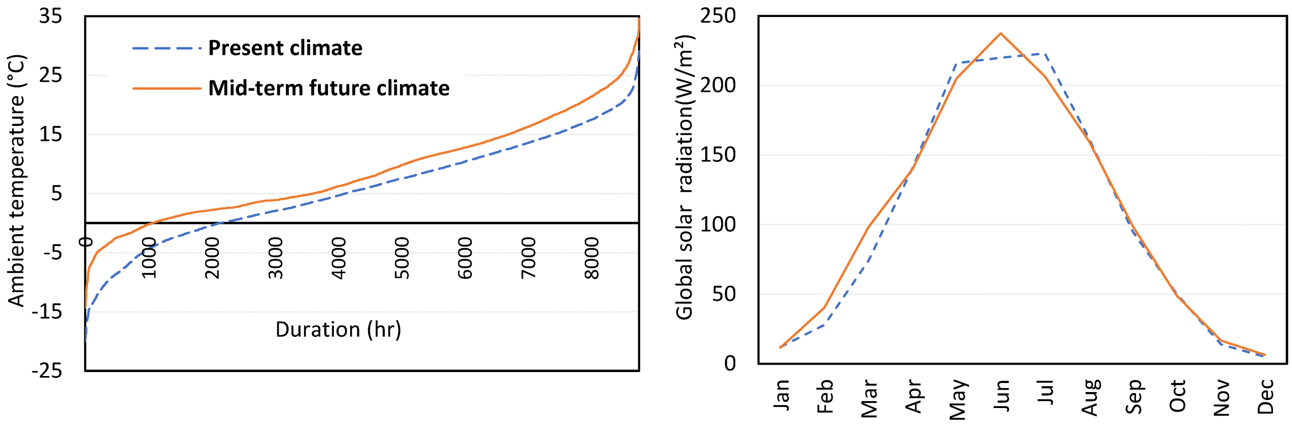

Figure 2: Temperature versus solar radiation curves for the Present and mid-future climates (left) and the related duration diagrams (right)

In order to verify the validity of the generated future data, historic regional climate model (RCM) data was modelled for the observation period (1986-2005). The collected observational data were compared with the modelled RCM data. The data were in good agreement, meaning that the bias corrected data had the same statistics as the observational data. Statistical distribution for dry bulb temperature for the simulated data and the observational data are shown in Figure 3. The figure depicts the frequency of recorded and the modelled temperature over the mentioned range for the observation period. As seen in the figure, the two displayed parameters are compatible.
Later PE_{PET} was calculated for Present and mid-term future climate and was found to be 67 and 63.5 kWh/ (m^2 and year) respectively. The calculated values fit within the NZEB requirements (PE_{PET} < 70 kWh/ (m^2 and year)) using the weighting factors of today [5].

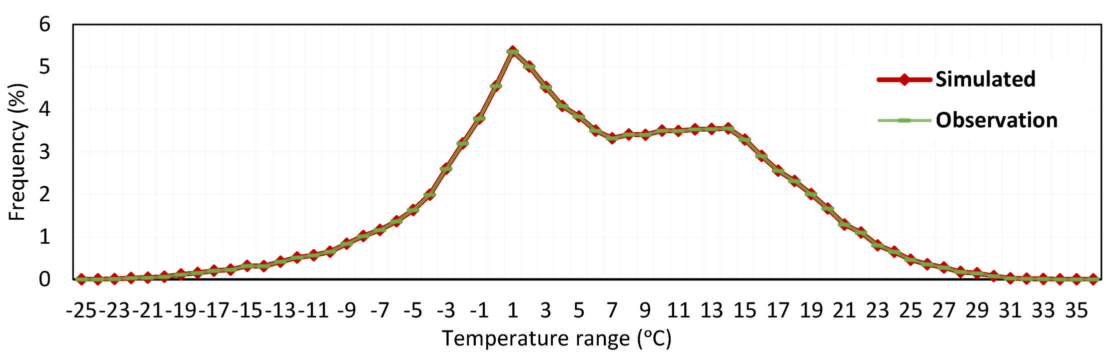

Figure 3: Comparison between the frequency of modelled historical RCM and observational data, period (1986-2005)

Analysis of case one result-evaluation of exceedance hours

The number of hours the operative temperature exceeds 28°C for the whole building are 2% and 28.4% for the Present and mid-term future climate files respectively. Exhaust temperature exceeding 28°C for HRV1 and HRV2 when employing the Present climate files are 6 and 14 hours and these values correspond to 249 and 322 hours for mid-term future climate respectively. By employing the mid-term future climate, the number of hours exceeding the defined threshold has

increased on average from 0.4% of the studied hours to 13%. The increase in total number of hours in need of cooling was also studied for a prototype residential building and the same conclusions were deduced [15].
These results highlight the importance of using a climate file that could possibly represent the future weather scenario, especially if a prototype building is to be investigated. This is vital since buildings have a long life span and given the exceedance hour results, the choice of resilient cooling technology and its robustness is considerable.

Analysis of case two result- evaluation of cooling requirement
The variations in cooling energy demand when implementing different cooling setpoints for the ideal coolers is shown in Figure 4. Ideal coolers have the ability to maintain the indoor temperature at the specified setpoint. The cooling demand for Present climate ranges from 2.4 to 0.9 kWh/m^2 for cooling setpoint 24-26°C respectively and these values correspond to 7.6 to 4.6 kWh/m^2, for mid-term future climate. On average, about 38% reduction in cooling demand is depicted between two consecutive cooling setpoints for Present climate. This value corresponds to 22% for mid-term future climate. Figure 4 depicts these values. The peak cooling demand ranges from 18.6 to 14.5 kW for cooling setpoints 24-26°C for the Present climate respectively. These values correspond to 28.8-26 kW for the mid-term future climate. Of the total outdoor air temperatures within June-August, 16% for Present climate and 56% for mid-term future climate are above 20°C.
Results show, on average, increase in cooling demand between the two climate files, with a factor of four. The variation in cooling demand among the studied setpoints depicts less discrepancy for mid-term future climate when compared to Present climate.
The comfort condition of the occupants was also evaluated by calculating the predicted percentage dissatisfied (PPD). This was to investigate the changes in comfort conditions in relation to each cooling setpoint. PPD is evaluated with the help of IDA-ICE and results are shown in Table 2. More number of occupants were predicted to be dissatisfied when using higher cooling setpoint. PPD values for the same setpoints, though different climate files, appear inconsistent with one another, even though the indoor air temperatures have the same setpoints. This is due to the increase in the operative temperature in each zone.

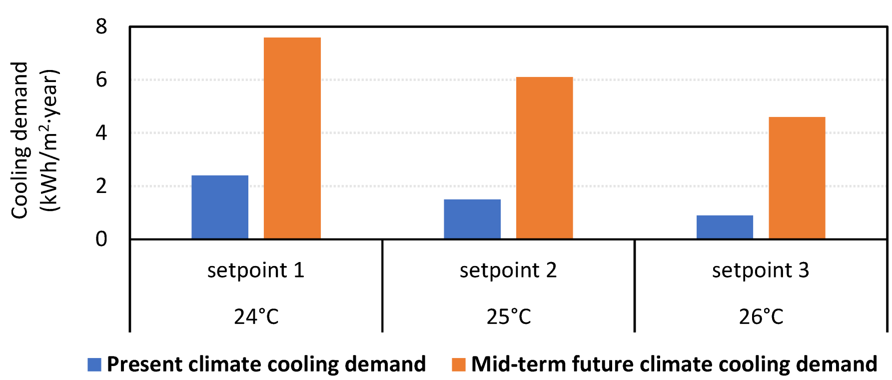

Figure 4: Cooling energy demand when implementing different cooling setpoints for the studied climate files

Table 2: Evaluated PPD result for all studied cooling setpoints and climate files. Results are in percentage

	cooling setpoint 24	cooling setpoint 25	cooling setpoint 26
Present	8	9	11
Mid-term	9	12	15

Use of night ventilation (NV) cooling could be considered as an approach [16] to more resilient buildings. NV, different geometrical configurations as well as inclusion of residential buildings within larger scales will be considered in future studies.

Limitations associated with the projection of the mid-term future climate file include different methods and combinations of global and regional climate models can be used to generate a TMY file. Data are calibrated against observational periods and the hourly observational data may not be available for all the required parameters or the investigated city. In addition, number of occupants, window operation for airing and shading effect from surrounding was not considered.

CONCLUSIONS

In this study, two research questions were designed to highlight the importance, and evaluate the impact of different climate files on energy performance of a preschool. The preschool matches NZEB requirements based on the Swedish building regulations (Primary Energy number < 70 kWh/ (m^2 and year) for non-residential buildings). Swedish building regulations are based on current typical meteorological year (TMY) which is known as Present climate file in this study. A mid-term future climate file was assembled to evaluate the climate-driven energy demand of the building compared to the Present climate. The projected climate file showed nearly 3°C increase in average outdoor temperature compared to Present climate.

Number of hours the operative and exhaust temperatures exceed 28°C for June-August for mid-term future climate was found to be on average 14 and 28 times the Present climate. This highlights the importance of a climate file used since buildings have a long life span. The cooling demand of the building, when using the mid-term future climate file, was evaluated for cooling setpoints 24-26°C for June-August. The energy use for mid-term future climate was found to be on average 4 times the Present climate file for the studied period. This work shows that near-zero energy public buildings which are normally designed to skip cooling systems today, should consider design with the climate of tomorrow.

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Analyzing the climate-driven energy demand and carbon emission for a prototype residential nZEB in central Sweden

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A B S T R A C T

The changes in climate and the expected extreme climate conditions in the future, given the long life span of the buildings have pushed the design limits. In this study, the changes in primary energy use (PE_{PET}), total energy use and CO_2 emission were investigated for a prototype residential building. The building fulfils nearly zero energy building (NZEB) characteristics, imposed by the Swedish building regulations. Different cooling technologies and various typical meteorological year (TMY) climate files assembled for different periods, as well as automatic shading were investigated. The assembled TMY files advocated for the present (2001–2020) and mid-future (2041–2060) period using the CORDEX data. Different cooling methods and set-points (24–28 °C) were defined to evaluate the cooling energy demand changes.

It was discovered that the freely available typical climate file fails to cover the induced changes in climate and its extreme implications on the building. The required cooling energy use increased from 1.7 to 5.8 times the freely available climate file, when using the projected TMY and the extreme climate files.

Addition of automatic shading system reduced cooling energy up to 75% within the studied cooling methods and set-points. Moreover PE_{PET} and CO_2 emission also decreased for the studied cooling methods, climate and weather files.

1. Introduction

Buildings are a major source of GHG emissions, and use large amounts of energy and natural resources. One third of the world's total energy use corresponds to the building sector [1]. With increase in population and more time spent indoors, the energy use of the building stock also increases. This increase in building energy use leads to increase in carbon emission [2]. Building construction and operation account for 36% of global final energy use and of 39% of energy related GHG emissions [3]. Awareness of the threat of a climate crisis and its recognition in global Sustainable Development Goals, and in European and national political targets, has increased the pressure to take necessary measures to reduce anthropogenic GHG emissions. Due to the impacts associated with the greenhouse gas (GHG) emission from energy sector and consequently the climate changes, they are now regarded as environmental problems rather than environmental issues [4]. To overcome these problems, the European (EU) commissions has introduced the European Green Deal to make Europe's economy secure and sustainable [5,6]. The European Green Deal consists of number of climate actions to cut the GHG emissions and preserve Europe's natural environment. One of the climate actions to reach the European Green Deal is the European Climate Law [7]. Based on this action, the European Union is trying to reduce the net greenhouse gas emissions by 55%, compared to 1990′s level by 2030, and further become a climate neutral continent by 2050. Alongside this, the European Union aims for a climate resilient society by 2050 as well [7]. To achieve improvement in the energy performance of the buildings as well as promoting policies that help obtaining stable conditions for investment decisions and the climate goals, the EU Commission has implemented the Energy Performance of Buildings directives and Energy Efficiency Directives as a legislative framework [8]. Within the mentioned framework, policies and measures have been developed to improve the buildings' energy performance. In addition to legislation, taxation and different benefit packages, environmental assessment methods can be regarded as a voluntary way to work with environmental governance and reduce GHG emission, which may also influence legislation [9]. For example, the Swedish environmental assessment method Miljöbyggnad has inspired a new legislation regarding climate declaration for all new buildings in Sweden, which is mandatory from January 2022

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1.1. Nearly zero energy buildings and primary energy number

Commission Recommendation (EU) 2016/1318 established in 2016 introduced guidelines for the promotion of NZEB, referring to a building with high energy performance that uses low amount of energy which is covered mostly by renewable sources [10]. Article 2 of the Energy Performance of Buildings Directive 2010/31/EU, defines energy performance as the amount of energy in the form of heating, cooling, ventilation, hot water, lighting and inter alia that is required by the building to meet its demands [11]. The European Commission within the Official Journal of European Union [12,13] provide guidelines on calculating the energy performance of buildings. The calculation starts with quantification of the building's final energy needs to assess the net primary energy use [10].

In order to improve the energy performance of the buildings, Directive 2010/31/EU emphasized the importance of Nearly-Zero Energy Buildings [11,14]. Therefore the EU member states were obliged to comply with the implications by providing their national or regional reflections in the definition of NZEB as well as presenting the numerical indicator of Primary Energy (PE) [14,15].

Primary energy is the energy that has not undergone any conversion and transformation and is used to anticipate the end-use energy [16]; it is a measure of how natural resources are used. In order to be able to evaluate energy use in terms of primary energy, delivered energy is used to estimate the primary energy. This can be done through a set of constants called Primary Energy Factors (PEF) and these are regarded as the ratio between the total used primary energy and total end use delivered energy [17]. Studies were conducted to calculate the PEF, for example in the USA [17], European Union member states [14] and Sweden [18]. A study was conducted by Duh Čož et al. [19] to calculate the PEF of district cooling system in Slovenia.

The PE number is a numerical indicator that is included in NZEB definition and it is expressed in kWh/(m^2•year). The majority of the EU members have been developing a PE numerical indicator to provide a comprehensive definition and a criteria of NZEBs on national levels [20]. The Swedish National Board of Housing, Building and Planning (Boverket) proposed a definition for NZEB in 2017 that set several building energy use-related limitations. This step was taken to reduce energy use in buildings. Building regulations also makes use of the term Primary Energy Number that is depicted as PE_{PET} and it is based on weighting factors of energy carriers present in the building (see more details in section 2.5). The method to calculate the PE number for Sweden is expressed in Swedish Building Codes [21] and later will be explained in section 2.5 of this study. Bounding the PE_{PET} below 75 kWh/ m$^{2\cdot}$ year, for residential buildings [21] is among the proposed regulation requirements which is the main focus in this research project.

1.2. Future climate

Building Performance Simulation (BPS) helps predicting/estimating the energy performance and indoor thermal condition of a prototype building during the design stage. To describe the dynamic energy behavior of a building, hourly weather data is required as it is considered as the external boundary condition for building simulation [22,23].

Future weather files are built based on multiyear observation data. The Typical Meteorological Year (TMY) files are a representative dataset, containing 8760 h, derived from multiyear recorded observational data to represent statistical trends over the recorded period [1,24]. A number of researches have tried generating TMY files over the years for regions including Greece [25], Italy [26], Malaysia [27], Nigeria [28], Argentina [29] and Sweden [30,31].

These single year weather datasets, as mentioned previously, are representatives of 2–3 decades of historic observational data and with the ongoing climate changes, these weather files generally fail to represent future climate conditions. The third assessment report of the Inter-Governmental Panel on Climate Change (IPCC) has contributed to climate change models and provided a collective picture of weather changes [32]. A number of researchers have tried to represent future conditions and extreme weather, using these historic datasets, however, they have reported that the weather datasets were not adequate [1,23,33]. Therefore to study the resilience of the building and its performance in the future, several methods have been developed to create future weather files [24].

The IPCC introduced the first set of scenarios to project future climate changes in the IPCC Special report on Emission Scenarios (SRES) in 1996 [34] and later in 2014, the Representative Concentration Pathways (RCP) was introduced [35]. These emission scenarios help in analyzing climate changes and its modeling, as well as the influence of the driving forces (socio-economic development, technological changes, etc.) on future emission outcomes by providing initial conditions for Global Climate Models (GCM) [22,34]. The GCMs are the numerical representatives of the global climate system's physical processes and their outputs cover the entire globe and these are used to assess the impact of climate changes, however, their resolution is too coarse (100–300 km^2) to be used for BPS purposes [36]. In order to be able to use the GCM data, these should be downscaled to the appropriate resolution of less than 100 km^2. Two downscaling methods have been introduced, statistical and dynamical downscaling methods [24,37].

Several researchers have studied the effect of future climate on the energy performance of the buildings. They have depicted an increase in cooling requirements and reduction in heating requirements of the buildings in different regions such as the USA [38], Iberian Peninsula [4], Hong Kong [39], Tokyo [40], Denmark [23], Sweden [41] and Finland [42].

Present buildings may not withstand the future heatwaves and extreme climate conditions considering the ongoing climate changes. Therefore, the resilience of the building has to be accounted during the design stage. Given that, current Swedish residential buildings and other buildings, such as kindergartens, are not equipped with cooling units. A number of resilient cooling strategies has been reviewed by Zhang et al. [43] based on categories created in IEA EBC Annex 80, to cool people or the indoor environment. Regulations and the typical climate files used for simulating purposes, especially to prove fulfillment of building regulation energy requirements, have to be updated to increase the accuracy of the simulated result for the buildings that are to be built or have to undergo deep renovations. The use of future climate files is not considered in updating the building regulations in Sweden and has to be considered to match the requirements of EU Commissions. This is a research gap that has to be accounted for.

This study aims to explore the impact of several factors on the energy performance, PE_{PET} and carbon emission of a residential building. Climate files representing different periods from past to future to cover the research gap mentioned earlier as well as different cooling strategies and technologies were investigated to meet the aim of the research project.

This study has raised two research questions: Is it possible to use currently available typical meteorological year (TMY) climate files to evaluate the future energy need of buildings?

And, how to improve the indoor thermal conditions and reduce CO_2 emission from building operation, and evaluate the effects on primary energy use?

The cooling demand assessment and heat load reduction as well as implementing solar shading are among the Key Performance

Indices (KPIs) proposed by IEA EBC Annex 80: *Resilient cooling of buildings*. Therefore the characteristics of the model building are aligned with these KPIs [44].

2. Methods

An overview of the considered case studies and the results to have a proactive design strategy is presented in Fig. 1. Furthermore, each of the case studies accounted in the study are explained in sections 2.1 to 2.6. Procedures to assemble future climate files are presented in section 2.1. In section 2.2, the building characteristics and construction details based on Swedish proposal for NZEB are presented. Different cooling methods are explained in section 2.3 and the CO_2 impact and emission calculation is depicted in section 2.4. The method to calculate the PE_{PET} is depicted in section 2.5. Finally, in section 2.6 the comfort model is described. Limitations of the study are presented in section 2.7.

2.1. Assembling future climate

In order to study the effect of climate change and its implications on the energy performance of the building, a TMY file was produced for the Mid-term future (2041–2060). To assemble the Mid-future climate file, the methodology proposed by Machard et al. [45] was implemented. The climate file was assembled from the European Coordinated Regional Downscaling Experiment (EURO-CORDEX) which can be accessed through the Earth System Grid Federation (ESGF) [46]. CORDEX strives to provide an internationally coordinated framework that delivers high resolution climate scenarios to standardize and improve regional climate downscaling methods [47]. As previously mentioned, two downscaling methods have been introduced, empirical-statistic and dynamical approach, which CORDEX takes into account [47].

After selecting EU-11 as the domain for Europe with 1-hour time frequency, REMO 2015 was selected as the downscaling method. The required climate variables to assemble the climate files were dry bulb temperature, relative humidity, atmospheric pressure, wind speed, total cloud cover and surface downwelling shortwave radiation. Representative Concentration Pathway (RCP) 8.5 was chosen as the socio-economic scenario for this study.

In the next step, the downloaded data were extracted for the city Gävle, Sweden (60.67°N, 17.14°E) using CORDEX-DATA Extractor.

The extracted data are not bias-adjusted, therefore these were post-processed using the multivariate bias correction algorithm (MBCn) method, proposed by Cannon [48,49]. The method is used for projection/ prediction of multiple climate variables. Bias-adjustment methods compare the distribution curve of the extracted data with observational data and help correcting climate variables distribution function [45]. The method helps linking the climate simulated by Regional climate model (RCM) with rural observation data at the gauging station. In this study, the extracted data were calibrated against 20 years of hourly historical observation data Finally, the TMY files were built using the EN-ISO 15927–4 method [26] for the Average (2001–2020) and Mid-future period (2041–2060). The TMY files are used to assess the long-term mean energy use. The same processes were carried out to produce a climate file for the period 2001–2020. This assembled climate file was used in this study to ensure the authenticity of the Mid-future climate file, as the observational data are available for 2001–2020 for comparison purposes.

2.2. Nearly-zero energy buildings

A prototype multifamily building in central-Sweden was modelled adopting the latest available features of constructed buildings from newest districts in Gävle. The construction material and specifications were developed based on the latest available materials in the market to achieve NZEB qualities. The studied future district in this research is a part of a construction project that comprises 6000 new residential buildings [50]. Buildings such as the one introduced in this study are common in new city districts [51]. The

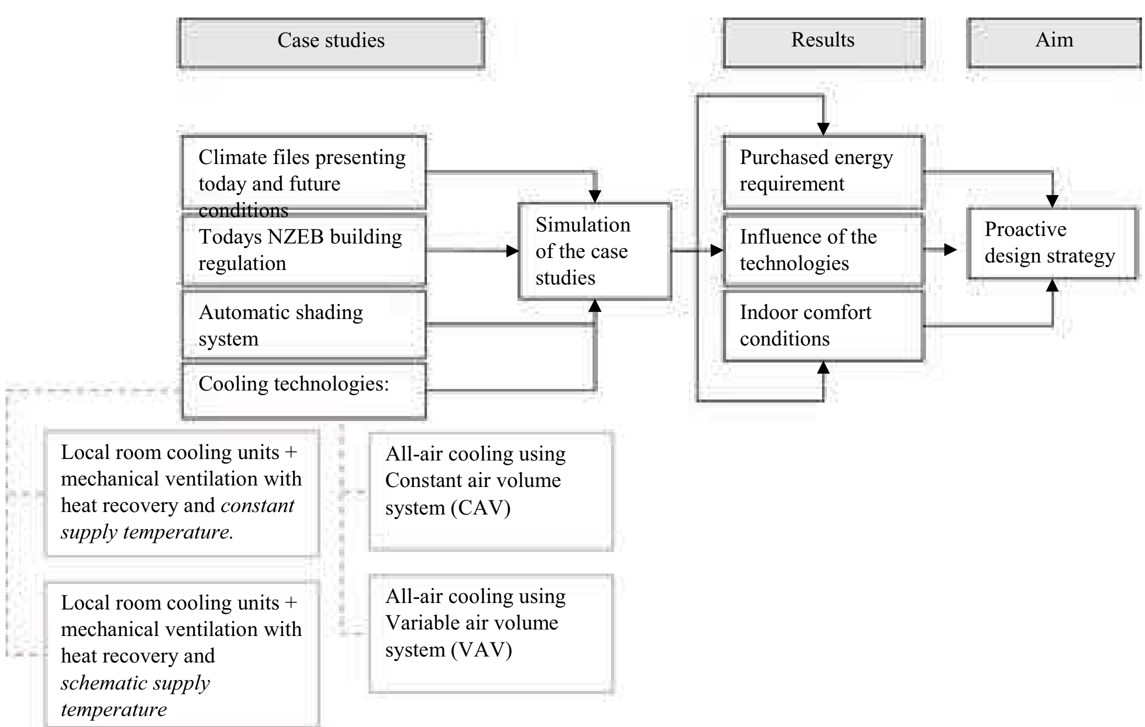

Fig. 1. Overview of the research process.

Table 1
Input parameters for the prototype modelled building.

Parameter	Values	Parameter	Values
U_{value} Glazing	0.8 W/m^2·K	Heating set-point [52]	21 °C
U_{value} Total Window	0.92 W/m^2·K	Heat exchanger efficiency	0.8
U_{value} External walls	0.1 W/m^2·K	Window to floor ratio	10%
U_{value} Roof	0.06 W/m^2·K	AHU specific fan power	0.75 kW/m^{3}s^{-1}
Number of occupants per zone	1.63	Total floor area	75 m^2 1414 m^2

internal gains (lighting, appliance and occupant gain) and building properties were defined based on the energy requirements defined in Swedish building regulations, as well as building simulation standards [21,52]. More information is provided regarding energy requirements in section 2.5. The building is shown in Fig. 2 and the building specifications are depicted in Table 1.

The building was modelled in IDA-Indoor Climate and Energy (IDA-ICE) [53]. The software has been validated using BESTEST Test procedure in ASHRAE Standard 140 [54]. Also the simulation result of the software have been validated against measured data in number of studies [55–58]. A number of researchers have used IDA-ICE in their researches and validated the simulated result against measured data [59–62].

Each apartment is considered as one large zone with calculated 1927 kWh/ year of total emitted sensible heat which corresponds to household electricity [63]. This study was carried out on 3000 newly built apartments, and the reported values are 30% lower than the values suggested by Sveby-standard.

The energy carriers are district heating and cooling for conditioning spaces and electricity for empowering facility and household equipment and lighting. The household electricity was assumed constant throughout all simulations including the future time.

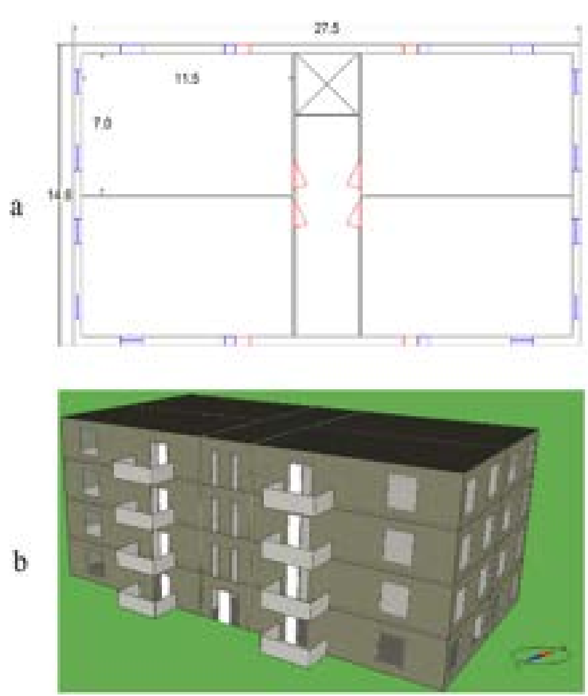

Fig. 2. Scheme of the model's geometry. (a) The plan of the building (dimensions are in meters); each apartment is modelled as a zone (b) Modelled building in IDA-Indoor Climate and Energy (IDA-ICE).

2.3. Simulations

In order to evaluate and improve the building's energy performance, different strategies were considered. Section 2.3.1 investigates the different cooling technologies and section 2.3.2 investigated the effect of automatic external shading on the energy performance of the building.

2.3.1. Investigation of different cooling technologies

Given the geographic location of the building, one strategy is to use the ambient air as cooling carrier; this in view that building regulations formulate to have mechanical ventilation system with heat recovery as a solution to fulfill both ventilation and energy requirements. The supply temperature was first considered constant (16 °C). Correspondingly, the supply temperature of the AHU also is 16 °C as long as the ambient temperature is below 16 °C. From this temperature and higher, the supply temperature will be the same as the ambient temperature.

The second investigated supply temperature strategy was a piecewise proportional controller. Fig. 3 depicts the applied strategy for this scheme. Correspondingly, when the ambient temperature is below 8 °C, the supply temperature would be 16 °C. It was noticed that from this ambient temperature onwards, the indoor temperature rises above the defined set-point with the defined ventilation strategy. By increase in the ambient temperature, the supply temperature gradually decreases. Similar to the previous strategy, the supply temperature would be the same as ambient temperature from 16 °C onwards. This is due to the absence of cooling coil in the ventilation system to compensate; ideal coolers were anticipated in the zones. Ideal coolers/ heaters are standalone units that are not connected to the plant [64], although their energy source is considered to be from district sources in this

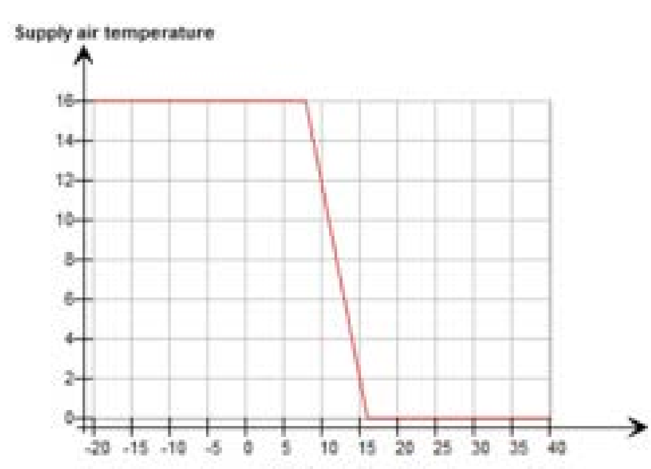

Fig. 3. Piecewise controller scheme depicting supply air temperature versus ambient temperature.

study. The depicted cooling strategy was chosen after analyzing different combinations of supply temperature to find the scheme that helps reducing the exhaust air temperature, which consequently reduces the cooling load.

In addition, two all-air cooling technologies, constant air volume (CAV) and variable air volume (VAV) ventilation systems were studied to assess their performance. In this case, the ideal coolers were removed. This was done to provide more realistic indoor conditions. Since ideal coolers have the ability to maintain a constant indoor temperature within the defined indoor conditions. Based on the return temperature, a minimum air supply temperature of 16 °C was considered. For the CAV system, to keep the indoor temperature within the defined range, a two-speed fan was defined. The fan supplies a maximum constant supply air flow 1 L/(s·m^2) and maximum exhaust air flow 1.1 L/(s·m^2) from May-July. The fan works half load, during the rest of the year with constant supply and exhaust of 0.35 and 0.37 L/ (s·m^2) for the rest of the year.

For the VAV system the minimum air flow rates for the supply and exhaust were 0.35 and 0.37 L/(s·m^2) and maximum 1 L/(s·m^2) and 1.1 L/(s·m^2), respectively. The amount of supplied air to the zone automatically varies within the defined minimum and maximum values in order to keep the zones at the defined set-points.

Based on Swedish guidelines for indoor climate specifications [65], two thermal classes Thermal quality 1 (TQ1) and Thermal quality 2 (TQ2) are defined. These describe the requirement for different thermal indoor climates. TQ1 and TQ2 accept indoor room temperatures above 26 and 28 °C respectively, for a short period during summer. Therefore five different cooling set-points 24–28 °C were selected to compare the energy performance of the building for three periods; Historic (1981–2010), Average (2001–2020) and Mid-future (2041–2060), as well as the hot summer weather of 2018. The Historic climate is the typical climate file that is used for building simulation purposes either for academic research or consultant and design purposes. In this research, it is referred to as Historic climate instead of Typical climate to maintain consistency in the names assigned to the climate files. This climate data file was created by Swedish Meteorological and Hydrological Institute (SMHI) after order from SVEBY [66], an organization that standardizes energy simulation in junction with building regulations. The file has been generated based on models and interpolation of data from the 30-year series 1981–2010 for energy calculation programs. The resolution is 11x11 km around the resort. It is aimed to analyze if it is appropriate to keep using this climate file for simulation purposes, especially, analyzing the future cooling demand of the buildings or if it should be updated for proactive design purposes.

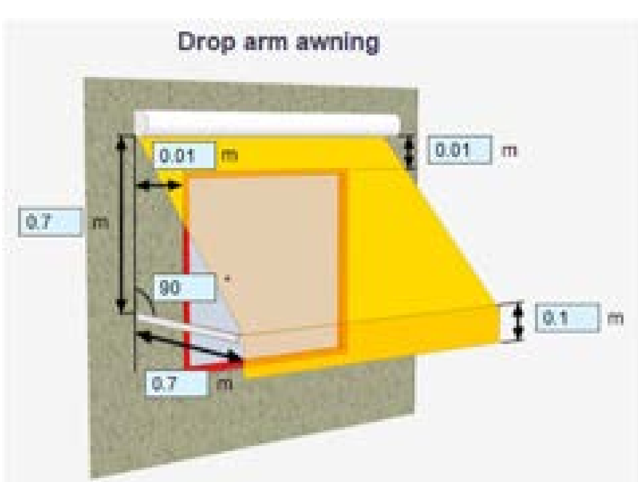

Fig. 4. Drop-arm awning configuration details. Figure from IDA to ICE software.

2.3.2. Addition of external automatic shading system

Automatic shades were added on the façade, above the windows. The shades are of the Drop arm awning type. Fig. 4 depicts the details of the awnings. These are utilized during warm period of May-August and the sensors are set to drop the awning to cover the windows when the solar radiation reaches 100 W/m^2 (1500 lx). Simulations were carried out for all the mentioned cooling technologies and for all mentioned periods.

2.4. Evaluation of changes in CO_2 emissions

Changes in CO_2 emissions were evaluated in this study. A framework was introduced by Levihn [67] which provides guidelines on the performance of different allocation methods to evaluate Carbon emission. This study considered the impact assessment for a future prototype building, therefore excluding the consequential analysis since no measurements or investment impacts were considered. Several studies have evaluated the emission changes in Sweden [6,68], Finland [69], etc., when different energy conservation methods (ECMs) are utilized.

Since the Swedish electricity grid is connected with Norway, Finland, Denmark, Germany, and Poland, considering a single national value for Swedish CO_2 emission is not relevant [70]. To evaluate the carbon emission changes, and analyze the impact assessment, the mean electricity composition mix for Nordic countries have been considered which corresponds to 90.4 gCO_2e/kWh [71].

The heat delivered to the buildings is considered to be from a District Heating System (DHS) with the following production mix for 2020 for the studied region: 60% residual heat from industry, 25% heat from combined heat and power plants that are fired with biofuels in the form of bark, 7% flue gas condenser, 7% wood from demolished buildings and other waste wood product and bio-oil and 1 % electricity [68,72]. The emission factor for DH for year 2020 was measured to be 3.66 g CO_2 equivalents/kWh [72]. District Cooling (DC) was considered as the cooling carrier for the building (cooling coil in the air handling unit as well as the local room cooling units). The Coefficient of Performance (COP) of the central chillers for the studied city were found to be four. Since the chillers use electricity as their energy carrier, the impact assessment for the cooling system was carried out using the mean electricity composition mix for Nordic countries. It is noteworthy that the Swedish electricity generation mix has a different value, however, the grid is highly interconnected and cannot be individualized [73]. This value was used to assess the carbon emission for Historic, Average and Extreme conditions. However, for the Mid-Future condition, based on the European Climate Law, mean electricity composition mix for Nordic countries was considered zero, since the Mid-Future climate is a presentative of 2050 s.

2.5. Primary energy number (PE_{PET})

As mentioned in the introduction section, primary energy is the energy in its natural state and it has not undergone any transformation. Therefore obtaining primary energy use can help calculating the environmental impact, since lower delivered energy cannot be concluded as lower primary energy use [16]. To calculate the building regulation PE_{PET}, weighting and geographical adjustment factors are required which are based on the National Board of Housing, Building and Planning building regulations [21]. The weighting factors are not the same as PEF, since the regulations has ambitions to navigate towards sustainable building solution, such as have a higher weight factor (high value is unfavorable) than the actual PEF. Based on Swedish building regulations, Eq. (1) is used to express the PE_{PET}. In order to meet the NZEB requirements, PE < 75 kWh/ (m^2•year).

$$PE_{PET} = \frac{\sum_{i=1}^{6}\left(\frac{E_{heating,i}}{F_{geo}} + E_{cooling,i} + E_{DHW,i} + E_{f,i}\right) \times WF_i}{A_{temp}} \quad (1)$$

where:

PE_{PET} Primary energy number, kWh/ (m^2 ·year)
$E_{heating}$ Energy for heating, kWh/year
F_{geo} Geographical adjustment factor
$E_{cooling}$ Energy for cooling, kWh/year
E_{DWH} Energy for domestic hot water, kWh/year
E_f Building operational electricity use, kWh/year
WF Weighting factor
i Index denoting energy carrier type

The operational electricity is related to the building's energy need, such as the electricity for pumps, fans, monitoring equipment, elevators, etc [9,21]. It should be pointed that tenant electricity is not considered in calculating the PE_{PET}. The value for F_{geo} and WF could be found in the building regulations [21]. The geographical factor is implemented to compensate for different climates in different regions [6] and is in this study F_{geo} = 1.1. The WF was chosen based on the energy carriers (district heating and cooling) with WF = 0.7 and 0.6 respectively.

2.6. Indoor comfort model

After finding the PE_{PET}, total energy use and CO_2 emission, a thermal comfort model was taken into account to explore the indoor conditions for each of the case studies. This is to evaluate the building performance from comfort point of view, also to ensure acceptable indoor conditions as lack of thermal comfort could lead to respiratory disorders [74]. In order to evaluate the thermal comfort conditions for all the cases considered, Predicted Percentage of Dissatisfied (PPD) was investigated. Based on the Swedish standard for indoor thermal comfort [75], different levels are considered for the indoor environment. If PPD is less than 6%, it is denoted as "Best". "Good" when PPD is less than 10% and "Acceptable" when PPD is less than 15%. However, PPD larger than 15% is considered "Unacceptable" [76]. To measure the thermal comfort in this study, an occupant was considered to be in the center of the zone, 0.6 m from the floor. The chosen metabolic value was 1.2 met, for the seated or relaxed condition. The clothing value ranges between 0.85 ± 0.25 clo. The PPD results were obtained by means of IDA-ICE simulation.

2.7. Limitations

Limitations associated with the generation of future climate files include the method and combination of GCM-RCM used, as well as the availability of observational data for the bias-correction process. Observational data may not be available on hourly basis or at all for all the climate variables. To overcome this issue, data has to be interpolated. Each apartment was considered as a zone. Also the building type and its geometrical configurations were limited in this study, although, it is within the scope of the project to evaluate more building geometries, and energy use, including commercial buildings, within larger scales in the future works.

3. Results and discussion

The results of the simulations are depicted in the following sections. Section 3.1 presents the result of the bias-corrected climate files to check if the process was well performed. In addition, figures are presented to show the evolution of the climate over time. Section 3.2 presents the result for energy performance of the different cooling technologies, for all five cooling set-points (24–28 °C), the mentioned climate files and the effect of shading on building energy use. Section 3.3 and 3.4 present the results for PE_{PET} and CO_2 emission for all the cases respectively. The comfort conditions for all the studied cooling technologies and climate files are investigated in Section 3.5.

3.1. Projection of future climate files

This section presents the result of the extracted and calibrated climate files. The calibration process was carried out by training a multivariate bias correction (MBC) method. The MBC model was used to predict bias corrected RCM data over the studied periods. Table 2 represents the statistical distribution of two climate variables. The data presented in the table include minimum and maximum as well as the quartiles (Qu), median and mean values for the observational, extracted and bias-corrected values. The bias-correction process has adjusted the simulated data to the observational data since the statistical distribution is the same as the observational datasets.

The frequency of the distributed representative variables of Table 2, for the observational and bias-corrected simulated data for the correction period (1986–2005) is shown in Fig. 5. Based on the result of the distribution frequency of the variables; the bias-correction process has calibrated the simulated data against the observational period.

Fig. 6 shows the regression evaluation for temperature and solar radiation for all the studied climates. The slope of the regression curve remains relatively the same regardless of the climate file used; however, the regression line is pushed upward when moving forward in time, representing the increase in ambient temperature while receiving relatively the same solar radiation. It could be concluded from the figure that cooling requirement of the buildings is dependent on the ambient temperature. Therefore, the type of cooling technology and the supply strategies are the key to keep indoor temperature within the defined range.

There exists a reduction in solar radiation for the Mid-future climate file. Global dimming has been studied in a number of studies [77–79]. GCM indicates a reduction in cloud cover over Europe therefore increase in surface solar radiation. On the other hand, RCMs do not show any significant changes in cloud cover, although the atmospheric absorption increases which leads to surface solar reduction [79]. Since the overall changes in solar radiation are relatively the same, as depicted in Fig. 6, it could also be inferred that the effect of shading systems, in terms of reduction in cooling requirement (kWh/m^2) remains quite unchanged over time.

Average and Mid-future climate files have been assembled based on CORDEX data, therefore uncertainties are inevitable. As can be seen from Fig. 6, there exists a line of data at 0 °C for these climate files which could be due to these uncertainties. The same figure was plotted for Average climate, though using an assembled TMY file from observational data for the same period (2001–2020). The "line" slightly above 0 °C was depicted, although not as clear as the line seen in the projected data. It is noteworthy that the latter mentioned figure is not presented in this study, as it was not within the scope and aims.

The curve of solar radiation against temperature is shown in Fig. 7 for monthly mean values in the studied city for all the four periods. Based on the results, the average monthly temperature increases over time. The changes in temperature are more perceptible during the summer period (May- August). The total average temperature of the Historic climate file is 5.8 °C while the average temperature for the present and mid-future TMY climate files are 6.9 and 8.8 °C. This implies the increased need in cooling demand of the building overtime to keep the indoor temperature within the comfort range.

Table 2
Statistical distribution dry bulb temperature and global solar irradiation for the historical period 1986–2005.

	Dry bulb temperature (°C)			Global solar irradiation (kJ/m^2)		
YEAR	Observation	Extracted	Bias-corrected	Observation	Extracted	Bias-corrected
Min. :1986	−27.4	−38.5	−27.4	0.0	0.0	0.0
1st Qu.:1991	−0.1	−0.8	−0.1	0.0	0.0	0.1
Median :1996	5.4	5.0	5.4	4.0	0.5	4.0
Mean :1996	6.0	4.9	6.0	108.4	88.7	108.5
3rd Qu.:2000	12.7	11.5	12.7	157.0	78.6	157.0
Max. :2006	33.9	33.4	33.9	803.0	801.3	803.0

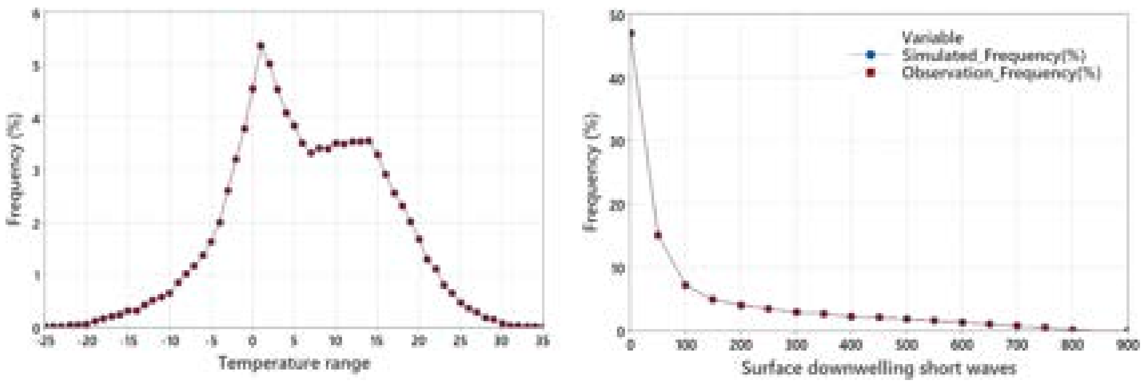

Fig. 5. Distribution frequency of two of the variables for observational and bias-corrected simulated data for the correction period (1986–2005).

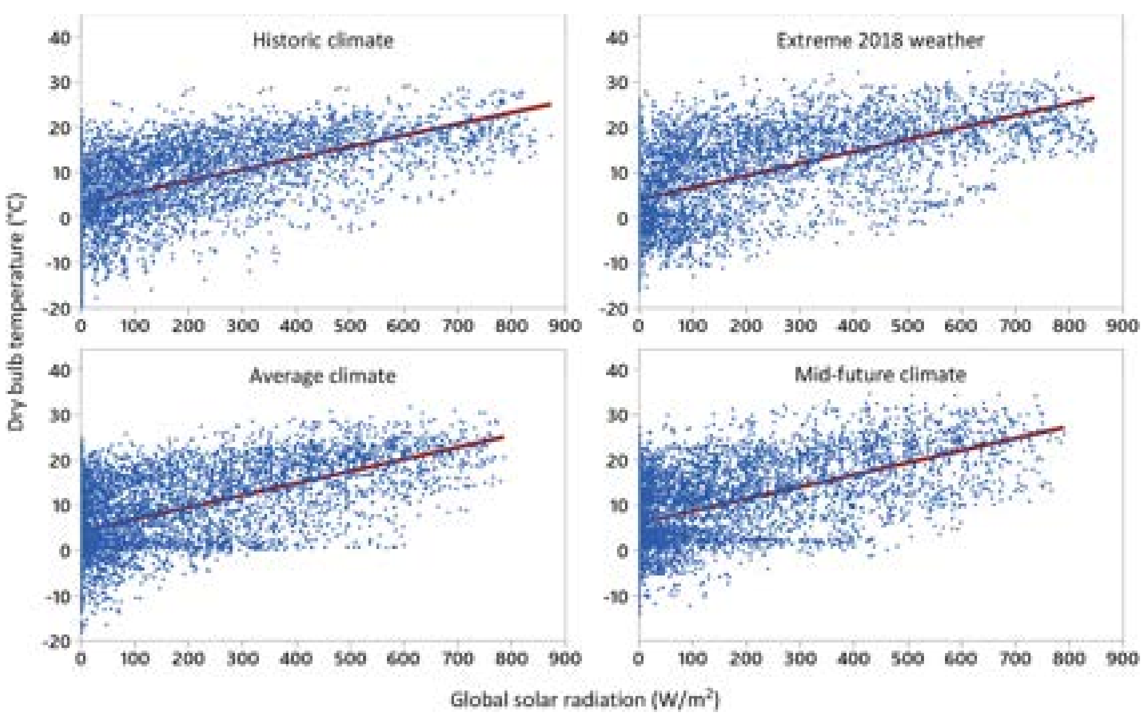

Fig. 6. Regression evaluation for the studied climates and the extreme weather 2018.

Depending on the models used, +0.8 °C to 3.5 °C increase in average temperature was depicted in [45]. Nik et al. [22] followed a different method based on [80] to generate weather files representing future climate. In their study, they also concluded increase in annual average temperature for the studied future climate files in relation to a baseline period 1960–1991.

3.2. Energy performance of the building

The result of the simulations (delivered energy) for the prototype building when employing the constant and schematic supply temperature strategies, for all cooling set-points and climate conditions are depicted in Fig. 8. Fig. 8a represents the case where

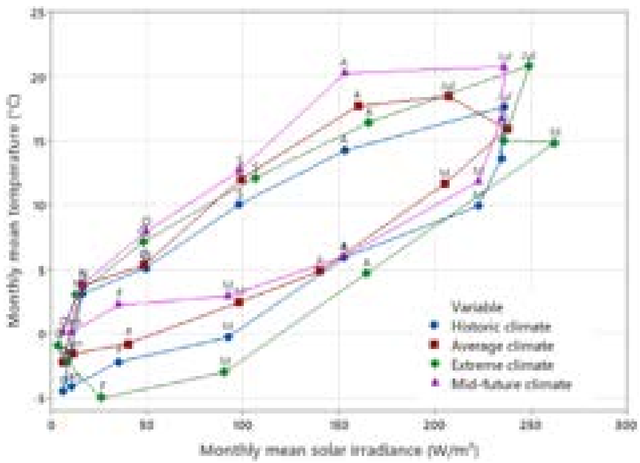

Fig. 7. Curve of average monthly solar radiation against temperature for all the climate files and the extreme weather 2018.

automatic shading system *was not* implemented and Fig. 8b represents the case where automatic shading system was implemented. The solid filled bars represent the case with constant supply temperature (16 °C) and the hatch filled bars represent the case with schematic supply scheme (Fig. 3). District heating includes both domestic hot water and zone heating, and tenant electricity is represented as *electricity*; aux is the annual energy used by facility equipment such as fans and pumps, 4.6 kWh/m^2. As it could be seen from Fig. 8, the required heating is lower when employing the Average and Mid-future climate files compared to the Historic climate file. On the other hand, the cooling demands, especially for the Extreme weather file, are higher.

From the breakdown of energy performance aspects in Fig. 8a, district heating increases 3% and district cooling decreases 16% for almost all the studied cooling set-points and climate files when using the schematic supply temperature compared to constant supply temperature. By examining the monthly energy use of the building, it was discovered that schematic supply strategy increases the heating requirement during September and October. The heating energy for the two implemented supply strategies was analyzed. It was found that during September and October, the ambient temperature distribution varies from 0 to 20 °C with mostly above 8 °C and below 16° C, which based on the scheme depicted in Fig. 3, within this range the heating coil is set to initiate reduction in the supply air temperature. Therefore, within this range, the supply air temperature for the AHU executing schematic supply strategy is below 16 °C, consequently the ideal heaters have to compensate for the deficiency of heat in the zones. Thus employing the schematic supply strategy increases the heat load in the zones compared to the constant supply strategy. On the other hand, when utilizing the schematic supply, the cooling load reduces due to the reduction in AHU's ambient supply temperature.

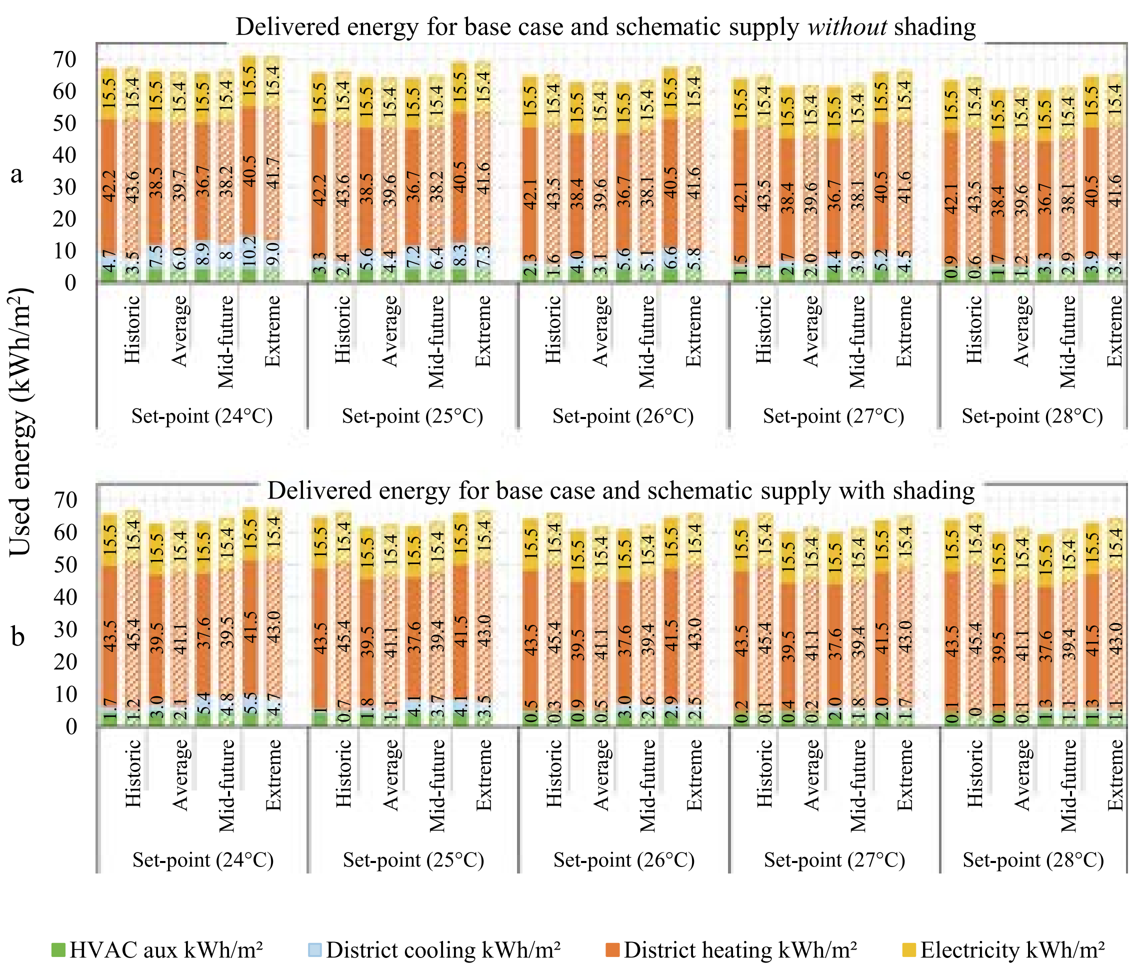

Fig. 8. Energy performance of the prototype nearly-Zero Energy Building (NZEB), a) constant and schematic supply strategy *without* shade. b). constant and schematic supply strategy with shade. *Solid filled bars* represent constant supply temperature. *Hatched bars* represent schematic supply temperature.

The increase in the heating demand and the GHG emission associated with it is not substantial from primary energy use point of view as the energy carrier for the heating system in district heating and renewable sources of energy are employed in the DHS. As mentioned in section 2.4, the carbon emission of the district heating system is 3.66 g CO_2 equivalents/kWh. However, the reduction of cooling demand on the other hand could be prioritized.

By comparing the heating and cooling energy use in Fig. 8b (where automatic shading was added) to Fig. 8a, it was discovered that on average, the heating energy use increased by 3%, cooling energy use decreased by 70%, for all the cooling set-points and climate files. The heating energy of the two supply strategies was analyzed to investigate these changes in heating energy use. Additional heating requirement (other than September and October) by the end of April and whole May was discovered. The shading system is scheduled to be activated during summer time (May-August). Since apart from cooling energy requirement, there is still some heating energy required during May, the shading system prevents the solar irradiation from entering the space, which blocks solar gain that helps reducing heating requirement during heating season.

Fig. 9 depicts the result of the simulations (delivered energy) when employing the CAV and VAV all-air cooling systems. Solid filled bars represent CAV and hatched bars represent VAV system. HVAC aux for CAV and VAV systems is almost 7 and 3.5 kWh/m^2 respectively. From the breakdown of energy performance aspects in Fig. 9a, district heating decreases 12% and district cooling increases 26% for almost all the studied cooling set-points and climate files when using the VAV system compared to CAV system.

By comparing Fig. 9a and b, heating demand has slightly increased on average 1%; cooling demand on the other hand has reduced, on average 45% for all the set-points when adding automatic shading. However, employing automatic shading appears more effective for VAV system compared to CAV system by comparing Fig. 9a and b. The changes in delivered energy is dominated by the reduction in cooling demand when adding shade for VAV system.

To analyze the effect of each cooling set-point on building's energy for all the climate files, Fig. 10 is plotted. Fig. 10a depicts the total energy use changes between Fig. 8a and b. Fig. 10b depicts the total energy use changes between Fig. 9a and b. The circle markers depict the constant supply strategy and the triangle markers depict the schematic supply strategy. From Fig. 10, it could be concluded that for every climate file by employing a lower cooling set-point, addition of shade helps in saving more cooling energy compared to higher set-points, regardless of the supply temperature or the ventilation strategies studied. The negative values represent reduction in energy use when automatic shades were added, compared to the case without shading system. It should be noted that total energy use i.e., district heating and cooling, electricity and HVAC aux were considered to plot Fig. 10.

When simulating using the lower cooling set-points (24, 25 and 26 °C), the cooling demand increases to keep the indoor temperature at the desired set-point. On the other hand, choosing higher cooling set-points (27 and 28 °C), reduces the cooling load required to maintain the indoor temperature. The Historic climate file shows the least amount of changes in total energy use, since during this period (1986–2010), the average annual temperature was 1.5 °C and 3 °C lower compared to Average and Mid-future climate files, respectively.

The slope of the presented results in Fig. 10a and b follow the same trend. Historic and Average climate, as shown in Fig. 7, have lower average monthly temperatures, therefore increase in heating load is more substantial compared to reduction of cooling load when adding the shading system. Therefore, this leads to a higher delivered energy than expected, as it was previously discussed in case of Figs. 8 and 9. On the contrary, in case of Mid-future and Extreme climate files, due to higher ambient temperatures, especially during summer, as presented in Fig. 7, changes in total delivered energy is dominated by the reduction in cooling load. The reduction in cooling load is more significant than increase in heating load, especially when using lower cooling set-points. Overall, both Extreme and Mid-future show the same energy change level as per Fig. 10. Based on Fig. 7, during summer, Extreme weather depicts higher solar radiation; though lower outdoor temperature. On the other hand, Mid-future climate shows lower solar radiation and higher outdoor temperature. The increase in the cooling demand corresponds to 1.7–5.8 times the Historic climate when employing the extreme and the assembled climate files.

These results are consistent with several earlier studies. Jylhä et al. [42] evaluated the heating and cooling demand for typical detached houses in Finland, reported 20–40% decrease in heating and 40–80% increase in the cooling requirements when employing projected climate file. A study carried out by Machard et al. [45] for a residential building in France also depicted increase in cooling requirement, by a factor 3 to 4 for future typical weather.

Thalfeldt et al. [81] studied the effect of automated external Venetian blind on the energy performance of NZEB in Estonia. The control schedule and the blinds were adopted from [82]. The shades were scheduled to be raised during winter. Beck et al. [82] reported a slight increase in heating and lighting demand and reduction in cooling demand especially for south orientations (over 70% reduction) in Stockholm. Similar result was depicted in this study, though with different external shade. On the other hand, Thalfeldt et al. [81] concluded that the shades were not economic due to high investment cost. Also for smaller windows, due to lower initial space cooling need, the reduction in cooling energy could not compensate the increase in heating and lighting, consequently it increased the primary energy use. However, these effectively reduced cooling need for large double or triple glazing windows.

3.3. The PE_{PET} evaluation for the studied prototype building

Fig. 11 presents PE_{PET} for all the cooling set-points, climate files and ventilation strategies. The values representing the CAV system and constant supply strategy are presented with circle markers. The values presenting the VAV system and schematic supply strategy are presented with triangle markers.

The extreme climate 2018 shows the highest PE_{PET} for each of the set-points, regardless of the ventilation or supply strategy in all the plots in Fig. 11. An average 3.3 K increase in temperature during year 2018, compared to 1961–1990 climatological mean was recorded [83,84]. The anomalies in the weather condition were caused due to high-pressure dominated weather and increased solar radiation due to clear skies as shown in Fig. 7. Therefore cooling demand was almost doubled compared to Average climate (the TMY assembled from 2001 to 2020). The second high PE_{PET} is associated with the Historic climate file. This is due to the relatively lower average monthly temperature, specifically for the heating season (September-May). The TMY file was based on the 30-year series data (1981–2010) from SMHI. Mid-future climate file has the third high PE_{PET}.

From the figure, when adding the automatic shading system, overall PE_{PET} decreases in all the studied climate and weather files. Cooling set-points 27 and 28 °C show the least reduction in PE_{PET} since addition of shades affect the cooling energy of the system, and as these two set-points do not require a high cooling energy, shading did not appear as effective when using lower cooling set-points.

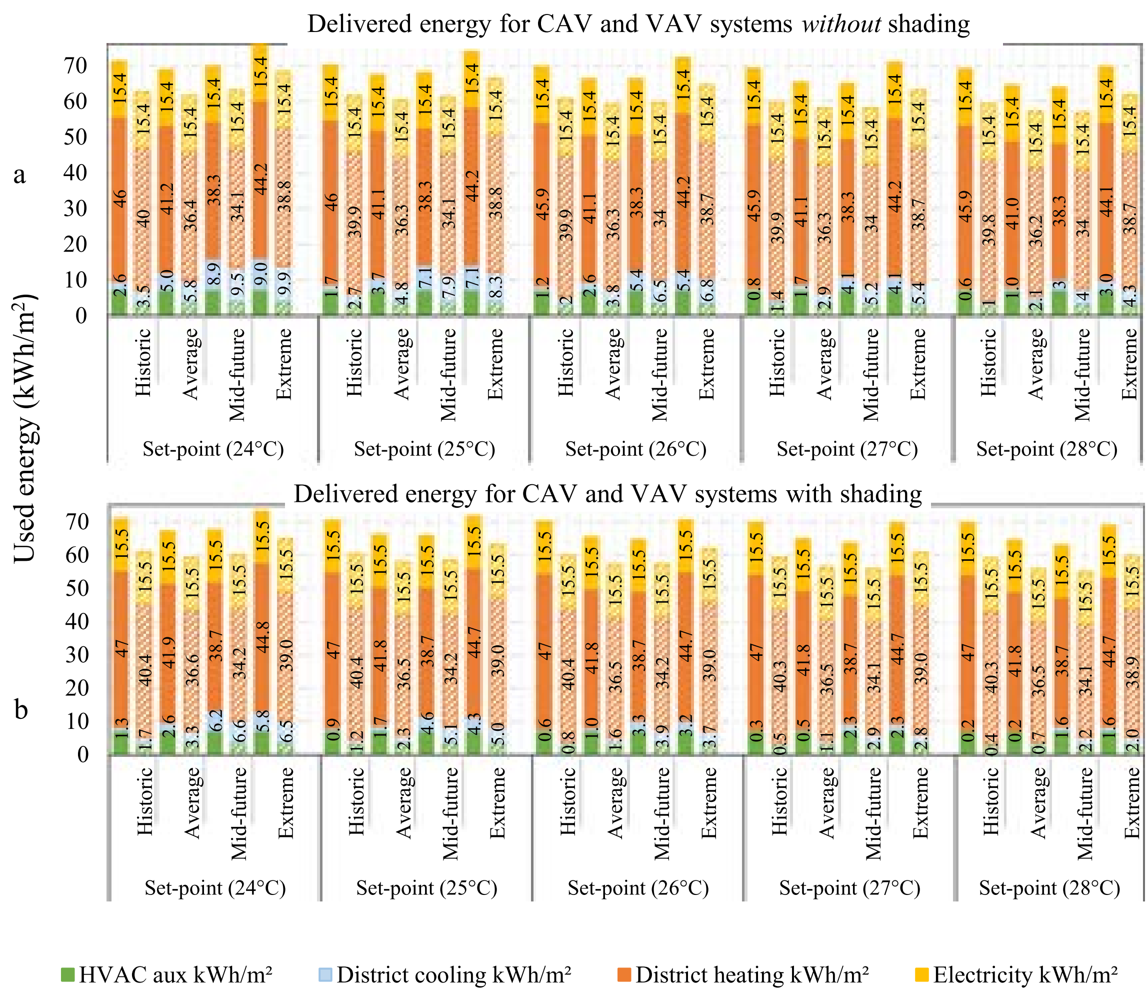

Fig. 9. Energy performance of the prototype nearly-Zero Energy Building (NZEB), a) CAV and VAV systems *without* shade. b). CAV and VAV system with shade. *Solid filled bars* represent CAV system. *Hatched bars* represent VAV system.

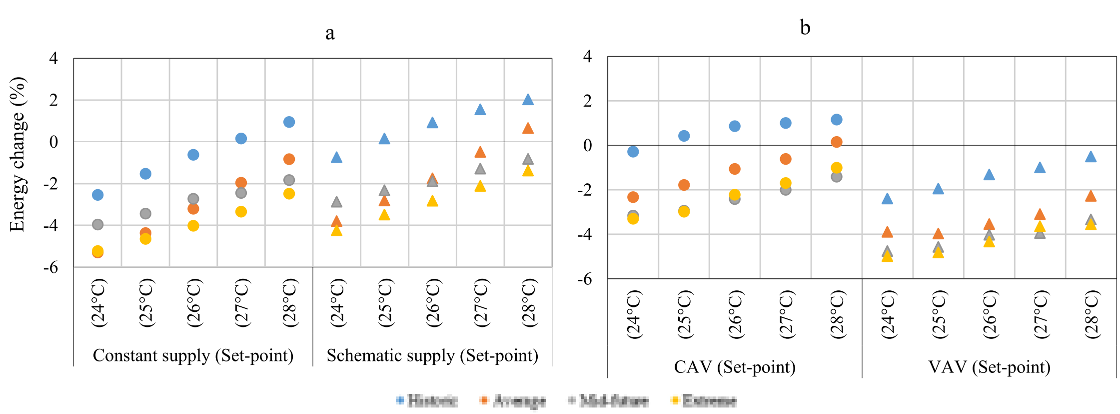

Fig. 10. a) Changes in total energy between Fig. 8a and b. b) Changes in total energy between Fig. 9a and b. The constant supply strategy and CAV system are represented with *Circle markers*. The schematic supply strategy and VAV system are represented with *triangle markers*.

In case of Historic and Average climate, the trend of result when adding the shades, is not as steep as the other studied climate files which is mainly due to the lower cooling demands, especially when operating with higher cooling set-points. PE_{PET} remains relatively the same when adding the shading systems for the mentioned climate files.

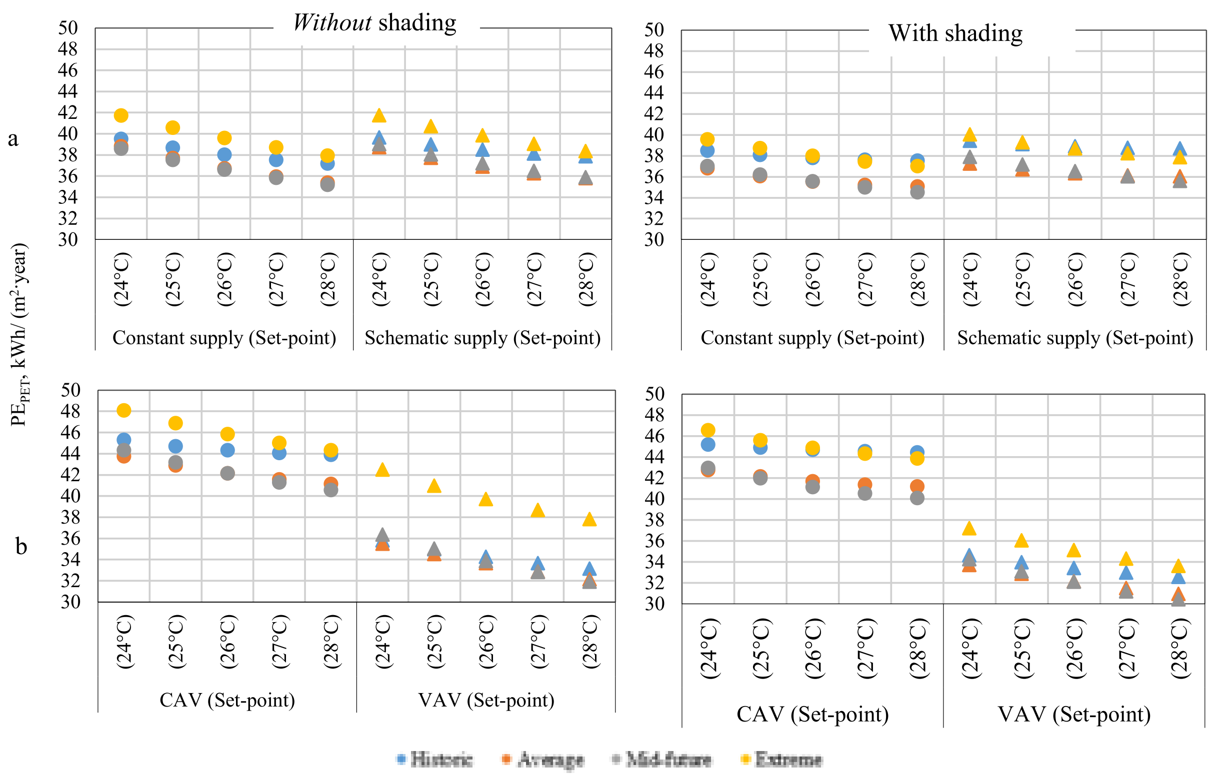

Fig. 11. *a*) PE$_{PET}$ for the investigated prototype building for constant and schematic supply strategies. b) PE$_{PET}$ for CAV and VAV systems. The constant supply strategy and CAV system are represented with *circle markers*. The schematic supply strategy and VAV system are represented with *triangle markers*.

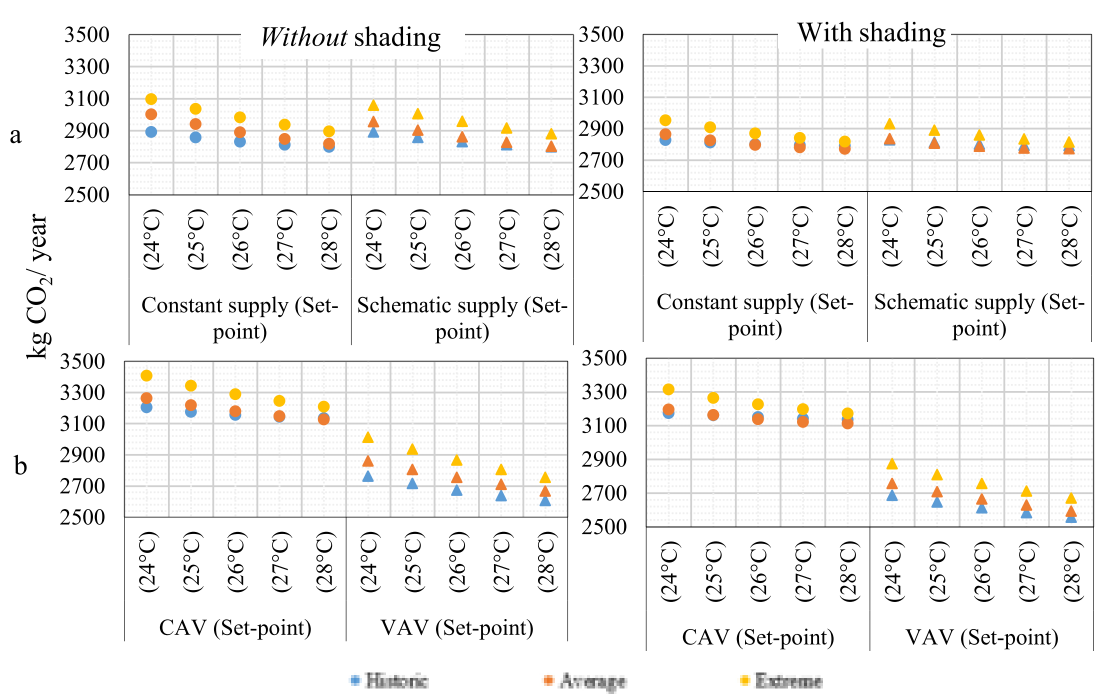

Fig. 12. The carbon emission for the Historic, Average and Extreme climate files and all cooling set-points. a) Depicts the CO_2 emission for constant and schematic supply strategy. b) Depicts the CO_2 emission for CAV and VAV system.

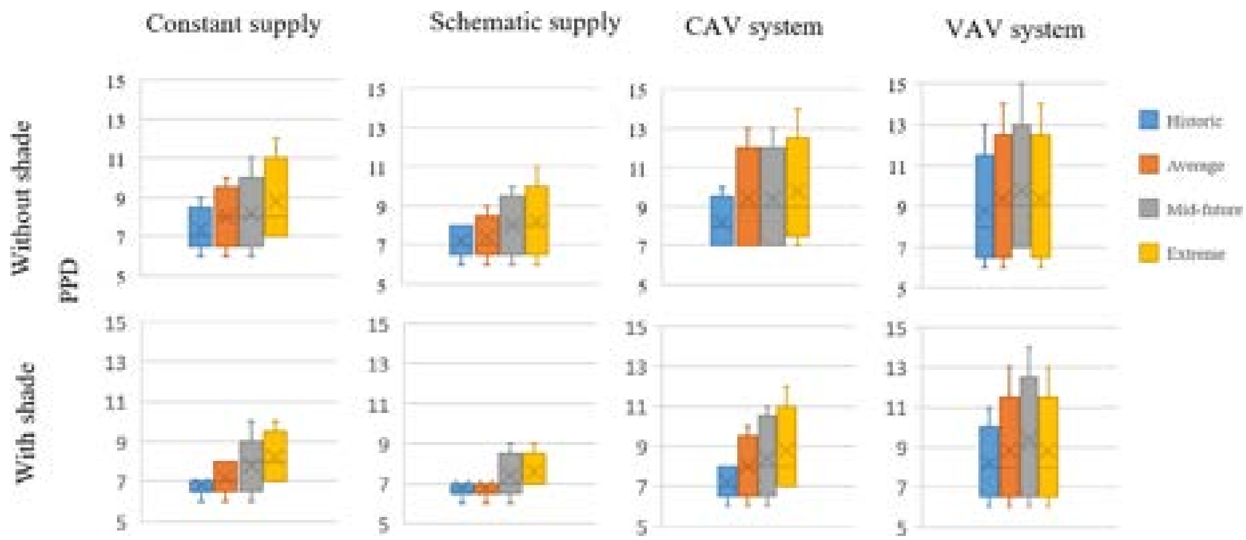

Fig. 13. Predicted Percentage of Dissatisfied (PPD) associated with all the cooling strategies.

3.4. CO_2 emission evaluation for the studied prototype building

The carbon emission from the building exposed to all the studied climate files and set-points have been plotted in Fig. 12. However as mentioned in the introduction part, based on the European Climate Law, the EU aims to become a climate neutral continent by 2050. Therefore, the emission factor for the Mid-future period was excluded from the calculations in order to match the European Climate Law.

Addition of shade reduces the carbon emission as it could be concluded from Fig. 12. Based on the results from Fig. 12a, the reduction in the CO_2 emission ranges from 0.3% to 4.7% for the studied climate files. The least amount of changes belong to the Historic climate with cooling set-point 28 °C and the highest value belongs to the cooling set-point 24 °C when employing the Extreme weather file. Overall addition of shades appear more advantageous when adopting the constant supply strategy and the reduction in the CO_2 emission is more evident when Extreme and Average climate files were employed. The mean electricity mix for the Nordic countries of today was employed as the allocating method to measure the CO_2 emission which corresponds to 90.4 g CO_2e/kWh [71]. The chillers in the DCS use electricity to match the cooling demand of the district. The COP for the system was found to be four. Historic climate was recognized as the climate file with the least cooling demand. Therefore, the carbon emission also is the least when using this climate file. On the other hand, the building shows higher cooling demand when employing the Extreme and Average climate files, therefore changes in cooling demand and consequently the CO_2 emission is more substantial. It must be noted that district cooling and heating use mostly free cooling and renewable sources of energy, as mentioned in section 2.4.

Much the same as the result from Fig. 12a, for Fig. 12b also addition of automatic shades helped in reducing the CO_2 emission for the two utilized all-air cooling systems. The least amount of changes belong to the Historic climate for CAV system, specifically when higher cooling set-points were employed for the ventilation system. On the other hand, VAV system shows further decrease in the CO_2 emission level after utilizing the automatic shading system. These reductions in the CO_2 emission range from 0% to 4.6% for the studied climate files.

3.5. Investigation of the comfort conditions

The predicted percentage of dissatisfied (PPD) associated with the studied ventilation strategies is depicted in Fig. 13. Boxplot was chosen to show the distribution of PPD over all the set-points for each climate. Each box represents the range of PPD for all the chosen set-points. Combination of schematic supply strategy and the automatic shading system depicts the least PPD, which overall lies within level "Good". However, employing the VAV system depicts the highest PPD within the studied cooling technologies that is placed in "Acceptable" level.

Fig. 14 depicts the exhaust air temperature for the studied cooling technologies during one year. The depicted results belong to the Historic and Mid-future climates, cooling set-point temperature 24 °C as a representative. The schematic supply strategy helps reducing the exhaust air temperature compared to the constant supply temperature. The reported exhaust temperature is the mean regulated value of the sum of exhaust airs from the zones. Decrease in exhaust air temperature, implies lower indoor temperature, therefore reduction in the cooling load when utilizing the schematic supply strategy. By evaluating the thermal indoor conditions, percentage of total occupant hours with thermal dissatisfaction associated with schematic supply strategy, indicated better indoor conditions compared to constant supply strategy. By comparing the variations of PPD ranges for CAV and VAV with the two supply strategies, it could be concluded that ideal local coolers maintained the temperature within the defined set-point, which is an ideal case. However, CAV and VAV adopt a more practical practice as the variations in PPD is larger, depicting the delay within the system to adjust to the set-points. By checking the maximum operative temperature for different zones, it was discovered that in the top floor zones, the operative temperature exceeds the cooling set-point for up to 3 °C. However, that is not the case for the constant and schematic supply strategy as an ideal local cooler is employed in each zone. It is usually acceptable for the room temperature to rise above

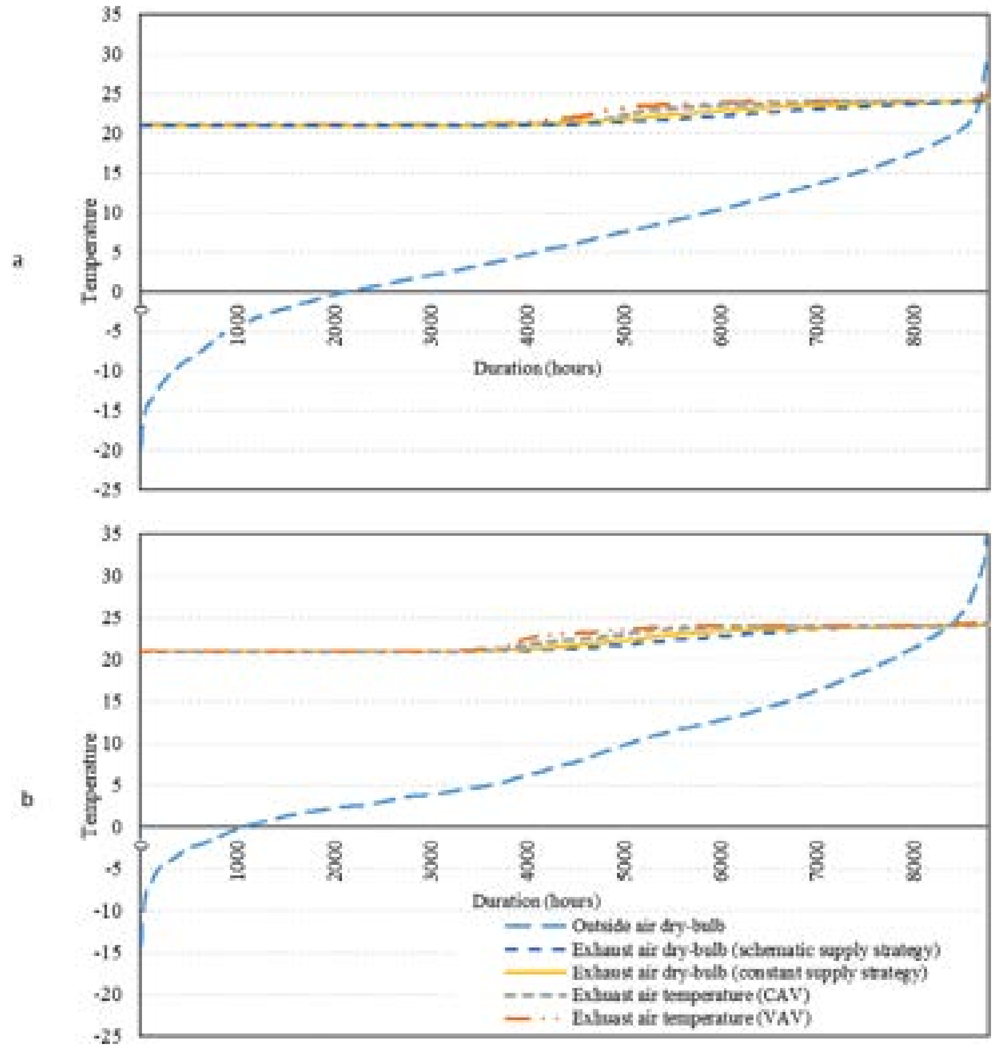

Fig. 14. Exhaust air temperatures for the studied cooling technologies for cooling set-point temperature 24 °C. a) Representing variables for *Historic climate*. b) Representing variables for *Mid-future climate.*

the defined set-point for short intervals as it requires an advanced HVAC system to keep a constant indoor temperature [85].

4. Conclusion

This study aimed to answer two research questions: Is it possible to use currently available typical meteorological year (TMY) climate files to evaluate the future energy need of buildings?

Moreover, how to improve the indoor thermal conditions and reduce CO_2 emission from building operation, and evaluate the effects on primary energy use?

The energy criteria to fulfil the Swedish building regulations are based on a typical meteorological year to estimate the energy use of the building, which in this study the climate was referred to as Historical climate. PE_{PET} also, is based on weighted values depending on the sources of energy the building uses. Historical, Average, Mid-future TMY files as well as an extreme weather file of year 2018 were used to evaluate the climate-driven energy demand. The Historical climate file, which is the typical weather file used for assigning regulation, underpredicetd the cooling demand for the residential prototype building. The required cooling energy use increased from 1.7 to 5.8 times the Historic climate file when employing the Average, Mid-future and extreme climate files, respectively.

This implied the need to update the climate files that are used for building simulations. Cooling systems should be designed and operated to be resilient under extreme conditions to protect occupants from potentially dangerous indoor thermal conditions.

Four different cooling methods were introduced. Two all-air cooling systems, constant air volume (CAV) and variable air volume (VAV) as well as two different supply strategies for air temperature, constant and schematic supply, for a mechanical ventilation system with room units were defined.

Increasing the cooling set-point reduced PE_{PET} up to 5.5%. The effectiveness of the schematic supply strategy was more perceptible compared to the constant supply strategy as it effectively reduced the cooling energy need of the building (up to 28%) by reducing the indoor air temperature. Therefore, more number of hours were found to be below the required set-points. However, addition of shade increased the heating energy need especially for schematic supply strategy due to the additional heating energy required during May. Therefore, combination of automatic shading and schematic supply strategy does not appear as effective as the same ventilation *without* shade from PE_{PET} and energy use perspective. However, PPD is higher for the latter case.

For the studied all-air cooling systems, VAV depicted a lower delivered energy compared to the CAV system. Addition of shades reduced the cooling and consequently reduced the PE_{PET}. The changes in energy were dominated by the cooling demand, which depicted 45% reduction on average.

From the studied cooling methods for the four climate files, combination of all-air cooling system, VAV, with automatic shading system, showed the least total energy use. The total annual energy use for the other cooling systems was 4–17% more compared to the mentioned technology. Constant supply strategy with automatic shading system could be considered, after the former mentioned combination. These two mentioned technologies, combined with the introduced shading system, showed to be more resilient towards the induced climate changes.

Apart from the thermal comfort improvement when combining shading system with the studied cooling methods, the CO_2 emission also reduced. The emission abatement is more substantial for cooling set-points 24–26 °C when adding the shading system, due to the larger cooling load.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Comparison of Space Cooling Systems from Energy and Economic Perspectives for a Future City District in Sweden

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Article

Comparison of Space Cooling Systems from Energy and Economic Perspectives for a Future City District in Sweden

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Abstract: In this study, the performance of different cooling technologies from energy and economic perspectives were evaluated for six different prototype residential Nearly Zero Energy Buildings (NZEBs) within a planned future city district in central Sweden. This was carried out by assessing the primary energy number and life cycle cost analysis (LCCA) for each building model and cooling technology. Projected future climate file representing the 2050s (mid-term future) was employed. Three cooling technologies (district cooling, compression chillers coupled/uncoupled with photovoltaic (PV) systems, and absorption chillers) were evaluated. Based on the results obtained from primary energy number and LCCA, compression chillers with PV systems appeared to be favorable as this technology depicted the least value for primary energy use and LCCA. Compared to compression chillers alone, the primary energy number and the life cycle cost were reduced by 13%, on average. Moreover, the district cooling system was found to be an agreeable choice for buildings with large floor areas from an economic perspective. Apart from these, absorption chillers, utilizing environmentally sustainable district heating, displayed the highest primary energy use and life cycle cost which made them the least favorable choice. However, the reoccurring operational cost from the LCCA was about 60 and 50% of the total life cycle cost for district cooling and absorption chillers, respectively, while this value corresponds to 80% for the compression chillers, showing the high net present value for this technology but sensitive to future electricity prices.

Keywords: nearly zero energy building (NZEB); primary energy number; district cooling; absorption and compression chillers; life cycle cost analysis; climate-resilient buildings

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1. Introduction

With the increase in population and urbanization, the energy needs for building sectors are increasing. In most cities, housing accounts for more than 70% of land use [1]. This value tends to increase due to the population growth rate. However, the pace of population growth has been shown to be falling below 1.1% in recent years [2]. Based on the report, it is expected that the population growth rate will continue to slow down towards the end of the century [2]. However, it is not expected to reach zero or a decline in the trend. Therefore, with this increase in the population, energy use within the building sector also increases which consequently leads to an increase in greenhouse gas (GHG in form of carbon dioxide equivalents CO_2 eq) emissions. This sector is considered a significant consumer, using around 40% of the total energy produced for heating and cooling purposes in the European Union [3]. Therefore, utilizing environmentally sustainable energy to limit GHG emissions and the global temperature rise to ensure a positive environment for energy transition is of concern [4].

1.1. Nearly Zero Energy Building and Primary Energy Number

The European Commission has introduced the European Green Deal [5]. It consists of several climate action initiatives to cut GHG emissions by adopting policies that fit net emission reduction through energy, transport, and taxation. The European Climate Law [6], European Climate Pact [7], and the European adaptation strategy [8] are among the climate action initiatives. Based on the climate law actions, the union tries to become a climate-neutral continent by 2050 which means on average a 2.6% reduction in CO_2 eq emission per year [4,6]. The European Climate Pact is an initiative that involves communities, people, and organizations in climate action [7]. Finally, the European Adaptation Strategy deals with the climate resiliency of Europe by setting principal objectives to enable adaptation to the unavoidable impacts of climate change [8]. The initiatives help reach the European Green Deal principles for a clean energy transition that consequently not only reduces GHG emissions but also enhances the quality of life for citizens [9]. However, the possibility of a 100% renewable power system by 2050 remains a question. Several studies evaluated this possibility in Europe [10–12] and Canada [13] and these have reported large capacity and investment requirements. However, the mentioned studies carried out for Europe concluded that even completely renewable systems might fail to deliver the planned carbon reduction.

The Energy Performance of Buildings Directive (EPBD) 2010/31/EU [14,15] has emphasized adopting cost-optimal energy efficiency measures and the importance of Nearly Zero Energy Buildings (NZEBs). Studies have been carried out on reviewing [16] and evaluating the operation of such buildings in, for example, southern Europe [17], Italy [18], Sweden, and Norway [19–21]. Commission Recommendation (EU) 2016/1318 [22] established guidelines promoting NZEBs in 2016, which regards them as buildings with high energy performance using a low amount of energy, mostly covered by renewable sources. On the other hand, to evaluate the energy performance of the buildings, guidelines were provided in the official journal of the European Union (EU) [23,24]. The energy performance of a building is defined as the building's energy demand in the form of heating, cooling, ventilation, lighting, and domestic hot water [23]. With the emphasis on NZEBs and improving the energy performance of the buildings, European member states were obliged to provide their definition, reflection, and a numerical indicator of Primary energy (PE) [14,15,25]. Primary energy is used to anticipate the end-use energy before it undergoes any conversions or transformations. Based on the Directive 2010/31/EU, primary energy factors should be included in energy performance indicators. These factors are based on national or regional values [26].

Studies were carried out to define primary energy factors and their application in Swedish buildings [26,27]. The Swedish National Board of Housing Building and Planning (Boverket) [28] has proposed the term "primary energy number" (PE_{PET}), which is based on weighting factors of energy carriers that are used in buildings. PE_{PET} is a numerical indicator for NZEBs that sets energy use-related limitations in buildings and it is expressed in kWh/m^2 per year. The calculation method is defined in the Swedish Building Codes [29]. Per 2020, bounding PE_{PET} below 75 kWh/m^2 contributes to fulfilling the criteria according to the NZEB definition for the residential sector [30].

From the year 2020 onwards, newly constructed buildings in Sweden are obliged to comply with the provided NZEB definition. The studied future district comprises 6000 new residential buildings and it is now in the planning phase and programmed to be fully utilized after 2040 [31]. Therefore, all buildings are obliged to be NZEBs to form an environmentally sustainable district.

1.2. Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) is marked as a criterion used in evaluating economic assessment and evaluating the efficiency of energy-saving measures in the building sector [32]. The importance of adopting a cost-optimal energy efficiency measure to enhance the desired energy performance has been proposed in Article 1 of regulations in EPBD [33]. This connects energy performance optimization with financial targets and emphasizes cost analysis tools to study the energy performance of buildings. Studies have been carried out to evaluate optimal economic performance on different levels. At the district level, Arrieta et al. [34] reported the use of photovoltaic cells for self-energy consumption to be profitable for primary energy use and energy cost reduction. At NZEB levels, [35] a cost-optimal set of technologies was introduced to be used in different contexts. Finally, at the building refurbishment level, [36,37] the performance of different ventilation technologies, fabric elements, etc. were evaluated and the optimal option was reported.

To evaluate the economic feasibility of certain energy reduction measures in this study, LCCA was adopted as it provides insight into the amount of investment and life cycle cost of the considered technologies. Having an insight into the life cycle cost of each cooling technology helps to plan more wisely for the district to find the optimized alternative from not only the energy perspective but also the economic perspective, when the district is still in the planning phase.

1.3. Motivation and Aim

The current study aims at predicting the future primary energy number and energy use for cooling of buildings for a future city district in central Sweden in the 2050s (mid-term future) given that the operative temperatures in buildings is expected to increase worldwide [38,39]. The district is to be developed in Gävle (60.6749° N, 17.1413° E), Sweden and the study is a part of the program concerning heating and cooling from the future energy system (TERMO program) held by the Swedish Energy Agency [40] with its focus on space cooling demand. The project tries to predict space cooling demand for reference buildings, which, scaled up, will map the cooling profile of the building types and of the city district. Based on the objectives of the program, the goal is to compare and evaluate the primary energy and economic-efficient cooling alternatives for the prototype buildings given that the case study district is one of the Swedish government's nine selected initiatives concerning development of future environmentally sustainable districts. Apart from that, from previous studies, an increase in the number of exceedance hours (zone temperature exceeding a certain threshold, such as 27 °C) has been reported when using a projected climate file or a heatwave weather file in the authors' previous works [20,41–43]. Therefore, this emphasizes the importance of anticipating the cooling demand for prototype buildings. Cooling alternatives encompass district cooling technologies versus in-house solutions that rely on district heating or electricity such as absorption chillers and compression chillers as their energy carriers and sources. Here, by in-house alternative, it is meant any local technology—in other words, technology that does not draw the required energy from a central station to many buildings or a campus. It is noteworthy that ventilative cooling should be assumed since residential buildings must have mechanical ventilation for heat recovery according to Swedish building regulations.

To obtain a better prospect of the energy performance of the buildings in the future, building performance simulations were considered. To describe the dynamic behavior of the buildings, annual hourly weather data was employed. The weather file used represents the mid-term future (2041–2060) and it has been projected and bias-corrected based on methodologies presented by Machard et al. [44] and Cannon [45,46] respectively. Detailed information regarding the projection of the future climate file for the studied city exists in the authors' previous work [41]. Lack of implementing a climate file that represents the future conditions for building design purposes was regarded as a policy gap in the authors' previous works therefore it is now expanded to a city district, given that it is regarded as an environmentally sustainable city district in which all buildings match the NZEB definition. The obtained climate file has been verified by a methodology introduced in IEA EBC Annex80: Resilient cooling of buildings [47]. It is noteworthy that validation of the assembled climate file is not possible as it represents the 2050s.

Based on the authors' previous works mentioned earlier and the studies carried out in different regions such as Sweden [48], Finland [49], and Denmark [50], the cooling demand will increase. Present Swedish residential buildings are not commonly equipped with cooling technologies; therefore, given the ongoing climate changes, the resiliency and robustness of these buildings in the future would be questionable. Therefore, this

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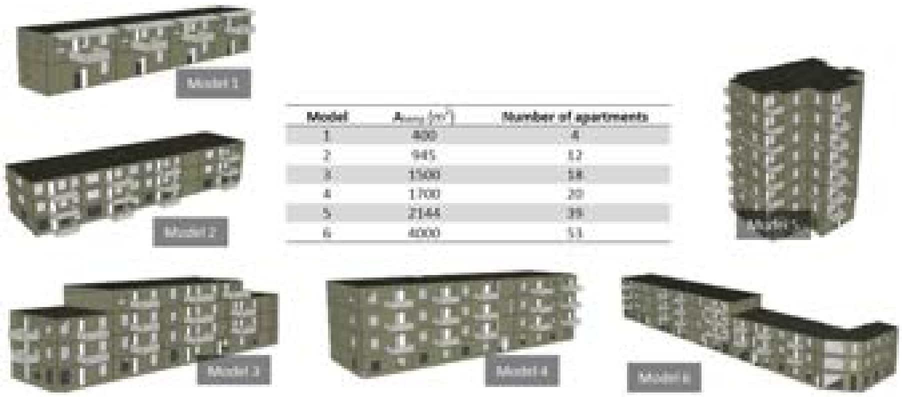
Which are the more suitable space cooling alternatives from primary energy number (PE_{PET}) and economic points of view for property developers/owners and energy suppliers for a residential district in Gävle, Sweden?

2. Materials and Methods

2.1. Framework

The studied district, Näringen in Gävle, is located in central Sweden and it is planned to be a residential district [31] consisting of 6000 new apartments and public service buildings, such as schools. The district is planned to be built between 2025–2050, starting the construction phase in 2025. Six different building models were chosen as representatives to be constructed in the area. The model buildings meet NZEB requirements and these were adapted from a report by Energiforsk [54], a research and knowledge institute that conducts and coordinates energy research in Sweden. Some of the represented models have been constructed in newly utilized neighboring districts [55,56]; however, these must be modified to match the NZEB expectations for the studied future district. Figure 1 depicts the representative building models. The prototype buildings were modeled in IDA Indoor Climate and Energy (ICE) version 4.8 [57]. The software has been validated using the BESTEST procedure [58]. It has also been validated against measured data [59,60]. More information regarding the validation process can be found in [61].



Model	A_{temp} (m²)	Number of apartments
1	400	4
2	945	12
3	1500	18
4	1700	20
5	2144	39
6	4000	53

Figure 1. The six building models used for evaluating energy use in the future area of Näringen.

Since the district is expected to be fully utilized after 2040, the climate file representing the mid-term future was used to describe the dynamic behavior of the buildings. A typical meteorological year (TMY) file containing 8760 h derived from multiyear data was assembled. The European Coordinated Regional Downscaling Experiment (EURO-CORDEX) was used to assemble the climate file. Data were downloaded from the Earth System Grid Federation (ESGF) [62]. The average annual dry-bulb temperature will be 8 °C whereas it is 5.8 °C at present [63]. July and December are the warmest and the coldest months. Average monthly temperatures for these months correspond to 20 and −1 °C respectively.

To address the aim of the study, a framework has been developed. The workflow to evaluate the economic and energy performance of different employed technologies is shown in Figure 2.

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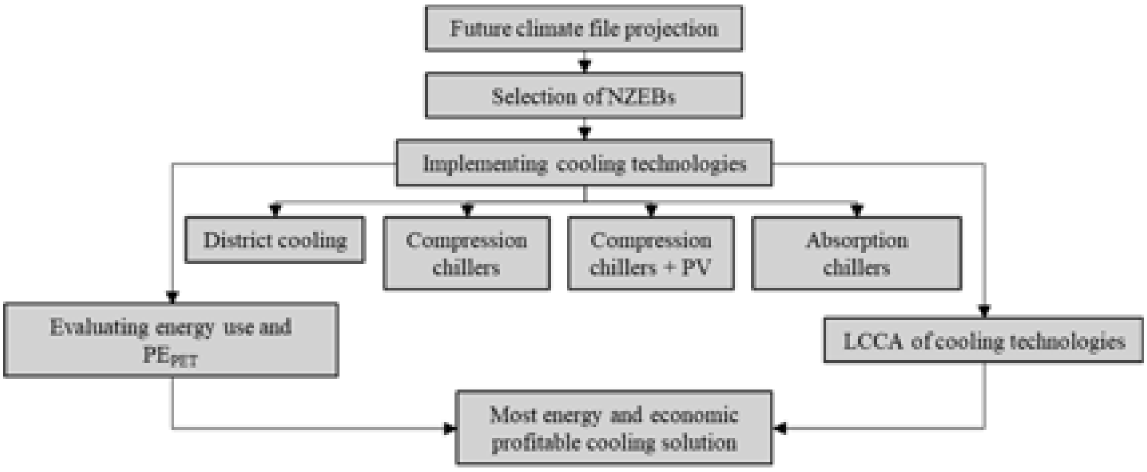

Figure 2. Overview of the workflow to evaluate the economic and energy performance of the cooling systems.

After assembling the future climate files and obtaining the prototype models that are planned to be built in the district, different cooling technologies as shown in Figure 2 were chosen to be assessed from primary energy number and economic perspectives. Finally, the most energy-efficient and profitable cooling solution will be reported.

Three different space cooling technologies were chosen to evaluate their performance for all the building models under same conditions. District cooling (DC), compression chillers coupled with solar photovoltaic (PV) systems (denoted as Chiller + PV) and uncoupled with a PV system, and finally, absorption chillers (Abs) driven by district heating were the cooling technologies considered in this study. The case of compression chillers was considered to evaluate the effects of PV systems on the electricity use for cooling, since PV systems are expected to reduce electricity use by employing self-produced electricity that leads to reduction of carbon emissions.

Given that the energy demand is predominantly heating, as district heating (DH) is the most widespread alternative in Sweden in more than 90% of multifamily buildings [64], the new district will have DH for space and domestic hot water heating. Therefore, DH will cover all heating demand irrespective of cooling options. Multifamily buildings are required to have mechanical ventilation systems according to building regulations, whereof systems with a heat exchanger involving heat recovery are common. This study assumes, independently of cooling source, that supply air is chilled by means of a cooling coil to meet the cooling demand (see [20] for more details). The energy efficiency of the heat exchangers was assumed to be 85%. Moreover, in the economic analysis, the costs of transfer of cold from the chiller unit to supply air has been omitted, i.e., assumes these are of the same order of magnitude. The cost differences studied between the technologies are in energy price, purchase of the cooling device, and the physical space these occupy. More details are described below on the cooling alternatives within the scope of this study.

2.1.1. Cooling Alternatives

District cooling is chosen as the first cooling choice. The local energy provider in the studied city, Gävle Energi AB [65], utilizes free cooling from a river and it is responsible for the operation and maintenance of the central compression chillers of the DC system. In this system, water in the network is cooled with the help of the river and if the temperature of the cold source (the river) is higher than 6 °C, two central compression chillers are utilized [66]. In the new district, heat for both space and domestic hot water is obtained from DH; therefore, laying the cooling pipes along with heating pipes at the construction stage of the district is easier and inexpensive. Considering the 4th-generation district heating (4GDH), the return pipes can be used even for a district cooling system, which reduces the investment costs [67]. The energy efficiency ratio (EER) of the central chillers is generally higher than that of the in-house chillers used in the central units in Stockholm with EER 6 [68]. Nevertheless, based on the information obtained from Gävle Energi AB, the EER of the central chillers is 4. Gävle Energi AB uses the nearby river for free cooling; therefore the EER of the systems tend to be lower than those of Stockholm, which has access to more free cooling via the Baltic Sea. The EER under standard rating conditions is defined as the ratio of the total cooling capacity [kW] to the effective input power to the device [69,70].

In this case, buildings are individually connected to the DC network and an installation cost is charged upon connection, based on the power, energy use, and location of the district.

Compression chillers with and without PV systems are chosen as a second cooling alternative. Chiller + PV is expected to be a common solution in the future and the excess PV-produced electricity can be delivered to the grid. This combination was chosen since it encourages self-electricity use, which consequently helps reduce GHG emissions to be on track with the EU commission goals. The panels help in producing the electricity for the compression chillers as it is concluded to be an efficient solution [27]. Apart from that, the impact of climate change on PV generation has been overall reported to be low [71]. To maximize the self-consumption of electricity produced from the PV system, different sizes were evaluated. Panel-to-roof area ratios of 100% and 50% and a panel-to-floor ratio of 10% were considered as the sensitivity analysis cases. Full self-use with minimized imported energy (electricity) could not be achieved and, as mentioned in [72], this is impractical as oversized PV systems are required. A ratio of 10% of floor area appeared to be the optimized ratio as it increased self-use from an average of 20% to 40% compared to the other two. The produced electricity when considering 100% panel-to-roof area is mostly sold to the grid, which is not an optimal choice since more self-use is encouraged. Therefore, a panel-to-floor ratio of 10% was used throughout the rest of the study.

The obtained cooling peak power demand ranges from 4–31 kW for the smallest to the largest models. The compression chillers are chosen from products manufactured by Carrier [73] to meet the cooling demand of the buildings. Two variable speed compression chillers, 17 and 21 kW in nominal cooling capacity, were found suitable to meet the cooling energy demand of the buildings. The number of buildings attached to each chiller and the building's cooling demand are shown in Table 1. This means that the chiller units may be shared among various buildings, especially depending on building size.

Table 1. Number of compression chillers and absorption chillers along with the chosen cooling capacity for the studied models.

		Compression Chiller		Absorption Chiller	
Model	**Number of Buildings**	**Capacity (kW)**	**Number of Systems**	**Capacity (kW)**	**Number of Systems**
1	4	17	1	17	1
2	12	17	6	35	3
3	18	21	9	35	6
4	20	21	10	17 35	5 5
5	39	17	39	35	19
6	53	17	106	17	106

The solar panels were sized based on the available products from SVEA SOLAR [74], a company that is one of the major producers of solar panels in Sweden. The system cost (including the panels, material, financing cost, permits, etc.) was projected based on a report from [75] and it is estimated to be around 10 SEK/W_p (1 EUR/W_p) in 2040s [76]. SEK stands for Swedish crowns. Based on the statistics presented by the European Central Bank [77], 1 euro has been equivalent to 10 SEK over the past years. This rate is considered in this study. The extra electricity produced was considered for sale to the grid at spot price of Nord Pool for Sweden. Data for the spot price is available over the past decade from [55].

The spot price for the analysis was calculated using a moving average with 3 intervals as the prior points to obtain the moving average, since fluctuations in the spot price do not allow obtaining a value by the normal averaging technique.

Finally, absorption chillers are implemented. These chillers use heat as their source of energy and these could be employed both for large buildings and in the central plant of DC system [78]. District heating (DH) has been the main form of heat supply for space heating and domestic hot water and it is expected to be available in the future as well. Therefore, absorption chillers were appropriate options given that DH is the most common form of heating in Sweden [37]. District heat is relatively clean and cheap as it uses mostly recycled heat (for production mix see Section 2.2.3). The emission factor for district heating has shown a large reduction over the past decade with an emission factor of 37 gCO_2 eq/kWh in 2010 to 4 gCO_2 eq/kWh in 2021 for Gävle [65] and it is expected to decline further. Apart from that, the heat generated during the summer can be utilized to provide cooling. The chillers in this study were chosen from Yazaki and their cooling coefficient of performance COP is reported 0.7 [79]. Two absorption chillers, SC5 and SC10, with a 17 kW and 35 kW cooling capacity respectively, were chosen. The number of chillers and required cooling capacity for buildings are shown in Table 1.

2.1.2. Energy Performance of the Buildings

This section is designed to evaluate the changes in PE_{PET}. The prototype buildings adopt the latest available construction features from the newest city district in the same city [80]. The building specifications are shown in Table 2. Appliance and occupant gains, lighting and building properties were chosen from Swedish building regulations and standards for building energy performance [30,81,82], where the latter reference implies 30% lower heat gains from modern household appliances than the older standard. Automatic blinds were added between the windowpanes. Blinds are drawn when the incident solar radiation exceeds 100 W/m^2 (1500 lx) on the outside of the glazing.

Table 2. Construction and general specifications of the buildings.

Parameter	Values	Parameter	Values
U_{values} Windows (W/(m^2·K))	0.92	Heating set-point [81]	21 °C
U_{values} External walls (W/(m^2·K))	0.1	Cooling set-point	25 °C
U_{values} Roofs (W/(m^2·K))	0.06	Heat exchanger efficiency	0.85–0.9
Window to floor ratio (%)	10	Number of residents [81]	1.42–2.18
Total area (m^2)	400–4000	Internal heat gain (kWh/m^2 per year) [82]	25–28

For a building to be considered an NZEB, the condition $PE_{PET} < 75$ kWh/m^2 based on the annual purchased energy must be satisfied. PE_{PET} is used for the evaluation since lower delivered energy does not necessarily imply lower primary energy (PE) use [26]. Equation (1) represents the calculation flow for PE_{PET}.

$$PE_{PET} = \frac{\sum_{i=1}^{6}\left(\frac{E_{heating,i}}{F_{geo}} + E_{cooling,i} + E_{DHW,i} + E_{el,i}\right) \times WF_i}{A_{temp}} \quad (1)$$

where:

PE_{PET} Primary energy number, kWh/m^2 per year
$E_{heating}$ Energy for heating, kWh per year
F_{geo} Geographical adjustment factor
$E_{cooling}$ Energy for cooling, kWh per year
E_{DHW} Energy for domestic hot water, kWh per year
E_{el} Building operational electricity use, kWh per year
WF Weight factor
i Index denoting energy carrier type

A_{temp} Heated floor area, m^2

The geographical and weight factors are based on the National Board of Housing, Building, and Planning regulations. F_{geo} for the studied city corresponds to 1.1 and weight factor *WF* for district heating, district cooling, and electricity are 0.7, 0.6, and 1.8, respectively [30]. It is noteworthy to keep in mind the difference between the term "zero energy building" and NZEB (used in this project). The Swedish definition of "zero energy building" demands on one hand the fulfillment of Swedish passive house criteria and on the other hand a building's zero energy balance in terms of import or export over a year [83].

2.2. Life Cycle Cost Analysis (LCCA)

LCCA is the economical assessment tool that is used to evaluate the economic performance of the different space cooling technologies studied. LCCA is generally employed to support the decision when there are alternatives to choose from [37]. The net present value (NPV) method is implemented to evaluate the economic performance of the alternative technologies. Equation (2) defines the requirements to implement LCCA for this method. The steps to evaluate and analyze the life cycle cost are from [37,84].

$$LCC_{TOT} = I_0 + LCC_{energy} + LCC_{maintenance} - residual\ value \tag{2}$$

where LCC_{TOT} is the total life cycle cost, I_0 is the initial investment, LCC_{energy} is the energy cost, and $LCC_{maintenance}$ is the maintenance cost. The residual value is the amount that is considered for parts of the system with extended life to meet the duration of the considered service time by assuming a replacement of these parts during the life cycle period. $LCC_{maintenance}$ was found to be on average 5% of the investment cost for the in-house solutions and zero for the DC since it is already included in its price and maintaining this system is up to Gävle Energi AB. The residual value was considered to be zero.

The entire life cycle cost of a product or building during an expected life period is estimated with the help of a chosen discount rate. The discount rate is referred to as the interest rate used to determine the present value of future cash flows in discounted cash flow analysis. The real discount rate (d) can be calculated from Equation (3).

$$d = nominal\ discount\ rate - inflation \tag{3}$$

Energy price increases or decreases at an estimated rate different from price inflation even if the energy use is the same from year to year. Equation (4) depicts the real energy price escalation (e).

$$e = Energy\ price\ escalation - inflation \tag{4}$$

In order to make comparisons between present and future costs, the present value must be calculated to convert the costs during the studied period at a discount rate [85]. To be able to compare the costs that occur at different stages and periods of a project, all costs are discounted to the present value. To carry on the calculations, the following two basic factors are considered:

Single present value (SPV), which is used when a cost occurs in a certain year (t) and the cost is discounted then is recalculated with regard to the discount rate to a present value. SPV is calculated based on Equation (5a).

$$\text{SPV}\ (d; t) = \frac{1}{(1+d)^t} \tag{5a}$$

Uniform present value (UPV), which is the current value of a future sum of money or series of non-uniform annually recurring amounts over n years, given a specified escalation rate. It is represented in Equation (5b).

$$\text{UPV}\ (f; n) = \frac{(1+f)^n - 1}{f \cdot (1+f)^n} \tag{5b}$$

where f is the net discount rate. It is presented as in Equation (6) and it includes the price escalation:

$$f = \frac{(d - e)}{(1 + e)} \quad (6)$$

2.2.1. Analysis Period

The analysis period was chosen to be 25 years for the absorption and compression chillers based on the general lifespan of the cooling system. This also matches the criteria from [86] from the Federal Energy Management Program which state that the service period is commonly set the same as the life of the system alternative. This period meets the maximum beneficial service period of 40 years. However, the lifespan for the DC system is generally 50 years due to the infrastructure of this system (the piping, etc.). Control systems and the heat exchangers are to be changed after 25 years. Therefore, the analysis period for the DC system also was considered 25 years, and the rest (the infrastructure cost) is counted as the residual value.

2.2.2. Inflation and Discount Rates

The average inflation rate in the past ten years has been 2.18% with the highest rate being 3.87% in 2021 and the lowest being −0.31% in 2014 [87]. The goal, based on the Central Bank of Sweden, is to keep the inflation rate at 2% [88]. However, the inflation rate is omitted by analyzing the real discount and price escalation rates.

The discount rate for the EU members, according to Building Performance Institute of Europe (BPIE), is between 1% and 7% [89]. In order to consider uncertainties in this study, three real discount rates of 3, 4 and 5% were chosen for sensitivity analysis based on [37].

The energy cost and price escalation were retrieved from a report by the Swedish Energy Agency [90]. Different electricity price scenarios have been considered in the report and are shown in Figure 3. Five scenarios are presented in the report as well as several sensitivity analyses. Three of these scenarios are presented as a basis for climate reporting from the Climate Reporting Ordinance [91,92] which places demands on those scenarios that will form the basis for the calculation of greenhouse gas emissions. Scenario reference EU is used for emission calculations for the EU Commission. The scenarios for lower energy prices and lower economic development for gross domestic product (GDP) have been developed corresponding to high and low GHG emissions respectively. Based on the Climate Reporting Ordinance demand, these are further used as a basis for the emission calculations.

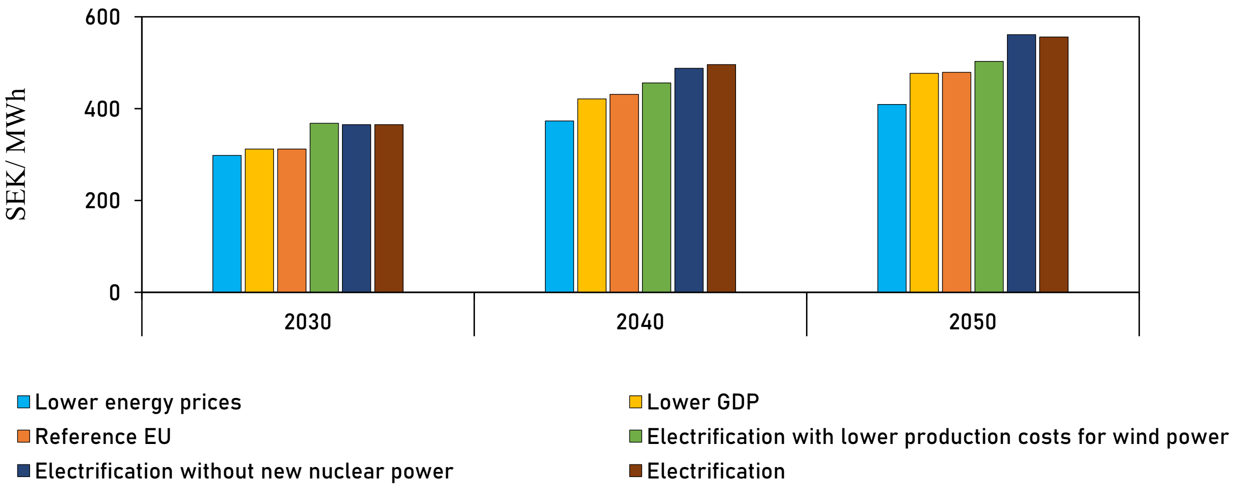

Figure 3. Electricity prices and electricity price development for each scenario until 2050 [80].
Figure 3. Electricity prices and electricity price development for each scenario until 2050 [80].

To carry out a sensitivity analysis on energy prices, three scenarios representing low, medium, and high price increases, namely lower energy price, reference EU, and electrification, were respectively chosen. The price escalation rate was estimated to be around 1–2% based on the differences in the prices for the mentioned scenarios. However, to cover a wider range of price increase, 0% in changes also was considered. Based on the report published in 2021 from [93], which surveys Sweden's municipalities and thus makes it

Electrification is the scenario developed with an increased degree of electrification compared to other scenarios; In addition, various sensitivity analyses have been performed for this scenario by the Swedish Energy Agency.

To carry out a sensitivity analysis on energy prices, three scenarios representing low, medium, and high price increases, namely lower energy price, reference EU, and electrification, were respectively chosen. The price escalation rate was estimated to be around 1–2% based on the differences in the prices for the mentioned scenarios. However, to cover a wider range of price increase, 0% in changes also was considered. Based on the report published in 2021 from [93], which surveys Sweden's municipalities and thus makes it possible to compare costs, yearly changes in DH price for the studied city was observed to be less than 1% in the past decade. Therefore, to examine all the scenarios and price escalation rates, different scenarios as shown in Table 3 were considered.

Table 3. Scenarios for energy price escalation based on the respective energy carriers.

Scenarios	Carrier	Price Escalation	Carrier	Price Escalation
Sc 1	El&DC	1%	DH	0%
Sc 2	El&DC	1%	DH	1%
Sc 3	El&DC	2%	DH	0%
Sc 4	El&DC	2%	DH	1%

2.2.3. Energy Cost

The DC energy cost was calculated based on the prices from Stockholm Exergi [68] for buildings using less than 50 kW cooling power. Based on the provided calculation procedure, a constant fixed price of 310 EUR and power price of 91.8 EUR/kW must be paid annually apart from the energy price (0.046 EUR/kWh for June–August). The values were taken from Stockholm Exergi since DC is already employed for residential cooling purposes in Stockholm; however, it has not yet been employed in Gävle.

A connection cost must be paid upon connecting the buildings to the system, for which the price is provided by Gävle Energi AB [65]. However, a cost for the heat exchangers and the control system has to be considered in the initial investment (I_0). This value is considered from [94]. It is noteworthy that the connection cost is assumed to be distributed over a span of 50 years, corresponding to network lifespan. Therefore, using the SPV method and considering half of the connection cost (half of the actual lifespan, 25 years), a residual value was obtained. This is carried out to maintain a fair assumption among the considered cooling technologies.

The energy cost for the compression chiller as the in-house cooling technology is calculated based on the cost of electricity. This cost was evaluated based on Gävle Energi AB's [65] structure for the total electricity price which accounts for the transfer cost, spot price, and energy tax. As mentioned earlier, data for the spot price and the energy tax prices over the past decade are available from [55] and were projected for the mid-term future, corresponding to 3.6 and 4.8 EUR/kW respectively. These prices are projected based on the moving average method projection. The electricity transfer cost corresponds to 0.014 EUR/kWh including VAT (which is 25%).

To calculate the energy cost for absorption chillers as the other in-house cooling technology, DH was considered. DH energy cost was calculated from the provided price list from Gävle Energi AB [65] for each season. The heat delivered to the buildings from Gävle's DH system consists mostly of recycled heat, corresponding to 60% residual waste heat from industry, 25% heat from combined heat and power plants depending on biofuels, and the rest is heat from flue gases [41]. DH prices correspond to 0.047 EUR/kWh for winter (January–March, November–December) and 0.040 EUR/kWh for autumn (April–May, September–October) and 0.015 EUR/kWh for summer [65].

heat from industry, 25% heat from combined heat and power plants depending on biofuels, and the rest is heat from flue gases [41]. DH prices correspond to 0.047 EUR/kWh for winter (January–March, November–December) and 0.040 EUR/kWh for autumn (April–May, September–October) and 0.015 EUR/kWh for summer [65].

3. Results and Discussion

3.1. Energy Performance of the Buildings

In this section the authors tried to map the cooling demand of each of the building models and evaluate PE_{PET}. The implemented climate file represents the mid-term future (2041–2060) since the district is to be utilized from 2040 onward. On average, the amount of annual property equipment electricity and cooling and heating demand for the buildings corresponds to 3.8, 3.4, and 40.7 kWh/m^2, respectively. The equipment electricity is the operational electricity related to the building's energy need. The heating and electricity use were not depicted in this section as these are out of the scope of the paper.

For the sake of comparison between the considered cooling technologies, the system boundary is set at building level and since the central chillers of DC will be outside of this boundary, the cooling demand of each model is considered for the calculations for the DC system. This implies that the EER of central chillers of the DC system are not considered in the calculation processes.

Results of the simulations for each of the prototype buildings and their respective used energy for cooling during June–August are shown in Figure 4 (left). Used energy is defined as the amount of energy delivered to the distribution system of the building by the plant or the heat generation or heat removal devices [95]. Since PE_{PET} is reported based on heated floor area, the used energy and the rest of the investigated parameters related to energy use of the buildings also are reported in this manner. Figure 4 (right) depicts estimated primary energy use over the cooling period (June–August) for each model and the implemented cooling technologies. In order to consider the estimated primary energy use for the cooling season, WFs from the National Board of Housing, Building, and Planning regulations [30] for electricity and district cooling, as mentioned in Section 2.1.2, are considered here.

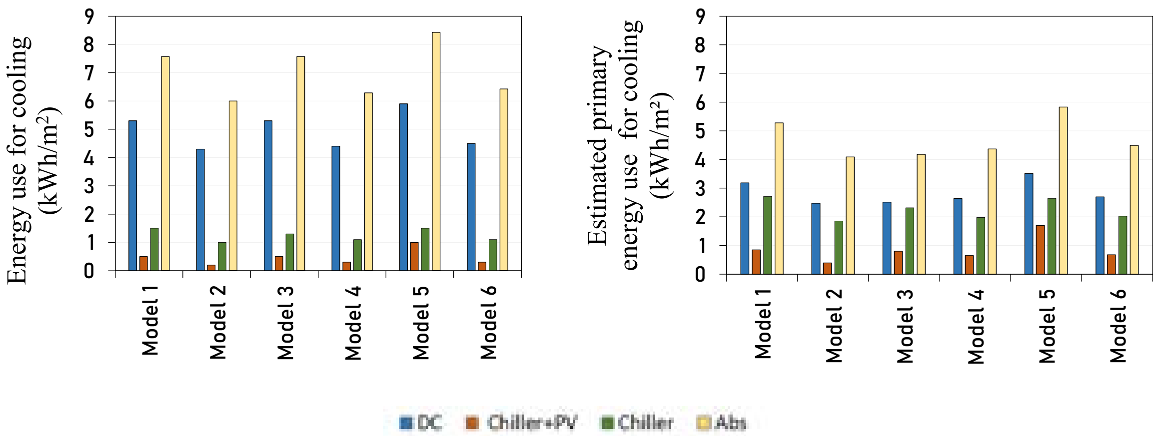

Figure 4. Used energy for cooling (**left**) and estimated seasonal primary energy use for June–August (**right**) for the studied building models and cooling technologies.

To investigate the changes in PE_{PET} when taking away the PV systems, Chiller without PV (denoted as Chiller), is depicted next to Chiller + PV. The used energy to meet the cooling demand for DC is on average 5.0 kWh/m^2 from thermal energy; this value corresponds to 0.5 and 1.3 kWh/m^2 for Chiller + PV and Chiller, respectively, in terms of electricity. In the case of Chiller + PV, PV systems are considered a complement to the in-house compression chillers to reduce the electricity use from the grid to obtain a lower primary energy use as compression chillers rely solely on electricity. The produced electricity for calculation purposes in this study is first assumed to be used for cooling purposes, the remainder of which is used for equipment; finally, the excess will be sold to the grid. Equipment electricity and cooling systems were chosen as the main consumers of the produced electricity since these factors are used in PE_{PET} calculation based on Equation (1). According to the NZEB definition and bounding conditions, these mentioned values must be maintained at a lower value to keep PE_{PET} < 75 kWh/m^2 [30].

energy use as compression chillers rely solely on electricity. The produced electricity for calculation purposes in this study is first assumed to be used for cooling purposes, the remainder of which is used for equipment; finally, the excess will be sold to the grid. Equipment electricity and cooling systems were chosen as the main consumers of the produced electricity since these factors are used in PE_{PET} calculation based on Equation (1). According to the NZEB definition and bounding conditions, these mentioned values must be maintained at a lower value to keep PE_{PET} < 75 kWh/m² [30].

As indicated in Figure 4, both energy use and primary energy use for the cooling season shows higher value for the absorption chiller and lower value for Chiller + PV for each model. Given the lower cooling COP of 0.7 for the absorption chillers, the used thermal energy for cooling is on average 7.0 kWh/m². In the case of Chiller + PV, the electricity produced by the PV installation helps in reducing the energy used for cooling.

From the obtained results of Figure 4 (right), it can be concluded that the weighting factor that is considered for DC systems underestimates the EER value. WF is 0.6 for DC and lower WF in the order of magnitude of 0.3 can be assumed for the DC system considering the possible available free cooling in DC networks [96], implying that the blue DC bars in Figure 4 (right) would be halved. Moreover, using higher WF values implies an inferior performance by the DCs central chillers, where water with colder temperatures than ambient air is used for heat rejection. This is seen as a gap in the policy-making procedures. Further detailed discussions about these factors will be considered in the authors' future work.

Figure 5 shows the result for PE_{PET}. As discussed in the Method section, different forms of energy use in the building are considered in the calculation of the PE_{PET}, thereby making it a comprehensible parameter in comparing and evaluating the energy use in buildings. However, in terms of DC, the national value of weighting factor 0.7 can be doubted since the local situation would imply 0.45 when using compression chillers without free cooling.

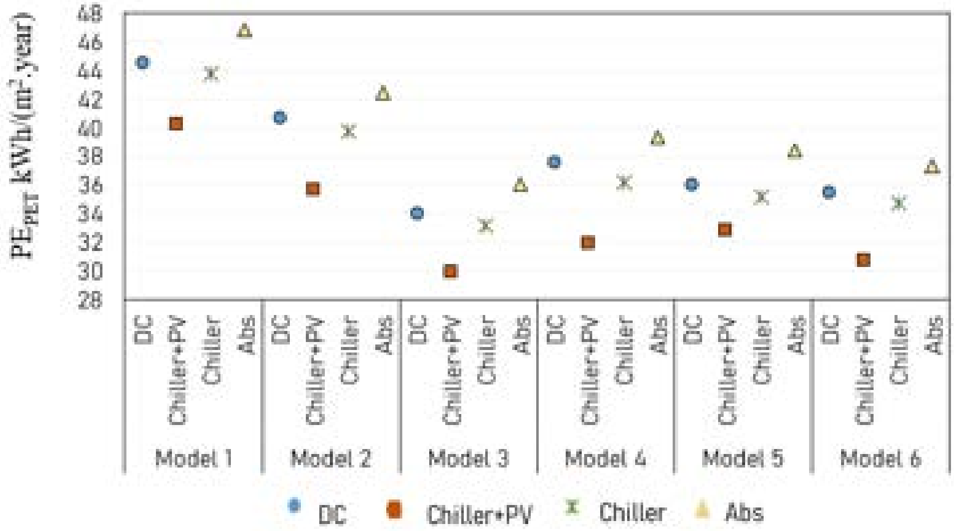

Figure 5. PE_{PET} for the investigated space cooling technologies, district cooling (DC), chiller with PV system (Chiller + PV), compression chiller (Chiller), and absorption chiller (Abs) for each of the prototype building models for a complete year.

By looking at the depicted result, it could be concluded that from the energy demand perspective, Chiller + PV indicates an optimal combination. This is concluded from the lower PE_{PET} compared to the other cooling alternatives. By comparing the two technologies, Chiller + PV and Chiller without PV, we can see that the PV system helps in reducing the PE_{PET} by on average 13%. However, from the cost perspective the system must be analyzed as well.

The influence of energy units on reporting the energy use of the buildings has been previously discussed by some researchers. Stephan et al. [97] have concluded that measuring energy efficiency of buildings per meter of floor area favors the larger buildings. Carlander et al. [98] utilized indicators kWh/(m² × hpers) (hpers = hours of use) and kWh/m² and concluded the former benefits buildings with high occupancy and low electricity use and the latter benefits buildings with low internal heat gains. Therefore, the importance of unit indicators plays a role when it comes to measuring energy efficiency of buildings. However, as was mentioned earlier, since the goal is to measure PE_{PET}, all units reporting energy demand are reported in kWh/m^2.

The influence of the shape factor (*SFv*) of the building also was considered to evaluate the effect of the geometry of the building on the PE_{PET}. The definition and impact of the shape factor on energy use of buildings is defined by Carpio et al. [99]. They defined SFv as the ratio of the enveloping surfaces to the volume and it is directly related to the heating energy demand in buildings. Energy exchange with the outside is increased if the surface of the building in contact with the outside is more significant. This may be beneficial or unfavorable in certain types of climates. This factor corresponds to 0.74 and 0.54 for models 1 and 2 respectively. For the rest of the models, this value is on average 0.41.

3.2. Life Cycle Cost Analysis

The overall result of this section helps in choosing the economically optimized cooling alternative for the prototype buildings. Detecting the energy-optimized technology or solution may not always be practical due to costs and expenses. This step is taken to make sure that the introduced solution as an energy-optimized technology is also economically acceptable.

The result of the LCCA for different cooling technologies, scenarios, and discount rates are shown in Figure 6. The LCCA result is depicted on the primary axis and the secondary axis depicts the energy use (kWh/m^2). The investment (EUR/m^2) has been highlighted with a transparent gray box on the bars for each technology and model; therefore, the unhighlighted part depicts the reoccurring values or the net present value. Since the chillers for the DC are central and only require a heat exchanger at the site, the extra cost to consider a utility room for the chillers and the respective installations in the buildings can be excluded for this cooling technology. On the other hand, the compression and absorption chillers are considered the in-house cooling alternatives; therefore, a utility room for all the equipment must be considered. The rental cost for the room was taken from [55] and it is estimated to be around 200 EUR/m^2 (i.e., as a loss of income). The size of the utility rooms was considered to be around 10 m^2 based on the required dimensions in catalogues from Yazaki [79].

As indicated in Figure 6, overall, Chiller + PV shows the lowest life cycle cost at the end of the studied period (25 years). At a discount rate of 3%, employing DC as a cooling alternative has from −11 to 35% different life cycle cost compared to Chiller + PV on average for all the scenarios and the studied models. This range corresponds to −10 to 41% and −8 to 47% for discount rates 4 and 5%. For absorption chillers, the range corresponds to on average 2–66% for discount rates of 3, 4, and 5%. The negative values depict lower LCC than that of Chiller + PV's.

The higher discount rate depicts lower present value of the future cash flows, which can imply that lower discount rates give more value for future reduced operational costs. It could be concluded from Figure 6 that the LCC follows the same trend as that of the energy use; i.e., smaller floor areas correspond to higher life cycle costs as can be seen for models 1 and 2 for all the scenarios and discount rates. These models are the smaller buildings with 400 and 945 m^2 respectively. Higher costs are associated with these buildings since the investment cost and energy use relative to floor area for these buildings will be higher and, as mentioned earlier, the unit indicator kWh/m^2 favors buildings with larger conditioned areas. The shape factor for model 1 corresponds to 0.74, which is the highest among the other studied models, and therefore the energy exchange with the outside increases. On the other hand, the area and shape factor for Model 6 correspond to 3925 m^2 and 0.41 respectively. Therefore, LCC for smaller buildings appear to be higher than the buildings with larger floor areas. Additionally, the initial costs are larger relative to floor area for smaller buildings in relation to the larger buildings. Moreover, the size of chiller and the utility room influence the LCCA for the Chiller + PV and absorption chiller. Since these two cases are regarded as in-house alternatives, the focus on sizing the systems was to try to employ a chiller for each building.

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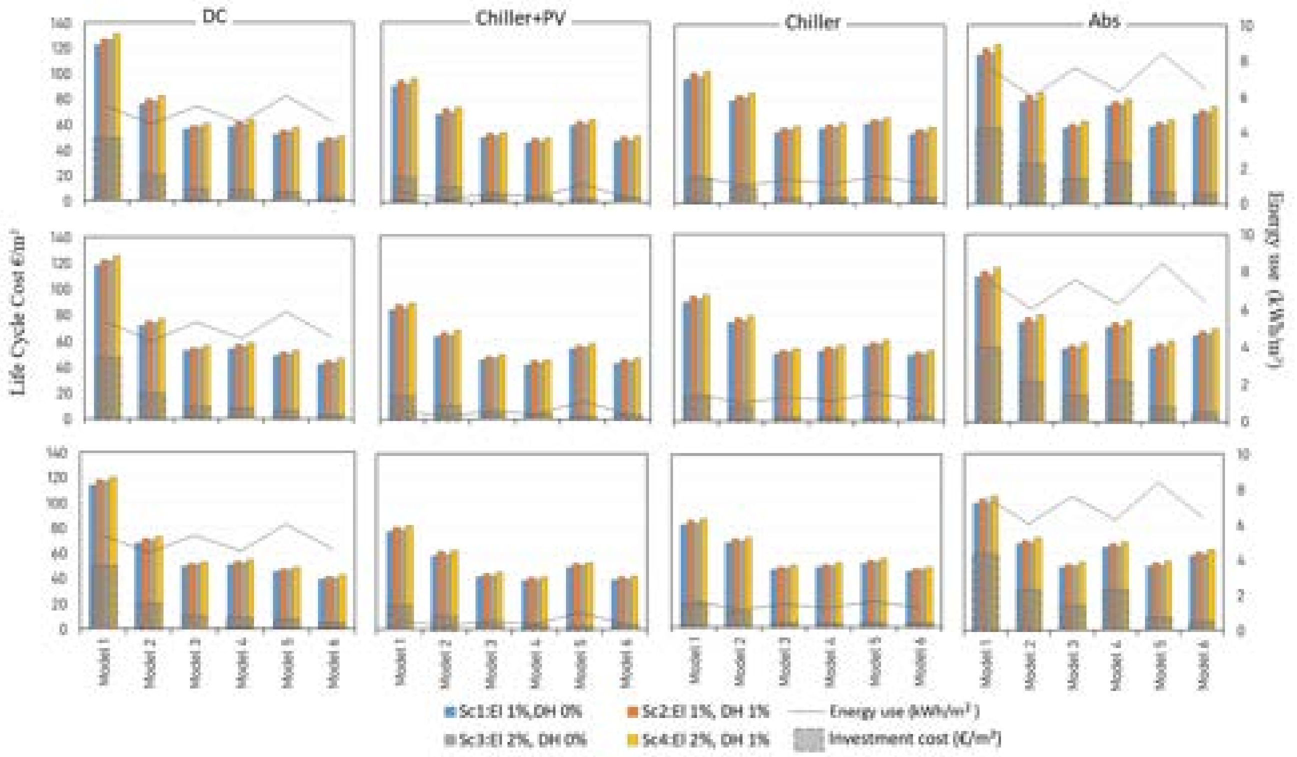

Figure 6. Life cycle cost analysis (SPV method) for the studied models, discount rates 3, 4 and 5% as well as different price escalation scenarios as depicted in Table 3 (primary axis). Energy use per heated floor area (secondary axis). For district cooling (DC), compression chillers with and without solar panels (Chiller + PV, Chiller) and absorption chillers (Abs).

Figure 6. Life cycle cost analysis (SPV method) for the studied models, discount rates 3, 4 and 5% as well as different price escalation scenarios as depicted in Table 3 (primary axis). Energy use per heated floor area (secondary axis). For district cooling (DC), compression chillers with and without solar panels (Chiller + PV, Chiller) and absorption chillers (Abs).

Gävle Energi AB provides the district cooling, which is mainly powered with the help of the nearby river for free cooling purposes. Auxiliary central compression chillers are employed when the temperature of the river is above 6 °C [65] and the river is also used for rejecting heat as opposed to using ambient (warmer) air. Therefore, the energy provider is responsible for the maintenance of the system and generally, DC systems as mentioned earlier tend to have a longer life cycle period (generally 50 years). However, in this study to maintain the consistency among the studied cooling technologies, life cycle period was considered the same for all the systems and the remainder of the connection cost was calculated as residual value (see Equation (2)). On the other hand, as depicted in Table 1, in most of the models, more than one building is connected to the compression or absorption chillers, which helps reduce the investment cost per building since using just one chiller for each building would lead to oversized equipment. However, for DC, each building must be individually connected to the system, which in turn affects LCC due to its higher investment cost.

The impact of price escalation on probability of different cooling technologies is also depicted in Figure 6. At a 3% discount rate, DC has the highest life cycle cost for different scenarios. Scenarios were defined in Table 3. As depicted in Figure 6, scenarios 1 and 3 depict the lowest life cycle costs. Increasing the DH price escalation from 0% to 1% in scenarios 2 and 4, DC and El from 1% to 2% in scenarios 3 and 4 increase the LCC compared to scenario 1. Therefore, scenario 4 has 6–10% higher life cycle costs compared to scenario 1 for the studied models, which is the highest range among the studied scenarios. Scenario 2 has 4–7% higher LCC compared to the first scenario. However, this range corresponds to 2–3% for scenario 3. In scenarios 2 and 4, DH has the dominant role as the price during winter (January–March, November–December) and autumn (April–May, September–October) are 0.47 and 0.040 EUR/kWh [51]. However, the cost during summer is 0.015 EUR/kWh, which is a point in favor of the absorption chiller. Apart from the

As indicated in Figure 6, overall, Chiller + PV shows the lowest life cycle cost at the end of the studied period (25 years). At a discount rate of 3%, employing DC as a cooling alternative has from −11 to 35% different life cycle cost compared to Chiller + PV on average for all the scenarios and the studied models. This range corresponds to −10 to 41% and −8 to 47% for discount rates 4 and 5%. For absorption chillers, the range corresponds to on average 2–66% for discount rates of 3, 4, and 5%. The negative values depict lower LCC than that of Chiller + PV's.

The higher discount rate depicts lower present value of the future cash flows, which can imply that lower discount rates give more value for future reduced operational costs. It could be concluded from Figure 6 that the LCC follows the same trend as that of the energy use; i.e., smaller floor areas correspond to higher life cycle costs as is seen for models 1 and 2 for all the scenarios and discount rates. These models are the smaller buildings with 400 and 945 m² respectively. Higher costs are associated with these buildings since the investment cost and energy use relative to floor area for these buildings will be higher and, as mentioned earlier, the unit indicator kWh/m² favors buildings with larger conditioned areas. The shape factor for model 1 corresponds to 0.74, which is the highest among the other studied models, and therefore the energy exchange with the outside increases. On the other hand, the area and shape factor for Model 6 correspond to 3925 m² and 0.41 respectively. Therefore, LCC for smaller buildings appear to be higher than the buildings with larger floor areas. Additionally, the initial costs are larger relative to floor area for smaller buildings in relation to the larger buildings. Moreover, the size of chiller and the utility room influence the LCCA for the Chiller + PV and absorption chiller. Since these two cases are regarded as in-house alternatives, the focus on sizing the systems was to try to employ a chiller for each building.

Gävle Energi AB provides the district cooling, which is mainly powered with the help of the nearby river for free cooling purposes. Auxiliary central compression chillers are employed when the temperature of the river is above 6 °C [65] and the river is also used energy price, the investment cost also is taken into consideration, the same way as DC. Therefore, DH has relatively high LCC compared to electricity and cooling life cycle costs.

The investment for DC and Abs is higher than Chillers and Chiller + PV. This value corresponds to up to 40% and 50% of the total life cycle cost (for the smaller models) for DC and Abs respectively. On the other hand, the investment corresponds to maximum 20% of the total life cycle cost for Chiller + PV (for the smaller models). As can be noticed from Figure 6, the reoccurring cost is higher for the Chiller + PV and Chiller. It could be concluded that by a change of policies and reduction of investment cost for DC and Abs, these technologies can be quite competitive with the Chiller + PV.

On the positive side, investment cost for the utility room is not required for the DC, given that it is fitted in the DH space. Utility rooms are regarded as wet rooms and need extra flooring and insulation to prevent damp, noise, and vibration transfer to the residential parts of the building and electric wiring. In contrast, DC is quite hassle-free for the building owner without requiring payment for the maintenance cost other than the annual subscription fee and DC has quite unlimited lifespan. Overall, it can be concluded that high investment costs yield to higher life cycle costs. Additionally, service costs that arise for the two in-house solutions and extra piping between buildings that are sharing cooling units have been neglected. Comparing discount rates of 3–5% for each price escalation scenario, it could be concluded that the lower discount rate gives higher future energy cost in comparison to the investment cost. This aligns with the findings from Khadra et al. [37]. To allow conversion of future costs at present value, discounting of the payments and income streams play an important role. Within this frame, harmonization of the costs at present and future within an economic assessment is made possible [89].

In order to evaluate the effect of the PV system on the LCCA, a case without a PV system coupled to the compression chiller was considered. Figure 7 depicts the difference in LCC between Chiller + PV and Chiller without PV system for scenario 1 as a representative. Removing the PV systems increases the LCC by almost 13% on average for all the models. The differences in the LCC between the Chiller + PV and Chiller are quite small since the saving from the produced electricity from the PVs have to finance its own investment cost. The PV systems play important role on the national level since the electricity sold to the grid allows hydropower and biofuels to be stored for the heating season; however, these may not appear economical for the tenants given the high investment cost and low spot price. The spot price considered for the electricity sold to the grid is calculated based on historic prices, which correspond to 0.036 EUR/kWh, which is a relatively low value, given the recent substantial changes in electricity price due to geopolitical changes. However, due to the mentioned reason, it is expected to have a higher spot price leading to more income from the electricity sold. It is noteworthy that no subsidies were considered for the PV systems either.

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Moreover, it can be noted that the difference between Chiller + PV and Chiller are more significant with low discount rates. As mentioned before, lower discount rates give more value for future savings.

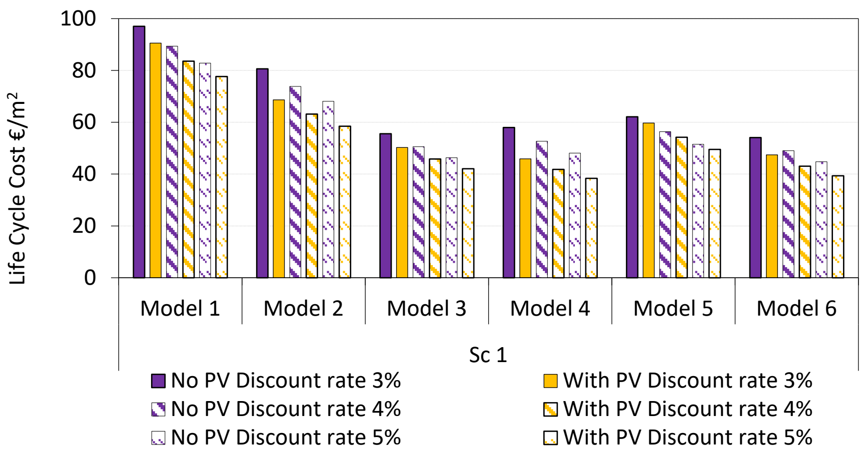

Figure 7. Changes in life cycle cost analysis (SPW method) when removing the PV systems from compression chillers for scenario 1.

Overall, based on the provided results in this section and Section 3.1, compression chillers coupled with PV systems appear to be the optimal choice in both energy and economic aspects. This could be depicted from PE_{PET} and LCC from Figures 5 and 6 respectively. However, as mentioned earlier, Abs and DC have high investment and lower reoc-

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3.3. Techno-Economic Evaluation of the Studied Cooling Systems

To touch upon the resilience aspect of the studied technologies, several characteristics, such as adaptive and restorative capacities as well as the recovery speed [51] have been looked upon in this section. The adaptive and the restorative capacities of the studied systems can be questioned in extreme ambient temperatures or heatwaves. Outdoor conditions such as temperature and humidity can affect the energy performance of the chillers. In this regard, compression chillers provide higher adaptive capacity compared to absorption chillers [51]. On the other hand, the DC system also possesses the ability to be incorporated with single or multiple cooling technologies in the central plant apart from the free cooling or other environmentally sustainable methods that can act as a heat sink or cold source [66,100] which helps increase the adaptive capacity. It is noteworthy to mention that if an increase in the cooling power is required, the whole unit for the in-house technologies must be changed; however, for the DC system, it is mostly sufficient to change the heat exchanger.

From the refrigerant point of view, absorption chillers and DC are more environmentally sustainable since the chillers employ eco-friendly fluids such as water and these are partially activated by thermal energy. DC can employ free cooling sources.

These studied systems cannot operate without power input. To compensate, these can integrate a local power production such as PV systems or energy storage units such as batteries to increase the resilience. Nevertheless, the space that the PV systems or the storage units occupy cannot be neglected, especially when considering an in-house alternative as the tenants might be obliged to bear the rental costs.

From the input source perspective, the major benefit of the absorption chiller is its operation scheme that can be carried out with a low-grade heat source such as waste heat similar to that of the studied district heating system in this project. Therefore, electrical energy can be reduced, resulting in lower carbon emissions. However, the system might need an additional heating source in case the provided primary source of heat is not sufficient to provide stable operation [51] which may need more development, given that they require district heating temperatures that are relatively high, especially during the non-heating seasons. DC systems also can benefit from free cooling technology and help in reducing the peak power demand, although 100% free cooling during high outdoor temperatures and heatwaves is not possible; therefore, other active cooling technologies must be employed in the system to provide the required cooling. It is notable that DC can reduce the peak demand, thereby reducing electricity use and GHG emissions. From the obtained results, DC appears to be an agreeable cooling technology for buildings with large floor areas. The system does not require spacious utility rooms; therefore, the extra space and the associated rental as well as the system maintenance costs are excluded for the tenants. As mentioned earlier, DC has a longer life cycle, it is hassle-free for the building owner, and, in the case of the studied district, free cooling was employed, which helps reduce the carbon emission and primary energy.

On the other hand, the other cooling alternatives require utility rooms. The extra cost for in-house cooling technologies, in terms of space and its associated investments such as extra insulation, flooring, dampers to reduce noise and vibrations, etc., were neglected to prevent complications in the calculation procedure, but instead considered to be a loss of income corresponding to the rent. Moreover, considering material and related investment costs adds more to the uncertainties. Based on a study carried out by Alrwashdeh et al. [101], both compression chillers and absorption chillers are effective when regarding the benefits over the total cost. However, compression chillers are easily available on the market and they have lower investment and operation costs. These systems also offer a wider range of nominal cooling sizes compared to absorption chillers.

4. Limitations

There are limitations associated with the building type and geometrical configuration. Each apartment was considered as one single zone and the number of occupants and the internal heat gains were all based on Swedish standards. All buildings are residential even though school and commercial buildings also are generally included in districts (450,000 m^2 are planned for non-residential buildings), which will be covered in future studies. These buildings were excluded to match the definition of the district which is "residential district". The considered energy prices, such as spot price and energy tax prices, fluctuate on a short-term basis though a constant value was considered for those parameters. The extra investment costs for the utility room when employing an in-house cooling technology were excluded from the calculations and considered as a loss of future rental income. The lifecycle of a DC system was confined to 25 years to attain a coherent result. The sizes available on the market today for the chillers are larger than the demand for each of the smaller buildings. This may involve practical problems when it comes to ownership of various buildings that would have to share a common cooling unit.

5. Future Work

Studies on possibilities and pathways to deep decarbonization have been carried out in Canada [13], France [102], and Greece [103] and were initially intended to be carried out in this study as well; however, due to the extent of the current work, it was decided to postpone the GHG emissions associated with each technology as future work.

6. Conclusions

This paper was framed around a research question that aimed at evaluating different cooling technologies and introducing the more suitable space cooling alternatives from primary energy number (PE_{PET}) and economic points of view. This was done from both a property developer/owner and an energy supplier perspective regarding a future residential district in Gävle, Sweden. The district is one of the Swedish government's nine selected initiatives concerning development of future environmentally sustainable districts. The cooling alternatives are district cooling (DC), compression chillers coupled and uncoupled with PV systems, and absorption chillers. Compression chillers without PV systems were considered to evaluate the effect of the PV systems on energy use of the building. PV systems were coupled with the compression chillers to reduce the electricity use of the system, since this is a solution that uses electricity as the energy source.

Primary energy number (PE_{PET}) was considered based on the Swedish National Board of Housing Building and Planning to represent the energy performance of the buildings. Accordingly, chillers coupled with PV system and absorption chillers had the least and the highest PE_{PET} among the studied technologies. Chillers alone appeared to be an agreeable alternative after chillers coupled with a PV system with on average 11% higher PE_{PET} value for the studied models, compared to the optimal case. However, generalized weighting factors may bias use of local chillers instead of central chillers used in DC.

Life cycle cost analysis was considered to evaluate the economic performance of each technology to discover the economically optimized alternative. Discount rates of 3, 4, and 5% as well as four price escalation scenarios were considered as sensitivity studies. Chillers coupled with PV systems appeared to be overall the optimal technology from this perspective. DC appeared to be an agreeable cooling technology for large buildings as it had up to, on average, 10% lower life cycle cost compared to chillers coupled with PV systems for the considered discount rates.

On the other hand, absorption chillers did not appear as an optimal choice either from PE_{PET} or economic perspective. From the primary energy analysis, the PE_{PET} value is 20% higher than the optimal technology. Based on the LCCA results, the lifecycle cost ranges from 2–48% higher than the optimal technology, i.e., chillers coupled with PV panels. It is noteworthy to mention that the energy carrier for this alternative is district heating, which is an environmentally sustainable source and mainly uses waste heat. From the electricity grid point of view, the absorption chillers are quite beneficial as there is abundance of unused heat from the district heating system during summer; therefore, the electricity can be exported or saved, given the interconnected grid. The drawback is the high supply and return district heating water temperatures required for efficient absorption heat pump use, thus reducing efficiency for both DH and DHC (district heating and cooling) application.

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Conceptualising a resilient cooling system: A socio-technical approach

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ABSTRACT

Prolonged and/or extreme heat has become a natural hazard that presents a significant risk to humans and the buildings, technologies, and infrastructure on which they have previously relied on to provide cooling. This paper presents a conceptual model of a resilient cooling system centred on people, the socio-cultural-technical contexts they inhabit, and the risks posed by the temperature hazard. An integrative literature review process was used to undertake a critical and comprehensive evaluation of published research and grey literature with the objective of adding clarity and detail to the model. Two databases were used to identify risk management and natural hazard literature in multiple disciplines that represent subcomponents of community resilience (social, economic, institutional, infrastructure and environment systems). This review enabled us to characterise in more detail the nature of the temperature hazard, the functionality characteristics of a resilient cooling system, and key elements of the four subsystems: people, buildings, cooling technologies and energy infrastructure. Six key messages can be surmised from this review, providing a guide for future work in policy and practice.

Key concepts

Antecedent conditions	The social, economic, infrastructural, institutional, community and environmental components that determine how a community can cope with, and recover from, hazards and the risks posed by hazards. These components, collectively and individually, are not in an equilibrium state.
Build Back Better	Reconstruction and recovery practices that focus on implementing positive social change and improving community resilience capacity
Cost-benefit analysis	A traditional cost-benefit analysis, applied to disaster risk management, compares the costs of an action against the benefits of avoided losses from that action. It relies, for example, on probabilistic estimation of risk and losses, and the application of a monetised value on benefits attributed to the actions.
Post-recovery activities	Actions imposed after a crisis that enhance community preparedness and reduce exposure to the hazard or the severity of impact of the hazard. Cost-benefit analysis is often used as the decision process for determining investment decisions in mitigation and recovery actions.
Resilience capacity	The continuing function of a system within the context of change and instability (a non-equilibrium state).
Resilience	An investment, planning and practice strategy that is an alternative to (or an expansion and extension of) the more

(*continued on next page*)

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dividend	familiar cost-benefit analysis. It specifically targets risk management investment actions that provide tangible and intangible co-benefits in times of crisis and non-crisis. It is not restricted by either the probability of future risks, or the monetised value of benefits.

NOTE: The terms reliability, resilience, robustness and redundancy are deliberately not defined in this table. The paper describes how different disciplines utilise these words within the context of the system being studied in this paper. The purpose of this paper is not to arrive at an agreed definition of these terms or to argue that there is a need for agreement on terminology: the focus of the paper is on providing a framework to describe the purpose and function of a resilient cooling system.

1. Introduction

1.1. The context

The weather event in Texas, USA in February 2021 provides a good example of how buildings, space heating equipment, and the energy network failed to protect people from the extreme cold temperatures (https://www.theguardian.com/us-news/2021/feb/20/texas-power-grid-explainer-winter-weather). People, buildings, cooling equipment, and energy systems are also vulnerable to heatwaves and extended periods of hot weather. Some of the risks associated with these temperature hazards include the possibility of overheating of buildings and technology; equipment failure or reduced ability to provide cooling services; insufficient electricity generation to meet demand; and enforced power outages to protect transmission networks or reduce secondary risks of bushfires.

Risks to humans include heat stress and high rates of morbidity and mortality. For example, there were an estimated 1200 heatwave related deaths in the USA for the period 2004–2013 [1]; heatwaves have accounted for more deaths in Australia than all other natural hazards, and modelling suggests significantly increased rates of morbidity and mortality, and associated public health implications, by the middle of this century [2–4]; and Hajat et al. [5] predict that heat-related deaths due to climate change in the UK are expected to rise by about 257% by the 2050s. This has led to the development of national and regional heatwave plans and strategies in attempts to prepare populations to anticipate and respond to the hazard and hence reduce the associated risks posed by the hazard [6–9]. These responses have typically included protective measures (e.g., warning systems and advisory information) and adaptation strategies, but the efficacy of such strategies is difficult to accurately evaluate due to the differences in hazard intensity, duration, and population exposure [10].

The efficacy of building regulations and product standards to protect building occupants is also under question, as the tools to evaluate the effectiveness of these measures typically utilise historic climate data and design parameters based on probability of exceedance of pre-determined temperature conditions (e.g., reliability or availability figures) [11] and averages of occupant satisfaction (e.g., percentage of persons dissatisfied) [12]. However, changes in mean temperature and temperature distribution are resulting in more frequent hot weather and record hot weather (Fig. 1), higher humidity, and worsening ozone levels and air quality [13] and associated impacts on human and ecosystem health [14–16].

1.2. The approach of this paper

Against this background, what is “resilient cooling”, the term used by the International Energy Agency Annex 80: Resilient Cooling of Buildings [18]? Resilience of what? For whom? Against what?

In this paper we present a conceptual model of a resilient cooling system and conduct an integrative literature review to characterise the hazard and risks; understand the desired functional state of the system as a whole; and analyse key factors and indicators that apply to different sub-systems or components within the system. Our approach is consistent with the view that resilience is a property of functions and systems [19] and that there is a need to define the elements of impacted physical and social systems [20]. Our approach is also novel in that it extends previous discipline-restricted system boundaries and combines disparate views of core aspects and elements of system functionality. Our approach uses the lenses of Disaster Risk Management (DRM) (understanding and managing risks) and Natural Hazards (NH) (vulnerability and resilience to risks posed by the hazard), thereby incorporating both engineering and social science perspectives into a framework to describe the purpose and function of a resilient cooling system. It is not restricted by a perceived need to have consensus of concept definitions [21], but rather embraces multiple definitions of system performance concepts.

2. Methodology

2.1. Development of the model

Our proposed model for conceptualising the resilient cooling system was developed through Annex 80 expert discussions and examination of existing disaster resilience frameworks. Our model, shown in Fig. 2, is an extension of the Disaster Resilience of Place (DROP) model [22] that provides a foundation for representing the relationship between vulnerability and resilience; highlights the antecedent (pre-existing) conditions within communities that serve as a baseline set of circumstances against which improvements in resilience can be measured; and presents resilience as a process. The antecedent conditions are determined by social, economic, infrastructural, institutional, community and environmental components, and play a role in how a community can cope with, and recover from, a hazard and the risks posed by a hazard [23]. Post-recovery activities lead to a ‘new’ state, through actions that enhance preparedness for future events (thereby reducing negative impact), or through actions that mitigate the hazard or risks (such as reducing likelihood or severity). Post-recovery actions may include both preparedness and mitigation.

To this model we have explicitly incorporated the properties of socio-economic and engineered systems as contributors to a community’s coping responses, and the complementary Sendai Framework for Disaster Risk Reduction [24]. This United Nations framework,

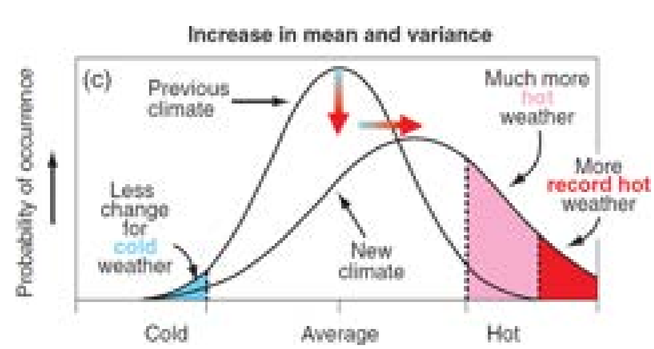

Fig. 1. Impact of changes to temperature mean and variance. Source: Ref. [17], page 155

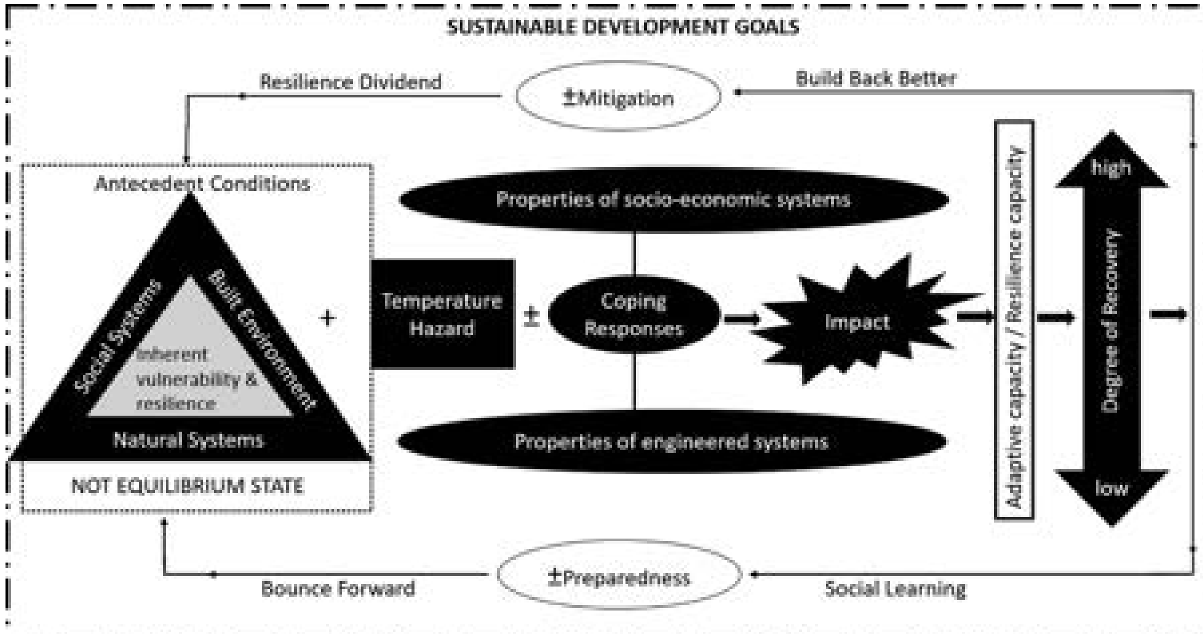

Fig. 2. Conceptual model of the resilient cooling system.

endorsed by the UN General Assembly in 2015, views resilience as both an outcome (the ability to cope with or bounce back from a hazard) and a process (that is, continual learning and taking responsibility for making better decisions to improve the capacity to handle hazards). Importantly it includes the concepts of social learning and "Build Back Better" (reconstruction and recovery practices that focus on implementing positive social change and improving community resilience) [25], a similar concept to the *resilience dividend (*the term used to describe the net benefit or cost of an investment in resilience, in the absence of a disruptive event). It is an alternative approach to the traditional return-on-investment mindset and assumption that there will always be a financial trade-off between adequate preparedness and potential future disaster response and recovery costs [26,27].

The other very important addition to the DROP model is the concept that our social, natural, and built environment systems are not an equilibrium state, but in a state of constant change [28,29]. This means that there is a need to highlight adaptive capacity and resilience capacity, focusing on the continuing function of the system within the context of change and instability, rather than a return to a pre-existing equilibrium state or to a new equilibrium state [1,30–33]. This resilient cooling system concept is then bounded by the United Nations' Sustainable Development Goals (SDGs) presenting a view that it is the universal right of all people to be protected from, and enabled to protect themselves from, the risks posed by the temperature hazard, and that any strategies adopted to mitigate or adapt to the hazard support rather than undermine the SDGs. Goal 7 – affordable and clean energy – is particularly important in the context of a resilient cooling system.

2.2. Integrative literature review

A critical and comprehensive evaluation of published research and practice was undertaken with the objectives of (a) adding clarity and detail to various components of this resilient cooling system; (b) highlighting the commonalities and differences in the terms used by different disciplines to indicate resilience; and (c) inferring the implication of our model for practice and policy. An integrative literature review process was used as it allows for the inclusion of theoretical and empirical research and perspectives from diverse sources to more fully understand complex phenomena [34]. A two-stage search approach was conducted using two databases (Science Direct and Scopus) for 1990 – 2019. In the first stage, key search terms (disaster, exposure, hazard, resilience, risk, and vulnerability) were applied to titles and abstracts to find literature relating to the subcomponents of community resilience (social, economic, institutional, infrastructure and environment) inferred in the DROP model [15] and other community resilience frameworks, such as Ref. [35]. Inclusion criteria included review papers and original research papers relating to human preparedness for, and responses to, hazards. Papers in languages other than English were excluded, unless the co-authors were fluent in the published language. The second stage extended the search criteria by adding additional functionality key words (such as criteria, definition, evaluation, framework, index, indicators, and metrics) and extending the inclusion criteria to incorporate credible grey literature (such as disaster and hazard related reports by international organisations and national governments) that might provide operational views and practices. The identified literature was then read in full and screened for relevance to the scope of this paper (temperature hazards, the need for cooling, and the systems on which cooling relies). Data from the resultant literature were then extracted and coded under three categories: (i) hazards and risk management; (ii) system functionality; and (iii) key factors and indicators relevant to the system or subsections of the system.

3. Characterising the hazard, risks and consequences

For the purposes of this paper, the term "temperature hazard" is used to denote increases in high temperature frequency, duration and magnitude that present a risk of overheating in buildings, threatening human health, activities, and productivity.

3.1. Temperature hazard criteria

The temperature hazard encompasses the concepts of sudden perturbations (shocks to the system beyond normal variability, such as heatwaves or sudden spikes in electricity demand) and slow or continuous stressors to the system (for example, gradual changes in temperature distribution and mean minimum and maximum internal or external temperature) [36]. Literature reveals seven key criteria that can be used to further characterise temperature hazards (Table 1),

Table 1
Characterisation of the nature of the threat.

Criteria	Sub-criteria	Reference(s)
Predictability	Regular; Irregular; Outside of collective experience	[37,38]
Origin of the threat	Internal; External	[37]
Spatial distribution	Household, community, city, region, nation	[39,40]
Temporal distribution	Timing of the hazard (e.g., early summer, during holidays, at night) and duration	[40]
Speed of onset	Slow; Rapid; Prolonged	[39]
Scope and magnitude of impact	Scale of population impacted or displaced (emergency, crisis, disaster, catastrophe)	[40–42]
Number of threats	Single or multiple stressors	[22,32,43,44]

and each of these have implications for coping, adaptation and risk management strategies.

Some metrics that are used to characterise one aspect of the temperature hazard - heatwaves - include Excess Heat Factor (EHF) (enabling localised comparison of heatwave intensity) [45], heatwave duration (HWD), heatwave magnitude (HWMt) and heatwave amplitude (HWAt) [46]. These are not resilience indicators, but metrics that characterise the hazard, in order to evaluate exposure and vulnerability. Electricity-related threats related to temperature are discussed later in this paper.

3.2. Vulnerability to temperature hazards

A NH approach, such as used in the social sciences, focuses not on the hazards or risks, but on community vulnerability and resilience to the risks posed by the hazard [47,48]. The resilience of a community is influenced by policies and actions to manage the risks, as well as on the communities' wider context, changes, and disturbances [49]. Individual and societal risk preparedness and risk management actions can also be influenced by personal, cultural, social and religious beliefs, such as fatalism, determinism, dependency, hopelessness, nationalism, collectivism and empowerment [50–53], and by the language used to convey risk. In 2004 the World Health Organisation (WHO) defined "natural disaster" as "a serious disruption triggered by a natural hazard causing human, material, economic or environmental losses, which exceed the ability of those affected to cope" [54]. Note that the hazard is natural, but the disaster is a consequence of the level of exposure and vulnerability of people, their structures, and their activities to natural hazards, and their capacity to cope with natural hazards. Some governments present a view that a natural hazard becomes a disaster when it impacts on what we value [55], and therefore use the term "natural disaster" when there is significant loss of life or property. In contrast, some academics argue that linking the terms "natural" (inferring outside of human control) and "disaster" (inferring impact on human life and property) can promote fatalism and helplessness, be an excuse for inaction, and limit risk mitigation actions such as better planning of human infrastructure and activities [56]. The importance of risk mitigation has been highlighted in long-term insurance industry data that showed that increasing insurance losses were predominantly driven by higher exposed values (i.e., human property and human life exposed to higher risk from natural events), rather than increasing hazards [41]. That report argued that investments in loss prevention (risk mitigation) were cost effective because they decrease losses (direct economic and human life costs). The financial and social benefits of investing in long-term resilience building (reducing exposure and vulnerability) were also reported by Cutter [57].

3.3. Managing temperature hazard risk

A DRM approach focuses on understanding and managing risk. The significance of the consequence of a disruptive event (a multiplication of likelihood and severity) considers the spatial scale and magnitude of *impact* as a continuum (Fig. 3), with each scale having a different range of effects and being managed with different resources from local, regional, national, or international authorities. This manner of communicating the scale of the impact is used, for example, in health-, energy-, and weather-related events [41,58]. It was recently evidenced in the U.S.A. government's Disaster Declaration [59] in response to the February 2021 cold-weather event in Texas that resulted in the failure of homes, heating appliances, and electricity generation and distribution systems to provide heating services to residents.

Some aspects of DRM are already embedded into our built environment, such as building codes, standards, codes of practice, and product declarations. In addition to general performance criteria such as functionality, robustness, and service life, DRM-driven criteria are typically added retrospectively in response to an undesirable impact of a hazard [11,60]. For example, local building regulations may change as a result of property damage or loss of life due to earthquakes, storms, floods, and hurricanes. Similarly, equipment may have risk mitigation requirements addressing electrical safety, fire safety, or indoor environmental quality. Technical equipment and infrastructure may have requirements to shut down in certain circumstances when safe operating conditions are close to being breached—for example, when overheating is imminent. These are all examples of strategies undertaken by societies to minimise future loss from these hazards.

This DRM approach, as applied to our built environment, has some limitations. The temperature hazard presents a significant risk to humans and the buildings, technologies, and infrastructure on which they currently rely to provide cooling, and it is widely accepted that the implications of climate change will need to be reflected in future building forms, materials, and services [61]. Despite this, the continuing utilisation of historical weather files to determine cooling loads

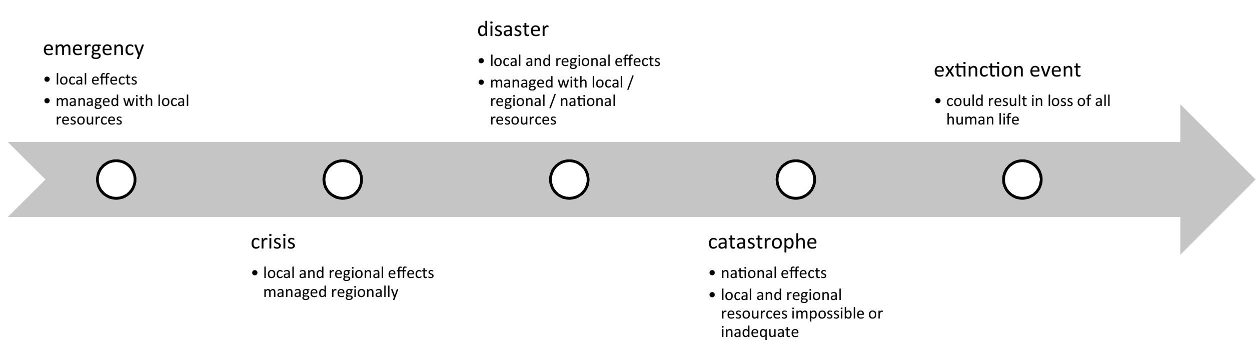

Fig. 3. The DRM continuum of the impact scale of consequences of hazards and risks.

and thermal comfort goals are arguably inadequate for evaluating the effectiveness of cooling solutions to prevent or reduce exposure of humans to overheating in buildings into the future [62]. This practice does not seem to recognise the dynamic nature of the climate system, and the social and built environment systems within the "resilient cooling system". This may be because design and engineering approaches to the built environment can encompass two different views of "resilience", both with limitations: a *redundancy* approach that accounts for some future uncertainty (e.g., oversizing components and spaces) but has no real adaptation to changing conditions; and a *robustness* approach that optimises safety, resource consumption and functionality to a specific brief and set of functions (i.e., a fail-safe system within a defined range of uncertainty) [62–65].

The adequacy of the engineering redundancy and robustness approaches to our built environment and risk management is being questioned, driven by (a) more frequent and intense natural hazards, new hazards, and growing potential for cumulative or concurrent large-scale natural hazards; (b) the interconnectedness, interdependencies, and complex interactions between infrastructure (e.g., essential services), people, environment, economy and technology and the reliance of our societies on these connections; (c) increased exposure and vulnerability of people and assets to natural hazards; and (d) the intangible, indirect, flow-on and cumulative effects of impacts that can trigger long-term challenges [55]. The following section presents characteristics of a functioning resilient cooling system, and subsystem characteristics and indicators.

4. System functionality and subsystem indicators

This section identifies key characteristics that conceivably relate to the functioning of the proposed model of the resilient cooling system, and components and indicators relevant to the different subsectors of the system.

4.1. Characteristics of socio-technical system functionality

One view of system resilience is from the perspective of exposure, dependent on the characteristics of both the hazard and the system [66]. It would seem obvious that the core function of a resilient cooling system is to provide cooling at different scales (individual, household, community, region) [67,68] in such a way that these stakeholders can "plan and prepare for, absorb, recover from, and more successfully adapt to" [69] the temperature hazard. A more nuanced understanding of system functionality (and hence exposure) can be gained from understanding community disaster resilience from different domains [70]. Table 2 proposes desirable system functionality characteristics, extracted from domains such as population and community resilience; humanitarian aid and community development; and health, financial, food and engineering systems.

An Intergovernmental Panel on Climate Change (IPCC) report [8] stresses the importance of understanding the difference between "coping" and "adapting", words that are frequently used in resilience definitions and frameworks. This review indicates that these words elicit different strategies based on different perceptions of the nature of the hazard and elicit different response timeframes and strategies (Table 3). This is evidenced, for example, in multiple existing community heatwave response mechanisms that appear to be based on perceptions that heatwaves are "events" that are infrequent and of short duration; hence, communities are advised to "cope" with the hazard by reducing their exposure (e.g., retreat to a local swimming pool or shopping centre) or reduce their vulnerability (e.g., drink more water, cease strenuous activities, and look out for neighbours). While these responses to immediate threats are important, one could argue that the increasing intensity, duration, and magnitude of both heatwaves and extended periods of hot weather presents our communities with challenges beyond their ability to withstand and cope.

Table 2
Characteristics of a resilient cooling system functionality.

Proposed desirable characteristics of a resilient cooling system	Reference(s)
Identifies and maps risk, exposure and vulnerability (to temperature hazards) at different scales	[71,72]
Anticipates (temperature hazards and associated risks and impacts) and builds a culture of safety and adaptation through knowledge, innovation and education	[6,8,10,23]
Withstands, copes with, absorbs impacts of, and recovers from (temperature hazards and associated risks and impacts)	[22,73]
Embraces change and uncertainty (i.e., a continual state of change, as opposed to a state of equilibrium or "norma")	[28,74]
Learns from shocks (by enhancing protective factors; reorganising; implementing diversity of strategies; increasing the buffer to reduce risk of failure and impact of failure; creating alternative paths in case of failure; using flexible decision making; and tracking the transformation process and outcomes)	[23,35,72,74–76]
Works collaboratively across all sectors (community, government, institutions) to implement transformational change	[71,73]
Retains control over the structure and functioning of the system, including planning for "orderly failure" to retain the system's main function (i.e., cooling for people)	[64,77]
Protects human life and health outcomes in daily function as well as during a temperature hazard and its aftermath (i.e., resilience dividend)	[78]
Recognises the global nature of the temperature hazard, and the roles and responsibilities of all stakeholders	[79]
Implements legal and policy frameworks to guide responses and establish accountability	[79]
Accounts for household learning and coping mechanisms; and decision-making agency and power	[30]

Table 3
Differentiating coping and adapting (derived from [8]).

	Coping	*Adapting*
Hazard/Stress	Imminent	Future
Response timeframe	Quick response, short timeframe	Continual, long term
Constraints	Knowledge of previous experiences	Assumptions about the future
Strategies	Previously successful tactics	Anticipating change
Goal	Protecting the individual	Protecting the system

As indicated by our resilient cooling model, system functionality is inherently dependent on the antecedent conditions and changes to these conditions over time. Table 4 shows examples of indicators that could be used to quantify some of these antecedent conditions at different scales, depending on data availability.

4.2. Key characteristics and indicators of subcomponent functionality

4.2.1. People

In the medical profession, stress resistance (of humans) incorporates the concepts of robustness and resilience, where "robustness" is defined as the ability to resist deviation from the original state, and "resilience" as the ability to recover after such deviation [82]. The human stress response is two-staged, involving first deviation, then recovery. Measures of robustness (deviation) include the magnitude of deviation and the time taken to reach the peak deviation. Measures of resilience include the time to recover and the completeness of the recovery. While both robustness and resilience can decline with age, these authors consider that resilience decline is universal, but robustness decline is not. They suggest that there are differences between robustness and resilience between men and women (better health

Table 4
Quantitative indicators for antecedent conditions (derived from Refs. [23,30,72,80,81]).

Component	Indicators of resilience assessment (antecedent conditions)
Social	% of population that is elderly, infirm, or very young (under 5 years of age) % of population living in dense urban environment % of population that is a minority or does not speak the predominant language
Economic	Per-capita income % of homeownership Household income, savings, and assets
Institutional	Presence of a temperature-hazard mitigation plan (offers a vision for the future) Presence of an insurance program (a means to reduce loss and promote recovery)
Infrastructure	Housing typology and density Emergency services and temporary shelters per 1000 population
Community health and well-being	Social assistance programs per 1000 population Health services per 1000 population Communication services per 1000 population Environmental Public Health Indicators (EPHIs)
Environment	Frequency of loss-causing weather events % of green space / tree cover / land available for temperature hazard mitigation (to address the urban heat island effect)

but worse survival in men compared with women) and that robustness and resilience have different effects on all-cause mortality. Some components of physiological aging (e.g., the slowdown) may universally contribute to the decline in resilience, but not necessarily in robustness. Blood pressure, for example, may deviate as a result of heat stress, and elderly individuals will likely recover (return to their usual blood pressure) less quickly and completely than younger individuals.

The indoor environment quality of our buildings often uses a “thermal comfort” criterion – an attempt to determine occupant satisfaction with the building’s indoor thermal conditions. Physiological, psychological, and environmental factors influence occupants’ thermal comfort over the course of a day and over time [83], but the temperature hazard requires consideration of more than thermal comfort. In the context of heat, an individual’s protective factor can be interpreted as the capacity of the body to respond to heat. Acclimatisation and thermoregulation determine human heat tolerance and vulnerability to heat stress [10], requiring consideration of a range of factors and conditions, as summarised in Table 5.

In practice, some “temperature threshold limits” are being identified, based on the outdoor temperature at which there is an increase in ambulance callouts, presentations of patients to doctors and emergency departments, and an increase in deaths. These thresholds are very location specific, reflecting population and individual acclimatisation, cultural practices, and urban and housing design. Location specific temperature thresholds reported in literature typically correlate heat-related deaths to outdoor ambient temperatures during heatwave events. Key findings from this literature are that (i) excess mortality is higher in tropical climates than in temperate climates [98,99]; (ii) mortality curves in hot temperature zones are steeper, with less variation in tolerance, compared with mortality curves in cold temperature zones [10]; (iii) mortality is influenced by high maximum (daytime) and high minimum (night time) temperatures [93,100]; and (iv) mortality per capita is higher in urban areas [99,101].

The factors discussed in this section have implications for our buildings.

4.2.2. Buildings

A key purpose of buildings is to shelter occupants from the outside environment, providing safety, health, and amenity. This purpose is reflected in many building codes, but these codes are currently reactive rather than predictive and proactive in response to climate [11,62]. Existing risk management approaches do not account for system vulnerabilities and interdependencies, nor for different levels of threat probability and severity [27,102]. It is clear that our built environment is failing in its purpose to shelter occupants from the risks associated with temperature hazards, as evidence links excess heat-related morbidity and mortality to a number of building-related factors (Table 6) and there have been calls for more studies in these areas [95,103]. Poor thermal performance of buildings has arguably contributed to occupants’ behavioural adaptations that have resulted in a rapid rise in the reliance on air-conditioning, changing cultural expectations, and practices regarding thermal comfort [104]. These changes are placing increased strain on electricity infrastructure [105,106] and undermining carbon reduction strategies [107].

Climate change will need to be reflected in future building forms, materials, and services [61]—in particular, by acknowledging that

Table 5
Factors and conditions affecting individual responses to temperature hazards (derived from Refs. [10,84–97]).

Factors	Key conditions
Thermoregulation - physiological	Range is very narrow (core body temperature 36.8 °C +/- 0.5; heat stroke occurs at 40 °C) and varies between individuals The upper range of heat exposure that humans can tolerate has not been defined, and may not be definable Heat sensitivity is affected by factors such as obesity, age, illness, medication, aerobic fitness, gender, and acclimatisation, with individual influencing factors of sweat capacity, cardio capacity and blood volume
Thermoregulation - behavioural	Relies on individual’s perception of body temperature and an individual’s ability to modify the environment to reduce body temperature Older people have less ability to perceive temperature Relies on personal actions: adjusting clothing (type and level), reducing activity, moving to a cooler space, hydrating, wetting the skin Relies on actions within buildings: operating windows, shades, or fans to reduce heat or increase air movement to enhance evaporation from skin The evaporative effect can be enhanced or restricted by clothing: not just the insulation level (clo), but also by fabric breathability and garment fit
Acclimatisation	Heat tolerance can be improved due to physiological adaptation to a new climate Sudden or extreme heat events can impact on typically acclimated residents New arrivals to a region can be unacclimated People experiencing predominantly air-conditioned environments can be unacclimated
Vulnerability	Physiological and behavioural factors are closely linked, and the impairment of either of these reduces thermal tolerance and increases sensitivity to heat Older people are particularly vulnerable to heat-related morbidity and mortality Physical and social vulnerability can limit adaptive capacity and increase exposure

Table 6
Factors impacting buildings’ ability to protect occupants from overheating.

Building Factors	Reference(s)
Housing characteristics (e.g., poor thermal efficiency, construction type)	[107,108]
Urban heat island effect in urban environments	[102,105,107]
Adaptation options available to occupants (e.g., operable windows)	[102,107]
Internal heat gains	[109]
Occupant vulnerability (e.g., age, mobility, pre-existing health conditions)	[102,107]
Strain on electricity infrastructure	[110,111]

adaptive opportunities for occupants are as important as the building envelope, especially if there is a risk of power failure [112]. Electricity network reliability and capacity are also important considerations in overheating risk, with suggestions that buildings could provide "cool retreat" spaces that can be efficiently air-conditioned during temperature hazard events, as opposed to attempting to cool whole buildings [113]. This solution may be limited to climates with infrequent and short duration heatwave events, as its effectiveness as a long-term strategy in climates with prolonged and frequent temperature hazards has not yet been evaluated.

Very few studies directly correlated the number of deaths during temperature-hazard events to temperatures inside buildings. However, there is a significant body of work that considers the role the building envelope plays in protecting people from high outdoor temperatures. Research has attempted, for example, to quantify overheating risk to human life [99,110]; to quantify the reduction of impact of overheating (e.g., lives saved) due to energy efficiency upgrades to buildings [111]; and to quantify the probability of overheating, based on the building stock [109]. A fairly comprehensive, if somewhat UK focused, review of research lessons relating to overheating in buildings can be found in [114]. A variety of approaches have been used by researchers, such as modelling [108,112,113], use of future weather files [115,116], scenario analysis [117], regulation analysis [118], adaptation [119], advanced technologies [120], occupant education [121], and post-occupancy evaluation and measurement [122].

Building metrics that could be adapted to quantify some aspect of "resilient cooling" in buildings are presented in Table 7. These metrics fall into two broad categories: those that focus on occupant thermal comfort, and those that focus on protection of occupant health (reducing the risk of heat stress). The thresholds set by these indicators can vary depending on the underlying comfort model (steady-state or adaptive comfort), the local climatic conditions, and the part of the building the metric applies to (e.g., bedroom or living room of a home). Some metrics, such as "hours of safety", attempt to embrace both thermal comfort and safety, while others incorporate consideration of one or more of the characteristics of the hazard, such as magnitude, duration, timing, and speed of onset. In a simplistic manner the thermal resilience of the building could be assessed, for example, in terms of the number of hours the indoor temperature is above a particular threshold. This is sometimes expressed as "exceedance hours", but that metric does not account for the temporal response of a building to an extreme heat event, the cumulative effect of the duration of a moderate heat event, or changes to occupant vulnerability. Even if some indicators include some cumulative effect, they do not include the risk to occupants due to successive exposure to indoor overheating. Successive exposure is more complex to define, as the thresholds themselves would need to adapt to the duration of the event and the evolution of the occupant's vulnerability. For example, consecutive warm nights can decrease the sleep capacity of individuals, which increases their fatigue and therefore their vulnerability. The issue of multiple hazards is also poorly addressed. A study by Mavrogianni et al. [123] seems to indicate that (i) existing overheating assessment criteria do not take into account the synergistic effects between summertime ventilation behaviour, indoor overheating, and air pollutant concentration, especially in social housing and free-running buildings; (ii) a static single temperature exceedance criteria [124] is simple to use but does not incorporate acclimatisation and adaptive capacity of occupants; and (iii) the adaptive external climate dependent criteria (CIBSE TM52 [125], BS EN 15251 [126]) was considered preferable for free-running buildings where occupants have higher adaptive capacity. The applicability of this criteria in buildings occupied by vulnerable individuals, or buildings in hotter climate zones, requires further investigation, as the standard is based on a running-mean outdoor temperature of up to 30 °C. More research is needed to determine the limits of adaptive comfort and circumstances under which hybrid cooling approaches may be needed. There is also a need to determine how to clearly communicate the limits of a building to protect occupants from the risk of overheating and the circumstances under which it is assumed occupants will need to rely on (and pay for) mechanical cooling technologies and services.

Table 7
Building resilience indicators relating to temperature.

Term or Metric	Reference
Building Heat Performance Index (BHPI)	[95]
Building Resilience (during power outage)	[127]
Comfort model (static) - Predicted Percentage Dissatisfied (PDD), Predicted Mean Vote (PMV)	[12]
Comfort model (adaptive) – relative to external mean monthly temperature or indoor mean ambient temperature	[12,128]
Constants of Proportionality - incorporates seasonal changes	[128]
Gain Utilisation Factor (GUF) –annual cooling energy needs	[129]
Hours of Safety (free running mode)	[130]
Indoor Heat Stress	[131]
Occupied Thermal Comfort Percent (occTCP)	[132]
Overheating Criterion	[124]
Overheating Escalation Factor	[117]
Passive Habitability	[132]
Passive-Survivability-Winter (PSW) and Summer (PSS)	[102]
Thermal Autonomy (TA) – with passive means only	[132]
Ventilation Autonomy (VA) – with passive means only	[133]

4.2.3. Cooling technologies

Passive, active and hybrid cooling systems in buildings are engineered systems. The resilience of engineered systems is often articulated using four properties: robustness, rapidity, redundancy, and resourcefulness [23,35]. *Resilience engineering* focuses on the safety and efficiency of system functionality, and the system's ability to respond, monitor, learn and anticipate [134]. Resilient active cooling systems within buildings, by inference, should exhibit the following operational behaviours:

- Response to regular or irregular disruptions or disturbances
- Monitoring of potential threats and the impact they can have on the system
- Ability to learn from experience (successes and failures)
- Anticipation of developments, threats, and opportunities into the future

Reliability engineering is another aspect of systems engineering, focusing on the aspects of dependability and availability. Cai et al. [135] espouse that availability comprises of a stable state of functionality, the time taken to recover from an event, and the number of events. This view takes account of one of the characteristics of the threat (number of events) as mentioned in Table 1, but assumes a stable state and a return to that state after an event. A different approach by Mahmoud et al. [40] incorporates temporal and spatial threat characteristics to evaluate cumulative disruption and recovery while also acknowledging the reliance on infrastructure, such as housing and power.

While active cooling appliances are typically supplied with performance and reliability data, to the authors' knowledge, they do not include consideration of all of the characteristics of the temperature hazard, the cumulative effect of multiple hazards, characteristics of the people for whom cooling is provided, or the reliance on infrastructure to continue functionality. This latter point is particularly important for engineered systems that rely on electricity for operation.

4.2.4. Electricity infrastructure

Electricity infrastructure (generators, transmission, and distribution networks, and distributed energy resources) is particularly important in the context of the temperature hazard because much of society is reliant on electrically driven cooling devices, and the electricity system itself is affected by temperature hazards. Similar to buildings and mechanical cooling devices, electricity systems are designed and rated to function within defined temperature limits [136]. When those limits are reached, the assets need to be de-rated for self-protection. High and extreme temperature events are challenging for power grids because (a) the ambient thermal conditions are more severe; (b) power demand often increases with the increase in ambient temperatures; and (c) more Ohmic heat is generated and accumulated in the power grid due to both higher electricity flows and temperature-induced increases in wire resistance. This means that the actual loading of electrical assets increases unless there are other control mechanisms, resources, pathways of energy supply, or load shedding. Increased loading puts electrical equipment under stress and accelerates aging, both contributing to the possibility of outages during extreme temperature events.

Within electric power engineering, resilience is often used interchangeably with, or seen to be equivalent to, reliability and robustness [137–140], but the links between these terms depends on the context and application. Traditionally, reliability in the power system includes two aspects: adequacy and security [141]. This results in power system design and operation for “normal conditions” and for abnormal but foreseen contingencies (low-impact high-probability events) [142]. In practice, the security component of the power system is often dealt with separately —for example, in terms of economic stability in energy systems [143]. Reliability is used to refer to the probability of no disconnection or load shedding [144].

One group of power grid resilience definitions considers reliability as complementary to resilience, rather than a component of resilience. For example, the U.S. National Infrastructure Advisory Council (NIAC) includes robustness, resourcefulness, rapid recovery and adaptability in its infrastructure resilience model [145], while the Pacific Northwest National Laboratory (PNNL) focuses on stress resistance and strain compensation [146]. A dominant reason for excluding reliability from resilience is the perception that a resilient grid would not experience outages, and reliability is the probability term for outage [139]. The differences between reliability and resilience in power engineering are summarised in Table 8.

In contrast, other infrastructure resilience models include reliability, allowing for the possibility of power system failure [150] and hence electricity utility management practices to include reliability considerations in multiple aspects of the power system (including stakeholder engagement, communication, supply chain investment, and services) [151], and strategies to deal with reaction to disturbance [152].

Resilience and robustness, often used interchangeably in other disciplines, have different meanings or impacts in electric power system studies, as summarised in Table 9. One of the key differences is that robustness often refers to targeted improvement of one defined class

Table 8
Distinguishing between reliability and resilience in power engineering studies (derived from [137,138,147–149]).

Criteria	Reliability	Resilience
Probability of events	High probability	Low probability
Impact	Low impact	High impact
System states	Evaluates power system states	Evaluates power system states and transition between states
Temporal features	Static, retrospective	Adaptive, ongoing (short and long term)
Areas of concern	Concerned with customers’ interruption time or frequency of interruption	Concerned with prevention, customers’ interruption and recovery

Table 9
Distinguishing between robustness and resilience in energy systems (derived from Refs. [137,139,148,155,156]).

Criteria	Robustness	Resilience
Target areas	Robust to a specific class of failures	System wide resilience, multifaceted
Event types	Predictable	High impact rare
Features	Stiff (may be brittle and fragile in some other ways)	Flexible, agile, adaptable, self-healing
Application	Network hardening	Network flexibility
Enterprise focus	Assets	Services
Security Active	approach	Passive
Value Operation	proposition	Design
Key function	Resistance to change in predictable events	Flexibility and survivability in unexpected extreme events

of failures. Such targeted actions, however, may result in increasing the vulnerability of another part of the electricity system. For example, a database topological error caused the 2003 US-Canada Northeast blackout [139]. The database was implemented to improve visibility of network, but this robustness improvement in the network caused a large-scale system failure resulting in billions of dollars in losses. Therefore, a resilient power system may need to be robust in quite a few areas and be flexible, agile, and adaptable at the same time. The focus of power system resilience frameworks such as those found in Refs. [138,151,153–155] appears to remain on risk-assessment for high-impact low-probability events, with no indication of how power system design and operation is responding to natural hazards that may be high-impact and high-probability (i.e., increased frequency extreme heatwaves).

The most used power system indicators relate to reliability [142,149,154,157], with a few less-used indicators encompassing sustainability [139,149], security [156], financial impact [149], or redundancy [158]. One resilience indicator combines three capability criteria (absorptive, restorative, and recovery capabilities) in an attempt to take into account interdependencies [159], while another seeks to quantify the relationship between the number of customers affected by a disruption and the time to restoration [160]. A contrasting perspective to these engineering and network perspectives of resilience in energy systems proposes four sustainability-related dimensions: availability, accessibility, affordability and acceptability [161], displaying a stronger socio-economic approach. It has also been highlighted by Molyneaux et al. [142] that there is a need for more research in the energy sector regarding the characterisation of different hazards; the estimation and criticality ranking of each component in the system; the development of more accurate fragility curves; better modelling of the complex process of restoration; and assessment of interdependencies with other key sectors.

As the climate changes, energy use and peak power demand are increasing. It may not be sensible to rely on the power grid alone to provide cooling; a broader systems-approach encompassing power systems, buildings and building equipment is required [162]. Methods of improving resilience within the power system include utilising and sharing renewable energy [163], leveraging distributed energy resources [164], incorporating energy storage, and developing active distribution networks [165]. The diffusion of rooftop solar equipment in Japan [166] is one example of the role that renewable energy can play in Building Back Better (a concept incorporated into our model of a resilient cooling system). The “bouncing forward” concept of our model is encapsulated in a recent definition of resilience with regard to modern energy policy: “the adaptive capacity of improving performance, as a result of learning and adaptation, informed by continuous change” [29].

5. Discussion and further work

This integrative review has shown that while each sector is in general agreement of resilience as a system outcome and process, the system boundaries, and the words used to describe functioning of that system, are quite varied. The need to fully understand the nature of the hazard, to protect people from the temperature hazard, and to appreciate the dependency of people on buildings, technology and energy infrastructure to provide this protection, lends support to our proposed model of the resilient cooling system. This conceptual model has served as a useful tool for evaluating the literature to add clarity to the concept. By focusing on the characteristics of the hazard and the system and subsystem functionality, we have demonstrated that it is not necessary to agree on exact definitions of terms used by different disciplines. The literature highlights that NH and DRM approaches provide concepts that enable the integration of both engineering and non-engineering perspectives. This integration into a conceptual model will help enhance the resilience of individuals, communities, buildings and engineered systems to temperature hazards. Six key messages from this review could be summarised as follows.

1. Resilient cooling strategies, first and foremost, do not start with buildings and engineered cooling systems, but must start with individuals, households, and communities as active agents in managing their own exposure and vulnerability, and in the selection and development of indicators that enable them to track progress towards resilience. This goes hand in hand with building design, engineered systems, regulations, and policies that need to collectively enhance adaptive capacity, resilience capacity, and the resilience dividend.
2. The natural, social, and built environment conditions in which people live are in a state of constant change, not a state of equilibrium. System resilience encompasses embracing change, adaptive capacity and flexibility, with an eye on implementing strategies that can benefit society in all situations (present and future), not just in times of disaster.
3. Resilience needs to be considered at different time and spatial scales.
4. The characteristics of the threat, the functioning of the system, and the vulnerabilities of system components need to be clearly understood and communicated to all stakeholders.
5. The performance boundaries of each of the components of the system also need to be clearly understood and communicated, and the system devised in such a way that different components can "fail safely" without compromising the ability of the system to provide cooling. This means that there is a high dependence on the role of buildings – without engineered systems – to provide a level of safety and protection to occupants.
6. Cooling strategies to enhance resilience should satisfy sustainability, energy efficiency, affordability, and greenhouse gas reduction goals, as well as provide a resilience dividend.

Our examination of socio-technical multidisciplinary resilience perspectives clearly demonstrates that some useful indicators already exist, within parts of the system, but that a single performance indicator cannot adequately quantify "resilient cooling". The complexity of resilience, and of our built environment, means that several indicators will be required. These indicators need to both quantify and communicate the nature of the threat and the nature (and limitations) of the cooling strategies. Further work is required to develop indicator sets relating to heat events, socio-cultural systems, buildings and their cooling systems, and energy networks. Evaluation of these candidate indicators will identify combinations of indicators that can be used for technical purposes such as benchmarking and measuring progress [23,167], as well as social purposes such as informing decision making and improving stakeholder participation [168]. These combinations of indicators could then be used to evaluate specific cooling technologies via building simulation and via case study reports.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Cooling Demand Reduction Approaches in a Nearly Zero Energy Building for Future City District in Central-Sweden

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Abstract

The increase in population and living standards, as well as global warming and heatwaves due to climate change, have created a challenge to meet the cooling demand in buildings. In this study, the cooling requirement for a multifamily building through simulations in a future city district in central-Sweden was determined. Different air supply set point strategies, window to floor ratio and building rotations were employed to minimize the cooling requirements. The building was modelled so as to meet the Nearly Zero Energy Building (NZEB) requirements. Window to floor ratio of 10% with a piecewise proportional controller for supply temperature was depicted as appropriate for the building. A 45° rotation of the building increased the cooling demand. The cooling demand of the building increased by employing the extreme climate condition, as a representative for future climate, with factors 3.8 and 6.4 for cooling set points 25°C and 27°C for window to floor ratio 10%. This implies the need for a resilient building to withstand future climate conditions. The requirement to update the climate files was also used for decision making in the design process and building regulation.

Key Innovations

- New Swedish building regulations may imply low energy use but high exceedance hours in the future.
- Evaluating the influence of window to floor ratio and building rotation on cooling demand for typival and extreme summer climate conditions.
- Use of typical climate condition and an extreme summer climate condition

Practical Implications

The need to increase the resilience of buildings, and the requirement to update the weather datasets used for designing and defining building regulations, according to buildings' future demand given that the present buildings in Sweden do not presently include cooling facilities.

Introduction

One-third of the world's total energy use is due to the building sector; the amount of energy use for a building can be calculated from the building envelope, equipment, outdoor climate conditions, and the occupants (Cui et al. 2017). This trend continues to grow with the increase in population, urbanization and comfort level with more time spent indoors (Pérez-Lombard et al. 2008). An increase in energy use leads to an increase in carbon emissions. With the ongoing climate changes, more extreme weather events are experienced and the building sector appears to be more vulnerable to these changes (Yau et al., 2013). These extreme events are expected to affect building energy use. Using currently available sources of energy to face the climate implications for buildings endangers future energy security (Jing et al., 2014).

Buildings that are optimized from an energy use perspective, must be made more resilient, especially to future climate changes. During recent years, heatwaves have been the reason for certain heat-related deaths. A study conducted on heatwave-related mortality in Sweden depicted that heatwaves increase mortality and coronary heart disease mortality in particular by approximately 10% and 15% respectively (Oudin Åström et al., 2020). A study conducted in France revealed thousands of excess deaths (Vandentorren et al., 2006). Certain causes were reported as the main reasons such as high temperatures on the top floors.

Studies have been conducted to evaluate the importance of climate change and the use of future climate files on the annual energy use of buildings. Santamouris (2016) investigated the future cooling energy use of a building by implementing three scenarios based on parameters such as future climate, population increase, etc. and an average cooling demand was calculated for the future scenario.

A study (Petersen, 2020) considered Typical Meteorological Year (TMY) weather files from historic data and three future climate scenarios (the 2020s, 2050s and 2080s) for a Danish office building. It was concluded that by employing the future climate scenarios, cooling demand increases and to have resilient buildings that would withstand future climate changes, it is better not to rely on historic data for building simulations.

To have a detailed assessment of the resilience of buildings and their performance in the long term, an insight into extreme climate is needed (Ramon et al., 2019). Different weather datasets were investigated for building simulations on a Flemish office building by Ramon et al. (2019), who reported the best combination of weather datasets to estimate the energy need of the resilient building.

The use of an "analogue scenario" has been introduced by (Belcher et al. 2005; Petersen 2020). In this method, the weather data of the studied building location that is expected to adopt the same behaviour as that of future

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climate condition could be chosen to study the effect of extreme climate on a building's energy performance.

One way of optimizing the amount of energy used is by applying an optimal supply temperature scheme. Wang et al. (2012) established a steady-state energy consumption model for AHU under the economizer cycle. Optimal supply flow and air temperature concerning outside temperature are obtained through an analytical optimization model. A control sequence was developed to meet the optimal supply airflow or supply air temperature to minimize the energy cost (Wang et al., 2012).

Therefore, implementing new approaches to reduce energy requirements in buildings to pave the path for energy transition to sustainable energy is an area of interest. With the ongoing climate changes, present buildings may not withstand future heatwaves and extreme climate conditions, therefore new regulations are required to increase the resilience of the buildings in future climate conditions. Given that current Swedish residential buildings are not equipped with any cooling units at all, this study aims to analyse and minimize the cooling requirement for a future multifamily building through simulations in a new city district in central Sweden. The simulations were carried out with IDA - Indoor Climate and Environment (IDA-ICE) software version 4.8. Buildings must meet the Nearly Zero Energy Building (NZEB) requirements enforced within Swedish building regulations by implementing optimum building and window specifications.
The characteristics of the model building are aligned with Key Performance Indices (KPIs) which are based on the proposed list from IEA Annex 80: Resilient cooling of buildings. Reduction of heat load, reducing cooling requirement and exceedance hours (number of hours the building exceeds its comfort range during summer period (Bakhtiari et al., 2020; Nicol, 2013)).

Methodology

A future multifamily building in central-Sweden has been modelled. The plan of the building is shown in Figure 1. The building model consists of four floors with floor to ceiling height of 2.7 meters. Each apartment's floor area is 77 m^2 and the total floor area is 1414 m^2. Different parameters such as equipment, lighting, window U-value and its shading factor were implemented based on the Swedish building regulations (Boverket, 2020; Sveby, 2012) to meet the NZEB requirements. Table 1 presents the efficiencies of the AHU and the heating/ cooling set point s. The AHU is a constant air volume system that is equipped with heat recovery. In each zone, an ideal heater is defined in order to maintain the operative temperature within heating set point during the heating season. Ideal heaters could be considered as standalone heaters (EQUA, n.d.). Ideal coolers also were implemented in order to evaluate the cooling load of the building during the cooling season. Based on the regulation, a Primary Energy number (EP_{PET}), that describes the energy performance of the building based on its primary energy use has been defined. In order for the building to be considered an NZEB, $EP_{PET} < 75$ kWh/ ($m^2 \cdot A_{temp} \cdot$year) should be satisfied. A_{temp} stands for the heated area (more than 10° C) in the building.

a

b

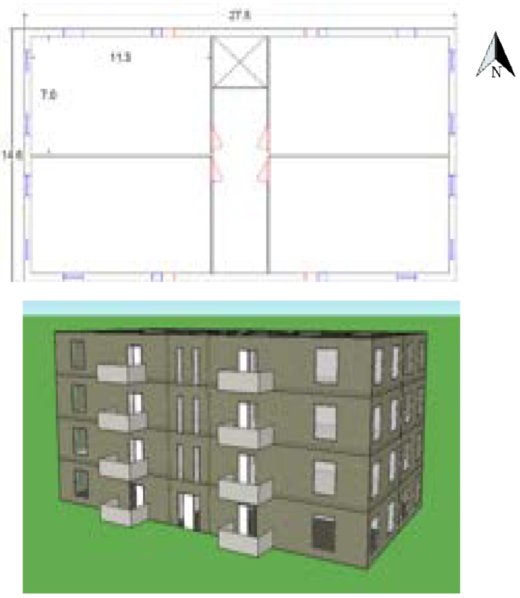

Figure 1: Scheme of the building model's geometry. (a) The plan of the building (dimensions are in meters). (b) Modelled building in IDA-Indoor Climate and Energy (IDA-ICE)

Table 1: Input parameters for the model building

Parameter	Value
Wind profile	Urban
Heating set point	21°C (Boverket, 2020)
Cooling set points	Air temperature 25°C, 27° C
AHU specific fan power	0.75 kW/(m^3 / s)
Heat exchanger efficiency (air to air heat exchanger)	0.85

The insulation material used in the building envelope is based on the latest material available on the market which leads to heavy inertia with an average U-value 0.21 W/ ($m^2 \cdot K$). The U-values for external walls and roof are 0.1 and 0.06 W/ ($m^2 \cdot K$) respectively. External floor and internal floors have U-values of 0.11 and 1.8 W/ ($m^2 \cdot K$) respectively. Glazing material used for the fenestration system also is based on regulations from Forum for Energy Efficient Buildings (FEBY) (2018). The glazing U-value and solar heat gain coefficient correspond to 0.8 W/ ($m^2 \cdot K$) and 0.4 respectively. Total window U-value is 0.92 W/ ($m^2 \cdot K$). Internal blinds with a solar gain multiplier of 0.65 were employed which are controlled by the solar radiation level in order to reduce solar heat gain. If the radiation level exceeds 100 W/m^2, the blinds would be drawn to cover the window. This value is chosen based on the global setting that is implemented in IDA-ICE (EQUA, n.d.). Surrounding buildings have been considered, 20 m from the model building in every orientation. Window to floor ratio of 10% is put into practice for the building model. The windows are set to be closed all the time in order to evaluate the cooling demand of the building without employing any cooling techniques. The supply and exhaust airflow of the system are 0.35 and 0.37 L/ ($s \cdot m^2$) respectively (Sveby, 2012).

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Each apartment is defined as one zone in the model. The total sensible heat emitted in each zone is defined based on (Westin, 2019) and is set to be 1927 kWh/ year per apartment. This amount corresponds to household electricity.

In order to investigate the effect of different supply temperature strategies, window properties and orientations, three different case studies have been defined in the following subsections. For each case, different parameters have been evaluated; the exceedance hour is defined as the total hours that the building exceeds the comfort range (Nicol 2013; Bakhtiari et al. 2020). In this study, the number of hours, exceeding operative temperature 27°C during a complete year, are considered in exceedance hour evaluation. Cooling degree-hours (CDH) is defined as the sum of the difference between room air temperature and a base temperature on an hourly basis, which is calculated using equation (1):

$$CDH = \sum_{j=1}^{N} (T_j - T_b)^+ \quad (1)$$

Where *N* is the number of hours in a given period, T_b and T_j are the base temperature and hourly mean room temperature respectively. The "+" superscript indicates that only positive values are considered in summation (Simson et al. 2015). The CDH is calculated over the summertime period (1st July-31st August). The base temperature is taken as T_b= 25 °C as well as T_b= 27 °C.

Case 1: Investigation of different mechanical ventilation strategies:

In this case, different control schemes for the supply air temperature and their effect on the indoor conditions were investigated. Window to floor ratio was 10%. A constant supply temperature of 16°C was first considered.

Correspondingly the AHU supply air temperature is always 16°C until the ambient temperature reaches 16°C. From that point onwards, the supply temperature would be the same as the ambient temperature.

The alternate mechanical ventilation strategy studied, was a piecewise proportional controller for the supply air temperature. Different combinations of supply temperature were examined in order to find the scheme that helps to reduce the exhaust air temperature and the exceedance hours in the zone which consequently reduces the cooling load. Figure 2 depicts the chosen supply air temperature scheme. Based on this strategy, when the ambient temperature is below 8°C, the supply air temperature is 16°C. The supply air temperature gradually decreases by the ambient temperature increase, until the ambient temperature reaches 16°C. Since no cooling coils are defined in the system, the AHU does not supply cooled air streams to the zones. When the ambient temperature is above 16°C, AHU supplies the same temperature as the ambient temperature.

Case 2: Window to floor ratio change

Initially, the window to floor ratio employed in the study was 10%%, which is the minimum ratio allowed to meet the daylight requirements in Swedish building regulations (Boverket, 2018).

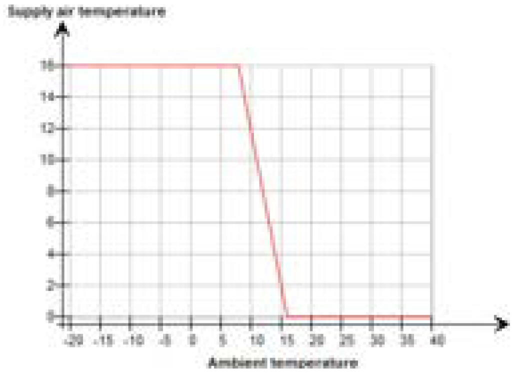

Figure 2: Piecewise controller scheme depicting supply air temperature versus ambient temperature

In order to study the effect of different window sizes, different window to floor ratios of 15% and 20% were considered by employing the chosen supply strategy from Case 1, which is the piecewise proportional controller for the supply air temperature. The maximum window to floor ratio (20%) was chosen based on the previous Swedish building regulation (Boverkets, 1988).

Case 3: Rotation of the building

The building was then rotated 45° in order to investigate the effect on the interior conditions. Later the building was rotated 90° and the simulations were carried out for this orientation as well.

Case 4: Extreme summer climate condition

The climate file used throughout the procedure has been the climate file based on the 30 years of data (years 1981-2010) from the Swedish Meteorological and Hydrological institution (SMHI, n.d.) to create a typical year climate file.

In this case, the extreme climate file for 2018 was used as a representative of the future climate condition. The extreme climate of 2018 was recorded to have the warmest summer with longer heatwaves (Wilcke et al., 2020). In this case, the effect of the same window to floor ratios (10-15% and 20%) and building rotation (45 and 90°) on cooling demand and the exceedance hours were investigated. Finally, a combination with the least cooling demand and exceedance hours is selected.

Results

After running the simulations for all the cases, the results are shown below. The typical year climate file has been used for the Base case, Case 1, Case 2 and Case 3. The extreme climate of 2018 has been employed for the last case (Case 4: extreme summer climate condition).

Case 1 (Base case):

Figure 3, shows the duration curve for the following temperatures: ambient, supply, exhaust air, operative for the worst zone (zones on the fourth floor), and best zones (first-floor zones) for two different supply air temperature schemes. Figure 3a shows the duration curve when constant supply temperature was employed and Figure 3b shows the duration curve for a piecewise controller

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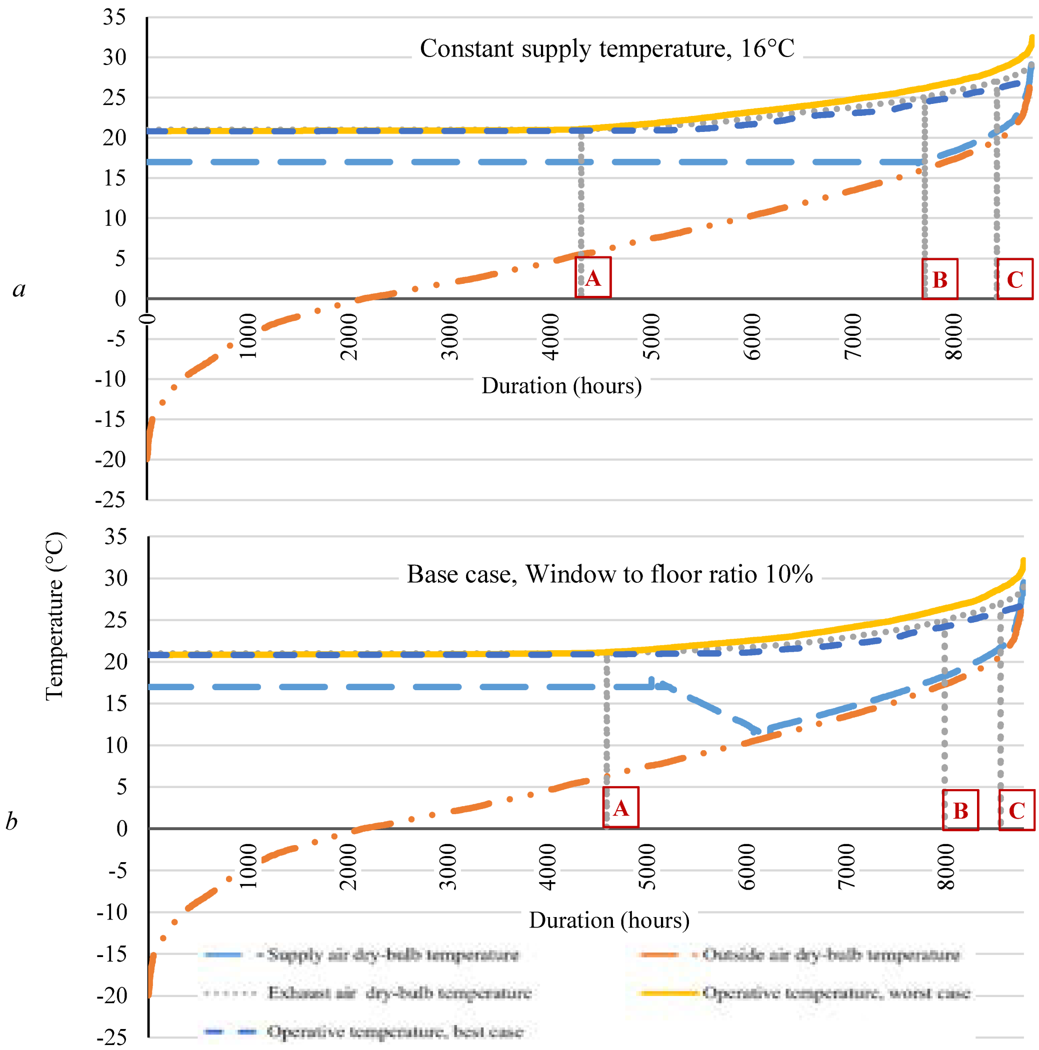

Figure 3: Duration diagram for base case, for the following temperatures: ambient, supply, exhaust air, operative. (a) Constant supply temperature (16°C). (b) Piecewise controller schedule

scheme for supply air temperature. The worst zones have the highest operative temperatures and the best zones have the lowest operative temperatures. The rest of the zones are considered average zones.

The lines A, B and C shown in Figure 3, represent the heating and cooling set point s. Line A shows where the exhaust air temperature (grey dotted line) exceeds 21°C. From this point onwards, the building does not require heating. Lines B and C depict where the exhaust air temperature exceeds the cooling set point s of 25°C and 27°C respectively. Exhaust air exceedance hours are calculated from these three lines onwards. Exhaust air exceedance hour represents the number of hours in a year in which the exhaust air temperature rises above the mentioned cooling set point s.

As it can be seen in Figure 3a, the heating set point (21°C) has been maintained for about 4300 hours during a year. In this case, CDH corresponds to 1379°Ch and 274°Ch for base temperatures of 25°C and 27°C respectively.

As mentioned in Table 1, two cooling set points were considered in the study. The second vertical line B indicates the exhaust air exceeding the cooling set point 25°C and the third line C, represents the exhaust air exceeding cooling set point 27°C. From these latter mentioned lines onwards, the building is in need of cooling. The cooling demands of the building for these two set points are 1.8 and 0.62 kWh/m^2 respectively for 25°C and 27°C cooling set point s.

The operative temperature in the worst zone is more than AHU's exhaust air temperature for nearly 4400 hours during the year due to the solar gain absorbed by the interior surfaces and windows (glazing) which increases the operative temperature. Exceedance hours correspond to 700 hours in worst zone and 350 hours in average zones in a year. Figure 3b, shows the duration diagram by implementing the piecewise controller with control strategy, depicted in Figure 2. The exhaust temperature is maintained at 21°C for about 4600 hours and rises above 21°C after this duration (line A). The new supply strategy has been able to delay the rise in exhaust air temperature, consequently leading to better indoor conditions for a longer time.

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Table 2: Exceedance hours, exhaust air temperature exceedance hours, the cooling degree hours and the cooling demand for the studied window to floor ratios when employing a typical year.

Window to floor ratio	**Exceedance hours**		**Exhaust air temperature exceedance hours**		**CDH (°Ch)**		**Cooling Demand (kWh/m²)**	
	Operative temperature above 27°C in average zones	Operative temperature above 27°C in worst zone	Exhaust air temperature above 25°C (Cooling set point)	Exhaust air temperature above 27°C (Cooling set point)	T_b=25	T_b=27	Cooling set point 25°C	Cooling set point 27°C
10%	260	610	800	200	1011	163	1.33	0.43
15%	610	1050	1100	470	1810	583	2.63	1.14
20%	870	1310	1400	700	2348	973	3.81	1.89

Line B represents the exhaust air temperature rising above the first cooling set point (25°C) at 8000th hours and line C represents the exhaust air temperature rising above the second cooling set point (27°C) at late 8000th hours. The exceedance hours in the worst zone are 440 hours and in an average zone are 260 hours. CDH is 1011°Ch and 163°Ch for base temperatures 25°C and 27°C respectively during the considered period (1st July- 31st August). These factors indicate the effectiveness of the new supply strategy. Therefore piecewise controller is implemented for further case studies in this research.

The cooling demands for the cooling set points of 25°C and 27 °C are 1.33 and 0.43 kWh/m^2 respectively.

The model building should meet the NZEB requirements by satisfying the primary energy number, PE_{PET}. PE_{PET} is 43.4 and 44 kWh/ m^2 respectively for constant supply temperature and controlled supply scheme. Both the obtained values are smaller than 75 kWh/ m^2 (Boverket, 2020). Therefore the model building satisfies the NZEB requirements. It should be noted that no cooling energy was considered in obtaining the PE_{PET} values since residential buildings in Sweden are not normally equipped with cooling units. However, PE_{PET} remains relatively the same when adding an ideal cooling unit with a cooling set point of 27°C. PE_{PET} corresponds to 44.6 and 45 kWh/ m^2 for constant supply temperature and controlled supply scheme respectively when a cooling unit with a cooling set point 25° C was employed.

Case 2:

Table 2 reports the exceedance hours (number of hours the operative temperature is above 27°C), the cooling degree hours (room air temperature above base temperatures 25°C and 27°C), exhaust air temperature exceedance hours (number of hours the exhaust air temperature is above cooling set point s) and the cooling demand for the given set point s of 25 °C and 27°C. Results for window to floor ratio of 10% also are presented for better comparison between the cases. Piecewise controller scheme for the supply temperature was employed for all the studied window to floor rations.

The maximum exhaust air temperature for window to floor ratio 10% is 29°C. By increasing this ratio to 15%, the maximum exhaust air temperature rises to 30.8°C. This indicates the increase in operative temperature as well. The operative temperature in the worst zones (zones on the 4th floor, especially facing south) increase by 2°C compared to the window to floor ratio10%. The operative temperature in the best zones increases by 1°C.

The same terms could be applied for window to floor ratio of 20%. The maximum exhaust air temperature, in this case, is 31.9°C and the operative temperature in the worst zones increases by 4°C compared to the case with window to floor ratio of 10%.

a

b

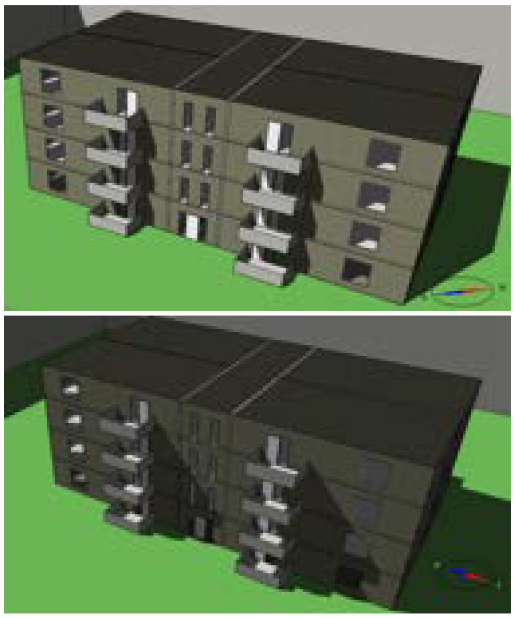

Figure 4: Solar irradiation on the building at 12:00, 15th July. (a) 45° rotation. (b) 90° rotation

As depicted in Table 2, by increasing the window to floor ratio, the cooling demand of the building also increases as can be seen from the CDH values reported. It could be concluded that window to floor ratio of 10% with the piecewise controller for the supply temperature is an appropriate combination among the studied cases.

Case 3:

Rotation of the building has no significant effect on exhaust air and operative temperatures. The exhaust air temperature remains relatively the same (maximum exhaust air temperatures are 28.6°C for the base case, 29.2°C when rotated 45° and 28.9° when rotated 90°). The same applies to the operative temperatures.

Table 3 shows the exceedance hours, CDH and cooling demand of the building for two cooling set points during

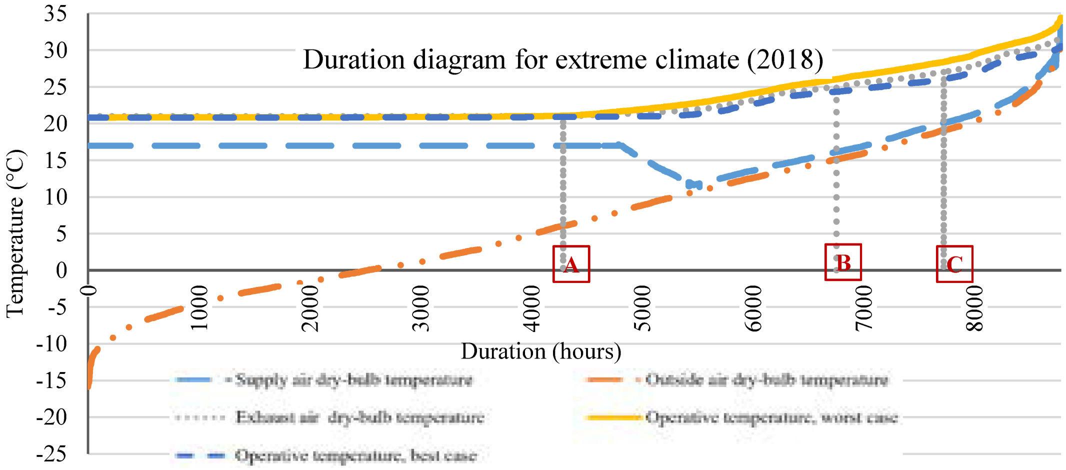

Figure 5: Duration diagram for extreme summer climate condition, for the following temperatures: ambient, supply, exhaust air, operative

a year for 45° and 90° rotation of the building. As can be seen from Table 3, the cooling demand of the building increases when rotated 45° compared to the building due south and 90° rotation. Solar heat gain absorbed by the building increases in case of 45° rotation, therefore the cooling requirement of the building also increases. Figure 4 shows the building on 15th July, at 12:00. Figure 4a and 4b depict 45° and 90° rotation respectively.

Table 3: CDH and exceedance hours and cooling requirements for Case 3, typical year

Rotation	**CDH (°Ch)**		**Exceedance hours**		**Cooling demand (kWh/m²)**	
	T_b=25	T_b=27	Average zones	Worst zone	Cooling set point 25°C	Cooling set point 27°C
45°	1096	200	350	700	1.45	0.50
90°	965	143	260	610	1.31	0.42

Extreme climate condition:

Table 4 depicts the exceedance hours (number of hours the operative temperature is above 27°C), the cooling degree hours (room air temperature above base temperatures 25°C and 27°C), exhaust air temperature exceedance hours (number of hours the exhaust air temperature is above cooling set point s) and the cooling demand for the given set point s of 25 °C and 27°C after employing the 2018 climate file. Piecewise controller scheme for the supply temperature was employed for the simulations. By comparing the obtained results (Table 4) to the presented result in Table 2, an increase in the cooling requirement of the prototype building could be seen. Table 5 shows the relative changes in cooling demand for both set points, comparing window to floor ratios 15% and 20% to window to floor ratio 10%. The exhaust air temperature shows a rise of almost 3°C compared to Case 2 (maximum exhaust air temperatures are 32.3°C, 33.8°C and 34.8° for window to floor ratios 10%, 15% and 20% respectively). This implies the need for change in the current cooling technique (passive cooling) for future buildings, as presently buildings in Sweden are not equipped with any cooling systems. These temperature changes show the importance of the weather dataset that should be used to update building regulations and to evaluate the resilience of buildings. The climate file that was used in the previous sections, was based on 30 years of historic data (years 1981-2010).

Table 5 shows the relative changes in exceedance hours for each of the studied climates. The exceedance hours for each window to floor ratios of 15 and 20% are compared to the window to floor ratio of 10% of their respective climate. As can be seen from the results in Table 6, the relative rise in exceedance hours when employing an extreme climate, does not change as that of the average year climate which is due to the low value for window to floor ratio 10% for average climate condition.

Table 6 presents the exceedance hours, CDH and cooling demand of the building for the given base temperatures and the cooling set point s after rotating the building 45° and 90° for building with window to floor ratio of 10%. Window to floor ratio of 10% was chosen since the cooling demand was the least among the other ratios, as could be seen from Table 4. Results depicted in Table 6 indicate small relative changes for the extreme climate condition.

Figure 5 shows the duration diagram when the extreme climate of 2018 was chosen as a representative for the future climate. Based on the results from the previous cases, building from the base case, with piecewise controller scheme for the supply temperature was chosen as the final and best combination for this case. From Figure 5 it could be concluded that more hours of cooling are required, as lines B and C have shifted to the left, meaning the extreme climate has affected the cooling requirements of the building. The cooling demand of the building with a cooling setpoint of 25°C and 27°C is 5.01 and 2.76 kWh/m2 respectively. Since the cooling demand has increased compared to the normal year with a factor of 3.8 and 6.4 respectively for the latter mentioned set points. Maximum exhaust air temperature would in this case be 32°C. Apart from the increase in exhaust air temperature, the operative temperature for both worst and best zones have increased by 2°C in this case cxompared

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Table 4: Exceedance hours, exhaust air temperature exceedance hours, the cooling degree hours and the cooling demand for the studied window to floor ratios when employing an extreme climate.

Window to floor ratio	Exceedance hours		Exhaust air temperature exceedance hours		CDH (°Ch)		Cooling Demand (kWh/m²)	
	Operative temperature above 27°C in average zones	Operative temperature above 27°C in worst zone	Exhaust air temperature above 25°C (Cooling setpoint)	Exhaust air temperature above 27°C (Cooling setpoint)	T_b=25	T_b=27	Cooling setpoint 25°C	Cooling set point 27°C
10%	1220	1840	2000	1050	2008	925	5.01	2.76
15%	1840	2270	2500	1600	2525	1301	7.50	4.66
20%	2100	2450	2600	1960	2904	1591	9.51	6.25

Table 5: Rise in exceedance hours in average and the worst zone for each climate condition when compared to window to floor ratio 10%

		Multiplyig factors when compared to window to floor ratio 10%			
Climate	**Window to floor ratio**	**Cooling demand, set point 25°C**	**Cooling demand, set point 27°C**	**Exceedance hours in average zone**	**Exceedance hours in worst zone**
Average year climate	15%	2.0	2.6	2.35	1.72
	20%	2.9	4.4	3.35	2.15
Extreme year climate	15%	1.5	1.7	1.51	1.23
	20%	1.9	2.2	1.72	1.33

Table 6: CDH and exceedance hours and cooling requirements for building rotation when employing the extreme climate

Rotation	**CDH (°Ch)**		**Exceedance hours**		**Cooling demand (kWh/m²)**	
	T_b=25	T_b=27	Average zones	Worst zone	Cooling set point 25°C	Cooling set point 27°C
45°	2089	978	1314	1927	5.28	2.96
90°	1981	904	1226	1839	4.98	2.73

to the base case with the same supply temperature scheme. The exceedance hours for the worst zone corresponds to 1660 hours and in average zones 1220 hours which shows an increase compared to the reported result for the base case with the same control scheme. The CDH was reported 2534°Ch and 1346°Ch for base temperatures of 25°C and 27°C respectively. PE_{PET} values for cooling set points of 25°C and 27°C were 46.1 and 44.5 kWh/ m² respectively. The PE_{PET} value was condidered throughout a complete year. Heating, cooling and facility electricity were considered to calculate this value. The extreme climate condition has adversely affected the cooling demand of the building.

Discussion

Today, the energy criterias for fulfilment of the Swedish building regulations are based on a typical year, where the criteria is based on energy use of the building. Moreover, it is a primary energy number which is based on weighted values depending on the sources of energy that the building uses.

Traditionally, building regulations and standards have focused on heating requirement and set minimum indoor temperature limits during the winter season. In view of future climate changes, both winters and summer will be warmer. In recent building regulations, energy for cooling has been imposed as part of the total energy requirement (Pet).

This paper focuses on cooling demand of a prototype building, given that Sweden has a limited tradition of passive cooling strategies for residences. In this situation, problems may arise for a residential building that fulfils today's NZEB in the future. The typical climate prescribed to be used in simulations, to check that fulfils enegy requirements, indicates minor cooling requirement and fairly low exceedance hours. The values presented in this paper would imply "let's build as usual – no active cooling systems in residences." However, the extreme climate indicates that increase in cooling requirement is substantial in comparison to the typical climate. Without a cooling system, the exceedance hours cannot be neglected. The typical climate cannot be used for design purposes (as concluded by Petersen (2020), and questioned if new building's energy performance should at all be based on past years recordings).

Conclusion

The effect of window to floor ratio, building rotation and different supply schemes on the cooling requirement of a prototype NZEB was investigated. The cooling requirement of the building was evaluated by calculating CDH value. By employing a piecewise controller, to control the supply temperature, CDH decreased 27% and 40% for base temperatures of 25°C and 27°C respectively, compared to constant air temperature supply. The cooling demand of the building also decreased 26% and 30% for 25°C and 27°C cooling setpoints respectively. Window to floor ratio of 10% showed the least cooling demand. A

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45° rotation of the building increased cooling demand by 8% and 3% for cooling setpoints 25°C and 27°C respectively, compared to building with no rotation. A 90° rotation did not have a significant effect on the cooling demand.

By employing extreme climate condition weather data (the year 2018), cooling demand and CDH increased for all the studied cases. By employing window to floor ratio of 10% with the schematic supply temperature for the prototype building, the CDH values increased 2.5 and 8 times the typical climate condition for base temperatures of 25°C and 27°C respectively. The cooling demand of the building also increased 3.8 and 6.4 times the typical climate for cooling set point 25°C and 27°C respectively. These changes indicate the need for increasing the resilience of the buildings and requirements to update the historic weather datasets used to design building regulations.

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How Will Mechanical Night Ventilation Affect the Electricity Use and the Electrical Peak Power Demand in 30 Years? -A Case Study of a Historic Office Building in Sweden

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How Will Mechanical Night Ventilation Affect the Electricity Use and the Electrical Peak Power Demand in 30 Years? – A Case Study of a Historic Office Building in Sweden

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SUMMARY

This study aims at assessing how well a mechanical night ventilation of today, will cope with delivering acceptable thermal comfort while minimizing the electricity use and the electrical peak power demand for cooling in a historic office building in Sweden at both typical current climate and typical future climate in 2050s. The method includes numerical study in IDA-ICE simulation program using the typical current and future climate profiles. The results show that, for coefficient of performance of 3 and specific fan power of 1.5 kW/(m^3/s), it would be possible to lower the electrical peak power demand and the electricity use in cooling machine by up to 2.2 kW (13%) and 1.4 MWh (48%) by night ventilation rate of 2.1 lit/(s·m^2) at typical future climate in 2050s. Corresponding figures for typical current climate are 4.6 kW (36%) and 0.9 MWh (72%) owing to cooler nights and more diurnal temperature differences.

INTRODUCTION

In order to achieve the goal of climate neutral European Union (EU) by 2050, it is required to adopt energy efficient and economically feasible measures to reduce the greenhouse gas (GHG) emissions by 80-95%, compared to the 1990 levels [1]. The EU building sector is responsible for around 40% of energy use and about 36% of CO_2 emissions [2]. Therefore, it is vital to focus on improving energy efficiency in the building sector to contribute to achieving these goals.

Cooling demand is a part of the total energy use in most buildings, especially in commercial and office buildings. Night ventilation (NV) is one of the promising strategies for both reducing energy use for cooling and improving thermal comfort in buildings [3], "The basic concept of NV strategy is to cool down the building structure overnight to provide a heat sink which is available during the periods with higher cooling demand" [4].

Several studies evaluated the potential of NV at current climates considering the effect of different building design and operational parameters such as NV rate [5]–[7] and NV period and duration [8]. The studies, for climates with relatively hight temperatures at nights, showed good potential for NV in lowering the indoor overheating by up to 1 ˚C with NV rates lower than 10 ACH for Spanish climates [5] and up to 39–96% reduction in the overheating hours (under free-floating conditions) and 48–94% energy reduction (with thermostatically controlled air conditioning systems) with the NV rates of 10–30 ACH for the Greek climate [7]. Bakhtiari et al. [9] showed that for different coefficient of performance (COP) values of the cooling machine, there are different maximum beneficial NV rates and that NV could lower the total electricity use for space cooling by up to 40%. NV, however, might be limited due to future climate change or extreme conditions. To this background, it is important to understand the performance of this strategy at anticipated future climate scenarios.

Some studies have investigated the potential of NV strategy for future climates. Jimenez-Bescos [10] showed that NV rates over eight air changes per hour (ACH) could reduce significantly the overheating in the buildings located in London Islington in the short term, while NV rates under 10 ACH have very low influence in this regard in the long term (the 2080s). Silva et al. [11] depicted that natural NV would be capable of reducing the total cooling demand of residential buildings in Switzerland by 38% in 2050s. According to the evaluation carried out by Heracleous and Michael [12], while natural NV is a promising measure to reduce the risk of overheating in educational buildings located in Cyprus for the current typical climatic conditions, it is only capable of reducing the overheating hours to a lower extent in future climates in 2050s and 2080s. The investigation by Weng [13] highlighted the superiority of natural NV than natural daytime ventilation in alleviating overheating in a semi-detached UK residential building in 2030s, 2050s and 2080s due to higher outdoor temperatures during daytime in future climatic conditions.

To the authors' knowledge, NV potential for historic buildings, especially the mechanical NV, in future climates has not been sufficiently covered in the literature. This study, accordingly, evaluates the potential of mechanical NV strategy in a case study of a historic office building located in Sweden (Nordic climate) and investigates the effect of this strategy on the electricity use and the electrical peak power demand for space cooling in the future climate of 2050s.

METHODS

Case study

The case study is the City Hall of Gävle, located in central Sweden with Nordic climate. This is a typical historic building, refurbished to an office, with a total floor area of around 2100 m^2. The building consists mainly of 66 spaces: small office rooms, corridors, open-plan offices/seminar rooms, stairwells/entrance halls, lunchrooms/kitchens, with heavyweight construction and large windows. Except for the open-plan offices/seminar rooms with the height of around 5 m, each floor level is around 4 m high [9]. The air-handling unit (AHU) is equipped with a cooling machine (an electric heat pump), which provides space cooling by maintaining the supply air within the cooling set points. A detailed description of the building is presented in the previous published paper by Bakhtiari et al. [14].

Overview of the methods

The dynamic simulation software, IDA Indoor Climate and Energy (IDA-ICE) version 4.8, was applied as the building energy simulation (BES) tool to carry out the numerical analyses. In the previous published paper by Bakhtiari et al. [9], in order to get the materials and the thermal performance of the building's structures reasonably accurate, a simulation model of a non-occupied office room in the building was calibrated against the results from a set of detailed on-site measurements as well as logged data in building management system (BMS) and, furthermore, a floor plan of the building was simulated for the parametric study. In the current study, the BES model of the whole building was created in IDA-ICE using the same methods and construction materials (confirmed by the calibration process) as in the previous published paper [9]. The building's BES model was applied to investigate the influence of mechanical NV strategy on electricity use and the electrical peak power demand for space cooling for both typical current and future climates. The applied current and future climate files in this study represent typical climates for the periods 1981-2010 and 2041-2060, respectively.

Projection of future climate

A future climate file for 2050s, representing the mid-term future, was assembled from The European Coordinated Regional Downscaling Experiment (EURO-CORDEX). Data, already downscaled using the REMO 2015 downscaling method, were downloaded from the Earth System Grid Federation (ESGF) and were extracted for the city Gävle (60.67°N, 17.14°E) [15]. The climate file includes dry bulb temperature, relative humidity, atmospheric pressure, wind speed, total cloud cover and surface downwelling shortwave radiation. These extracted data were calibrated against historic observational data (1986-2005) based on multivariate bias-correction algorithm (MBCn), which is an image processing technique used for transferring all aspects of an observed continuous multivariate distribution (e.g. color information) to the corresponding multivariate distribution of variables from a climate model [16]. Finally, a single Typical Meteorological Year (TMY) file containing 8760 hours was assembled.

Parametric study on NV potential

In order to investigate the effect of mechanical NV on both the electricity use and the electrical peak power demand for space cooling at both typical current and future climates, the BES model of the building was run with local ideal coolers in office rooms for the period 1 June – 31 August. The maximum ventilation rate was measured as 1.66 air change per hour (ACH) in one of the office rooms in the building. AHU was modelled as constant air volume (CAV) type. Two NV rates (NVR) were investigated for the parametric study including 1.66 ACH, i.e. 2.1 lit/(s·m^2), and 0.5 × 1.66 ACH, i.e. 1.1 lit/(s·m^2), for the whole building. Daytime ventilation rate for all cases was set at the minimum requirement, i.e. 0.35 lit/(s·m^2) + 7 lit/(s and person) [17]. *Table 1* shows the defined internal gains in the BES model for the parametric study.

The COP value of cooling machine and the specific fan power (SFP) for AHU's supply and return fans were defined as COP= 3 and SFP= 1.5 kW/(m^3/s). This SFP value was set at the maximum ventilation rate (1.66 ACH) and other SFP values, for ventilation rates below the maximum flow rate, were calculated based on part-load performance data for VAV fan systems according to ASHRAE standard 90.1 [18]. Hours 20:00-06:00 were defined as NV schedule. NV is in operation during this period if three conditions are simultaneously fulfilled: (1) AHU's return temperature is over 18˚C, (2) the ambient temperature is over 10˚C, and (3) the ambient temperature is at least 2˚C lower than the return air temperature. The maximum acceptable operative temperature (T_{op}) during summer for a seated person in the middle of each office room with 1.2 met activity level and 0.5 Clo clothing insulation was defined as 26˚C. In order to keep this maximum limit for operative temperatures in office rooms, the air temperature setpoint in office rooms in the BES model was specified as 24.5˚C. Finally, the electricity use and the electrical peak power demand for space cooling were evaluated at the two typical climatic conditions at the mentioned NV rates.

Table 1. The internal gains from different sources in different zones in the BES model [19]

Zones	Occupants (W/Zone)	Equipment[1] (W/Zone)	Lighting[1] (W/m^2)	Schedule
Small offices	126[2]	135	12	08:00-12:00 + 13:00-17:00
Open-plan offices	126	135	12	08:00-12:00 + 13:00-17:00
Lunch/Pause rooms	754[3]	5[4] [20]	12	12:00-13:00
Corridors	0	280[5] [21]	6	08:00-17:00
Entrance Halls	0	0	6	08:00-17:00

[1] for the case with typical future climate (2050s), 70% of the values were defined [22]; [2] corresponding to internal gains from one person with 1.2 met activity level; [3] for six persons; [4] in W/m^2; [5] corresponding to 1100 W for copy machine plus 550W for printer, average diversity= 46%

RESULTS

Electricity use for space cooling

Figure 1 shows the electricity use in cooling machine and in AHU's fans. Electricity use in cooling machine at typical future climate (2.9 MWh) is more than 2 times higher than the one at typical current climate (1.3 MWh). NVR= 0.5 × 1.66 ACH and 1.66 ACH could help reducing the electricity use in cooling machine by 0.6 MWh (49%) and 0.9 MWh (72%) at typical current climate and by 0.9 MWh (31%) and 1.4 MWh (48%) at typical future climate, respectively. The total electricity use for space cooling (i.e. electricity use in cooling machine and in fans) is, however, increased by 0.2 MWh (13%) and 4.1 MWh (305%) at typical current climate and by 0.1 MWh (4%) and 5.1 MWh (173%) at typical future climate, respectively.

Electrical power demand for space cooling

Figure 2 illustrates the duration diagram for electrical power demand in cooling machine during working hours. The peak and average electrical power demands are 4.9 kW and 2.5 kW higher and the cooling machine operation is 72 hours longer at typical future compared to current climate. NVR= 0.5 × 1.66 ACH and 1.66 ACH could reduce the electrical peak power demand by 2.5 kW (20%) and 4.6 kW (36%) at typical current climate and by 1.2 kW (7%) and 2.2 kW (13%) at typical future climate, respectively. NVR= 0.5 × 1.66 ACH and 1.66 ACH could reduce the cooling machine operation period by 95 hours (21%) and 170 hours (37%) at typical current climate and by 63 hours (12%) and 102 hours (19%) at typical future climate, respectively.

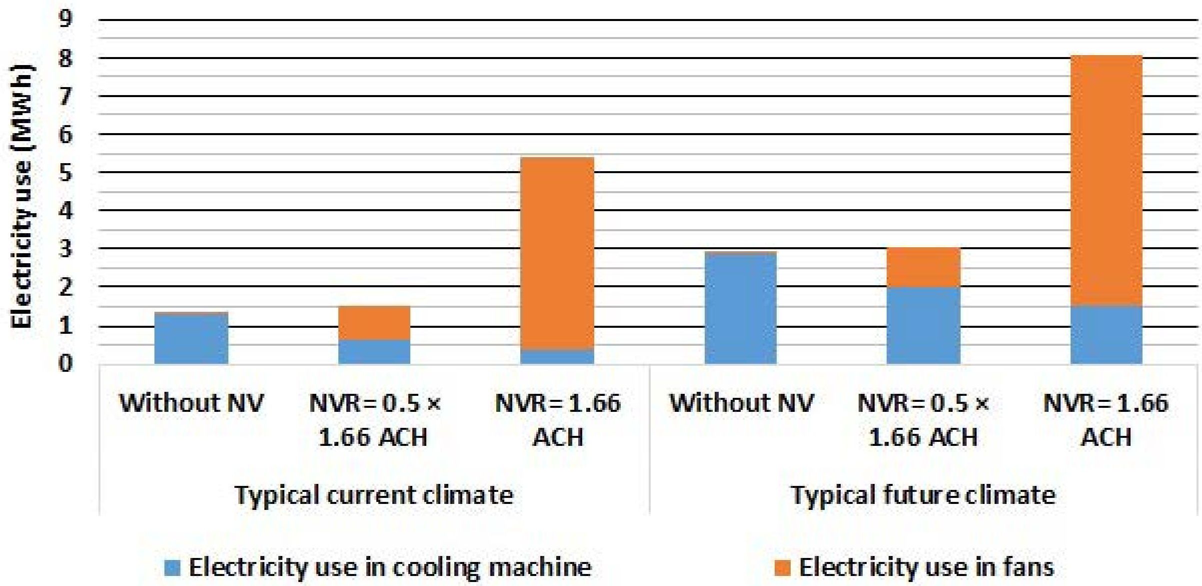

Figure 1. The electricity use in cooling machine and in AHU's fans, 1 June – 31 August

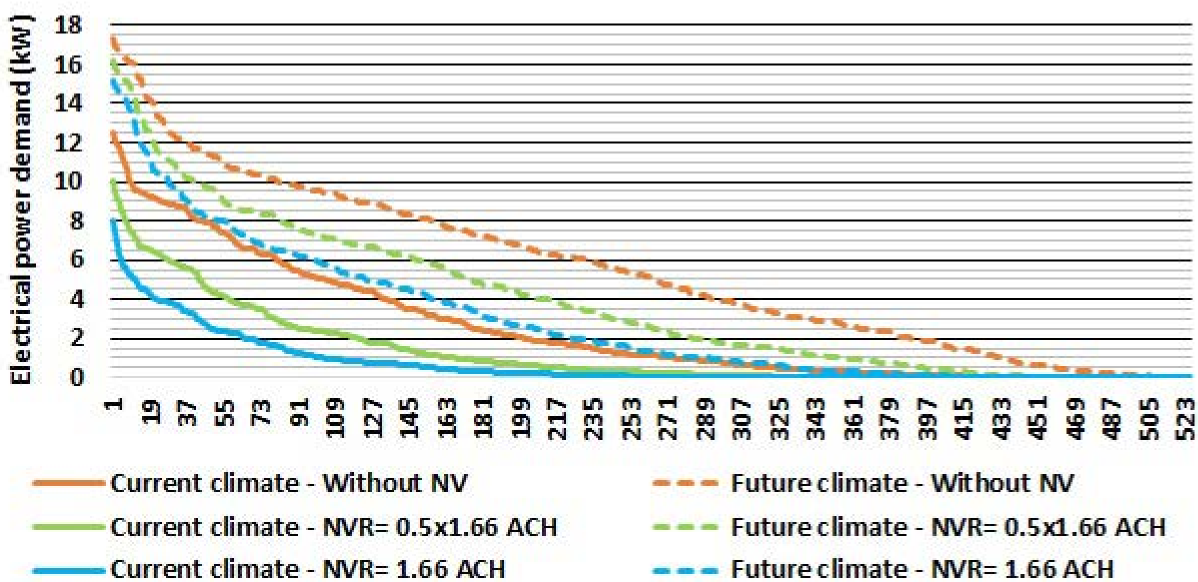

Figure 2. Duration diagram for electrical power demand in cooling machine during working hours, 1 June – 31 August

Figure 3 shows the electrical peak power demand at both climates. Ambient temperature during NV schedule is in the ranges of 14-25˚C (the average is 17˚C) and 18.5-28˚C (the average is 23˚C) at typical current and future climates. The average difference between daytime and nighttime ambient temperatures is 10˚C and 5.5˚C at typical current and future climates, respectively. With NVR= 0.5 × 1.66 ACH, it is possible to lower the average and peak electrical power demands for space cooling during the working hours by 2.7 kW and 2.5 kW at typical current climate and by 1.7 kW and 1.2 kW at typical future climate, respectively, at the cost of 1.7 kW extra electrical power use in AHU's fans during NV operation period. Whereas, with NVR= 1.66 ACH, 11.1 kW extra electrical power use in fans during NV operation period contributes to decreasing the average and peak electrical power demands for space cooling during the working hours only by 5.1 kW and 4.6 kW at typical current climate and by 3 kW and 2.2 kW at typical future climate, respectively.

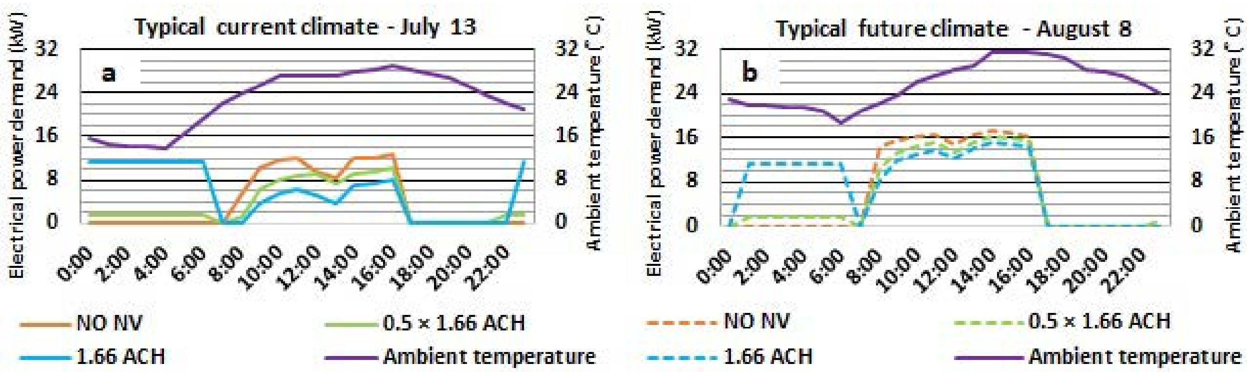

Figure 3. Electrical peak power demand (a) July 13, current climate (b) August 8, future climate

DISCUSSION

With fans with SFP= 1.5 kW/(m^3/s), the amount of reduction in electricity use in cooling machine does not outweigh the extra electricity use in fans during NV period. Therefore, the total electricity use for space cooling increases when NV is applied. NV strategy is more effective at typical future climate considering the absolute values of reduction in the electricity use in cooling machine. However, if the reductions are presented as the proportion (percentage) of the electricity use in cooling machine, the influence of NV strategy is higher at typical current climate.

The absolute value of reduction in electricity use in cooling machine at typical future climate is higher due to the longer NV operation periods. During the schedule defined for NV (20:00-06:00), the ambient temperature is lower than 10˚C (the minimum ambient temperature limit in NV control strategy to avoid condensation on internal surfaces in the building) for 15% of the time at typical current climate, compared to only 3% at typical future climate. On the other hand, portion of time during which the ambient temperature is at least 2˚C cooler than AHU's return temperature is not significantly lower at typical future climate (93%) compared to typical current climate (99%). Thus, NV is in operation only for 74% of the time during the defined NV schedule at typical current climate, while it is in operation for 90% of the time at typical future climate. The negative influence of shorter NV period seems to outweigh the positive impact of higher NV potential at typical current climate compared to typical future climate. This higher potential is due to lower nighttime ambient temperatures (the average is 12.3˚C vs. 17.1˚C) and higher difference between nighttime and daytime ambient temperatures (the average is 5˚C vs. 3.5˚C).

The electrical peak power demand in cooling machine at typical current climate is more decreased by both NV rates compared to the typical future climate. This is because of lower ambient temperature during the NV schedule, larger difference between daytime and nighttime ambient temperatures and a slightly longer NV period at typical current climate compared to the typical future climate during the dates that peak power demands occur (according to *Figure 3*). The operation period of the cooling machine is more decreased by both NV rates at typical current climate compared to the typical future climate. The reason is that the electrical power demand in the cooling machine, in average, is notably lower at the typical current climate compared to the typical future climate (according to *Figure 2*). This means that there are longer periods with relatively low electrical power demands in cooling machine and, which is why, the heat sink provided by NV is capable of eliminating the need for the operation of cooling machine during longer periods at typical current climate compared to the typical future climate.

CONCLUSIONS

The electricity use and the electrical peak power demand in cooling machine at typical future climate are nearly two times higher than the ones at typical current climate for the case study of the historic office building located in central Sweden with Nordic climate. The potential of night ventilation (NV) in reducing the electrical peak power demand in cooling machine is lower at typical future compared to current climate. NV rates of 1.1 lit/(s·m^2) (0.5 × 1.66 ACH) and 2.1 lit/(s·m^2) (1.66 ACH) can lower the electrical peak power demand in cooling machine by 2.5 kW (20%) and 4.6 kW (36%) at typical current climate, but only by 1.2 kW (7%) and 2.2 kW (13%) at typical future climate in 2050s. The same NV rates could reduce the electricity use in cooling machine (with COP=3) by 49% and 72% at typical current climate and by 31% and 48% at typical future climate in 2050s, respectively. This is, however, achievable at the cost of extra electricity use in AHU's fans (with SFP= 1.5 kW/(m^3/s)) during NV periods leading to higher total electricity use for space cooling (electricity use in cooling machine and in fans) when NV is applied. The total electricity use for space cooling may be reduced by applying NV strategy for situations with more efficient AHU's fans (lower SFP values). The best option for the case study of the historic office building in Sweden is the case with the NV rate of 0.5 × 1.66 ACH as it nearly uses the same total electricity as the case without NV (only 13% and 4% higher at typical current and future climates), with the benefit of shaving the electrical peak power demand in cooling machine. The economic calculations will be done in the future research to show the financial benefits of NV application.

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Overheating calculation methods, criteria, and indicators in European regulation for residential buildings

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A R T I C L E I N F O

Keywords:
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A B S T R A C T

With the ongoing significance of overheating calculations in the residential building sector, building codes such as the European Energy Performance of Building Directive (EPBD) are essential for harmonizing the indicators and performance thresholds. This paper investigates Europe's overheating calculation methods, indicators, and thresholds and evaluates their ability to address climate change and heat events. e study aims to identify the suitability of existing overheating calculation methods and propose recommendations for the EPBD. The study results provide a cross-sectional overview of twenty-six European countries. The most influential overheating calculation criteria are listed the best approaches are ranked. The paper provides a thorough comparative assessment and recommendations to align current calculations with climate-sensitive metrics. The results suggest a framework and key performance indicators that are comfort-based, multi-zonal, and time-integrated to calculate overheating and modify the EU's next building energy efficiency regulations. The results can help

Abbreviations: ANSI, American National Standards Institute; ASHRAE, American Society of Heating, Refrigerating, and Air-Conditioning Engineers; CEN, European Committee for Standardization; CIBSE, Chartered Institution of Building Services Engineers; CCD, Cooling Degree-days; EEA, European Environment Agency; EPBD, Energy Performance in Buildings Directive; EPC, Energy Performance Certificate; EU, European Union; HDD, Heating Degree-days; IEA, International Energy Agency; IPCC, Intergovernmental Panel on Climate Change; ISO, International Standardization Organization; nZEB, nearly Zero-Energy Building; PMV, Predicted Mean Vote; PPD, Predicted Percentage of Dissatisfied; UK, United Kingdom; WWR, Window to wall ratio.

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policymakers and building professionals to develop the next overheating calculation framework and approach for the future development of climate-proof and resilient residential buildings.

Nomenclature

A_G	Net floor area [m^2]
A_{util}	The useful area of the living spaces following the definition of section 4.6 of HE0 (Spain regulation)
$A_{w,p,k}$	Area of the opening k [m^2]
$A_{W,j}$	Window area of zone j [m^2]
$F_{sh,obst,k}$	Reduction factor for shading by external obstacles (includes all the elements outside the window gap such as overhangs, lateral protections, setbacks, obstacles, etc.), for the month of July, of the gap k
FF_k	Frame fraction of the gap k (in a simplified way, the value of 0.25 can be adopted)
$g_{tot,j}$	Total energy transmittance of the glazing, including sun protection zone j
$g_{tot,sh,wi,k}$	Total solar energy transmittance of the glazing with the mobile shading device activated (closed) for the month of July and for gap k
$H_{C,D,juli,or,zi}$	Direct heat transfer coefficient by transmission between the heated space and the outdoor air except for the ground floor for orientation or in zone zi [W/K]
$H_{C,ve,juli,or,zi}$	Direct heat transfer coefficient through ventilation for orientation or in zone zi [W/K]
$H_{gr,an,juli,or,zi}$	Direct heat transfer coefficient by the transmission for building elements in thermal contact with the ground for orientation or in zone zi [W/K]
h_{juli}	Total time over the month of July
$H_{sol,juli}$	Average accumulated solar irradiation for the month of July (kWh/m^2 month) in the studied location considering the inclination and orientation of the opening k
$H_{T,\ overh}$	Conduction heat transfer coefficient [W/K]
$H_{V,\ overh}$	Monthly ventilation heat transfer coefficient [W/K]
i	Recursive index in a summation
in	Indoor
m	Recursive index in a summation for the month of the year
out	Outdoor
$Q_{C,HP,juli,or,zi}$	Extract energy from the cooling unit by the booster heat pump for orientation or in zone zi [kWh]
$Q_{C,nd,juli,or,zi}$	Cooling demand for orientation or in zone zi [kWh]
$Q_{g,\ overh,m}$	Monthly solar and internal heat gains [MJ]
$Q_{sol,juli}$	Solar gains for the month of July of the windows and openings of the thermal envelope with its mobile solar protections activated (closed) [kWh]
T_{op}	Temperature operative [°C]
$T_{Setpoint,i}$	Set point temperature
up	Upper limit of comfort/heat-balance range
wf_i	Weighting factor (dimensionless)
$\eta_{util,\ overh,m}$	Utilization factor depending on the ratio between the monthly heat loss and heat gain

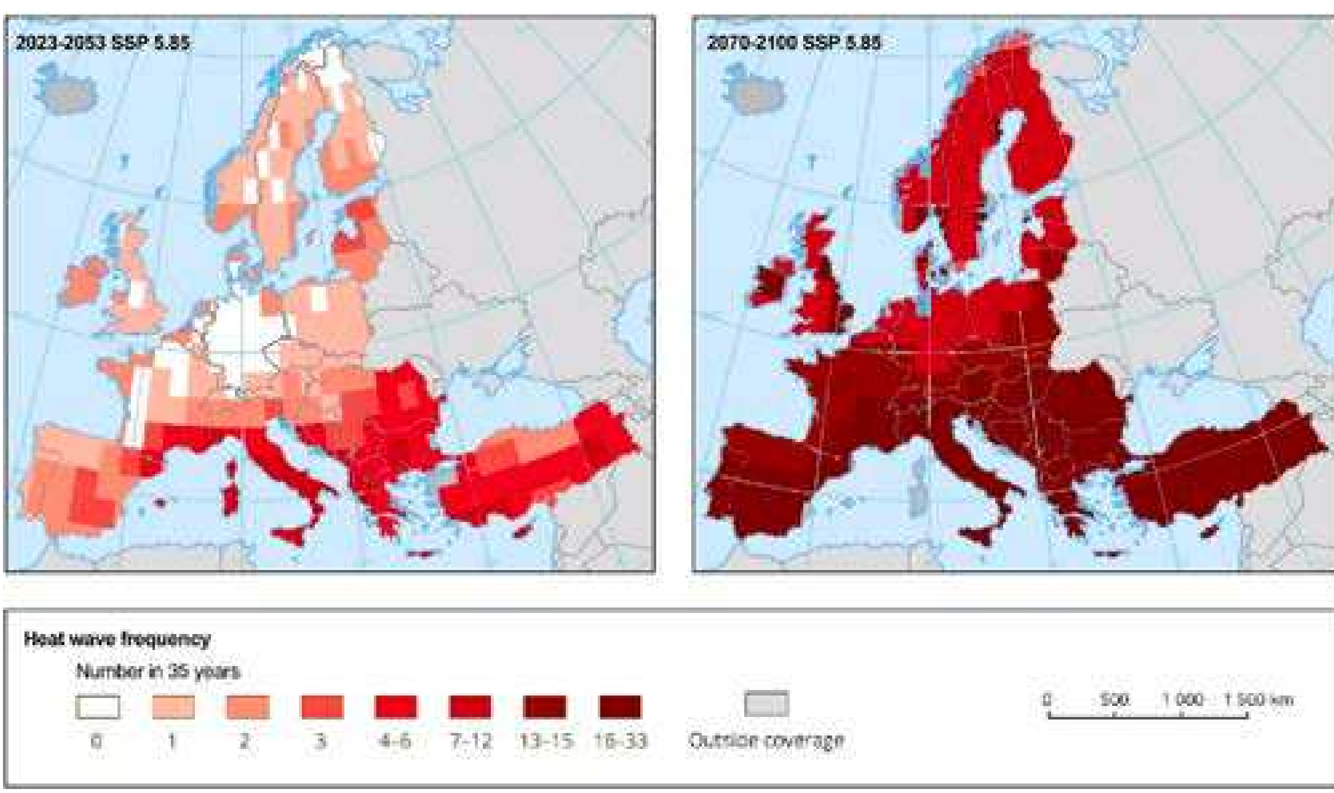

Fig. 1. Number of extreme heat waves in future climates under the SSP 5.85 forcing scenarios based on the EEA data [4].

1. Introduction

Climate change is expected to drive an increasing frequency of heat waves, which can cause significant morbidity and mortality [1]. High ambient temperatures in cities are associated with many health risks, including the increase in premature mortality of the senior population [2]. According to the European Environment Agency (EEA), mortality risk increases by 0.2 and 5.5 % for every 1 °C increase [3]. For example, the excess mortality in the EU climbed to +16% in July 2022 from +7% in June and May. According to the EEA and Eurostat statistics on excess mortality, Europe might reach an annual +60.000 to 165.000 premature death by the end of the 2080s, with the highest impact in Southern Europe [3,4].

With the increase and repetition of heatwaves, dwellings are at risk of overheating and potentially increase of cooling demand. Fig. 1 indicates the number of extreme heat waves in future climates under the SSP 5.85 forcing scenarios of the IPCC AR6. SSP 5.85 refers to the Shared Socio-economic Pathway describing the socioeconomic trends underlying the Fossil-Fueled Development scenario in the year 2100 [5]. The pattern of heatwaves frequency and intensity [4] and the increase in tropical nights [6] indicates the likely occurrence in the near and long future. Therefore, peak and mean summer temperatures will increase by 10 °C across most European capitals by 2080. The trapping of internal and external heat gains causes overheating, and the latter is expected to worsen with further urbanization and climate change.

Indoor overheating has already been identified in European dwellings [7]. Most studies found in the literature confirm the like hood of overheating risk increase and discomfort in households due to global warming [8,9]. The contemporary construction of highly insulation nearly-zero and net-zero energy buildings (nZEB and NZEB) across Europe results in periodic overheating in today's climate in Southern Europe [10], Eastern Europe [11], and even in Western and Northern Europe [12]. The Energy Performance of Energy Directive (EPBD) was strongly influenced by the Passive House Standard principles [13,14]. During the last ten years, the focus of the EPBD has been mainly on closing the energy efficiency gap [15]. However, the new EPBD recast of 2021 made special attention to thermal comfort [16]. More importantly, the 2023 recast is expected to address climate change and overheating more appropriately. All member states must revise their national energy calculation methods and address discomfort problems under climate change scenarios by the end of 2025.

In this context, the International Energy Agency (IEA), through Annex 80 on Resilient Cooling in Buildings, reviews existing standards and regulations on overheating calculation methods, criteria, and indicators. The preliminary findings indicate disparities between the methods and the lack of common and consistent calculation methods. Standard CEN 13790:2008 (or ISO 52016–1:2017) for energy performance calculation of buildings is the basis of overheating calculation in Europe. The standard is under serious critique because it adopts an old heat balance approach [12] and does not consider the modern thermal comfort estimation approach based on the six thermal comfort parameters [17].

Overheating refers to high indoor temperatures and affects occupants' health and productivity. Therefore, the overarching aim of this paper is to improve the well-being of residential buildings in European countries. Epidemiological studies have shown that heat wave vulnerability occurs at night in nursing and residential homes [18]. According to the Lancet Countdown Report of 2019, exposure to extremes of heat results in a range of health consequences. With Europe's aging populations, the effects of heat waves are increasing. The study focuses on residential buildings where the risk of heat stress and heat stroke is the highest during heat waves. Improving well-being requires preparing and adapting new and existing buildings to be climate-proof against future extreme scenarios [19]. Also, we excluded other types of buildings because residential buildings have a specific occupancy density, occupation schedules, and, more importantly, a different architecture than office buildings or other commercial buildings.

In this context, we identified a need to provide an overview of overheating calculation methods, criteria, and indicators in European regulation for residential buildings. The objective of this paper is an attempt to respond to the following research questions:

- What are the methods and criteria to assess thermal comfort and overheating in European building codes based on the EPBD?
- How to characterize and compare different methods and criteria?
- What is the main difference that distinguishes different methods? What is the unique overheating national method?
- What factors should be considered to advance the overheating assessments in future revisions of building regulations?

By answering the questions above, this paper provides a critical overview of assessment methods used for overheating based on thermal comfort criteria. The paper's novelty is an exhaustive and longitudinal study that continued over three years as part of the IEA Annex 80 activities. 26 EU member and non-member states, including the UK and Switzerland, were investigated. A comprehensive review report was developed. Representative publications and standards screening were performed, and available experts were interviewed and surveyed. To the best of our knowledge, this is the first paper that provides relevant information on overheating calculation methods and key performance indicators to tackle discomfort during summer in the European continent. The originality of the paper is twofold. First, the paper compares overheating calculation methods and indicators regarding nearly and net zero energy buildings in compliance with EPBD, ISO, and CEN. Secondly, the paper identifies key overheating calculation methods and indicators considering climate change and heat waves. The paper identifies the overheating indicators and calculation approach within a thermal resistance and resilience paradigm [20]. Finally, the paper provides a concrete set of recommendations that can be considered in the next EPBD recast towards a consistent and unified calculation approach that caters to the climatic and socio-economic variability of people of the continent.

2. State of-the-art

Overheating is excess heat in living, sleeping, and working spaces [21]. European public health stakeholders raised concerns about heat-related death and called for preventive measures [22]. Many factors affect overheating in dwellings, including dwelling characteristics, environment and urban climate, and dwelling design [7]. Nevertheless, the calculation of overheating remains one of the major challenges. The calculation of overheating can influence the passive and active design measures. In Europe, the prevalence of active cooling (AC) is low, where 15% to 30% of residential buildings have AC. Depending on the overheating calculation methods and thermal comfort thresholds, AC demand will increase drastically, increasing the energy demand and GHG emissions.

There is somewhat less research applicable to the European context on overheating because past research has been conducted on the assumption of broadly stable climate and heating-dominated regions.

Several studies have aimed to document the overheating phenomena in European residential buildings [23]. The first group of studies investigated the global causes and effects of overheating in European dwellings and recommended directions for adaptation and mitigation. The recent work of Alrasheed and Mourshed (2023) critically reviews the factors that influence the overheating risk in dwellings and presents state-of-the-art on possible mitigation strategies [7]. The study developed a framework that illustrates the effect of overheating factors on the cooling efficacy of passive strategies. In 2019, Chen presented an editorial article on the challenges and opportunities of overheating in residential buildings [8]. Next, the work of Lomas et al. (2017) aimed to describe this phenomenon and its causes [21]. Also, the work of

Santamouris and Kolokotsa discussed issues related to the impact of urban overheating on vulnerable populations in Europe [22]. More recently, Santamouris presented the risk factors arising from urban overheating in a holistic and integrated way[24]. The study described the current and future impact of urban overheating on the urban population.

The second group of studies aimed is case study-based that modeled overheating and focused on the calculation approach and indicators choice [25]. In an earlier study, Robert et al. (2013) estimated the future performance of UK dwellings built in compliance with the Passivehaus standard requirements. The study confirmed that the super-insulated Passivehaus dwellings at already at risk of overheating in the UK and Northern Europe [26]. The study is ten years old but provided valuable insights into the overheating phenomena. Four years later, Figueiredo et al. (2016) performed a sensitivity analysis for a Passivhaus in Portugal and found a long period of overheating during summer. The study complied with the Passivhaus thermal comfort criteria and proved the ability to avoid active cooling through improved building envelope design and operation. Also, in 2016, Mulville and Stravoravdis (2016) simulated a typical UK case study in free-running mode and applied the UK national calculation method [27]. They proved that the current overheating calculation methods are out of order and not fit to purpose. Then, the work of Brotas and Nicol looked at the criteria from CIBSE TM52 and discussed their applicability to a single UK dwelling archetype [28].

Another example is the work of Simson et al. (2017) modeled overheating in five Estonian apartments and investigated the impact of thermal zoning on the simulation-based overheating assessment calculation [29]. The study suggested a temperature measurement-based approach for pre-assessing overheating as part of the regulations compliance process. Then, Narozny et al. (2016) applied a post-occupancy evaluation method to understand the influence of occupants on overheating and their ability to interact with cooling and ventilation systems [30]. Similarly, Morgan et al. (2017) monitored 26 new homes and documented the overheating causes, including the high insulation and occupants' behavior [31]. The study reported the significant influence of occupants on mitigating overheating.

Sepulveda et al. (2020) published a recent case study that simulated the overheating risk in a Spanish residential unit. The study applied the Spanish regulations and focused on reducing the overheating risk by manipulating the window-to-wall ratio and night ventilation [32]. In Sweden, Tettey and Gustavsson (2020) explored the climate change implication on a renovated housing unit [33]. The study confirmed that with climate change, the space heating demand would decrease significantly in Sweden, and the space cooling demand would increase remarkably. Attia and Gobin modeled a Passivehaus case study for timber construction under climate change in Belgium. The study indicated the high risk of overheating associated with newly constructed timber construction [34]. Dartevelle et al. investigated the overheating risk in nZEB and applied the European EN 16798 [35] and CIBSE standards [36]. They proved the difficulty of mainlining comfortable thermal conditions in nZEB houses despite the temperature climate of Belgium.

The third group of studies comprises an article that reviewed and compared the calculation methods and indices for overheating in buildings. The work of Carlucci et al. (2018) is a review paper on adaptive thermal comfort models in regulatory documents [37]. The paper focused on comparing the standards from an international perspective, including ISO 17771–2 [38], EN 16798 [35], ASHRAE 55, Dutch ISSO 71, and the Chinese thermal comfort standard. The study focused mainly on adaptive thermal comfort and provided general recommendations for commercial buildings. The authors recommended that a harmonized method for multi-zone models, which can include multiple indices, should be found to improve regulations. More recently, Rahif et al. [39] reviewed time-integrated overheating evaluation methods for residential buildings. The study focused on residential buildings and was limited to Western Europe. The study looked into five national building codes based on the Energy Performance of Building Directive (EPBD) in Belgium, France, Germany, the UK, and the Netherlands.

Among the three groups of studies, the last group on review articles appeared the most interesting. Additional screening and filtering pinpointed three outstanding indicators that quantify overheating duration and intensity in buildings. Some of the three indicators are found in existing standards, and one is only used in scientific research studies. The summary below frames the literature review outcomes and provides a profile of the unique overheating-related found in the literature:

1. Percentage of occupied hours when an operative temperature exceeds a certain threshold of the annual occupied hours based on a PMV/PPD or adaptive comfort model for a specific comfort category (I, II, III or IV) (ISO 17772). The indicator is used by many European standards that address overheating calculation, including CIBSE (Guide A, TM52, and TM59), The Passive House Standard, CEN 16789, and ISO 17772.
2. Standard Effective Temperature (SET) is a commonly used index in thermal comfort evaluation. It was established based on a two-node model reflecting the thermal regulation process of the human body based on the six thermal comfort parameters: air temperature, radiant temperature, air velocity, humidity, clothing, and metabolism. The SET has been reintroduced into the ASHRAE 55 calculations to determine the cooling effect of air movement. Moreover, the United States Green Building Council (USGBC) RELI rating system has used the SET indicator as a thermal resilience indicator.
3. The Indoor overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*), and overheating escalation factor ($aIOD = AWD$) were developed by Hamdy et al. (2011) [40]. The Indoor Overheating Degree (IOD) index is the summation of the temperature difference between the indoor operative temperature and a preferred comfort temperature. The difference is averaged over the total number of zonal occupied hours. The three indicators are used by several studies and recommended by the IEA Annex 80.

Despite the three groups of studies found in the literature to date, no study provides a comprehensive review of overheating calculation methods in the EU regulatory documents. Several studies have focused on the UK and addressed CIBSE Guide A (2006), CIBSE TM52, CIBSE Guide A (2015), CIBSE TM59, and Passive House standards. A comparative approach is lacking for analyzing overheating calculations for residential buildings in the EPBD. Most investigated studies did not address long-term climate change impacts and short-term heat wave effects. In addition, the impact of the urban heat island effect on the overheating risk is almost not addressed in the reviewed studies concerning thermal comfort in residential buildings.

Therefore, the objective of this study is to bridge this knowledge gap, analyze, and compare overheating calculations for residential buildings in the EPBD regulatory in twenty-six countries: Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, Poland, Portugal, Romania, Slovakia, Spain, Sweden, Switzerland, the United Kingdom (UK), and the Netherlands. The study is part of the International Energy Agency (IEA) Annex 80 on Resilient Cooling in Buildings. The study builds upon previous work as part of Annex 80, reviewing the overheating indicators [39] and the overall discomfort parameters, including humidity in residential buildings [41]. Therefore, the study provides a valuable guide to developing the EPBD and a comprehensive list of recommendations and conclusions to address overheating in the regulations of the residential sector in Europe and Worldwide.

3. Methodology

The research methodology is qualitative, similar to previous studies

[10,42], and comprises three main stages. Fig. 2 illustrates the study's conceptual framework. First, the study goal, scope, and boundary conditions were defined to have a practical set of questions to guide the investigation of thermal comfort and overheating calculations in each country. This step included selecting representative experts from EU member and non-member states. Also, an initial questionnaire was created and tested through a pilot study for validation. Secondly, the data collection process was conducted through one-to-one interviews and a literature review. Finally, the analysis of interview results and comparison of the calculation methods took place. At this stage, the analysis of the results through focus group discussions allowed us to select the most outstanding calculation methods, criteria, and indicators and develop a set of refined recommendations to be integrated into the regulation of each country and more globally in Europe through the Energy Performance of Buildings Directive (EPBD). In the following paragraph, we explain in detail the research methodology.

3.1. Boundary conditions

26 European countries were selected, namely Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Poland, Portugal, Romania, Slovakia, Spain, Sweden, Norway, Switzerland, and the United Kingdom. The study scope covered residential buildings in European countries and excluded nursing homes and elderly houses. The temporal study period was the summer overheating. The investigation of overheating calculation for heat waves during the shoulder periods was excluded. Also, the study focused on overheating and did not adopt an overall discomfort concept. Humidity was excluded to focus on the thermal aspect of heat, assuming that humidity will be controlled [43]. Countries with no overheating calculation methods embedded in their EPBD were excluded after screening the six countries. Focusing on thermal comfort in residential buildings, the study avoided preference or bias towards overheating calculation methods based on specific resilient technologies, including passive [34] and active solutions [35]. Economic and other social aspects of thermal comfort perception were excluded.

Next, a questionnaire was created and tested through pilot interviews with pseudo-experts. The questionnaire comprised nine key questions focused on new and existing residential buildings. They evolved around one central question mentioned below:

- What are your country's thermal comfort/overheating limits for residential buildings?

The questionnaire is available in an open-access repository (see Appendix 1). Moreover, 31 interviewees were requested to fill in an exhaustive table with specific information about their national regulations. The table comprised five major elements relevant to the overheating calculation. Fig. 3 illustrates the relation between overheating calculation and weather representation, envelope prescriptive or performance-based requirements, simulation model type (static or dynamic), occupancy type, and thermal comfort model—the five elements were translated into questions embedded in the table.

3.2. Target countries' regulation

The study targeted the energy performance of buildings regulation between 2021 and 2023. The focus of the study was residential buildings. The Energy Performance of Building Directive requires all EU

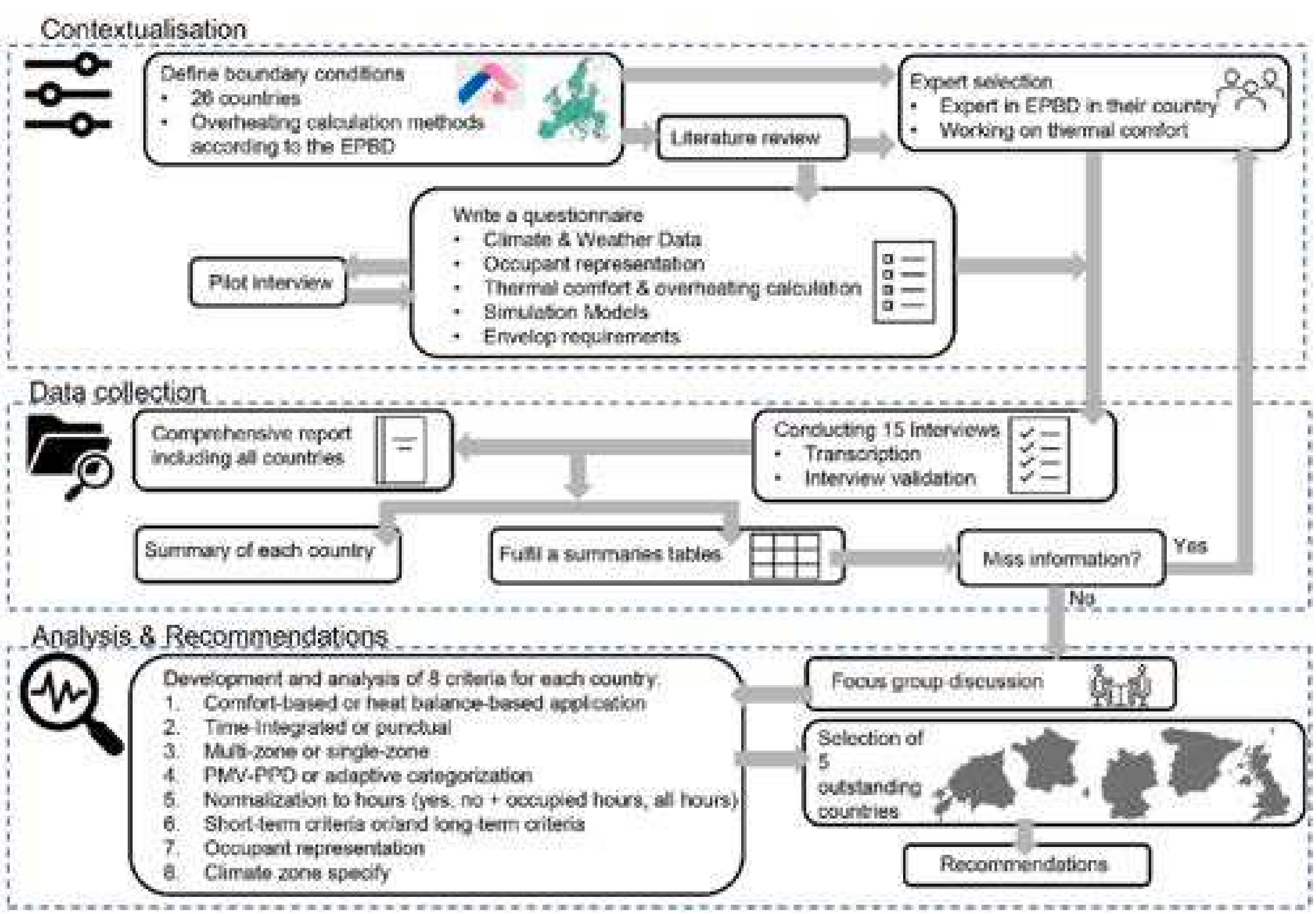

Fig. 2. Study Conceptual Framework.

Fig. 3. Key elements influencing overheating calculation in European residential building standards.

member states to develop energy performance certifications and calculations for residential buildings. Therefore, the exclusion criteria were used to narrow the scope of the study except for the UK, Norway, and Switzerland. Twenty-six national experts on thermal comfort (Austria, Belgium, Bulgaria, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Ireland, Latvia, Lituania, Romania, Poland, Portugal, Spain, Sweden, Norway, Slovakia, Spain, Sweden, Switzerland, and the UK) were extensively consulted to validate the data produced during the interview stage. As part of the IEA Annex 80 activities, we contacted experts from the annex and experts who are not associated with the annex to cover the 26 countries. More than 250 articles, standards, reports, and websites were consulted and reviewed based on the input provided by the first authors of two literature review papers [39,41]. We focused mainly on national and international standards and included reports and studies published by the building energy efficiency industry and scientific community.

3.3. Climate zone

The different EU countries' climate disparity and geographical context are part of the study. The study adopted a sensitive approach to cluster and group countries climatically. Overheating calculation and thermal comfort thresholds depend strongly on the local climate and topographical relief. Therefore, the study was inspired by the European Environmental Agency map that divides the continent into four nuanced climatic zones [44]. As shown in Fig. 4, the subtropical climates cover most of the southern part of Europe, including Bulgaria, Cyprus, Croatia,

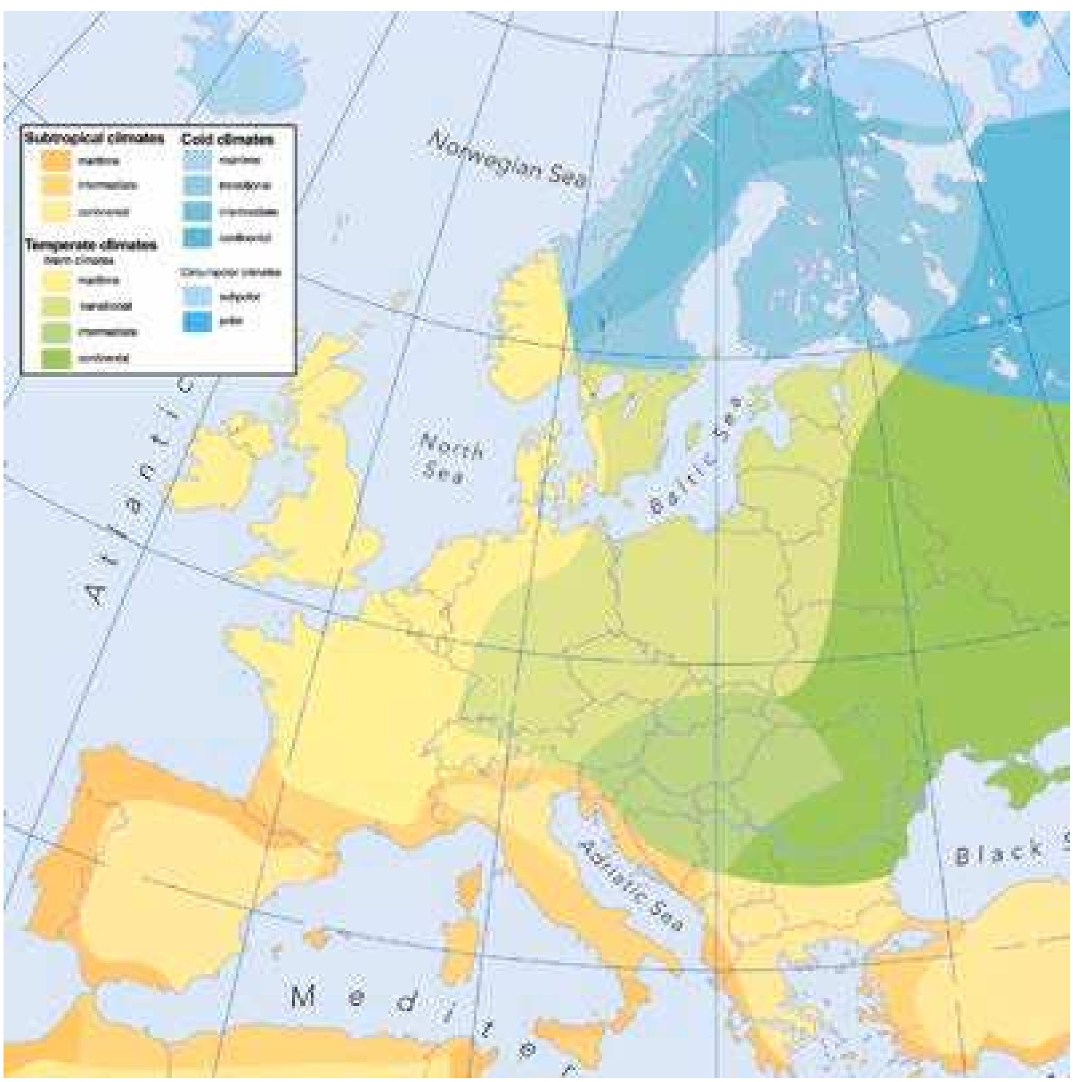

Fig. 4. The four major European climate zones according to the European Environment Agency (EEA) [44].

Italy, Spain, Greece, Portugal, and France. The main characteristics of this climate are dry winter and hot summer. The temperate climate with warm climates covers the East, West, and North of Europe, including Belgium, Czechia, Hungary, Latvia, Lithuania, Norway, Romania, Slovakia, Sweden, Austria, Denmark, Switzerland, Estonia, France, Germany, Netherlands, and Poland. The main characteristics of this climate are without a dry season and warm summer. The temperate climate, with a group of cold climates, covers the extreme north of Europe, including Norway and Sweden. The main characteristics of this climate are cold winter and temperate summer. The circumpolar climates do not concern this study because it is in the extreme North of Europe. Under this classification, the study aimed to generate climate-sensitive recommendations and evaluation the existing calculation methods from a wide pan-European climate perspective, beyond the limit of national approaches.

4. Result

A detailed report (see Appendix 2) was published, including all interview answers and filled-in tables [43]. However, for this paper, we selected the essential outcomes and classified them under five sections, described below:

4.1. Summary of the main regulations on thermal comfort in residential buildings (inventory)

Existing calculation methods and criteria to assess thermal comfort and overheating in 26 European building codes were analyzed based on the national EPBD regulations. Based on Fig. 3, a comparative table with five classification criteria for all investigated countries was created. The table is large and cannot be visible in this article but can be found in Appendix 3. To visualize the comparative table, a representative figure was created. Fig. 5 is an infographic illustration of the comparative table in Table 1 and Appendix 3. The Figure indicates a huge disparity and diversity between the calculation methods found. Almost every country has its calculation method. The calculation methods disparity does not reflect modern and climate change fit methods.

Next, a summary of overheating calculations and indicators in the investigated countries was created. The result of the standards reviews shown in Table 1 lists the equations and parameters of the overheating calculation. Table 1 and Fig. 5 are considered the basic form of the screening results. Table 1 results from the literature review presented in Section 2 and provided a more detailed comparison of overheating calculation methods. Table 1 is one of the early results used as an inventory for the further analysis step presented in the following section.

Fig. 5. Infographic of the information gathering during interviews.

Table 1
Summary of overheating evaluation methods for each country including the nomenclature.

Country	Overheating indicator	Equation
Austria	Daily maximum of the hourly operative temperature of the room (DM)	$DM = max_{day}(T_{op,i,})$ Where $i = 1am\, to\, 12pm$
Belgium (Brussels)	Percentage of hours outside the range (%PhOR)	$\%\text{PhOR} = \frac{\sum_{i=1}^{occupiedhours} wf_i.h_i}{\sum_{i=1}^{occupiedhours} h_i} \times 100$ Where $\begin{cases} wf_i = 1;\ T_{a,i} > 25^{\circ}C \\ wf_i = 0;\ T_{a,i} \leq 25^{\circ}C \end{cases}$
Belgium (Flanders and Wallonia)	Time-integrated overheating index (I_{overh})	$I_{overh} = \sum_{m=1}^{12} Q_{excessnorm,m}\ [Kh]$ With $Q_{excessnorm,m} = \frac{(1-\eta_{util,\,overh,m}).Q_{g,\,overh,m}}{H_{T,\,overh} + H_{V,\,overh}}.\frac{1000}{3,6}$
Bulgaria	Operative temperature	T_{op}
Croatia	Operative temperature	$T_{op} + T_{SolarRadiationGains}$
Czechia	Maximum daily indoor air temperature in the critical room (DM_{cr})	$DM_{cr} = max_{day}(T_{op,i,criticalroom})$ With $i = 1am\, to\, 12pm$
Denmark	Operative temperature	T_{op}
Estonia	Hours of exceedance of the indoor temperature (He)	$He = \sum_{m=June}^{August}\sum_{i=1}^{24h} wf_{i,m}.h_{i,m}$ Where $\begin{cases} wf_i = 1;\ T_{op,i,m} \geq 27^{\circ}C \\ wf_i = 0;\ T_{op,i,m} < 27^{\circ}C \end{cases}$
Finland	Air temperature	T_{air}
France	Statistical summer discomfort duration: degree hours (Dh)	$Dh = wf_i \sum_{i \in occupiedhours} \cdot T_{op,i} - T_{Setpoint,i}$ Where $\begin{cases} wf_i = 1; \begin{cases} T_{op} \geq 26^{\circ}C to 28^{\circ}C(day) \\ T_{op} \geq 28^{\circ}C(night) \end{cases} \\ wf_i = 0; \begin{cases} T_{op} \leq 26^{\circ}C to 28^{\circ}C(day) \\ T_{op} \leq 28^{\circ}C(night) \end{cases} \end{cases}$
Germany	Solar transmittance index (S_{vorh})Hours of exceedance of the indoor temperature (He)	$S_{vorh} = \frac{\sum_j (A_{W,j} + g_{tot,j})}{A_G}$ and $S_{zul} = S_1 + S_2 + S_3 + S_4 + S_5 + S_6$ and $S_{vorth} \leq S_{zul}$ $He = \sum_{year}\sum_{i=1}^{24h} wf_i.h_i$ Where $\begin{cases} wf_i = 1; \begin{cases} T_{op} \geq 25^{\circ}C(climateA) \\ T_{op} \geq 26^{\circ}C(climateB) \\ T_{op} \geq 27^{\circ}C(climateC) \end{cases} \\ wf_i = 0; \begin{cases} T_{op} < 25^{\circ}C(climateA) \\ T_{op} < 26^{\circ}C(climateB) \\ T_{op} < 27^{\circ}C(climateC) \end{cases} \end{cases}$
Greece	Operative temperature	T_{op}
Hungary	Average internal heat (qb)Average temperature difference between indoor and outdoor (Δtb)	$qb = \frac{\sum_{i \in ocuupied\ hours} Q_i}{A_{floorbuilding} \sum_{i \in ocuupied\ hours} i}\ \Delta tb = \frac{\sum_{i \in dhoursday} T_{in,i} - T_{out,i}}{\sum_{i \in hoursday} i}$
Italy	No overheating criteria only operative temperature	T_{op}
Latvia	Hours of exceedance of the operative temperature (He)	$He = \sum_{m=May}^{September}\sum_{i=1}^{24h} wf_{i,m}.h_{i,m}$ Where $\begin{cases} wf_i = 1;\ T_{op,i,m} \geq 27^{\circ}C \\ wf_i = 0;\ T_{op,i,m} < 27^{\circ}C \end{cases}$
Lithuania	Average indoor temperature (At)	$At = \frac{\sum_{i \in non-heating\ season} T_{op,i}}{\sum_{i \in non-heating\ season} i}$
Netherlands	Cooling demand and heat transfer coefficient index ($TO_{Juli;or,zi}$) Hours of exceedance of PMV by + 0.5 (GTO)	$TO_{Juli;or,zi} = \frac{(Q_{C,nd,juli,or,zi} - Q_{C,HP,juli,or,zi}) \times 1000}{(H_{C,D,juli,or,zi} + H_{gr,an,juli,or,zi} + H_{C,ve,juli,or,zi}) \times h_{juli}} GTO = \sum wf_{i,NTA8800}$
Norway	Hours of exceedance of the outdoor temperature (He_{out})	$He_{out} = \sum_{m(1year)}\sum_{i=1}^{24h} wf_i.h_{i,\,out}$ Where $\begin{cases} wf_i = 1;\ T_{op,i,m} \geq 26^{\circ}C \\ wf_i = 0;\ T_{op,i,m} < 26^{\circ}C \end{cases}$
Romania	PMV indices	PMV indices of ISO 7730 and $-0,5 < PMV < +0,5$
Slovakia	Operative temperature	T_{op}
Spain	Solar gains indicator ($q_{sol,jul}$)Percentage of exceedance hours (%He)	$q_{sol,jul} = \frac{Q_{sol,,juli}}{A_{util}}$ Where $Q_{sol,,juli} = \sum_k F_{sh,obst,k} \cdot g_{tot,sh,wi,k} \cdot (1 - FF_k).A_{w,p,k}.H_{sol,juli}$ $\%He = \frac{\sum_{m=June}^{September}\sum_{i \in hours} wf_i.h_{m,i}}{\sum_{m=June}^{September}\sum_{i \in hours} h_{m,i}} \times 100$ Where $\begin{cases} wf_i = 1; \begin{cases} T_{op} > 25^{\circ}C, i \in [3:00;10:59]pm \\ T_{op} > 27^{\circ}C, i \in [11:00\text{pm};6:59\text{am}] \end{cases} \\ wf_i = 0; \begin{cases} T_{op} \leq 25^{\circ}C, i \in [3:00;10:59]pm \\ T_{op} \leq 27^{\circ}C, i \in [11:00\text{pm};6:59\text{am}] \end{cases} \end{cases}$
Sweden	Operative temperature	T_{op}
Switzerland	Operative temperature	T_{op}
UK	Percentage of exceedance hours (%He) Percentage of sleeping hours outside the range (%$PShOR$)	$\%He = \frac{\sum_{i=1}^{occupiedhours} wf_i.h_i}{\sum_{i=1}^{occupiedhours} h_i} \times 100$ Where $\begin{cases} wf_i = 1;\ T_{op,i} - T_{op,i,up} \geq 1^{\circ}C \\ wf_i = 0;\ T_{op,i} - T_{op,i,up} < 1^{\circ}C \end{cases}$ $\%PShOR = \frac{\sum_{d=1}^{d=365}\sum_{10pm}^{7pm} wf_i.h_i}{\sum_{d=1}^{d=365}\sum_{10pm}^{7pm} h_i} \times 100$ Where $\begin{cases} wf_i = 1;\ T_{op,i} > 26^{\circ}C \\ wf_i = 0;\ T_{op,i} \leq 26^{\circ}C \end{cases}$

4.2. *Develop a set of criteria for overheating calculation in Europe*

In this section, the focus is on the evaluation and comparison of the methods, criteria, and indicators for detecting and characterizing overheating. A set of criteria can be used to assess different overheating evaluation methods. Some of these criteria have been developed in previous studies [45], while others are newly defined. It is important to note that the specific criteria used in the evaluation may vary depending on the specific application or context. However, having a set of universal criteria can provide a useful starting point for evaluating different methods and comparing their effectiveness. Eight criteria are used that are described below as a result of analyzing the inventory presented in Section 4.1.

1. **Thermal comfort-based or heat balance-based:** This criterion assesses whether the method is based on comfort parameters or the heat balance between indoor and outdoor environments. Comfort parameters refer to variables that affect human comfort, such as air

temperature, radiant temperature, relative humidity, air velocity, metabolic rate, and clothing factor. Methods based on comfort parameters typically aim to maintain a comfortable indoor environment for people by controlling these variables. In contrast, a heat balance approach considers the thermal behavior of the indoor and outdoor environments. This approach considers factors such as the building envelope, ventilation, and solar gains and aims to maintain an overall balance between the heat gains and losses in indoor and outdoor environments [46].

2. **Time-Integrated or punctual:** This criterion assesses whether the method is time-integrated or punctual. Time-integrated methods quantify overheating over a span of time, giving a more thorough picture of thermal performance over a given period. Punctual methods, however, are *"right now"* and *"right here"* approaches to limit instant overheating in buildings.
3. **Multi-zone or single-zone:** This criterion evaluates whether the method considers building a single-zone or multi-zone environment. A single-zone approach assumes the building is a single space with uniform thermal conditions. In contrast, the multi-zone approach recognizes the differences in thermal conditions between different parts/zones of the building [47].
4. **Static and/or adaptive thermal comfort model:** This criterion assesses whether the method relies on a comfort model and, if so, what model is used. Static and adaptive thermal comfort models are two main categories [48], with the former using fixed parameters to provide comfortable conditions and the latter using real-time data to adjust comfort limits [49] based on changing outdoor weather conditions [50].
5. **Normalization to occupied hours:** This criterion assesses whether the index of a method is normalized to occupied hours. Normalized indices allow for the possibility that different buildings may have varying occupancy profiles and thus have varying cooling/heating requirements at different times. Normalizing the index to the occupied hours makes it possible to compare different buildings with varying occupancy profiles more meaningfully. This enables the fair comparison of buildings with different usage patterns, leading to more accurate and credible overheating risk assessments.
6. **Short-term criteria or/and long-term criteria:** Short-term and long-term criteria are used to set threshold values for limiting overheating in buildings during different time scales [51]. Short-term criteria focus on hourly, daily, or weekly periods to prevent overheating during resiliency events [52], such as heatwaves and power outages, which can lead to sudden impacts on the thermal comfort of building occupants. The role of thermal mass and heat storage of the building structure and surfaces is essential. In contrast, long-term criteria limit extensive overheating over longer periods, such as monthly, seasonal, or annual, and consider the cumulative effects of temperature increases over time [53]. Both indicators and metrics are needed to increase the thermal resilience of residential buildings during heat events [54].
7. **Occupant representation:** This criterion examines, if it exists, the occupant representation model defined for overheating simulations/calculations. The occupant representation describes the behavior of the occupants in the building, which includes the number of occupants, the use of spaces, etc. Stochastic and deterministic models are the two principal models for occupant representation. The stochastic models are based on statistical data to establish random occupant behavior, whereas the deterministic models are more detailed and accurate.
8. **Climate zone-specific:** This criterion evaluates whether the method is tailored to the specific climate conditions of a particular region. The methods or criteria that are effective in one climate zone may not be effective in another and may lead to overestimation/underestimation of overheating incidents.

4.3. Classify and categorize regulations according to similarity (classification)

Table 2 and Fig. 6 identify the main difference that distinguishes the overheating calculation methods. Table 2 compares each country's overheating calculation methods and requirements based on the eight criteria listed in Section 4.2. Fig. 6 illustrates and compares the studied countries spatially. Based on the study report [43], 26 countries were analyzed.

4.4. Selection of six outstanding countries (selection)

This section aimed to identify the most outstanding overheating national calculation method based on the eight study criteria explained in Section 4.2. The eight criteria represent the state-of-the-art for evaluating overheating in residential buildings based on comfort-based and multi-zonal modeling. Table 3 presents a summary of the mapping results. The following paragraph lists and describes six European countries' most outstanding overheating calculation methods.

Switzerland:

The Swiss comfort calculation is based on a specific summer period definition. The calculation utilizes a Design Reference Year that includes average heat waves in the Swiss climate. Future climate change scenarios will be incorporated into the standard, with two scenarios for 2035 and 2050. The future weather files available can be used in the calculation. The thermal comfort calculation is based on operative temperature and adaptive comfort limits diagrams that define thresholds for naturally ventilated and air-conditioned buildings [55]. For naturally ventilated buildings, the maximal upper-temperature limit is higher than for actively cooled residents. The calculation methods allow for personalized local cooling and consider the proximity of occupants to heating, cooling, and ventilation systems. Also, the standard has specific occupancy schedules. The simulation is fully dynamic, and its calculation varies between one hour to a few seconds. The overall building thermal model is multi-zonal.

Spain:

The Spanish overheating calculation method is based on a detailed climatic zoning approach. The calculation method follows a heat balance approach. The country is divided into twelve parts and has five levels of winter from the most temperate zone A to the coldest E and three levels of summer from the mildest 1 to the warmest 3. The overheating calculations are only mandatory for the summer climate zone and are based on the data file of 2005. Solar gains are calculated assuming that solar radiation during July must not exceed 2.00 kWh/m^2.month for any opening; otherwise, the heat gain must be reduced through shading systems, WWR reduction, and the modification (lowering) of the g-value. Between June and September, temperatures in living and sleeping rooms must not exceed more than 4% of the total annual hours for new constructions and newly renovated buildings. The operative overheating temperature is at 27 °C (from 11:00 pm to 6:59 am -> have night limitation) and 25 °C (from 3:00 pm to 10:59 pm) [10]. The calculation method is based on a dynamic simulation model with a 1-hour calculation time step. The modeling approach allows for single-zone and multi-zone models based on pre-set hourly schedules.

Estonia:

Estonia's overheating calculation method is based on a dynamic model with hourly occupancy profiles. Indoor air temperature is used as the overheating indicator. Residential buildings should comply with 150 Kh above 27 °C for the indoor temperature (long-term criteria). The calculation model considers local, personalized heating/cooling & ventilation systems. The calculation approach allows adopting an adaptive thermal comfort approach based on CEN 16798; the cooling systems are sized with static thermal comfort requirements. Four major prescriptive requirements must be met in living rooms and bedrooms regardless of the simulation results: 1) the limitation of the WWR $\leq$ 0.4; 2) window-to-floor ratio $\leq$0.15; the presence of effective openable

Table 2
Characterization by the criteria of overheating calculation methods.

Country	1: Comfort based or heat-balance based calculation	2: Time-integrated or punctual calculation	3: Multi or single zone calculation	4: PMV-PPD or adaptive thermal comfort model	5: Normalization to occupied hours	6: Short-term or long-term criteria	7: Occupant representation	8: Climate zone-specific
Austria	Comfort	Time-integrated	Single-zone	Adaptive	No	Long-term	Yes	Yes
Belgium (Brussels)	Comfort	Time-integrated	Multi-zone	PMV-PPD	Yes	Long-term	Yes	Yes
Belgium (Wallonia and Flanders)	Heat-balance	Time-integrated	Single-zone	PMV-PPD	Yes	Long-term	Yes	Yes
Bulgaria	Comfort	Punctual	Multi-zone	PMV-PPD	No	No	No	Yes
Croatia	Comfort	Punctual	None	PMV-PPD	No	No	No	No
Czechia	Comfort	Time-integrated	Single-zone	PMV-PPD	No	Long-term	No	No
Denmark	Comfort	Time-integrated	Single-zone	Adaptive	Yes	Long-term	No	No
Estonia	Comfort	Time-integrated	Single or multi-zone	Adaptive and PMV-PPD	No	Long-term	Yes	No
Finland	Comfort	Time-integrated	Multi-zone	PMV-PPD	No	Long-term	Yes	No
France	Comfort	Time-integrated	Multi-zone	Adaptive and PMV-PPD	Yes	Long-term	Yes	Yes
Germany	Both[a]	Both[a]	Single-zone	Adaptive and PMV-PPD	No	Long-term[a]	Yes	Yes
Greece	Comfort	Time-integrated	Single-zone	Adaptive	No	Long-term	Yes	Yes
Hungary	Both[b]	Both[b]	Single-zone	PMV-PPD	Both[b]	Short-term[b]	No	No
Latvia	Comfort	Time-integrated	None	PMV-PPD	No	Long-term	No	No
Lithuania	Comfort	Time-integrated	Single-zone	PMV-PPD	No	Long-term	No	No
Netherlands	Both[c]	Time-integrated	Multi-zone	PMV-PPD	No	Long-term	Yes	No
Norway	Comfort	Time-integrated	Multi-zone	Adaptive or PMV-PPD	No	Long-term	Yes	No
Romania	Comfort	Punctual	Single or multi-zone	PMV-PPD	No	No	Yes	Yes
Slovakia	Comfort	Punctual	Single-zone	PMV-PPD	No	No	No	Yes
Spain	Both[d]	Time-integrated	Single or multi-zone	PMV-PPD	No	Long-term	Yes	Yes
Sweden	Comfort	Punctual	Multi-zone	PMV-PPD	No	Long-term	Yes	No
Switzerland	Comfort	Time-integrated	Multi-zone	Adaptive	No	Long-term	Yes	No
UK	Comfort	Time-integrated	Multi-zone	Adaptive and PMV-PPD	Yes	Long-term	Yes	No

window as a fraction ≥0.1; 3) g-value and 4) WWR × g ≤0.2, for single-family [42].

Germany:

The German calculation approach classifies the country into three summer climatic regions. In general, the operative temperature should exceed 26 °C. However, in Regions C, which represents metropolitan areas, upper and the middle Rhine, the operative temperature should not exceed 27 °C. The dynamic calculation method is based on a single-zone model with hourly or fewer calculation time steps. A detailed occupancy schedule is used with an internal gain of 100 Wh/m^2_{NFA} for residential buildings [56]. Two calculation approaches are possible: a simplified solar transmittance static indicator method and an adaptive method for the thermodynamic simulation method. Overall the overheating temperature hours per year should not exceed 1200 Kh [57].

UK:

The British overheating calculation methods allow using local weather files for design summer years: DSY1 = the 2020s, DSY2 = 2050s, and DSY3 = 2080. However, the use of those files is not mandatory. The two main calculation indicators are 1) hours of exceedance and 2) the operative temperature. The modeling approach is multi-zonal with an hourly dynamic simulation [58]. The calculation approach distinguished homes that are predominantly naturally ventilated and predominantly mechanically ventilated [59]. For mechanically ventilated households, occupied rooms' operative temperature should be below 26 °C and can only exceed 3% of annual occupied hours.

For naturally ventilated, the exceedance hours (May to September) are set for living rooms, kitchens, and bedrooms. In bedrooms, the operative temperature should stay lower than 26 °C and cannot exceed 1% of annual hours of sleeping between 22:00 to 07:00. The methodology recommends a *g-value* for all external and internal building elements, plus additional shading features. Airspeed in space is considered, assuming the presence of a ceiling fan or other system that can generate air movement. The Maximum sensible heat gain of 75 W/person and a maximum latent heat gain of 55 W/person in living spaces should not be exceeded. An allowance for 30% reduced gain is considered during sleeping [60].

France:

The French overheating calculation is based on climatic zoning that divides the country into eight geographic zones. Heat waves are considered a basic event in all simulations' weather files. The calculation is based on a normalized indicator of occupied hours overheating as degree hours that should not exceed 2600 °C.h per year. A distinction between naturally ventilated and air-conditioned buildings are made. The modeling approach is multi-zonal with a schedule representation of occupancy presence. The Predicted Mean Vote – Percentage of People Dissatisfied (PMV-PPD) model is used during the night, where the operative temperature should not exceed 26 °C (20:00 to 07:00). This is a mandatory requirement in naturally-ventilated households. An adaptive thermal comfort model based on CEN 16798 is applied during the day. The operative temperature threshold falls between 26 °C and 28 °C, considering the occupant's capacity for adaptation [61]. The model is dynamic, with a time step of at least one hour. The designer must install an active cooling system if the building cannot meet the thermal comfort in any thermal zone [10].

In summary, the study findings (Table 3) pointed out France as a European country with one of the most advanced overheating calculation methods. The French calculation method is based on a bioclimatic approach with highly ambitious energy efficiency requirements (10 kWh/m^2/year), sometimes exceeding the PassiveHaus standard [14]. On the other hand, the French calculation approach allows the application of static (PMV/PPD) or adaptive thermal comfort models. More

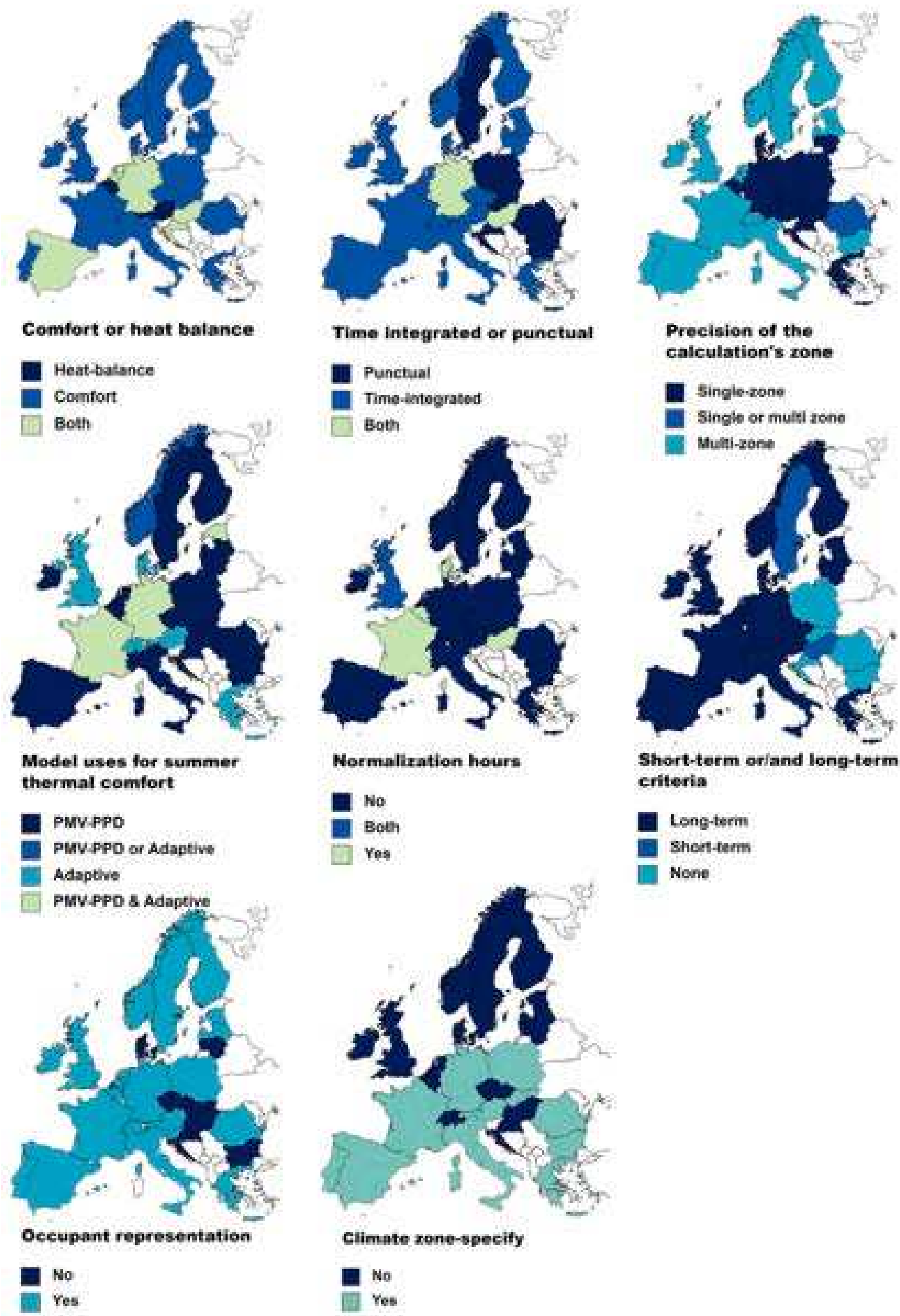

Fig. 6. Mapping of overheating calculation methods across Europe.

importantly, the RE2020 protects occupants and requires a mixed/mode operational model for naturally ventilated households, where the operative temperature should not exceed 26 °C (20:00 to 07:00) in sleeping rooms. This is the first standard in Europe that adopts a mixed-mode approach for overheating calculations.

4.5. Propose factors that should be considered to advance the overheating assessments in future revisions of building regulations (future criteria)

Finally, the analysis and discussions taken in this study on overheating calculation methods highlighted the key factors that should be

Table 3
Classification by the eight criteria from the more advanced to the less advances overheating calculation methods.

Country	Score	Criteria	Categories	Weighted point
France	**9**	1: Comfort based or heat-balance based calculation	Heat-balance	0
UK	**8**		Comfort	1
Germany	**7**		Both	1
Estonia	**6**	2: Time-integrated or punctual calculation	Punctual	0
Spain	**6**		Time-integrated	1
Switzerland	**6**		Both	1
Austria	6	3: Multi or single zone calculation	Single-zone	0
Greece	6		Single-zone or multi-zone	0
Belgium (Brussels)	6		Multi-zone	1
Belgium (Wallonia and Flanders)	5		Single-zone and multi-zone	1
Denmark	5	4: PMV-PPD or adaptive thermal comfort model	PMV-PPD	0
Finland	5		PMV-PPD or Adaptive	0
Netherlands	5		Adaptive	1
Norway	5		PMV-PPD and Adaptive	2
Hungary	4	5: Normalization of hours	No	0
Sweden	4		Yes	1
Bulgaria	3	6: Short-term or/and long-term criteria	Short-term	1
Czechia	3		Long-term	1
Latvia	3	7: Occupant representation	No	0
Lithuania	3		Yes	1
Romania	3	8: Climate zone-specific	No	0
Slovakia	2		Yes	1
Croatia	1			

considered to advance the overheating assessments in future revisions of building regulations. Experts intensively pinpointed the following topics:

- Climate change and more current historical data and future climatic scenarios are essential in future calculation approaches.
- Consideration of the urban heat island effect and limitation of night cooling is needed. There is a need for the use of local weather files to quantify the effects of ventilative cooling [62,63]. Addressing heavily populated areas must be brought into calculation methods.
- There is a need for short-term criteria or/and long-term criteria to prepare a building for thermal resilience and not only thermal resistance.
- There is a need to use a common language for calculation (ISO 52000–1 2017 [64] and CEN 13790 [65]) and push the concept of symmetry. By symmetry, we mean conducting calculations for the summer and winter. The winter season must be considered in any future overheating calculation approach.
- There is a need to refine the calculation methods and introduce multiple parameters based on real measurements, including wind speed, radiant T°C, and humidity…
- Despite the importance of the performance-based approach, there is a need to define prescriptive requirements for imposing building envelopes (external shading, WWR limits, and maximum *g-values* …)
- There is a need to explore the operation of buildings in mixed modes using PMV-PPD and adaptive models directly related to occupants' health and well-being, especially in sleeping rooms [66].

5. Discussion

This study provides a cross-study to identify the difference in the overheating calculation in European regulation. It provides recommendations for harmonizing and improving the Energy Performance of Buildings Directive. In the following section, we present the key study finding and recommendations. The strength and limitations of the paper are discussed, followed by a discussion on the implication on practice and future scientific research.

5.1. Study findings

The situation of overheating calculation methods is very complex in Europe. There is a huge disparity between countries and almost no common approach to addressing overheating in residential buildings [40] rigorously. For this study, we compared the regulations, indicators, and thresholds in 26 countries over three years to understand the different calculation methods and to be able to distinguish them. We understand that a huge continent like Europe has different climates and behavioral thermal adaptation measures [67]. However, none of the investigated countries dedicated enough resources to develop an optimum climate change-sensitive approach that fits Europe's aging population. Most of the current calculation methods are outdated and do not fit the purpose of well-being [68]. Most countries rely heavily on a PMV-PPD model that requires active cooling systems, models households as single zones and does not distinguish between living and sleeping rooms. Therefore, there is a need to join forces and address overheating collectively.

Out of 26 countries, the study findings pinpointed Switzerland, Spain, Estonia, Germany, the UK, and France as leaders in evaluating overheating in the domestic sector. Based on Table 3, France has been ranked as the most consistent and climate-sensitive calculation approach. Other investigated countries have already revised their calculation methods addressing different climate comfort models and thermal zone. However, the pace of change is still slow and does not address the issues raised by experts in Section 4.5. Thus, there is no solid or comprehensible distinction between air-conditioned, naturally ventilated, and mixed-mode building operations. In our opinion, the lack of standards on the mixed-mode operation of the residential building is one of the key challenges to a suitable calculation method.

Our review indicates three key indicators that quantify overheating duration and intensity in buildings. Firstly, the percentage of occupied hours when an operative temperature exceeds a certain threshold of the annual occupied hours based on a PMV/PPD or adaptive comfort for a specific comfort category (I, II, III or IV). The indicator is used by many European standards that address overheating calculation, including CIBSE (Guide A, TM52, and TM59), The Passive House Standard, CEN 16789, and ISO 17772. Table 4 provides example of the exceedance hours indicators in existing thermal comfort standards. Secondly, the Standard Effective Temperature (SET) is based on the six thermal comfort parameters: air temperature, radiant temperature, air velocity, humidity, clothing, and metabolism. Regardless of the thermal comfort (PMV/PPD or adaptive) model used, we urge using more flexible indicators that consider the effect of airspeed and humidity. Thirdly, the Indoor overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*), and overheating escalation factor ($aIOD = AWD$) developed by Hamdy et al. (2011) [68] and adopted by the IEA Annex 80 [69].

Finally, the paper proposes eight overheating calculation criteria

Table 4
Examples of exceedance hours thresholds in existing thermal comfort standards.

Standard	Temperature threshold	Exceedance hours threshold
ISO 17772–2 CEN 16798–2	26 °C (Cat. II)	6% (annually) – 25% (monthly) – 50% (weekly) during occupied hours
Passive House Standard	25 °C	10% (Annually) all hours (not only occupied hours)
CIBSE Guide A (2019)	=>27 °C (Cat. II)	Mechanically heated and cooled 3% (annually) during occupied hours
CIBSE TM52	=> 27 °C (Cat. II)	Free running buildings – 3% during occupied hours during Typical non-heating season (1 May to September)

presented in Section 4.2 that can help designers and practitioners to compare and select an appropriate methodology for climate-proof building design. New criteria and metrics for the thermal resilience of residential buildings are needed during heat events. In a changing climate, there is increasing concern about the risk of overheating in EU domestic buildings. A consistent and unified approach to overheating calculation in buildings is needed. This paper identifies key performance indicators to develop a consistent and appropriate overheating calculation methodology for the EPBD within a resilience paradigm [20]. The indicators can be elaborated and extended through performance thresholds and prescriptive requirements to form a common framework for future Europe calculation approaches.

5.2. Study recommendations

Therefore, we strongly recommend developing a common climate-sensitive calculation framework based on European standards for overheating estimation and thermal autonomy [70]. Eight parameters related to the overheating calculation are recommended: Time-Integrated or punctual to quantify overheating over a while, multi-zone or single-zone, static and adaptive thermal comfort model, normalization to occupied hours, short-term criteria or/and long-term criteria, occupant representation, and climate zone-specific. Based on the study findings, we recommend a set overheating indicator including the Indoor overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*), overheating escalation factor ($aIOD = AWD$), and Standard Effective Temperature.

The study indicates that the French regulation is the most advanced regarding the overheating calculation in Europe according to the eight criteria reported in Sections 4.2 and presented in Section 4.4. The French Standard RE2020 fixes a maximum temperature of 26 °C in sleeping rooms at night. It requires an adaptive thermal comfort model based on CEN 16789 that allows the operative temperature to fluctuate between 26 and 28 °C in other housing zones. However, the upper limit of operative temperature can be further pushed to higher ranges if air velocity and humidity change. Therefore, we strongly recommend using the Standard Effective Temperature (SET) as an additional indicator to allow for higher upper operative temperatures during heatwaves in households while increasing the air velocity (beyond ASHARE 55 [72, p. 55]) and controlling humidity.

Also, there is a need for a constantly updated climate classification map that includes recent heating-degree days (HDD) and cooling-degree days (CDD) data provided by the European Union (EU). Without a detailed climatic and topographic standard map for Europe, we will fall under national climatic classifications that impede any unified calculation approach [72]. Next, a set of thermal comfort criteria with commonly acceptable thresholds for minimum comfort must be defined concerning the climate specificity represented in HDD and CDD. Also, issuing Energy Performance Certificates (EPC) must include a design review step associated with a post-construction inspection to address overheating risk for building design and renovation [73]. The variation in thermal performance of the building with the same EPC is any more acceptable [58]. EPC should make overheating calculations across member states more comparable.

Moreover, there is a need for mandatory prescriptive requirements for the WWR and g-values. More importantly, external shading protection must be mandatory in cooling-dominated, and overheating risked households. It is time that Europe introduced mandatory envelope requirements. Finally, an advanced dynamic simulation approach must be generalized in all countries to test future climate scenarios and extreme heat wave events and allow for a multi-zonal approach that distinguishes sleeping rooms. For further details, see Section 4.5.

5.3. Study strengths and limitations

In this study, we created a cross-sectional study that provides a snapshot and advice for overheating calculation methods across Europe. We gathered detailed information on 26 Europe countries in a systemic ay involving more than 15 national experts. The study included experts on the IEA Annex 80 on Resilience Cooling in Buildings. It was developed in close consultation with the annex activities as part of Group D [74]. To the best of our knowledge, no existing study compared overheating calculation methods comprehensively in Europe like this study [46]. The implications of this study can benefit countries beyond the EU, allowing the exploration of different indicators and thresholds. Also, the study succeeded in proposing an updated and detailed study report, in line with the EPBD, that pinpoints the weaknesses and strengths of the current regulatory landscape.

At the same time, we know the study is qualitative and could have been more valuable if it had adopted a quantitative modeling approach. Also, once published will be considered outdated due to the continuous modifications introduced in the regulations of 26 member and non-member states and the new EPBD recast that should be published in 2023 or 2024. However, the study remains highly valuable because it presents a snapshot and comparison of Europe's current overheating calculation methods. This is the first study that provides such an exhaustive comparison and dataset that is the first step to conducting quantitative analysis afterward. More importantly, the study presents constructive and futuristic recommendations of utmost utility and benefit for the future EPBD recast.

5.4. Implications for practice and future research

There is a need to revise the EPBD calculation framework and calculation method approach. Soon, European environmental regulations will require building with timber and bio-based materials. As a consequence, the risk of overheating risk in lightweight construction is increasing [34]. Overheating is a critical problem that will be manifested across European households during this century. The current calculation methods require more accurate ways to help the designer to adapt buildings and renovate beyond the current overheating calculation methods' limitations. There is a need for funding projects that allow the development, testing, and implementation of novel methods of overheating calculation. The direct implication of such development is enabling architects and engineers to design climate-proof buildings that can consider future weather scenarios.

Future research should compare the different calculation methods for benchmarking purposes. Researchers should seek to develop calculation methods in mixed-mode operations [75]. There is a need to learn from similar studies on thermal resistance and resilience calculations in other regions [76]. Modeling resiliency events such as power outages and extreme heat waves requires further investigation [77]. Also, experimental validation of simulation and measurement-based overheating assessment approaches for residential buildings is needed [78]. Monitoring summer indoor overheating in cities is essential. More case studies should be presented to test the different control logic [79] and strategies [80], overheating indicators, and thresholds concerning public health and mortality rates. The next step of this research is to test the different overheating calculation methods through a quantitative approach that involves building modeling for benchmarking.

6. Conclusion

The suitability of existing overheating calculation methods in the EPBD was investigated and compared against new and emerging methods [69,81]. Eight parameters related to overheating calculation were selected: Time-Integrated or punctual, multi-zone or single-zone, static and/or adaptive thermal comfort model, normalization to occupied hours, short-term criteria or/and long-term criteria, occupant representation, and climate zone-specific. This comprehensive study indicates a need for more research and deeper investigation – particularly regarding the following areas and possible recommendations for which the current study indicated significant gaps between the EPBD and the best available calculation methods [74].

- Considering climate change and the urban heat island effect using more current historical data and future climatic scenarios is essential in future calculation approaches.
- Adopting short-term and long-term indicators prepares a building for thermal resilience and not only thermal resistance.
- Refine the calculation methods to use a comparative calculation approach based on existing standards such as ISO 52000–1 2017 [64] and CEN 13790 [65]) and allow for mixed-mode operation [82].
- In parallel to the performance-based approach, define prescriptive requirements for imposing building envelopes (external shading, WWR limits, and maximum g-values …).
- Explore the operation of buildings in mixed modes using PMV-PPD and adaptive models directly related to occupants' health and well-being, especially in sleeping rooms [66].

Planned future work should develop calculation methods in mixed-mode operations. Also, simulation studies on European home models should be further developed to incorporate the concepts of thermal resistance and resilience for climate-proof buildings.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Questionnaire

To download the questionnaire: https://doi.org/10.7910/DVN/LCBTNX.

Appendix 2. Report

To download the study report: https://doi.org/10.7910/DVN/LCBTNX.

Appendix 3. Countries table

To download the comparative table of countries: https://doi.org/10.7910/DVN/LCBTNX.

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Resilient cooling strategies – A critical review and qualitative assessment

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ABSTRACT

The global effects of climate change will increase the frequency and intensity of extreme events such as heatwaves and power outages, which have consequences for buildings and their cooling systems. Buildings and their cooling systems should be designed and operated to be resilient under such events to protect occupants from potentially dangerous indoor thermal conditions.

This study performed a critical review on the state-of-the-art of cooling strategies, with special attention to their performance under heatwaves and power outages. We proposed a definition of resilient cooling and described four criteria for resilience—absorptive capacity, adaptive capacity, restorative capacity, and recovery speed —and used them to qualitatively evaluate the resilience of each strategy.

The literature review and qualitative analyses show that to attain resilient cooling, the four resilience criteria should be considered in the design phase of a building or during the planning of retrofits. The building and relevant cooling system characteristics should be considered simultaneously to withstand extreme events. A combination of strategies with different resilience capacities, such as a passive envelope strategy coupled with a low-energy space-cooling solution, may be needed to obtain resilient cooling. Finally, a further direction for a quantitative assessment approach has been pointed out.

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1. Introduction

Climate change and extreme heat are critical issues faced by all countries. The Intergovernmental Panel on Climate Change (IPCC) defines climate extreme as "the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable" [1]. The long duration and high intensity heatwaves are becoming a potential natural hazard that presents significant risk and challenge to humans, buildings, and building-related systems. The extremely high temperatures can cause heatstroke, heat exhaustion and other heat-related diseases, which are particularly dangerous for vulnerable populations, such as the elderly or low-income communities [2]. A most well-known hazard was the European heatwave 2003, which resulted in 14,800 excess deaths in France; 74% of these excess deaths occurred indoors [3]. EuroHEAT estimated that the increase in mortality ranges from 7.6% to 33.6% during heatwaves by analyzing the impact of long heatwaves in nine European cities (Athens, Barcelona, Budapest, London, Milan, Munich, Paris, Rome and Valencia) [4].

Resilience is a concept widely applied in disaster risk management. It refers to "*the ability of a system and its components parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions*", as defined by IPCC [5]. Resiliency in the context of the building environment refers to the ability of buildings and their systems to continue functioning as intended in the face of natural hazards imposed by climate change [6]. Buildings shelter humans from the outdoor environment and it is crucial that buildings maintain safe thermal conditions during extreme events, such as heatwaves. Current building and building-related system designs strongly focus on energy efficiency to mitigate climate change through reducing carbon emissions. However, energy efficient strategies (technologies and practices) are not always consistent with strategies that improve resilience to extreme heat; often there is a trade-off between these two objectives [7]. Ren et al. [8] contend that "Excessive striving for energy efficiency" could compromise a building's ability to maintain comfortable thermal conditions during heatwaves, such as higher insulation and airtightness. Another limitation for current building and building system design is the use of typical weather or historical weather files for the calculation of cooling demand and evaluation of the effectiveness of cooling strategies [9,10]. As a consequence, the building and its systems may not be prepared to cope with heatwaves or climate change. This is supported by the findings of several studies [11,12,13], which show that the low-energy cooling strategies that work well today might not remain effective under long-term climate change, or in extreme events such as a heatwave or a power failure.

Like energy efficiency, sustainability and economic affordability, resilience should be considered as an important property of buildings and their systems in the early design phase. Ceré et al. [14] note that resilience is already part of recent architectural and structural building design practices.

The recently formed International Energy Agency (IEA) Energy in Buildings and Communities Programme (EBC) Annex 80 "Resilient Cooling of Buildings" addresses this need by developing, assessing and communicating strategies for resilient cooling and overheating protection against climate change and the consequent hazards or events [15]. Many cooling technologies and solutions

Table 1
Definitions provided in literature for the concepts of resilience.

Ref	Definition	Characteristics	Threats	Scale	Year
[29]	"Building resilience is defined as a building's ability to withstand severe weather and natural disasters along with its ability to recover in a timely and efficient manner if it does incur damages."	Withstand, recover, rapidity	Climate and natural disasters	Building	2013
[26]	"A resilient building is a building that not only is robust but also can fulfill its functional requirements (withstand) during a major disruption. Its performance might even be disrupted but has to recover to an acceptable level in a timely manner in order to avoid disaster impacts."	Withstand, absorb, recover, rapidity	Climate extremes	Building	2019
[24]	"A resilient built environment as one designed, located, built, operated, and maintained in a way that maximizes the ability of built assets, associated support system (physical and institutional) and the people that reside or work within the built asset, to withstand, recover from, and mitigate the impacts of threats."	Withstand, recover, mitigate	Natural hazards (geo-hazards and hydro-meteorological hazards)	Built environment	2008
[14]	"The intrinsic ability of the built environment to react positively before, during and after the presence of the adversely exogenous input (e.g., landslides), i.e., the ability to absorb external disturbances, in order to maintain the system's original states or reach a new set of steady states for serving its normal functionalities."	Vulnerability, adaptive capacity, recoverability	Geo-environmental hazards	Built environment	2017
[21]	"Resilient urban energy system needs to be capable of "planning and preparing for", "absorbing", "recovering from", and "adapting" to any adverse events that may happen in the future. The complex, dynamic, and adaptive systems (e.g. cities) would not necessarily return to an equilibrium state."	Preparation, absorption, recovery, adaptation	Disruptions in energy supply	Urban energy systems	2016
[27]	"Resilience can be understood as the ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance)."	Robustness, redundancy, resourcefulness, rapidity	Earthquake	Community (technical, organization, social, economic)	2003
[5]	"The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions."	Anticipate, absorb, accommodate, recover	Climate extremes and disasters	System	2012
[28]	"Resilience is a continuous process starting from a reliable initial condition, followed by a vulnerability-survivability state after a disruptive event and eventually a recoverability phase aimed at achieving a new stable equilibrium condition."	N/A	Flood	Infrastructure system	2012

are available both in the market and are under development. Previous studies have systematically compared various active and passive cooling strategies in terms of energy performance [16,17,18], thermal comfort and air quality [19], capital expenditure [16,18] and applicability in different climate zones [20]. However, the resilience of cooling strategies has not been widely discussed in the literature and it lacks a clear definition of resilient cooling and the criteria for assessing it.

The present study aims to fill this knowledge gap. First, we define resilient cooling and propose the criteria that can be used to assess the resilience of a cooling strategy. Second, we review the state-of-the-art of existing cooling strategies, assessing their physical principle, typologies, and performance, with special attention to resilience, applicability and technology readiness level. Finally, we use the proposed resilience criteria to qualitatively evaluate cooling strategies under various extreme events, such as, heatwaves and power outages.

2. Resilience and characteristics of resilient cooling

This section reviews the definition of resilience and the characteristics of resilient systems, and further discusses resilient cooling and the criteria for assessing it.

The concept of resilience originated in physics and psychology, where it described the ability of an object to return to its initial condition after a disruption [21,22]. The definition and interpretation of resilience vary from one discipline to another. Table 1 summarizes various definitions of resilience within the context of buildings and building-related systems.

One critical prerequisite for a comprehensive definition of resilience is to identify the threats or external perturbations to the systems, which can be summarized into an essential question as "resilience to what?"[23]. The threats faced by buildings and building-related systems are diverse and include both natural hazards and human hazards. Natural hazards can further be divided into geo-hazards, such as earthquakes, tsunamis, landslides, hydro-meteorological hazards (e.g., hurricanes and floods), wind storms and extreme temperature [24]. In the concept of resilient cooling, the building and its systems are mainly challenged by extreme heat events (heatwaves) and power outages. High power demand from air-conditioning during a heatwave strains and destabilizes the electrical grid [25]. Extreme heat can also impede power generation. For example, during the heatwave in 2003, the river water levels in France dropped so low that the cooling process of nuclear reactors became impossible and the nuclear power plants had to shut down [26].

Bruneau et al. [27] proposed four dimensions of resilience: technical, organizational, social, and economic. This study will mainly discuss resilient cooling from the technical point of view and the other dimensions will be treated as supplementary conditions. The resilience researches [5,21,27] considered various scales from micro (building or building element) to macro (district, city, or urban). The current study will address the resilience of building-scale cooling strategies over the life of the building.

Some studies tended to define resilience by considering the phases that systems undergo with external disruptions (initial condition, vulnerability-survivability state, recoverability state, new stable equilibrium state) [14,28], but most defined resilience through its features and systems abilities [5,21,24,26,27,29]. Several words commonly found in the literature to characterize resilient systems include "absorb", "withstand", "recover", and "rapidity". Therefore, this study proposes to summarize the resilient characteristics of cooling strategies by four criteria – absorptive capacity, adaptive capacity, restorative capacity and recovery speed.

- **Absorptive capacity** is the degree to which a system is able to absorb the impacts of disruptive events and minimize their consequences with little effort. For example, heavy thermal mass in a building (capacitance) can absorb unwanted solar gain and can minimize and/or delay the air temperature increase in the building without the use of cooling energy.
- **Adaptive capacity** is the ability to adjust undesirable situations by undergoing some changes. The system can learn from the event, evaluate the system performance and modify its configurations, and make it more flexible to future disruptions. Adaptive capacity is distinguished from absorptive capacity in that adaptive systems change in response to adverse impacts, especially if the absorptive capacity has been exceeded. For example, a façade solar shade may be activated, when the air temperature in the building starts to increase because the storage capacity of the thermal mass has been exceeded.
- **Restorative capacity** is the ability to return to normal or improved operation. For example, night cooling can remove unwanted heat gain accumulated in the thermal mass during the day and provide a heat sink for the next day.
- **Recovery speed** is the speed of the recovery process. Recovery may be accelerated if absorption activities are well implemented and the system can quickly mobilize and effectively use all the resources at its disposal [21]. For example, the speed with which night cooling can remove heat from the building's thermal mass and restore the building to its desired condition depends on the ventilation flow rate and the outdoor air temperature.

Therefore, Annex 80 defines resilient cooling as a capacity of the cooling system integrated with the building that allows it to withstand or recover from disturbances due to disruptions, including heatwaves and power outages, and to adopt the appropriate strategies after failure to mitigate degradation of building performance (deterioration of indoor environmental quality and/or increased need for space cooling energy) [23].

3. Review method

To provide an overview of the state-of-the-art of existing cooling strategies, and assessing their resilience under various extreme events, a systematic literature review was performed. The review was carried out through a critical analysis of existing literature. Different databases have been used to identify peer-reviewed academic literature, including Elsevier (ScienceDirect), IEEE, Google Scholar, Scopus, SpringerLink. To address the resilience of cooling strategies under extreme events, the keywords for the search included resilience, overheating, heatwave, climate change, power outage, disruptive events, cooling strategies/solutions/techniques. Additional searches were performed by combining the keywords for each cooling strategy. Take ventilative cooling as an example, the following keywords were used: ventilative cooling, ventilation, natural/mechanic/hybrid ventilation, night cooling, air-based system. Besides peer-reviewed articles, relevant books and technical reports have also been taken into account. There was no strict limitation on the publication period, but priority has been given to recent publications to address the state-of-the-art research. Table 2 summarizes the statistic of reviewed literature for different cooling strategies.

4. Resilient cooling strategies

Annex 80 has created four cooling-strategy categories based on their approaches to cooling people or the indoor environment.

Table 2
Statistic of reviewed literature for different cooling strategies.

Cooling strategies	Number of references	Year of publication
Solar shading/glazing	172	1982–2020
Cool envelope materials	256	1975–2021
Green roofs, roof pond, and green facades	39	1969–2020
Ventilated roofs and facades	47	2001–2020
Thermal mass including PCMs	89	1982–2020
Ventilative cooling	84	1996–2021
Adiabatic/evaporative cooling	33	1991–2020
Compression refrigeration	9	2008–2019
Absorption refrigeration including desiccant cooling	10	1992–2019
Ground source cooling	79	1987–2020
Sky radiative cooling	32	2002–2021
High-temperature cooling system: Radiant cooling	28	1995–2020
Personal comfort systems	26	1979–2020
Dehumidification including desiccant dehumidification	27	1993–2020

A. Reducing heat gains to indoor environments and people indoors
B. Removing sensible heat from indoor environments
C. Enhancing personal comfort apart from cooling whole spaces
D. Removing latent heat from indoor environments

This section will review the above cooling strategies from the following aspects: physical principle, typologies, performance with attention to resilience under extreme events, and technology readiness level (TRL). The technology readiness level is based on the guidelines from the U.S. Department of Energy [30].

4.1. Reduce heat gains to indoor environments and people indoors

4.1.1. Advanced solar shading/advanced glazing technologies

Windows are inserted into walls and roofs to provide a view to the outdoors for occupants, and to admit and control daylight, sunlight, and air. While windows usually comprise only a small fraction of the overall envelope area (typically 5–35%) the impacts of these transparent surfaces on cooling energy use, peak cooling loads, and occupant comfort can be very large. Windows (glass, sash, and frame elements) are commonly accompanied by shading systems. When mounted on the building exterior, shading devices are more effective in managing solar loads, but more costly. The combined ability of window and shading technologies to provide resilient cooling depends on the intrinsic properties of the window/glazing package as modified by any shading technologies. Shading elements are commonly relied upon to manage solar gain in the event of a heatwave or power outage.

To better assess the window/glazing/shading response in terms of resilience it is useful to divide the available technology options into static and dynamic technologies, and to further divide dynamic solutions into manually operated and automatically operated.

Glazing technologies manage cooling loads from solar gain by absorbing, transmitting, and reflecting solar energy by virtue of the materials used in the construction of the glass and glazing system. Traditional clear glass has a very high solar transmittance; glazing systems used in most windows today use body tints and coatings for absorption and reflection, and can be further combined into multiple glazings in an insulated glazing unit with two or more glazing layers that provide a wide range of thermal management capabilities. Several thousand different variants of glass are commercially available with documented wavelength-dependent optical properties [31]. The solar properties of the complete glass package in a window, optimized for structural needs as well as energy control, can be readily determined by simulation [32,33]. The most effective and widely used glazing products incorporate low thermal-infrared emittance ("low-E") coatings which can serve two purposes. All reduce the window thermal transmittance ("U-value") and when properly positioned within an insulating glass unit will reduce solar heat gain. Some low-E coatings provide spectral control and admit most daylight [visible transmittance (Tv) > 60%] while effectively reducing solar gain [solar heat gain coefficient (SHGC) less than 0.30]. A wide range of light-transmitting glazings is available with a light-to-solar-gain-ratio (LSG = Tv/SHGC) ranging from 0.5 to 2.3 [34]. The ability to admit daylight but minimize solar heat gain can reduce building cooling loads attributable to electric lighting.

Glazings with fixed solar optical and thermal properties do not have the flexibility to respond dynamically to changing environmental conditions or to grid demands. After a 20-year R&D effort manufacturers have commercialized several different "smart glazing" products. Thermochromic glass technologies have solar optical properties that vary moderately with temperature [35,36]. The solar-optical properties of electrochromic and liquid crystal-based glazings are altered over a wide range with an applied voltage [37,38]. These show promising performance in laboratory studies and field studies in buildings but adoption has been slow because they are expensive and require new sensors and controls. There is a significant global investment in ongoing R&D regarding new or enhanced electrochromic solutions, as well as in other active glazing technologies based on liquid crystal devices. This is expected to provide new market options in the near term [39,40]. One approach is to control visible transmittance and NIR transmittance independently. This facilitates improved performance in northern climates, and the window can reduce SHGC in warmer climates but still admit daylight [41,42]. An emerging technology solution incorporates transparent or semi-transparent photovoltaic layers in the glazing to manage solar heat gain and generate electricity [43].

Shading solutions for windows are diverse in terms of function, materials, and operation in both homes and commercial buildings. Shading systems can be static or dynamic, and are mounted either exterior or interior to the glazing [44–50]. More complex solutions utilize the cavities between glazing and shading layers to manage air flow and heat removal or recovery; these ventilated facades are discussed in more detail in section 4.1.4. The best-known shading solutions are operable shades, blinds, and drapes on the interior, and screens, shades, blinds and fins/overhangs on the exterior [51–53]. The newest generation of exterior solar shading can incorporate power generation (i.e., PV arrays) in the shading elements [54]. Since the solar loads depend on ever-changing solar position, even fixed shading solutions will have an annual performance that varies with latitude, orientation, and geometry. An interior operable shading system will always be less efficient than a similar exterior system since the absorbed solar radiation is trapped within the building [49]. Operable systems have limited effectiveness and resilience if they are not triggered and operated appropriately in response to climatic stress. The promise of improved controls, wireless sensors, and better integration with building control systems should reduce costs and improve reliability [55–58]. Ongoing studies on occupant response to glare and preferences in managing the tradeoffs between daylight control, solar control, and glare [59,60] are influencing design and deployment trends for the years ahead.

Market availability and acceptance varies across these technology solutions and also by region. Both spectrally selective static glazing as well as high insulating glazing solutions, are widely available. Active and passive smart glazing solutions are still offered by a limited number of companies globally. Fixed exterior shading systems are available in the global market, although they are infrequently used in many countries and for multiple building types. Multiple solutions for operable interior or exterior shading systems are also widely available. Exterior systems are in use in Europe but less widely in the U.S. These systems are commonly operated manually. Automated or motorized solutions are limited but they are entering the market in increasing volumes.

4.1.2. Cool envelope materials

A cool envelope material (CEM), typically a reflective roof or wall product, provides a solar-opaque surface that reduces net radiative heat gain at the envelope [(solar absorption - fluorescence) + (thermal infrared absorption – thermal infrared emission] to decrease heat flow into the occupied space [61–65]. Strategies include static high solar reflectance (light-colored or ultrabright-white CEM) [66–72], static high near-infrared (NIR) reflectance (cool-colored CEM) [73–82], temperature-sensitive high solar reflectance (thermochromic CEM) [66,83–86], angle-sensitive high solar reflectance (directionally selective reflector CEM) [87–89], static solar retroreflection (solar-retroreflective CEM) [90,91], and static near-unity solar reflectance + static selective thermal emittance (daytime sky radiator CEM) [92–94].

Except for daytime sky radiators, CEMs reduce heat flow into the occupied space but do not increase heat flow out of the occupied space. Therefore, CEMs must be coupled with heat modulating strategies, such as thermal storage, or heat-dissipating strategies, such as night ventilation, evaporative cooling, or mechanical cooling, if the outside air is uncomfortably or dangerously hot.

CEMs save cooling energy in an air-conditioned building when power is available; lower indoor temperatures in an unconditioned ("free-running") building when power is unavailable, or the building lacks cooling equipment, and provide a combination of energy savings and indoor temperature reduction when power is available, but the cooling equipment is undersized for an exceptionally hot day. Hernández-Pérez et al. [95] summarize cooling load or cooling energy savings simulated in over 20 studies; additional simulations can be found in later studies [63,66,84,96–108]. They also review space temperature reductions measured or simulated in over 30 studies and discomfort hour reductions simulated in 4 studies; later works also report reductions in indoor temperature [102–119] or discomfort hours [97,101,110–112,114,120], with heat-wave benefits assessed by Porritt et al. [121,122]. Cool-roof monitoring studies have measured reductions of about 1 to 3 K in top-floor air temperature [98,99,123–126] and up to about 5 K in top-floor operative temperature [112,127].

The ability of a CEM to reduce the envelope's net radiative heat gain on a sunny day provides an "absorptive" capacity for heat resilience by helping the cooling equipment meet its load, or by diminishing the temperature rise in an unconditioned building. As passive solar-control measures, CEMs help whenever the sun shines, and continue to mitigate unwanted solar heat gain during a power outage or heatwave. However, their absorptive capacities diminish when cloudy, hazy, or smoky skies reduce incident sunlight. A thermochromic CEM may provide adaptive capacity if a heat event accelerates its switch from low to high solar reflectance. While CEMs do not directly provide restorative or recovery capacity, their abilities to reduce heat flow into the occupied space make it easier for heat-modulating and heat-dissipating strategies to moderate interior temperatures.

Both white and cool-colored roof materials are mature technologies that are widely available to both building owners and building contractors [68,128], and identifiable via mature product rating systems provided by the Cool Roof Rating Council [129] and the European Cool Roofs Council [130,131]. Cool wall materials, such as light-colored paints, claddings, and sidings, and some cool-colored wall products, are similarly mature and available (Appendix P of [70]), but their product rating system is still under development [132]. Some novel CEMS such as directionally selective reflectors are specialty products with limited availability; other CEMs, such as daytime radiators, solar retroreflectors, fluorescent cool colors, and thermochromics remain under development.

4.1.3. Green roofs, roof pond, green facades (evaporative envelope surfaces)

Evaporation on the outside of the building envelope is an efficient cooling technique, which can be managed with vegetated surfaces, water films, ponds, and sprays [133–136] (Fig. 1).

The primary difference between façades (green or watered, Fig. 1a,b,c) and roofs (green roof or roof pond, Fig. 1d,e) is linked to the vertical water runoff, which amplifies the thermal transfer due to the increased sensible and convective heat transfer in the water stream. Moreover, evaporative façades require continuous water spray or water supply to permanently irrigate the upper part, while roof ponds and green roofs may adapt more easily to various climate conditions without water supply.

The water retention potential is a key design parameter for roof ponds [137] and green roofs [138]. A permanent water supply may be required (for façades, or during dry periods), which brings out the optimal control of the evaporative dynamic for a resilient cooling strategy, and low water consumption. E.g., to increase the evaporation process of a roof pond, Erell et al. [139] recommended

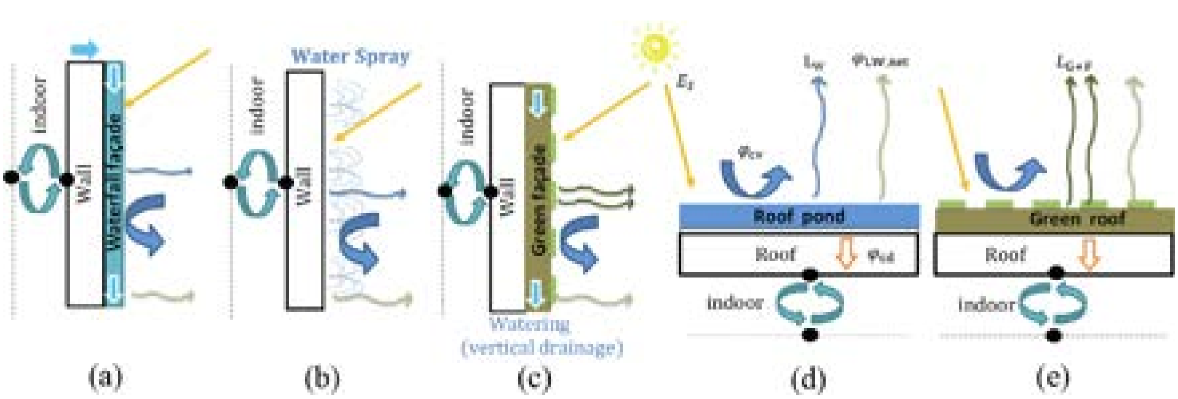

Fig. 1. Heat transfer in evaporative envelope surfaces, including (a) a waterfall façade, (b) a spraying system, (c) a green façade, (d) a roof pond, and (e) a green roof. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

droplet sizes of 0.5 to 1 mm, spray rates of about 1–1.5 volumes of the roof pond per hour, and a spray height of 50 cm.

Innovative evaporative envelopes include the combinations of increased albedo, the development of porous materials, or movable claddings [140,141].

However, for hot, temperate and even cold climates, evaporative envelope surfaces demonstrated strong cooling effects of the roof and façades surfaces for summer conditions [142,143]. E.g., the surface temperature of the south-oriented wall can decrease by 9.8 °C in Moscow, and 18.7 °C in Riyadh [139], while energy cooling loads can decrease up to 100% in Brasilia and Hong Kong with green roof and façades. These cooling techniques are also widely recommended for their stormwater retention potential, and their impact on sewer overflow, which translates into some local policies such as the Toronto (Canada) green roof policy [144]. This can be an efficient solution even considering the effects of climate change, but some parameters like plant species [145] or roof water retention capacity may have to be adapted.

Regarding evaporative surfaces, the most advanced TRL (TRL 9) concerns green roofs and façades, which are widely available, and included in policies and standards. However, few alternatives for water retention systems on roofs exists, e.g., typical gravel roofs (TRL 9). Most of these alternatives are only at a research or prototype stage, including various roof pond typologies with/without radiative protections, or porous material, all mainly available as lab prototypes, or full-scale experiments (TRL 4–6) [146].

4.1.4. Ventilated roofs and ventilated facades (ventilated envelope surfaces)

Ventilated roofs and façades have been widely developed as an adaptive element for both winter heat recovery and summer heat dissipation. An additional opaque or transparent cladding forms a ventilated double-skin, which allows various airflow strategies (see Fig. 2) to cool the external side when required. Ventilation patterns and additional controls, such as venetian blinds [147–150], make these techniques highly adaptable to seasonal changes and climate change.

The air-tightness and winter solar gains of the closed cavity façade (Fig. 2a) are a good option for temperate climates, while it can support high temperatures (up to 90 °C) with a long service life without maintenance [138]. Yet, overheating of the air gap under extreme summer conditions has led to the development of more performant solutions, such as movable blinds and natural ventilation. The solar heat gains observed in an experimental setup in China were reduced from 330 to 28 W/m^2 with Venetian blinds [149]. The cooling performance is improved with ventilation openings designed to remove heat, and outdoor or indoor air ventilation strategies [151]. The indoor ventilation can be designed with air outlets through the roof [152] or the wall (Fig. 2b,e), which can be efficient for air-conditioned buildings even in extreme hot climates. Driven by the outside air–gap stack effect (amplified by solar gains), the airflow may be intensified by the mechanical ventilation system of the building. Similarly, outdoor air can be used as the heat sink for the double-skin air gap (Fig. 2c,d). The study of a ventilated pitched roof in Djibouti [153] demonstrated a heat gain reduction of about 50% for the building, which underlines the effectiveness of this ventilation technique in extreme summer conditions, given the high solar gains of the roof, and the temperature differences between the roof and outdoor air.

The ventilation rate is a key parameter for this technique's cooling efficiency. This ventilation rate is highly dependent on the opening design. Then, the design and the optimal perforation rate of outdoor façade claddings vary greatly depending on the location and orientations [154,155]. The optimal perforated percentage varies between seasons, and variations between 10 and 60% were found to be optimum for Japan [143]. However, these optimal cooling performances will drop under extreme heatwave events and climate change, due to the outdoor air temperature increase. Yet, some design parameters such as solar orientation [156] and prevailing wind direction [156,157], will be much less sensitive to climate change.

Regarding ventilated surfaces, double-skin façades are very well developed in the construction sector, from the first Trombe walls in the 1920′s to the transparent double-skins for high-rise office buildings [158] (TRL 9). These techniques include many innovations, such as the perforated and the closed cavity façades; yet many lab developments are still ongoing (TRL 6), and some biomimetic solutions are arising, such as adaptive façades similar to a natural foliage [159] (TRL8). Ventilated roof for cooling can be found in research studies [153] (TRL5-6), but very few construction products are available for this typology [160] (TRL9).

4.1.5. Thermal mass utilization including PCM

Thermal Energy Storage (TES) systems absorb, store, and release thermal energy on a cyclical basis (usually daily) to regulate internal temperature and improve thermal comfort in buildings [161]. Thermal energy can be stored as a change in internal energy of a material as sensible heat (e.g., ground, water tanks and aquifer energy storage), latent heat (e.g., Phase Change Materials, including organic and inorganic substances and ice storage), or chemical energy (e.g., thermochemical storage). It should be noted that the cooling capacity (in [kWh]) of a latent thermal energy storage comprises both a fraction of sensible and a fraction of latent energy.

TES systems increase the generation capacity by releasing the stored energy during high demand which allows a smaller production unit to be installed.. TES systems operate as a cost-saving measure by shifting the energy demand to low-tariff periods [162]. TES systems also increase the cooling system reliability and can easily be integrated with other functions such as on-site fire protection water storages [163]. However, TES system performance is not guaranteed during the days with small temperature swings. Storage cycle efficiency (i.e., long-term heat loss reduction) and high

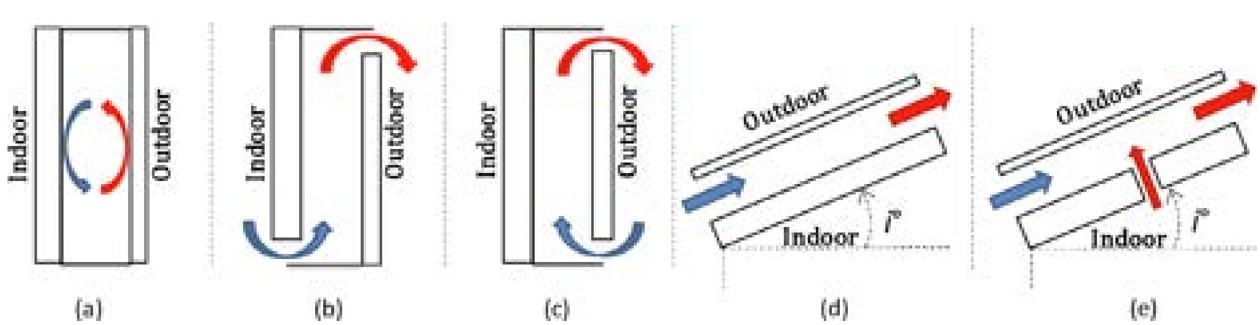

Fig. 2. Typologies of ventilated envelope surfaces: (a) closed cavity façade; (b) exhaust air façade; (c) outdoor air curtain façade; (d) ventilated roof; (e) ventilated roof coupled to a natural ventilation of the building.

investment cost in latent and thermochemical heat storage are further limitations of TES systems [164].

The performance of a TES is characterized by its storage capacity and its ability to provide cooling or heating power as a function of the state of charge of the storage. TES systems have shown to be effective measures in reducing peak indoor air temperature and dampening temperature variations in buildings during extreme events such as heatwaves or power outages. TES cooling performance under extreme conditions is highly sensitive to the temperature gradient between cyclic cold (e.g., night) and warm (e.g., day) periods. For instance, consecutive days with high nighttime outdoor temperatures deteriorate the cooling capacity of TES systems significantly [165]. Kuczyński & Staszczuk [166] indicated that the cooling effect and efficiency of increased thermal mass do not change during the heatwaves and remain independent of the duration and distribution of heatwaves. In their analysis, the use of concrete ground floors and walls in a detached single-family house, combined with nighttime ventilation and shading devices, substantially reduces the risk of overheating and the need for the installation of active cooling systems.

PCMs are applied mostly for energy-saving purposes but have shown some advantages in reducing overheating hours and improving thermal comfort. Similar to increased thermal mass, installing PCMs can reduce indoor air temperature variations [167]. The effectiveness of PCMs in overheating reduction in buildings relies on PCM properties and climate [168]. Some studies report a 50% reduction of discomfort hours [169,170]. However, Kuznik et al. [171] found that while the use of PCMs is beneficial in some periods during the year, it is not effective in very hot days because it remains liquid throughout the day. According to Ramakrishnan et al. [172] who optimized PCM melt temperature for resiliency, parametric optimization for the current heatwave events will not work for future heatwaves. Baniassadi et al. [173] analyzed the effectiveness of wall-integrated PCMs during the loss of air conditioning (i.e., power outage) coincident with heatwaves. They found that although PCM application can mitigate overheating during power outages, its resiliency is highly correlated to temporal factors (initiation time and duration of a power outage), PCM properties, and climate. They stated that the PCM melt temperature is a crucial factor in determining its resiliency. In most climates, the optimum melt temperature for resiliency differs from the optimum temperature for energy efficiency [173]. Considering the fact that energy efficiency is the main driver of the installation of PCMs, in most cases, there is no significant added resiliency advantage by using PCMs [173]. However, in some climates, there is a chance to select a melt temperature that has benefits for both energy efficiency and resiliency [174].

Common materials for thermal mass utilization are concrete, stone or masonry, bricks, and tiles. These materials are available all around the world as they do not necessarily require special technology to be produced. TES systems based on sensible heat such as water tank or underground storage methods are widely available, but devices based on latent heat such as PCM are mostly under development. The higher costs of PCMs is a barrier to widely enter the markets. The cost difference between sensible TES and PCM is even higher in active applications. Another barrier is related to the stability of the PCM materials. Further research and development are needed in PCM to adopt these technologies in more cost-effective manner.

4.2. Remove sensible heat from indoor environments

4.2.1. Ventilative cooling

Ventilative cooling (VC) uses the cooling potential of the outdoor air, and can be achieved with natural solutions (either by wind-driven or buoyancy-driven flows), mechanical technologies (fan), or a combination of both (i.e., mixed-mode or hybrid ventilation). Some studies [175,176] categorized VC into daytime comfort ventilation (or direct cooling) and night cooling (or indirect cooling). Daytime comfort ventilation introduces the flow of outdoor air through the building during the day to directly remove heat gains. It aims to improve the occupant's thermal comfort via convective heat transfer, increasing the evaporative cooling effect on the occupants' skin, and decreasing indoor air temperature. Night cooling has a double effect: on the one side it utilizes the building's thermal mass during the night, where thermal mass works as a heat sink during the occupied period, and, on the other side, it decreases indoor air temperature during the night hours.

The cooling performance of ventilation systems under extreme events is strongly correlated to ventilation types (natural or mechanical), building characteristics, local climate and occupant behavior [177,178]. Alessandrini et al. [179] investigated the overheating risk in a naturally ventilated dwelling during heatwaves under the weather condition of France, Paris. They observed that by natural ventilation, the maximum indoor operative temperature could be maintained 6–9 °C lower than the maximum outdoor temperature which reached 39 °C during the five days of heatwaves. Their study demonstrates that a well-designed natural ventilation system can mitigate the surging cooling demand during an extreme heat event. Architectural elements such as a solar chimney, atrium, or double-skin façade can help facilitate natural ventilation. A study by Lomas and Ji [180] demonstrated that buildings with such architectural elements integrated with advanced ventilation controls could provide greater resilience to future climate change than single-side natural ventilation.

However, ventilative cooling will be less beneficial when climate change makes heatwave events more frequent [181]. Artman et al. [182] quantified the effect of global warming on the night-time ventilative cooling potential in Europe. They compared the climatic cooling potential (CCP) index between monitored climate conditions (1961–1990, European Climate Assessment and Dataset) and possible future climate conditions (2071–2100, IPCC SRES scenarios A2, more divided world, and B2 [183], world more divided but more ecological). Their study indicated that future warming would have a significant impact on the night-time ventilative cooling potential across Europe. The CCP was expected to decrease by 20–50% in Central and Northern Europe by the end of the 21st century. At the same time, for Southern Europe, CCP was found to become negligible in summer and decrease by 20–55% during the transient season at the end of the 21st century. Campaniço et al. [177] evaluated the impact of climate change on direct ventilation for the Iberian Peninsula area. They predicted a 20% reduction of CCP in the future climate (2070–2100) along the annual cycle and up to 60% reduction in the summer season. The impact of climate change on the uncertainty of thermal comfort in a naturally ventilated office was investigated by Breesch and Janssens [184]. The probability of discomfort increases significantly when recent and warmer weather data sets are assumed. To reduce the risk of overheating in a warming climate, natural night ventilation should be combined with additional measures, such as mechanical ventilation coupled with cooling coil or passive cooling strategies (earth-air heat exchanger, indirect evaporative cooling), or increased thermal storage in the building. Mechanical ventilation increases resiliency, on the other hand, it will increase energy consumption. It is therefore recommended to perform a full life-cycle assessment to ensure energy efficiency and overheating resilience over the long-term building life span [185].

Natural ventilation through openings and other passive devices is widely available for most applications. Traditional examples developed through centuries of trial and error are modified to provide contemporary solutions. Mechanical ventilation techniques and solutions are also readily available for most applications. Both natural and mechanical solutions are available on the marked reaching a TRL 9, although specific innovative solutions and control techniques are under development at different TRL levels.

4.2.2. Adiabatic/evaporative cooling

Evaporative cooling is based on an adiabatic process in which the sensible air temperature is reduced. Evaporative cooling may be classified into two main approaches: direct coolers (e.g., desert coolers) and indirect coolers (e.g., evaporative chiller units for fan coil) [186,187]. Direct evaporative cooling (DEC) evaporates the water directly into the air stream, while indirect evaporative cooling (IDEC) evaporates water into a secondary air stream. The secondary air stream cools the main air stream through a heat exchanger without adding humidity.

Direct evaporative cooling systems have been well known since ancient times. Several historical buildings in hot (and dry) climates show DEC solutions, such as the Ziza Palace in Palermo, Italy, or Red Ford in Delhi, India [188,189]. The efficiencies of DEC systems depend on the local wet bulb temperature depression, and they are best suited to hot and dry locations. Performance of IDEC depends on wet bulb effectiveness, dew point effectiveness, cooling power, power consumption, and coefficient of performance [190]. Water scarcity may limit the application of evaporative cooling systems in desert or semi-desert areas.

The impact of climate change on the cooling potential of evaporative cooling has been studied by Campaniço et al. [177]. The climatic cooling potential index has been calculated under past (1970–2000) and future weather conditions (2070–2100) in the Iberian Peninsula. A 10%-15% decrease in CCP (ventilative cooling) is expected in the further climate due to increased outdoor temperature, while evaporative cooling is shown to be more resilient to climate changes than ventilative cooling. Osman et al. [191] found that building design strategies in a hot and arid region should shift from natural ventilation to more active cooling by the year 2070, and that two-stage evaporative cooling comprised of DEC and IDEC is the most resilient strategy for all of Khartoum's seasons in the future climate. Furthermore, the population of arid regions is growing and climate changes are increasing human thermal stress in arid areas. Evaporative cooling solutions and green infrastructure (evapotranspiration from vegetation) are essential technologies supporting resilience, although the potential reduction in water availability requires high efficiency solutions.

Passive DEC systems are generally low cost, nevertheless, they need high maintenance to avoid microorganisms and connected diseases (e.g. legionella). DEC may be a valid dissipative system for open or semi-open spaces, in where the growth of air absolute humidity is mitigated by natural air movements [192,193]. In enclosed spaces, DEC systems can be controlled to prevent too high humidity values by adopting a control system. From the TRL point of view, several DEC systems have been installed in different building typologies. This technology is at the market level (TRL9), nevertheless, new researches are under development for new porous materials, and to develop specific systems connected to ventilative cooling solutions. In these cases, lower TRL may be found. Finally, movable simpler evaporation solutions (e.g. personal evaporator fan systems) independent by building system integration are commercialized in everyday shops.

4.2.3. Compression refrigeration

Vapor compression refrigeration is certainly the most used "active" technology to produce a cooling effect. The system mainly comprises an evaporator, a compressor, a condenser and an expansion device. A working fluid (refrigerant) successively flows through these components and follows a thermodynamic cycle [43].

Vapor Compression Air Conditioning units (ACs) can be classified by the heat source and heat sink (e.g. air, glycol–water, water, or soil), function (AC unit-cooling, heat pump-heating, reversible ACs- heating or cooling modes, AC with heat recovery – heating and cooling simultaneously), compressor technology, refrigerant type (natural or synthetic)), configuration [194] (packaged units (including window ACs and rooftop units), split ACs (including ductless mini-split systems, ductless multi-split systems and central ducted split-systems) and chillers (air-cooled, water-cooled, evaporative cooled). The other classification of interest when considering resilient technologies is cooling capacity. Vapor compression refrigerant technology covers a large range of cooling capacities going from a few hundred watts (household refrigerators) to tens of megawatts (industrial chillers and large-scale heat pumps) [44].

The cooling capacity of compression refrigeration systems is more constrained by the design and size of the machine than by the available capacity of the natural heat sink. Even though the COP of the system might decrease due to the high outdoor temperature during heatwaves, a well-designed system can still retain sufficient cooling capacity to confront the heatwave, indicating that compression refrigeration technology provides a high adaptive capacity. Hajidavalloo and Eghtedari [195] investigated the impact of outdoor air temperature on the COP of a split-air-conditioner with an air-cooled condenser. They found that when the outdoor temperature increases to 49 °C from 35 °C, the cooling capacity of this air-conditioner decreases to 5.6 kW from 6.8 kW, and COP decreases to 3.14 from 4.56. The study also found that this problem could be mitigated by using an evaporative-cooled condenser, which maintained the cooling capacity of the air-conditioner at 6.7 kW when the outdoor air temperature was 49 °C.

Vapor compression systems rely on electricity and are not very robust to the power outage. An approach to increase its robustness is to connect with local electricity production, such as photovoltaic (PV) panels in buildings. Chillers are more likely to operate simultaneously to PV electricity production compared with heat pumps, i.e., the highest cooling demand usually coincides with the large intensity of solar radiation. It is hence a good candidate to improve building self-consumption. On the other hand, chillers connected to energy storage (batteries, thermal storage units of building thermal mass) can also apply as a backup solution to the management of electrical grids by the flexibility provided by such combinations. This flexibility is activated by a time of use tariff as a demand side management (DSM) mechanism. It should be stressed that heatwaves lead to electricity peak demands on the grid and DSM mechanisms become of paramount importance. Average cooling demand around the world is responsible for 15% of peak electricity demand; but during hot days, cooling can be responsible for up to 50% and more of residential peak electricity demand [196]. Moreover, for buildings equipped with on-site generation, the use of thermal storage combined with specific net-metering programs can promote better load matching between production and consumption [197]. Another approach is to integrate the vapor compression system with ice storage systems, which can help limit the impact on the electricity grid of highly fluctuating distributed renewable energy sources. Actually, they offer a mechanism of building electricity consumption flexibility that can take profit of dynamic electricity rates.

Vapor-compression ACs for buildings, with a wide range of capacities and numerous configurations, show TRL values of 9. In 2020, roughly 2 billion AC units were in operation in the world, with residential ACs representing 68% of these units [196]. The market of AC units is growing in an accelerated way, with estimated sales increasing by 10% between 2018 and 2019 (mainly in emerging and developing countries) [196]. Building contractors and engineering offices define the most appropriate cooling/heating plants depending on the availabilities of heat sink/heat source, on the building characteristics, on the ease of installation, on the cost of the solutions, on the cost of energy (and the presence of local electricity production), on local regulation/incentives, but also on the customer's expectations. AC efficiency rating varies from one country to another, but it is always an image of the ratio of the cooling effect to the electricity consumption (W/W). Average efficiency rating of installed AC units has increased by 15% between 2010 and 2020 [196], but still far behind the most efficient products on the market [196].

4.2.4. Absorption refrigeration including desiccant cooling

Desiccant cooling systems were developed to handle sensible and latent heat loads independently [198]. The dehumidifier absorbs the moisture of the supplied air and afterward will pass to the regeneration unit to recover its initial moisture absorption capability [199]. The dry supplied air stream passes the cooling unit for sensible cooling and is then routed to the conditioned space. Additional heat exchangers could be added on different points such as economizers to increase the system efficiency.

Desiccant systems are classified as solid or liquid desiccators [200]. A rotary wheel with solid dehumidifiers is a compact system made from matrix-shaped parallel channels coated with desiccant material, such as SiO_2, $TiSiO_4$, or Al_2O_3, that operate continuously with low corrosion probability [198]. The liquid desiccant materials, such as ClLi, LiBr, $CaCl_2$, TEG HCOONa, HCOOK, CH_3COONa, CH_3COOK, or a combination of these solutions, ideally should be stable, odorless, non-toxic, non-flammable, inexpensive, non-crystalized in the operating temperature range, non-corrosive and non-volatile with good heat transfer characteristics and low surface vapor pressure at the contacting temperature [201]. The low cooling capacity of solid desiccants and the corrosivity of liquid desiccants are important limitations. Therefore, new desiccants including bio-desiccants, composite desiccants, and polymer desiccants have been introduced; some of them could provide an absorption capacity 2–3 times of traditional absorbers [202].

The major benefits of absorption cooling are discussed in Refs. [198,203,204]. The system uses eco-friendly fluids including air and water, which have no negative impact on the environment. It could operate with diverse thermal energy sources, even low-grade resources, in the regenerators. The required electrical energy can be less than 25 % of conventional refrigeration systems and this technique acts as an energy-efficient method, especially for hot dry and hot humid areas. Finally, the desiccant cooling system works near atmospheric pressure, which makes them easy to construct, install, preserve and maintain. The major limitation of desiccant cooling is that it needs an additional heat source for regenerating the desiccant to provide stable operation [199]. However, the heating power can be provided by any source such as the waste heat from industries through a district heating network or via solar collectors or ground source heat pumps. This improves the overall efficiency of desiccant coolers because the heat requirement can be gained from sources with lower primary energy factor, i.e. waste heat from a combined heat and power plant, industry or solar energy which are also available during the cooling season. Moreover, to make the system more environmentally friendly, the required electrical power can be provided by renewable sources, for example, tidal energy in marine facilities, solar cells, or wind turbines.

High outdoor air temperature during a heatwave might decrease the efficiency of absorption refrigeration systems, depending on the type and design of the systems. Kim et al. [205] simulated the cooling performance of an air-cooled LiBr–water absorption chiller in extremely hot weather. It was found that when the ambient temperature increases to 50 °C from 35 °C, the cooling capacity of the absorption chiller decreases 37.5% and 35.6% for direct air-cooled chiller and indirect air-cooled chiller compared with their cooling capacity at 35 °C, respectively. Grzebielec et al. [206] confirmed that the outdoor air temperature plays an important role in the efficiency of absorption refrigeration. However, by using a spray-evaporative heat exchanger, the effect of outdoor temperature can be reduced and the average cooling capacity can be up to 44% higher than those with dry air cooler devices.

Although the absorption refrigeration systems are partially activated by thermal energy, the systems are not robust during the power outage events because the cooling water distribution system cannot operate without power input. Like compression refrigeration, the system could integrate local electricity production and energy storage to increase its resilience during the power outage.

Desiccator wheels are used for residential and primarily for non-residential purposes. However, these usually use a simple system with basic equipment and more advanced systems are not widely implemented, though. Desiccant cooling technology could be categorized in TRL 9 according to the Technology Readiness Assessment Guide issued by the U.S. Department of Energy [207]. TRL 9 signifies that the technology operates and can achieve defined requirements. For instance, desiccators can be used in various applications and are available in the market [208,209]; therefore as a mature technology providing cool and dry air, desiccant coolers can be categorized in TRL9.

4.2.5. Ground source cooling

The working principle of ground-source cooling is based on the fact that the ground temperature below approximately 10 m remains fairly constant all year round at about mean annual ambient air temperature [210]. Thus, ground temperature over the cooling period is less or not affected by hourly and daily temperature variations, regardless of outside air temperature. It rejects heat to the ground by circulating a working fluid through ground heat exchangers. Based on the heat transfer medium (air or liquid), the system can be further categorized as an earth-to-air heat exchanger (EAHE) or a borehole heat exchanger (BHE). Ground-source cooling can also be classified as direct ground cooling (passive) or ground-source heat pump (active). The direct-ground cooling system utilizes ground as the only source for cooling the working fluid without any mechanical refrigeration. In a ground-source heat pump system, the cooling is provided through a mechanical refrigeration system using the ground as a sink for dissipating the heat [211]. Ground source systems may also be used to pre-heat a heat transfer medium in winter seasons, nevertheless, for this paper, only their cooling potential is analyzed.

Since the subsurface temperature below a certain depth is insensitive to seasonal and diurnal variations, ground-source cooling shows a high resilience under heatwaves. However, the cooling capacity of ground-source cooling might be affected by climate change. The sensitivity of ground-source cooling (EAHE) to future climate was investigated by Chiesa et al. [212] considering historical and future North America climate conditions - future climate were based on Five General Circulation Models (GCMs) from the CMIP5 (Coupled Model Intercomparison Project Phase 5) multi-model ensembles [213]. Results showed an expected reduction in climate EAHE sensible cooling dissipative potential in future years, while variations in the soil surface average temperature were identified to be a synthetic index to analyze variations in EAHE cooling potentials.

Several measurement studies have shown that ground-source systems perform better under peak-load conditions than under off-peak load conditions [214–216]. This is partly because under peak load conditions the ground heat transfer is higher, due to a larger temperature difference between working fluid and the ground. The percentage share of the parasitic energy consumption of circulation pumps and other auxiliary equipment under peak load conditions is also lower. Passive ground-cooling systems have larger absorptive capacities than active ground-cooling systems because they are bigger and because of their greater ability to adjust the working fluid conditions to match the cooling demand of the building. The systems can adjust to extreme events including heatwaves in many ways, such as by pre-cooling the building at night and off-peak periods, by using active thermal energy storage systems like chilled water or ice storage for load shifting, or by reducing peak loads at the expense of lower thermal comfort. The restorative capacity of ground-source cooling systems under heatwaves is high, as the heat injected into the ground is dissipated to the earth surrounding the ground heat exchanger. This can be done using dry coolers at nighttime when the ambient air temperature is lower. Depending on the soil's thermal diffusivity, it can take several hours to a few days for the system to fully recover from heat injections to the ground [217,218]. However, the impact of different recovery times have on the restorative capacity of the ground is generally considered in the design of ground-cooling systems.

The resilience of ground-source cooling systems to power outages depends on the degree of disruption and the type of the ground cooling system. The ground-source heat pump systems require substantial electrical energy to operate the refrigeration cycle and the auxiliary components. The direct-ground cooling systems require much less electricity as the only energy input to the system is the work required to drive the circulation pumps.

At the system level, ground-source cooling is a fully mature technology at TRL 9. It has been used worldwide for several decades and there are thousands of actual systems operating over the full range of possible conditions. There exists a great wealth of knowledge concerning design methods, installation procedures, operating practices, and application examples in literature. Moreover, there are several scientific and professional bodies defining norms and standards, protocols and guidelines, and best practices at local, national, and international levels. At the subsystem level, the heat exchangers and grouting materials used in ground-source cooling systems are widely available commercially and are at TRL 9. Nevertheless, there is still ongoing research into developing innovative heat exchanger designs and materials to enhance the ground heat transfer. The TRLs of the new developments range from early lab-scale (TRL 1–3) to commercial demonstration (TRL 8).

4.2.6. Sky radiative cooling

Sky radiative cooling represents the passive process in which any object located on the Earth's surface (sky facing terrestrial object or surface) releases heat to the sky through net loss of long-wave (thermal infrared) radiation [219,220]. The incident solar radiation during the day, the convective heat transfer (for a higher outdoor air temperature than the radiator temperature), and cloud coverage can have a negative impact on the net cooling output [92,221–226]. Thus, currently, this technology is mostly associated with nighttime, when the sky can reach temperatures below 0 °C [222,227] and there is no incident solar radiation. Still, the radiative heat exchange with the sky can take place both during night and day. Heat can be released in the broadband (4–30 μm) or a selective band (8–13 μm), the latter leading to a higher efficiency during an all-day cycle [92,228]. Thus, ideal material properties for radiative cooling should present a maximum reflectivity in the short-wave range (0.25–2.8 μm) to reflect solar radiation while the emissivity should be as close as possible to unity especially in the atmospheric window band (8–13 μm) and zero otherwise [92,228].

In buildings, roof paints can be employed as a passive radiative cooling solution to increase both solar reflectivity and emissivity of the surfaces, although this may increase the heating energy use during the heating season [92,228]. However, buildings can also make use of roof ponds, movable insulation systems, radiators, or existing solar heating systems integrated as passive or active systems (with or without pumps and fans) that extract the heat from the indoor environment and release it to the sky [92,226,228]. This way, sky radiative cooling presents the ability to restore the indoor thermal environment to its original state, making it a resilient cooling technology.

Nevertheless, as the cooling potential is influenced by air temperature, relative humidity, air speed, and clouds (e.g. the cooling potential is decreased in very hot and humid environments) [222,224–226] its restorative capacity is dependent on the outdoor climate. Thus, like other renewable energy technologies (e.g. wind, solar), its recovery speed (rapidity of the restorative capacity) can vary as well with the outdoor environmental conditions. Furthermore, the presence of solar radiation makes sky radiative cooling time dependent. As objects (e.g. other buildings) can block the radiative heat exchange with the sky while lack of space can drastically reduce the surface area facing it [220,228], their restorative and recovery capacities can be further limited in dense urban environments. Clouds, if present for a short and long period (hours to days), will reduce both its restorative and recovery capacity for the respective period. Still, even for a clear sky when the radiative heat exchange is not hindered by clouds, the convective heat exchange could counter its effect for a high outdoor temperature [221–226]. Therefore, the best sky radiative cooling solution must be chosen according to the climate and setting (high versus low building density), i.e. good planning is required for a high exploitation potential.

If used passively, sky radiative cooling cannot be adequately controlled and relies solely on favorable environmental conditions and material properties to achieve its maximum potential. However, reduced time dependency and a constant recovery speed could be achieved by employing night radiative cooling actively combined with different storage techniques (e.g. building thermal mass, storage tanks). This would allow the system to store cooling during periods with favorable conditions and use it at later times when the sky radiative cooling potential is limited. Furthermore, when using the technology actively, parameters such as the flow rate of the heat storage medium can be controlled [220,221,223,229], allowing higher exploitation (higher recovery speed), especially during periods when the potential is high, thus using the available resources in a timely manner.

After heatwaves, the sky radiative cooling's restorative capacity was rated as low to moderate, as the cooling capacity could be reduced by increased humidity and outdoor temperatures also during night time [92,225,228]. For example, an increase in relative humidity (50 to 100%) and outdoor air temperature (9 K) could reduce the cooling power of thermal solar collectors by 18% to 41%, respectively [225]. However, recent progress in solar reflective materials with high emissivity in the atmospheric window may further enhance the sky radiative cooling's restorative capacity as cooling could be achieved concurrently with the demand, i.e. during the day [92,228]. Blackouts would not pose an issue and thus the sky radiative cooling restorative capacity after blackouts was rated as moderate. The recovery speed on the other hand could vary between low and high depending on the way sky radiative technology is employed, passively or actively. If the technology is passively used, no additional auxiliary energy (e.g. pumping power) would be required to start the process. Therefore, in those situations, the recovery speed can vary from low (unfavorable environmental conditions) to high (favorable environmental conditions) during both heatwaves and blackouts. On the other hand, active use could ensure an increased recovery speed through an increased flow rate of the heat transfer medium (e.g. air, water).

Although not an issue for short-term blackouts, one challenge for active use during a long-term blackout, e.g. days, would be ensuring the circulation of the heat transfer medium. In those situations, without backup power the recovery speed would be low.

As the sky is a free cooling source, night sky radiative cooling is a renewable technology available for any consumer. Moreover, it is ready for market implementation since it can be employed through existing technologies such as solar collectors and PV/Ts [222,223,225]. However, further development and research can improve and optimise both the equipment and the systems employed, especially for daytime use [92,228]. Although it can be used directly by any consumer, the experience of design engineers and building contractors might improve its use leading to an optimum operation of the desired application.

4.2.7. High-temperature cooling system: Radiant cooling

A hydronic radiant cooling system refers to a system in which water is the heat carrier and more than half of the heat exchange with the conditioned space is by radiation [230,231]. Heat transfer from indoor spaces is by a combination of radiation and convection via cooled surfaces. The convection is usually natural, unless the air movement over the conditioned surface has been enhanced—e.g., by supplying air from a ventilation diffuser. These systems employ high-temperature cooling, where the heat-transfer medium is near room temperature. The system conditions large surfaces in indoor spaces, usually floors, ceilings, and walls, and the large conditioned surface areas make it possible to cool indoor spaces with a small temperature difference between the conditioned surfaces and the room. Supply water temperatures in radiant systems are usually 16 – 23 °C for cooling.

Radiant cooling systems can be classified as radiant cooling panels, radiant surface systems, and thermally active building systems (TABS) [230]. Radiant panel systems and radiant surface systems can be used in both new buildings and renovated buildings. However, TABS needs to be installed in the construction phase of a building, which limits the use of TABS in renovation projects. To address this limitation and to bring the benefits of TABS to renovation projects and to lightweight buildings, a particular type of radiant ceiling panels has been emerging. This technology combines PCMs with radiant ceiling panels to create a similar system to TABS—i.e., PCM radiant ceiling panels. Pipes are embedded in the PCM. Water is circulated in pipes to control the charging (melting) and discharging (freezing) behavior of PCM, which in turn controls the thermal environment in indoor spaces. This is a promising solution and has been proven to perform similar to TABS in terms of operation, energy performance, heat removal from rooms, and resulting thermal indoor environment [232–235].

Radiant cooling systems have many benefits compared to more conventional (e.g., all-air) cooling systems. The use of high-temperature cooling enables the system to couple to natural heat sources and sinks, such as ground, lake water, or seawater [236–238]. It also creates favorable operating conditions for heating and cooling plants (mainly due to operating temperature ranges and return temperatures), increasing the efficiencies of heat pumps, chillers, and boilers [81 83]. Radiant cooling systems have the possibility of transferring peak cooling loads to off-peak hours, reducing peak power demand [237]. Further benefits of radiant systems have been summarized by Kazanci [206]. One of the major characteristics of radiant systems is that they address only sensible heating and cooling loads. Therefore, they need to be coupled with ventilation systems, usually in the form of a dedicated outdoor air system (DOAS). The main function of ventilation systems is to regulate humidity (i.e., to dehumidify the air) and provide fresh air to indoor spaces [230]. There are various combinations according to the location of radiant surfaces and air distribution principles. A summary of the coupled system configurations and their performance in terms of thermal comfort and air quality have been systematically discussed in [239].

Radiant heating and cooling systems can be applied in almost all climates and building types. The main challenge for using radiant cooling systems is avoiding condensation; therefore, its applications in humid climate zones require careful design and operation considerations. Studies have shown that when properly designed, controlled, and coupled with an appropriate ventilation system, radiant cooling systems can also be applied in hot-humid climate zones without problems [240–243].

Radiant systems have similar characteristics under heatwaves and power outages. The absorptive and adaptive capacities of radiant systems under heatwaves and power outages range from low to high - low for radiant ceiling panels, high for TABS, and in between those two systems for the radiant surface systems. This is because these systems have different amounts of thermal mass, and, therefore have different operations, heat removal, and heat storage characteristics. For example, due to the available thermal mass, TABS can provide cooling even if there is no active heat removal from the TABS structure for a period (e.g., no chilled water circulation in the pipes in case of a power failure) and under a heatwave, the pre-cooled thermal mass will be able to absorb a certain amount heat from the space.

The restorative and recovery capacities of radiant systems under heatwaves and power outages are high. This is because all system types have the ability to return to normal or improved operation once the heatwave is over or power is back, and this can be done immediately.

The previously described radiant cooling systems (i.e., radiant cooling panels, radiant surface systems, and TABS) are available in the market. These systems and their components can be purchased by building owners (e.g., for a residential building) and also by building contractors. Note that, whereas the radiant ceiling panels with PCMs that were described in this chapter, are not yet available in the market, all of their individual components are market available (i.e., PCMs, piping, and metal panels).

4.3. Enhance personal comfort apart from space cooling: Personal comfort system

A personal comfort system (PCS), also known as personalized conditioning system, is a device to heat and/or cool individual occupants directly or heat and/or cool the immediate thermal environment of an individual occupant, under the control of the occupant without affecting the thermal environment of other occupants [244].

In contrast to total volume systems which condition entire indoor spaces, PCS devices condition the immediate surroundings of the occupants, creating micro-environments that can (1) extend the range of temperatures that is generally perceived as comfortable, thereby reducing the energy used by mechanical space conditioning; and (2) accommodate the interpersonal thermal differences that are inherent in any occupancy, thereby increasing the percentage of comfort in the space over that possible with uniform environmental control. The improved comfort may also increase occupants' productivity.

Cooling PCS devices may involve the following technologies:

- Vertical-axis ceiling fans and horizontal-axis wall fans (such fixed fans differ from pure PCS devices in that they may be operated under imposed central control or under group or individual control)
- Small desktop-scale fans or stand fans
- Furniture-integrated fan jets
- Devices combining fans with misting/evaporative cooling

- Cooled chairs, with convective/conductive cooled heat absorbing surfaces
- Cooled desktop surfaces
- Workstation micro-air-conditioning units including personalized ventilation, some including phase change material storage
- Radiant panels (these are currently used less for PCS than for room heat load extraction)
- Conductive wearables
- Fan-ventilated clothing ensembles
- Variable clothing insulation: flexible dress codes, variable porosity fabrics.

PCS devices offer both comfort and energy benefits. PCS devices use very small amounts of energy, making them inherently suitable for resilience applications and adaptable for use during energy emergencies. PCS devices allow occupants to personally control their thermal microenvironments and thereby satisfy their individual comfort requirements. Such comfort requirements differ due to variations in gender, age, body mass, clothing habits, and metabolic rate, and thermal adaptation [245]. The only published case of a field study of office workers reporting 100% satisfaction involved PCS installed in each workstation [246]. In a large-scale field study, Kroner and Stark-Martin [247] suggested that it is possible to increase productivity by at least 2% using PCS.

PCS devices offer an opportunity to save HVAC energy in buildings. Since it is possible to relax the room temperature range in either the hot or cold direction due to the use of personalized heating, ventilation or cooling, total HVAC energy use can be reduced at a rate of 10% per K room temperature setpoint relaxation [248,249]. Savings of this magnitude exceed those of virtually any energy-conserving technology available in the industry. Widening the temperature range for energy must continue to ensure occupants' comfort, or at least provide the same level of comfort as in current buildings. Occupants themselves require far less energy to heat and cool than does the entire indoor space that houses them. PCS offers the opportunity to accomplish this. With small amounts of energy, it can provide individual comfort within a broader range of indoor ambient temperatures (varying over both time and space).

The application of PCS enables relaxing the temperature requirements for the ambient zones in buildings. This is based on the assumption that the occupants have available to them individually controlled PCS devices at their workstations and that there is general elevated air movement provided in other zones of the building where they may spend time. Advantages for resilience include

- Flexibility in space heating and cooling temperature setpoints - the possibility of extended setpoints compared to traditional systems such as extending the room temperatures below 20 °C in the heating season and extending the room temperatures above 26 °C in the cooling season; these temperatures are based on the Category II of EN 16798–1:2019 [250]. This possibility will allow operating flexibility and will not load the cooling plant unnecessarily during an extreme event (e.g., a heatwave) or coming back to normal operation after an extreme event, and occupants can still be comfortable at high indoor temperatures, as they would have personalized cooling systems.
- Possibility of reduced-size cooling plant or a plant that is run part-time during periods beneficial to the electricity grid and supply sources.

PCS devices have no absorptive capacity under heatwaves, as absorptive capacity mainly relates to building envelope and structure. Under heatwaves, PCS devices have a high adaptive capacity as PCS or the user controlling the PCS can adjust its cooling output until its maximum capacity.

PCS devices have no absorptive capacity under power outage events, as absorptive capacity mainly relates to building envelope and structure. Assuming that there are no batteries or emergency power generators during the power outage, PCS have a low adaptive capacity as only certain PCS technologies will be able to keep on functioning (such as conductive wearables, fan-ventilated clothing ensembles or PCM assisted PCS).

PCS devices have high restorative and recovery capacities under heatwaves and power outage events, as the PCS will be functioning normally once the heatwave or power outage is over, and it will be able to recover immediately as long as the system has not been physically damaged.

PCS devices are applicable in all climate zones. The above-listed PCS devices are commercially available; however, their availability could change from country to country. Even though there are commercially available products, the technology is not as mature as some of the other technologies e.g., compression refrigeration.

4.4. Remove latent heat from indoor environments: High-performance dehumidification including desiccant dehumidification

Removing latent heat from indoor environments through dehumidification is an essential and important method, especially in hot and humid climates, to reduce cooling load and increase human comfort [251]. In high-performance buildings, the percentage of dehumidification energy consumption from the building's total energy consumption can be as high as 13–22 % [252]. There are many dehumidification methods reported in the literature and applied in practice, including desiccant dehumidification, refrigeration dehumidification, ventilation dehumidification, and thermos-electric dehumidification. Desiccant dehumidification is to utilize the humidity-absorbing material to absorb moisture. Refrigeration dehumidification uses a conventional vapor compression cycle to dehumidify the humid air through cool-reheat processes. Thermos-electric dehumidification is to utilize the thermoelectric effect (Peltier effect) to convert electricity into a temperature difference across a Peltier module. The module includes cold-side heat sink and hot-side heat source. Humid air driven by the fan flows over the cold side heat sink and the air is dehumidified. Ventilation dehumidification replaces humid indoor air with dry outdoor air.

Dehumidification technologies absorb the impacts of heatwaves by decreasing the humidity of indoor air, which improves the comfort level and relieves part of the pressure of other cooling systems. Desiccant refrigeration (see Section 4.2.4) and thermos-electric dehumidification technologies work in principle in areas with humidity higher than comfort level, while ventilation dehumidification technology works in areas with dry outdoor air. Desiccant, refrigeration, thermoelectric dehumidification, and mechanical ventilation dehumidification each require electricity and therefore are not very robust to power outages. Ventilation dehumidification through natural means could operate during a power outage, but its capacity to remove latent heat depends on building characteristics, local climate, and occupant behavior (see Section 4.2.1). Although dehumidification technologies could improve the thermal comfort level during a heatwave or recovery the thermal condition after a heatwave, their cooling capacity is limited due to the fact, they only take care of the latent heat in the indoor environment.

All these technologies have been well developed and commercial products are available in the market in the forms of either large dehumidification plants or small household dehumidifiers. Both individual consumers and building contractors are quite free to purchase dehumidification products, although the desiccant dehumidification plants are usually purchased by building contractors.

5. Assessment and comparison of resilient cooling strategies

A qualitative assessment of the resilience of cooling strategies is performed based on the criteria developed in Section 2. The resilience criteria include absorptive capacity, adaptive capacity, restorative capacity and recovery speed. Different disruptions or extreme events will have different effects on the cooling systems. 'Temperature hazard' was identified as the primary risk associated with the cooling strategies in buildings, which represents the overheating risk in buildings that threatens human health, activities and productivity [253]. Heatwave and associated power outages are identified as major disruptions because they have direct impacts on the thermal environment of buildings and they are listed as dominant threats faced by cooling systems, as stated by Attia et al.[23]. Therefore, the four resilient cooling criteria are evaluated separately for two extreme events in this study: heatwave or power outage. The resilient cooling strategies assessment framework is illustrated in Fig. 4.

We present the following approach to evaluate the resilience characteristics.

- **Absorptive capacity** can be calculated as the ratio of the absorbed heat load (or heat storage) to the change in heat load during a certain disruption.
- **Adaptive capacity** can be calculated as the ratio of the heat load reduction to the change in heat load during a certain disruption.
- **Restorative capacity** can be calculated as the ratio of the heat removed from the building to the heat stored after a certain disruption.
- **Recovery speed** can be calculated as the time required to remove the stored heat from a building until reaching a designed thermal condition.

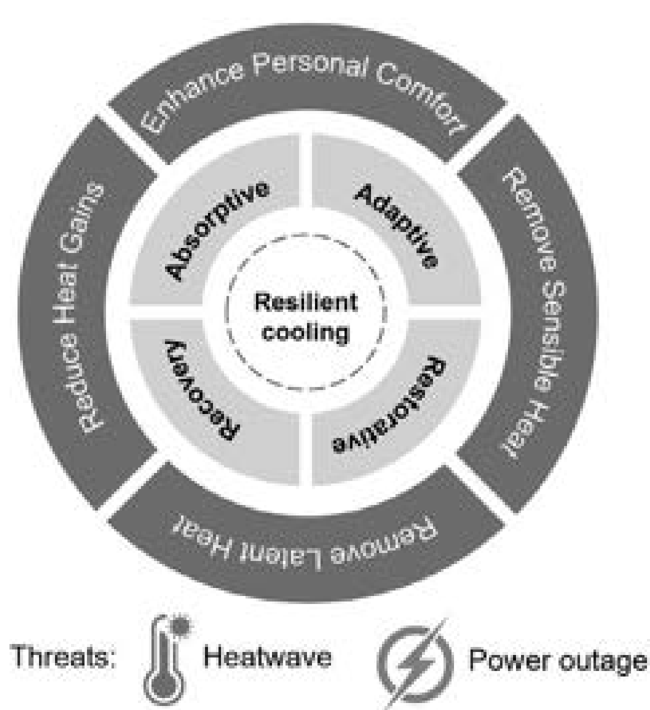

Fig. 4. Resilient cooling strategies assessment framework.

The resilience capacities can be evaluated into three categories: high, moderate and low. For recovery speed, high is within one hour, moderate is several hours, and low is one or more days. The other capacities are categorized by the following criteria:

- High: the strategy can maintain or even increase its cooling or heat-load-reduction capacity during a certain event. For example, a building's heat load might double during a heatwave or power outage due to the extreme high outdoor temperature or the failure of the mechanical cooling system. (The strategy can increase its cooling capacity to deal with a high heat load during a heatwave or power outage.)
- Moderate: the strategy can maintain its cooling or heat-load-reduction capacity most of the time during a certain event. (The strategy keeps the same cooling capacity during a heatwave or power outage.)
- Low: the strategy will experience a decrease in cooling or heat-load-reduction capacity during a certain event. (The strategy reduces cooling capacity during a heatwave or power outage.)

Besides the resilience capacities under extreme events, the cooling strategy's applicability in terms of climate zone and technology readiness level are summarized in Table 3. The climate zone classification is based on ASHRAE Standard 169 [254], as illustrated in Fig. 5.

A qualitative method is used in this study, which relies on the literature review carried out in Section 4 and focus group discussion. IEA-EBC Annex 80 participants were invited to provide evaluations of the resiliency capacities for all cooling strategies based on the categories proposed above. The participants are scientific and professional experts in the field of cooling technologies and building environments. The collected results were compared and discussed within the focus group based on the results of the literature review and their expertise and experience, to reach a final rating for each cooling strategy.

Table 3 presents assessment results of different cooling strategies where addresses the four resiliency criteria, application and technology readiness level. We obverse that cooling strategies contributing to reducing heat gains to the indoor environment generally show a moderate to high absorptive capacity under heatwaves. These strategies, such as solar shading/glazing, cool envelop materials, ventilated or evaporated envelop and thermal mass, mainly relate to the design of building structure and envelope, and should be considered in the early design phase of the buildings.

The cooling strategies with dynamic or flexible control present a high adaptive capacity under heatwaves. For example, a well-designed mechanical cooling system, such as compression refrigeration, absorption refrigeration, or active cooling with natural heat sink, could adjust its cooling capacity to fulfill the demand based on the change of the indoor and outdoor conditions or even prepare the system before the extreme event occurs if predictive control is available. However, active cooling systems strongly rely on the power supply and are not robust to the power outage. As mentioned in Section 4, an alternative approach to increase their robustness is to have local or on-site power production or connected to electrical or thermal energy storage. Another group of cooling strategies that show a high adaptive capacity under heatwaves is PCS devices, such as local fans, local cooled surfaces, or wearable systems. Instead of providing space cooling, these devices could enhance personal heat loss, and allow thermal comfort with higher ambient temperatures. In addition, PCS allow personal control of the microenvironment without affecting the thermal environment of other occupants. Even though PCS devices require a power supply, they could reduce cooling plant size or run part-time during periods beneficial to the electricity grid and supply sources.

Table 3
Assessment of cooling strategies, in term of resilience capacities, applicability, and technology readiness.

Cooling-strategy categories	Cooling strategies	Resilience under extreme events								Climate zone	Technology readiness level (TRL)
		Heatwave				Power outage					
		Absorptive capacity	Adaptive capacity	Restorative capacity	Recovery speed	Absorptive capacity	Adaptive capacity	Restorative capacity	Recovery speed		
A	Static solar shading/glazing	Low-Moderate	Low	N/A	N/A	Low-Moderate	Low	N/A	N/A	All	9
	Dynamic solar shading/glazing	Moderate-High	High	N/A	N/A	Low	Low	N/A	N/A	All	9
	Cool envelope materials	High	N/A (High for thermochromic CEMS)	N/A	N/A	High	N/A (High for thermochromic CEMS)	N/A	N/A	All (preferable for 0-4B)	Light-colored and cool-colored CEMs: 9; other CEMs: 4–6
	Green roofs, roof pond, and green facades	High	Moderate- High (Low for some plant species)	Moderate-High (Low for some plant species)	Moderate-High (Low for some plant species)	High	Moderate-High (Low for some plant species)	Moderate - High (Low for some plant species)	Moderate-High (Low for some plant species)	All	Green roofs and façades: 9 - roof ponds and evaporative systems: 4–8
	Ventilated roofs and facades	Low-Moderate	Moderate - High	Moderate-High	Moderate-High	Moderate-High for passive system; Low for activity system	Moderate for passive systems; N/A for active systems	Moderate - High	Moderate-High	All	4–9
	Thermal mass including PCMs	High	N/A	Low-High	Moderate	High	N/A	Low - High	Moderate	All (less effective 0–2)	4–9
B	Passive ventilative cooling	Low	Moderate	Moderate	Low - Moderate	Moderate-High	Moderate	Moderate	Low - Moderate	All (less effective in 0A, 0B, 1A, 1B)	9
	Active ventilative cooling	Moderate	High	High	Moderate - High	Low	N/A	High	Moderate - High		
	Adiabatic/ evaporative cooling	Moderate	High	High	Moderate - High	Moderate	Moderate	High	Moderate-High	All except 0A, 1A	9
	Compression refrigeration	N/A	High	High	High	N/A	N/A	High	High	All	9
	Absorption refrigeration including desiccant cooling	N/A	High	High	High	N/A	N/A	High	High	All (preferable 0A,1A, 2A)	9
	Passive ground source cooling	Moderate	Moderate	High	Moderate - High	High	Moderate	High	Moderate - High	All	9
	Active ground source cooling	High	High	High	Moderate - High	N/A	N/A	High	Moderate - High		
	Sky radiative cooling	N/A	N/A	Low-Moderate	Low-Moderate	N/A	N/A	Moderate	Low - Moderate	Increased performance in climates that are cold or with high seasonal variation (4, 5, 6) and dry (C, B) compared to hot and warm (2, 3) humid (A) climates.	7–9
	High-temperature cooling system: Radiant cooling	Low - High	Low - High	High	Moderate - High	Low - High	Low - High	High	Moderate - High	All	9

Table 3 (*continued*)

Cooling-strategy categories	Cooling strategies	Resilience under extreme events								Climate zone	Technology readiness level (TRL)
		Heatwave				Power outage					
		Absorptive capacity	Adaptive capacity	Restorative capacity	Recovery speed	Absorptive capacity	Adaptive capacity	Restorative capacity	Recovery speed		
C	Personal comfort systems	N/A	High	High	High	N/A	N/A or Low (e.g., fan-ventilated clothing ensembles)	High	High	All	5–9
D	Dehumidification including desiccant dehumidification	N/A	Moderate- High	Moderate	Moderate	N/A	N/A	Moderate	Moderate	All (preferable 0A,1A, 2A)	9

The cooling strategies used to remove sensible and latent heat present moderate to high restorative capacity. Mechanical cooling systems, such as compression refrigeration and absorption refrigeration can efficiently remove the surplus heat from the indoor environment in a timely manner regardless of the outdoor climate. However, the cooling systems utilizing natural heat sinks can remove the surplus heat only when there is a temperature difference between heat sinks and the indoor environment. Depending on the physical properties of natural heat sinks, ground-source cooling and evaporative cooling are more efficient than ventilative cooling under heatwaves. The recovery speed of cooling systems is influenced by the cooling potential (cooling capacity of mechanical systems, the temperature difference between natural heat sinks and indoor environment for natural or hybrid systems), design of the cooling system (for example, the window opening area and amount of thermal mass), and control or operation of the cooling system (for example, occupant behavior on window opening). In some situations, a certain cooling or building design might benefit to one resilience criteria but results in a negative impact on the other criteria. For example, a building with heavy thermal mass might have a high absorptive capacity, but have a low recovery speed due to all the stored energy that needs to be removed before the indoor environment can return to acceptable thermal conditions.

6. Discussion

6.1. Findings and recommendations

This section presents the primary findings of this study and provides recommendations to the building designers and engineers on how to address resiliency characteristics in the early design stages.

1. Resilience should be considered as an important property for cooling systems integrated with the building, together with energy efficiency, sustainability and economic affordability. Energy efficient cooling strategy does not equal to resilient cooling strategy. Sometimes, "Excessive striving for energy efficiency" could compromise a building's ability to maintain comfortable thermal conditions during extreme events.
2. The resilient characteristics of cooling strategies are summarized by four criteria – absorptive capacity, adaptive capacity, restorative capacity and recovery speed. The definition of the criteria and a qualitative approach for evaluating the resilience characteristics are proposed in this study.
3. As suggested by Attia et al. [23] and Miller et al. [253], the assessment of resilience must be based on the identification of a specific threat or disruption. 'Temperature hazard' is identified as the primary risk associated with the cooling systems in buildings, and heatwave and associated power outages are identified as major disruptions since they have direct impacts on the thermal environment of buildings.
4. Cooling strategies for reducing heat gains to the indoor environment present high absorptive capacity under heatwaves. These cooling strategies strongly relate to the design of building structure and envelope, and should be considered in the early building design phase. Cooling strategies with dynamic or flexible control present a high adaptive capacity under heatwaves. These strategies could adjust their operating mode depending on the indoor and outdoor condition or even prepare the systems or buildings before the extreme event occurs. PCS devices also present high adaptive capacity, which could allow thermal comfort with relatively higher ambient temperatures and provide personal control over the microenvironment without affecting the thermal environment of other occupants. Cooling

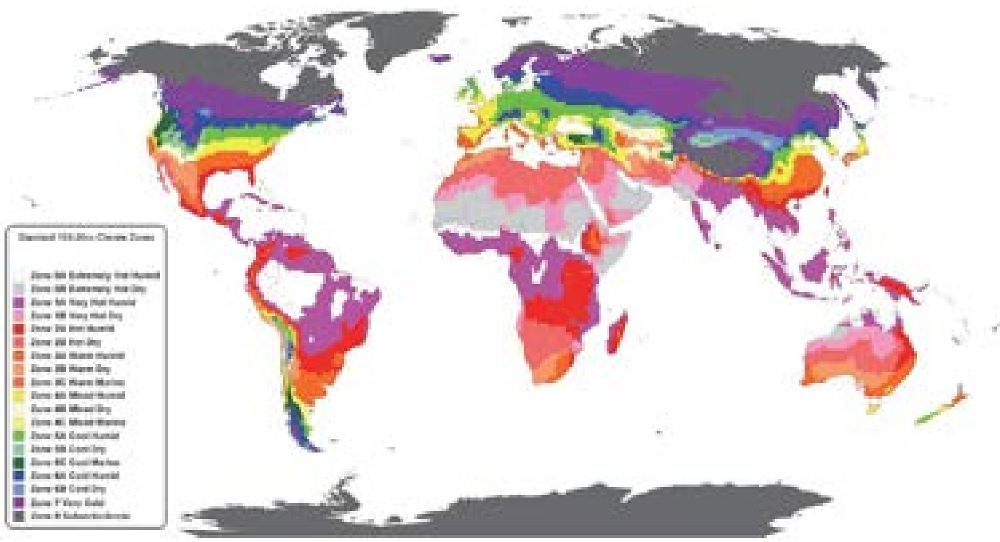

Fig. 5. Climate zone classification scheme used in ASHRAE Standard 169 [254]

strategies for removing sensible and latent heat present high restorative capacity. The mechanical cooling systems can remove surplus heat from the indoor environment efficiently without being influenced by the outdoor climate. For those cooling strategies that use natural heat sinks, such as air, water, ground and sky, the temperature difference between the heat sink and indoor environment is critical for the efficiency of these cooling strategies. The recovery speed (rapidity) of cooling strategies depends on multiply factors, such as cooling potential, design of the cooling system and control or operation of the cooling system.

5. To attain resilient cooling, the four resilience criteria should be considered from the design phase. The building and relevant cooling system characteristics should be considered simultaneously to withstand extreme events. The literature review indicates that a single cooling strategy normally does not contain all the capacities or high levels of capacities. Therefore, a combination of cooling strategies with different capacities might be needed to obtain resilient cooling, and there may not be a universally optimal solution as certain cooling strategies might perform better in certain climates.

6.2. Limitation and future directions

The study applies a qualitative approach to assess the resilience of various cooling strategies. Some limitations observed by using the qualitative approach, are explained below.

First of all, the amount of literature that discussed the resilience of cooling strategies under extreme events is limited. The literature review indicated that resilience is still a relatively new concept for the development, characterization and evaluation of cooling strategies. The current researches strongly focus on the energy efficiency and performance of the system under ‘typical’ operating conditions. However, the systems perform and respond to the disruptions, and the strategies for increasing the system resilience require future research. Secondly, the literature studies analyzed cooling performance under very different boundary conditions, from weather datasets, reference building, system design and operation, to performance indicators, which is difficult to conduct a direct comparison between different cooling strategies based on the results of these studies. Finally, the resiliency capacities proposed in the current study are qualitative and theoretical concepts. Even though we proposed categories for evaluation (low, moderate and high), the outcome is a rather subjective assessment of resilience than reaching an objective measure.

As a consequence, it is a challenge to provide a concrete assessment and direct comparison between different cooling strategies based on the qualitative approach. There is a strong need for a more technical or quantitative resilience assessment methodology. A numerical approach with consistent and measurable metrics for the characterization of resilience capacities will be the further direction of Annex 80.

7. Conclusions

Resilience should be considered as an important property of the cooling systems integrated with buildings, to cope with extreme events such as heatwaves and power outages. This study performs a systematic literature review on the state-of-the-art of cooling strategies, with special attention to their performance under extreme events. A definition of resilient cooling is developed and four criteria are proposed to describe resilience characteristics, including absorptive capacity, adaptive capacity, restorative capacity, and recovery speed. The developed resilience characterization scheme is used to assess the resilience of various cooling strategies qualitatively.

The literature review indicates that resilience capacities depend on many parameters: the function of cooling strategies (reducing heat gains, removing sensible/latent heat, or enhancing personal comfort), the driven forces (passive or active), design feature, and control and operation of the cooling system. A single cooling strategy normally does not contain all the resilience capacities, therefore, a combination of cooling strategies with different capacities is important to obtain resilient cooling of buildings.

The limitation of the qualitative resilience assessment approach is discussed. There is a strong need for a quantitative assessment framework with specified boundary conditions and consistent and measurable performance indicators. A numerical-based approach will be developed and discussed in further study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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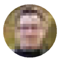

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Chapter

Review on District Cooling and Its Application in Energy Systems

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Abstract

This chapter investigates the implementation of district cooling systems by exploring several research studies reported in the literature. The topics addressed include typologies and design parameters, benefits and limitations, applications of the system, and the technology readiness level. District cooling systems are generally regarded as cost-efficient and environmentally friendly solutions. One might think that district cooling is only a solution for areas with a very warm climate. However, based on the reported results of the surveyed studies, the number of operating district cooling systems has increased over the years, with the Scandinavian countries taking the lead in this market within European countries. Implementation of these systems concluded reduction in primary energy and electricity use, they also proved to be an environmentally efficient way.

Keywords: district heating and cooling system, district cooling, free cooling

1. Introduction

With the increase in population and urbanization, energy use also has grown rapidly worldwide. Energy use in the building sector (commercial and residential buildings) has increased between 20 and 40% in developed countries [1]. Several researchers have worked on moderating the use of fossil fuels by introducing alternative energy sources such as industrial waste heat, biogas and biomass, nuclear energy, geothermal and solar energy, groundwater [2–5]. The European Union is responsible for 33% of the total CO_2 emission [2]. Based on the European Green Deal, the European Commission has provided an action plan to ensure energy transition as the EU aims to become the first climate-neutral continent by 2050 [6]. To oblige with these implications, energy-saving technologies have to be integrated into different energy sectors, especially the building sector since the energy demand is 36% of the global final energy use [7]. Studies have been conducted to analyze the increased use of biomass to reduce CO_2 emission in different sectors such as transportation and building sectors [8, 9]. One way of reducing the amount of resource use is to connect several customers' heat and cold demands with the available sources [10]. District energy systems are said to promise energy security as they offer flexibility in their energy use compared to individual energy systems [11]. The heating or cooling resources can be from renewable sources of energy as well as non-renewable sources.

The cooling energy demand for buildings varies depending on countries and their outdoor temperatures. Buildings have various cooling demands due to the differences in the construction material, size, occupant behavior, the purpose of the building, etc. However, it should be pointed that even identical buildings have different cooling demands depending on the kind of activities within the building. Due to the recent changes in climate and its implications on the energy performance of the buildings and indoor thermal conditions, different space cooling technologies have gained more attention. It is likely to predict the growth of cooling demand in Europe due to rising ambient temperatures (including heat waves), heat island effects, higher thermal insulation levels, increased comfort desires/requirements, and the fact that saturation of cooling demand is significantly lower than in the USA and Asia. Estimated cooling saturation for commercial and residential buildings in the USA was 80 and 65%, respectively, and Japan had 100 and 85%, respectively, in the year 2005. Corresponding cooling saturation numbers for Europe were 27 and 5%, respectively [12]. The cooling saturation for EU27 has passed 40% for the service sector and is around 7% for residential buildings [12]. It has been estimated that 10% of all building areas in EU28 were cooled and covered around 16% of the total cooling demand in the year 2014 [13]. In Europe district cooling was introduced in the 1990s; however, it is still a rather uncommon cooling solution with a market share of only around 1% of the cooling market in 2014 [12].

The desired indoor conditions can be met using individual cooling devices such as air conditioners, central air conditioning systems, or district cooling system (DCS). The district cooling system supplies chilled water for cooling and dehumidification to a group of buildings in a district (city, neighborhood, or campus). The coolant (usually water) is typically generated at a central chiller plant and circulates through a distribution network between a central cooling plant and the buildings in the district [14, 15]. **Figure 1** depicts a DCS using a natural source such as a lake/sea to cool the buildings. It is generally referred to as free cooling.

Water in the district cooling network gets cold from nearby natural cold sources, such as a river/sea, and if needed from the cooling machines, that is, when the temperature of the cold source (the river) is high. The combination of free-cooling and cooling machines demands less electricity compared to separate heat pumps or cooling machine installations in every building.

Water from the river/sea is used to cool the water in the district cooling network. When the district cooling water is cooled to 6°C, it is pumped to the connected building/consumers through the distribution network that comprises supply and

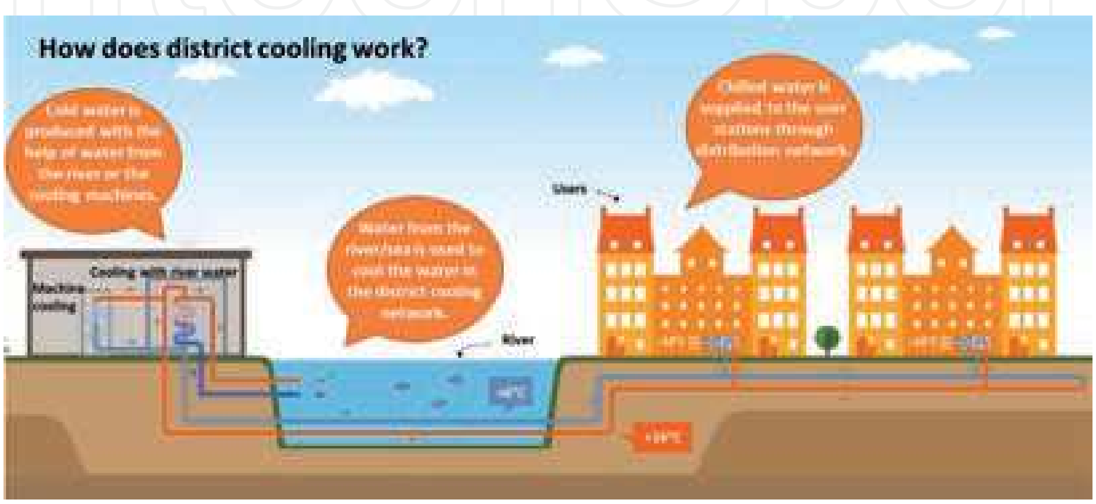

Figure 1.
Schematic of a district cooling system (DCS). Reprint with permission from Gävle Energi AB [16].

return pipe. The cold and heat carriers in the district network are generally in the form of pressurized water and to be economical, the dense urban areas appear to be a fulfilling choice as the distribution pipes should be short [10].

Cold is delivered to the consumers (offices, buildings, industries, server halls, etc.) through the district cooling network with the help of the heat exchangers at user buildings [17]. Cold can be delivered to the cooling coils (to cool the supply air in the air handling units) or via chilled beams installed in the building zones.

Overall, as seen in **Figure 1**, four major parts could be introduced in a district heating or cooling system: the main supply unit, distribution networks, user stations, and finally the heating or cooling system inside the building's zones. Cold can be supplied for industrial purposes too, such as food preparation, although it is beyond the scope of this chapter.

It is possible to incorporate either a single or multiple cooling technologies in the DCS central chiller plant depending on the available energy sources (thermal or electrical), environmental and economic considerations as well as the demand profile. Absorption chillers are among the available options for chiller plants. Absorption chillers use heat and not electricity as their primary source of energy [18]. They possess a lower COP (coefficient of performance); however, the electricity consumption and primary energy use are reduced in these chillers and the mechanical compressor of a compression chiller is substituted by a thermal compressor [19]. Renewable thermal energy such as biomass waste or solar energy could be utilized using heat-driven chillers or thermal power plants. In such plants, the heat could be transferred to electrical or mechanical energy to drive the vapor compression chillers. The triple-effect lithium bromide absorption chillers could be exploited for DCS as they could be driven by higher-grade sustainable heat sources [20].

Free cooling is another option for a central plant. The available natural cold sources are involved in cooling the building; the heat will naturally flow out without the need of the compressor and the vapor-compression refrigeration system [15, 21–23]. Rivers, lakes, the sea, and outdoor air are among the natural cold sources. By using seawater air conditioning, deepwater conditioning could be employed as in this situation, and the water temperature is well below the ambient temperature (generally around 5°C). For such DCS, it is possible to utilize 100% free cooling. However, given the lack of natural cold sources, free cooling could be combined with other cooling technologies such as absorption chillers to compensate for the lack of available cold from the lake/sea, especially on a seasonal basis. An approach to using naturally cold water is cold district heating and cooling [24]. In this context, the cold water from the lake, sea, etc., is used for direct or active cooling in the system and serves as the cooling fluid. With the help of the decentralized chillers or pumps, the water is chilled or heated for the district system. A research project introduced seawater district cooling and analyzed the system through a case study in Diego Garcia [25]. It was concluded that the system was economically efficient and reduced maintenance and electricity usage.

This book chapter aims to investigate the implementation of district cooling systems by exploring research studies reported in the literature. The topics addressed include typologies and design parameters, benefits and limitations, applications of the system, and the technology readiness level.

2. Review method

To provide an overview of the available district cooling systems and their performance for different applications in various climate conditions, a literature review was performed.

Different databases have been used to identify available books and academic literature, including ScienceDirect, Google Scholar, and Scopus.

Keywords such as district energy, district cooling system, free cooling, absorption chillers, the resilient building were used. No limitation was applied on the publication period, though recently published works were prioritized.

3. Typologies (classifications) and design parameters

In this section, three different classification groups are proposed. The primary proposed classification is based on the system: Centralized and decentralized DCS. The former category is suitable for large-scale regions where the energy is distributed among several buildings in an area. The latter category is more suitable for small capacities where the energy conversion takes place in the units outside the buildings and then is transferred to the buildings [2, 26–28].

The second proposed category is based on the central plant: free cooling systems or the use of heat pumps and chillers [29–31].

The third category is based on the occupant behavior as well as the building typology, which is design parameters that can affect the energy use in the buildings. Occupant behavior mainly consists of interactions with operable windows, lighting, blinds, thermostats, and plug-in appliances. Building types are such as villa, retail, public office.

4. Benefits and limitations

Literature covers the benefits and limitations (disadvantages) of DCS. These benefits and limitations are categorized from three perspectives; environmental, operational, and economical.

Environmental advantages:

- District heating and cooling (DHC) possesses the ability to be integrated with renewable resources, consequently reducing greenhouse gas (GHG) emissions, and saves energy. The central water-cooled chiller plants on the large scale use a lower amount of energy and appear more efficient compared to the on-site small capacity systems [20, 32–34]. Therefore, DCS appears more successful in dense areas in a city or municipality since nearby these areas, there are generally some natural cooling or waste energy sources available [35]. However, these two criteria can be found in many areas and cities.

- A DHC system aims at saving primary energy, electricity, space, inhibiting air pollution, and reducing environmentally harmful refrigerants [36].

- A DHC system aims at saving energy and space, and inhibiting air pollution, and helps to eliminate environmentally harmful refrigerants [36, 37].

- District cooling can greatly reduce the electricity use and peak power demand, and thus reduce energy use, during the cooling season [35].

Environmental disadvantages:

- Depending on the central plants, DCSs may not totally be environmentally friendly as long-term use of the free cooling sources such as sea or lake might affect the temperature of the sources and limit the cooling capacity if no anticipating measures are considered. It also could affect the ecosystem of the sources [38].

- A free cooling system uses a vast amount of water, which is a problem in areas lacking water [30].

Operational advantages:

- Prevention of intensive use of chillers and machinery space in the user stations [39].
- Noise and structure load reduction [39].
- Saves space by removing the cooling tower and chiller plant from the buildings or roofs [39].
- A wide range of production methods and always the latest type of equipment are integrated with DCS due to mitigation measures against global warming [30, 40].
- District cooling has less requirement for technical staff on building level [34].

Operational disadvantages:

- Heat loss within the plant itself as well as the building serviced by the DHC due to distribution losses in pipes and heat exchangers is inevitable [41, 42].

Economic advantages:

- The transparency of costs and future proof investment due to easy payment of utility bills [30].
- The DCS is relatively flexible as different central plants could be utilized based on the fuel cost, therefore reducing the cooling cost [20, 35, 43].
- Owned by the municipality, a district cooling system can capture cash flows that were previously paid for imported natural gas or electricity [35].
- DCS can provide more job opportunities as it provides more reliable and flexible services by a specialized professional team [39].

Economic disadvantages:

- Selection of a system that shows large environmental benefits may, in fact, end up not being economical as both the environmental and economic aspects have to be considered together [32].
- In purpose to utilize cogeneration of district system and electricity, larger DHC is required [44].
- High initial investment costs and lack of negotiable prices and tariffs from the customer's side as DCS are often owned by few local energy companies, and there is a risk of monopoly for the cooling prices and tariffs [10].

5. Application, technology readiness level, and performance with a focus on resilience

In this section, DC cooling technologies, energy sources, operational aspects, and the applications of DC systems are reviewed based on implemented DC technologies through published DC design and analysis research. Before heading to the applications of the DC systems, the concept of resilience is introduced.

The resilience of the building is its ability to withstand extreme weather conditions and recover from the possible incurred damages efficiently and quickly [45]. Chen et al. [46] investigated the resilient cooling strategies and Hay [47] investigated resilience as a developing planning tool for communities. District energy was recommended as the technology that can balance the relationship between the communities and the region [47]. Sharifi et al. advocated for developing district energy systems, net-zero buildings, and neighborhoods as criteria for assessing urban energy resilience [48].

Based on a report from International District Energy Association (IDEA) [49], in 2019, 303 buildings and Ca 10.8 million ft^2 were added to the district systems, beyond North America, which is a strong growth in the district systems employment. The number of buildings and the area that was used for the system in 2018 correspond to 156 buildings and Ca 50 million ft^2. Based on the statistics in [50], 70% of residential end users in high-population areas in Europe were powered by fossil fuel in 2015. Hence, DHC networks show great potentials that can help in decarbonization and improvement of indoor air quality as these systems help to reduce the primary energy use by utilizing renewable sources of energy and reducing the thermal losses [51].

A few studies are introduced to show the performance of DCS through simulation and real data collection in different climate conditions and their effects on building's cooling loads. The studies that were dedicated to Asian countries are presented to show the diversity of DHC systems as Asian countries are developing more DHC systems to reduce air pollution, primary energy use, etc. Later in this section, research projects dedicated to DHS in Europe are introduced.

A study was conducted on the performance of DCS vs. individual cooling systems (ICS) in Hong Kong considering different chilled water pump schemes [52, 53] for commercial buildings. Based on the simulation results, DCS consumes around 15% less energy compared to ICS. The annual operation cost of DCS also is 10% lower than ICS under the electrical tariffs of Hong Kong.

Energy modeling of DCS was conducted in [14] in the South East Kowloon Development Project in Hong Kong for residential and commercial buildings. Based on the simulation results, chilled water, eutectic salt, and ice storage could respectively result in a 38, 38, and 22% reduction in installed cooling capacity. An et al. [54], Yan et al. [55], and Nagota et al. [56] analyzed the performance of DCS in districts in China and Japan and concluded the energy-saving effect of DCS. Studies were conducted with absorption chillers as the cooling technology in other parts of Asia such as Thailand [57], Turkey [58], Iran [59] and concluded the energy and carbon emission-saving effect of DCS. As it could be seen from the mentioned studies so far, the positive economic implication of the DHC system is generally observed from the conducted studies.

The Scandinavian market is taking the lead with 49 operating DCS, followed by Germany (28 operating DCS) and Italy (14 operating DCS) [30].

A detailed study on the market of DCS in Sweden is done by [60]. Major district cooling systems appear in Stockholm, Gothenburg, Linköping, Solna-Sundbyberg, Lund, and Uppsala. Based on the statistics reported by Energiförtagen [61], deliveries for 2018 totaled 1156 GWh. It was a record year for Swedish district cooling and an increase of 26 percent compared to 2017, due to an exceptionally hot summer. The total length of district cooling pipelines increased to 627 km, while in 2019, deliveries totaled 991GWh. **Figure 2** shows deliveries and network length from 1996 to 2019 [61].

From **Figure 2**, and the economic and environmental benefits provided through the expansion of DC capacity, a continued growth in DCS is expected.

Fahlén et al. [62] presented a study based on the DHC system of Gothenburg. Combined heat and power (CHP) plants and excess heat from industries supply about 80% of the heat. The study assesses the potential of absorption cooling technology to improve the economic and environmental performance of the DHC system. The results show potentials for cost-effective CO_2 emission reduction.

The use of absorption chillers in a DCS in Sweden was studied in [63, 64] and the energy performance of the system appeared to improve. A DCS was initiated in 1995, in the city center in Södermalm, Stockholm. Later, it was expanded and another area was added to the system. Both the districts are connected by pipes located in lake Mälaren [65]. In the Södermalm DCS, existing heat pumps in Hammarbyverket were used.

DCS design has evolved over the years from for example constant to variable flow in the distribution loop. These evolutions and updates in design practices have continuously been upgraded and employed in the system. A long-term security of supply is a driving factor in the heating/cooling systems especially in DHC since the heat/cold is generally supplied by local units. Therefore, it is important to upgrade the design in such a way as to achieve this aim. To be able to express a general reliability level, a definition has been anticipated as the system reliability rate for a

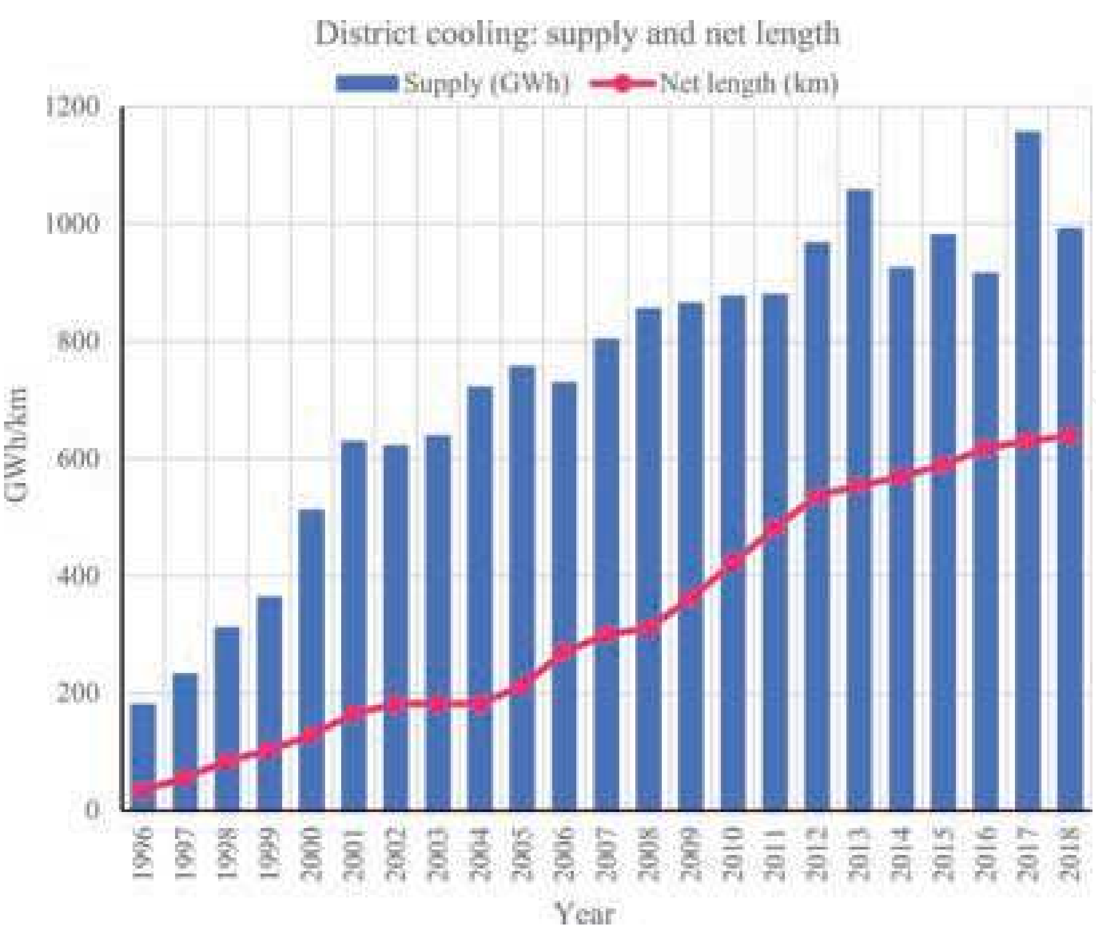

Figure 2.
District cooling deliveries (GWh) and network length (km) in Sweden [61].

DH system [10]. The rate is regarded as the ratio between the numbers of supplied available district heating to the customers during a year by total hours in a year [10]. Many factors are responsible for low system reliability rates such as the fuel supply, pipe failures in the distribution networks, water leakages caused by corrosion or pressure surges, and power outages. The latter mentioned factor also influences the short-term reliability of the system. All the mentioned incidents affect the resilience of the system. To compensate for the power outage, a backup electricity generation is generally anticipated for the main distribution pump. To measure the technology readiness level also, the U.S. Department of Energy has introduced a method to calculate the readiness level [66].

Another problem associated with DHC systems that affect the resilience of the system is the high delta-T syndrome. Due to several reasons, degradations occur over time, which deteriorates the standard temperature difference between the supply and return water that in turn affects the performance of the system. A research project was conducted on the low delta-T problem of the DCS in Gothenburg, Sweden [67]. The problem was analyzed by collecting operational data from the Gothenburg district cooling system along with chilled water systems from 37 of the connected buildings. The results depicted several solutions in the district cooling system to overcome a low delta-T and increase the return temperature. For instance, it was recommended to comply with the building design guidelines as well as limit the flow on the primary side of the heat exchanger, and this helps to restrict the operation in the saturation zone of the heat exchanger. A similar study was carried out by Henze et al. [68] on two university campuses in Massachusetts and Colorado and proposed a solution that provided additional cooling load to the campuses with the same central plant system. The mentioned issues raise the importance of maintenance of the system since the system has to be able to retain its ability to withstand future shocks such as those mentioned above, as well to extend its technical lifetime to remain resilient.

6. Energy efficiency and life cycle analysis

To quantify the energy efficiency of the DCS, three energy efficiency factors were proposed [55]. These factors are presented using Eqs. (1)-(3) and each is explained in this section.

"Coefficient of performance" of the chiller plant is represented by COP_{Plant} (Eq. (1)) where Q is the total cooling supply of the chiller plant. W_{plant} is the energy use of the DCS plant.

$$COP_{\text{plant}} = \frac{Q}{W_{\text{plant}}} \tag{1}$$

WTF_{distri} represents the "water transport factor" of the cooling distribution network system (Eq. (2)) where W_{distri} is the energy use of the cooling distribution system which is the total energy use of all secondary water pumps for chilled water.

$$WTF_{\text{distri}} = \frac{Q}{W_{\text{distri}}} \tag{2}$$

SCOP represents the "system coefficient of performance," which is the overall energy efficiency of the chiller plant and the distribution system (Eq. (3)). Based on the previous studies, 80% of the energy consumed by the chilled water pumps leads to cooling loss, which is due to the chilled water distribution; therefore, it must be accounted for in the calculation process.

$$SCOP = \frac{\left(Q - 0.8WTF_{\text{distri}}\right)}{W_{\text{plant}} + W_{\text{distri}}} \tag{3}$$

Keeping the efficiency of the system aside, the feasibility of a DHC system could be investigated by taking into account the cost analysis. To provide an effective evaluation of the energy system and the cost-effective alternatives, life cycle cost analysis (LCCA) could be considered. The energy performance and cost analysis of DCS have been evaluated in several studies [69–71].

LCCA takes into account the costs involving the construction, operation, and demolition phases [72]. The life cycle cost (LCC) is as below [71]:

$$LCC = C_{IC} + \sum_{1}^{n} PWF(i,n) \times \left(C_{\text{fuel}} + C_{OM}\right) - PWF(i,n) \times C_{\text{Dispose}} \tag{4}$$

$$PWF(i,n) = (1+i)^{-n} \tag{5}$$

where $PWF(i,n)$ is present worth factor; C_{IC} is initial capital cost; C_{fuel} is natural gas cost; C_{OM} is operational and management cost; C_{Dispose} is abandoned equipment cost; n is life cycle period and i is interest rate.

The dynamic payback period (PP) of investment, considering the time value of the capital, is calculated using Eq. (6):

$$PP = \frac{\ln\left[\left(1 - \frac{i \times C_{IC}}{C_{\text{power}} + C_{\text{cool}} + C_{\text{heat}} + C_{\text{hotwater}} - C_{\text{fuel}} - C_{OM}}\right)^{-1}\right]}{\ln(1+i)} \tag{6}$$

where C represents cost and the subscripts represent the respective parameters.

7. Conclusions

With the increase in energy demand, especially cooling energy due to climate changes and the rise in comfort requirements in buildings, meeting the future energy demand has gained more attention. Resilient, economic, and environmentally friendly solutions are required to meet the future energy demand. To fulfill the growing cooling demand and the community's growing concern about carbon footprint reduction and energy resilience, DC systems are becoming increasingly attractive to communities. District energy is a flexible system in terms of the sources as they can accommodate both cooling and heating. The main focus of the chapter was the district cooling systems and it was aimed to outline the possibilities and benefits of using a district energy system specifically the DCS. Three classification groups based on the system, central plant, and occupant behavior were proposed.

DCS can reduce electricity use and peak demands and be integrated with renewable resources, and, therefore, contributes to reducing greenhouse gas emissions and air pollution. Several sources can be used—free cooling together with electricity or thermally driven chillers. These systems are more efficient in more populated districts. Since the coolant is produced in the central chiller plant, not only the use of space in the building is minimized, but the noise pollution also is reduced. District cooling systems have been reported as economic and environmentally friendly solutions to meet the cooling demand of buildings. The investigated studies in this chapter reported a decrease in energy use when DCS was implemented.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

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Abbreviations

CHP	combined heat and power plant
CO_2	carbon dioxide
COP	coefficient of performance
COP_{plant}	coefficient of performance of a chiller plant
DC	district cooling
DCS	district cooling system
delta-T	temperature rise of the cooling water
DH	district heating
DHC	district heating and cooling
GHG	greenhouse gases
ICS	individual cooling system
SCOP	system coefficient of performance
Q	cooling supply of a chiller plant
W_{distri}	energy use of a cooling distribution system
W_{plant}	energy use of a chiller plant
WTF_{distri}	water transport factor
$PWF(i, n)$	present worth factor
C_{IC}	initial capital cost
C_{fuel}	natural gas cost
C_{OM}	operational and management cost
C_{Dispose}	abandoned equipment cost
C_{cool}	cooling cost
C_{heat}	heating cost
C_{hotwater}	hot water cost
n	life cycle period
i	interest rate

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