Slutrapport

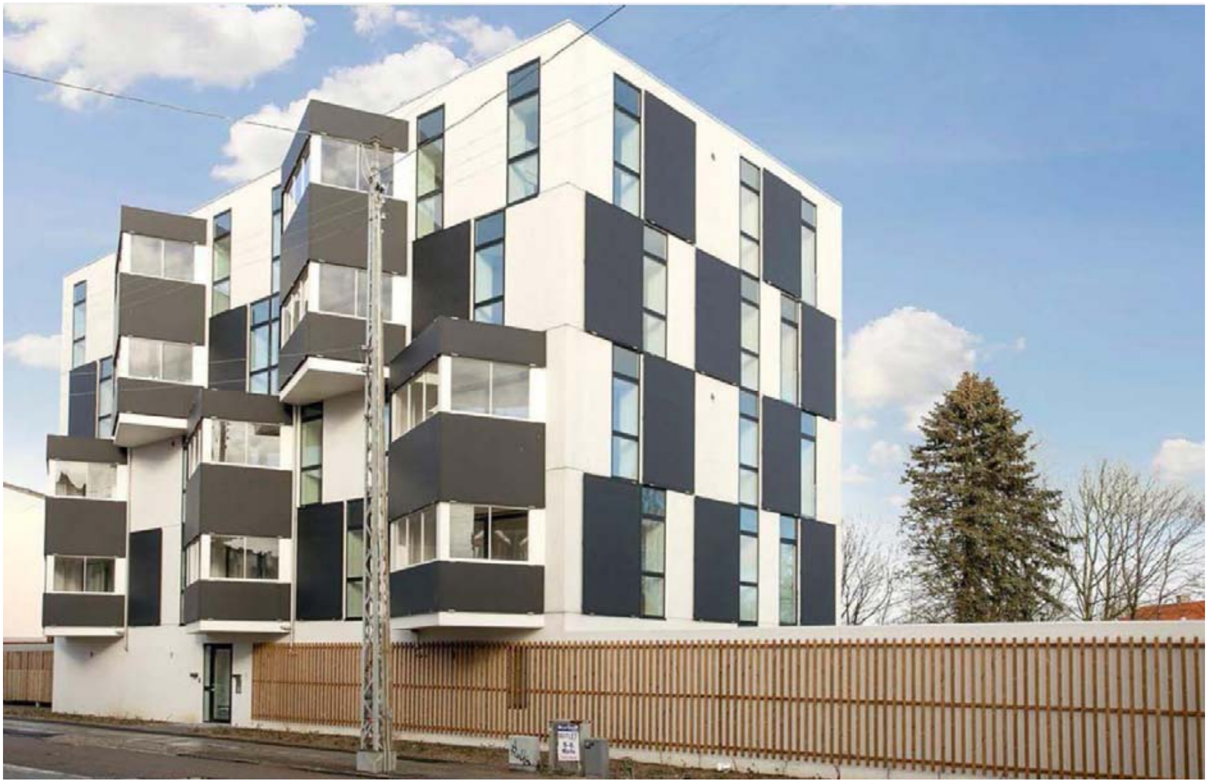
Energistyrelsen–EUDP 14-II

Journal nr. 64014-0561

Demonstration af kombineret solcelle- og solfangermodul (PVT) til etageboliger

Fase II

Oktober 2017



RACELL SAPHIRE Technologies ApS
MAP Architects
Priedemann GmbH
DTU Byg
A/B Nørrebrogade 233-237, Andelsboligforening

Forord

Denne rapport er slutrapport for projektet "Demonstration af kombineret solcelle solfanger modul (PVT) til etageboliger" er støttet af Energistyrelsen gennem energiforskningsprogrammet EUDP 2014-2 (journal nr. 644014 - 0561, og gennemført af følgende projektkonsortium:

I projektet deltog følgende:

- RACELL SAPHIRE Technologies ApS
- MAP Architects
- Priedemann GmbH
- DTU Byg
- A/B Nørrebrogade 233-237, andelsboligforening

Racell stod som projektansøger og projektansvarlig.

De enkelte partnere har følgende hovedroller:

- Racell er projektleder og fokuserede på det produktionsmæssige i udviklingen af PVT-modul/system, som baserer sig på deres viden og produktionsudstyr.

- Racell indgik en aftale med COWI om assistance, dels med administration, kommunikation, koordinering og planlægning af aktiviteterne, dels ved medvirken til at definere og analysere løsningerne, set ud fra et helhedssyn, hvor integrationen i byggeprocessen, økonomien og det lovgivningsmæssige spiller ind.

- MAP Architects medvirkede i team med de øvrige deltagere i udviklingen med design og arkitekturaspekter, herunder med at opstille krav, der kan sikre fleksibilitet og tilpasning.

- DTU bidrog til udviklingsfasen med ekspertviden. Demonstrationen af teknologien blev flyttet fra Nørrebrogade til et testområde på DTU og DTU-BYG stod for opførelse, indsamling af målinger og analyse.

- Andelsboligforeningen Nørrebrogade 233-237 (bygherren) deltog som bruger og blev inddraget som sådan. Endvidere bidrog foreningen med data mv., der brugtes som eksempel i udviklingsarbejdet. Grundet manglende byggetilladelser o.lign. problemer der gjorde det umuligt at opføre anlægget på Nørrebrogade som planlagt, blev der efter godkendelse af EUDP i stedet opført et anlæg på DTU. Desuden blev der mulighed for at afprøve bygningsintegrationen af PV elementerne på både facader og tag i fuldskalaforsøg på Bolig+, en ny etageejendom i Gladsaxe.

Projektet var fra starten tænkt som et projekt i to faser. Første fase blev afsluttet i 2015 og slutrapport er indsendt til EUDP i december 2015, var søgt i særpuljen for bygningsintegreret solceller, og bestod af udvikling og afprøvning af solcellemoduler til integreret anvendelse.

Denne rapport er slutrapport for 2. fase af projektet som blev bevilget særskilt af EUDP under den almindelig pulje (EUDP 14-II).

Indholdsfortegnelse

Side

Indholdsfortegnelse

Sammenfatning og konklusion

EUDP projektet har forsøgt for alvor at løse grundlæggende problematikker for PV til etageejendomme.

Brugen af solenergi er på trods af den ekstremt store vækst indenfor solcellebranchen og kraftigt faldende priser ikke slået igennem i urbane områder med etageejendomme. Dette er en kolossal udfordring i mange lande idet eksempelvis 40% af det samlede elforbrug i USA forbruges af højhusene i USA's storbyer.

EUDP projektet har målrettet udviklet løsninger til årsagerne for at PV teknologien endnu ikke anvendes til de højtforbrugende etageboliger. Projektet har således fundet løsninger til følgende grundlæggende problemer:

(A) Solceller på facaderne kan ikke udnyttes fordi nabobygningerne giver skygger en stor del af dagen.

EUDP løsningen: Der er udviklet en ny type facademodul PVT-E med en indbygget energiabsorber der medfører at modulet producerer varme- eller køleenergi også når der er skygger og også om natten.

(B) Solceller kræver et stort skyggefrit areal og dvs. at kun tagarealet er skyggefrit og kan benyttes. Dermed gælder, at jo højere en etagebolig er desto mindre solcelleareal er der til rådighed pr. lejlighed.

EUDP løsningen: PVT-E modulerne producerer op til 3 gange så meget energi som standard PV moduler. Derudover kan selve solcellerne køles aktivt af absorberen, så der kan produceres 15-30% ekstra elenergi.

(C) Ved bygninger med fritstående facader kan solceller ikke anvendes af æstetiske grunde, da der som regel kræves arkitektoniske facader.

EUDP løsningen: Der er udviklet moduler i alle størrelser som kan tilpasses bygningens former og farver.

(D) Solceller monteret på facaden kræver ventilation for at beskytte bypassdioderne og kræver dermed et kostbart stativmontagesystem. Kan af samme grund ikke kombineres med isolering af en bygnings gavl.

EUDP løsningen: PVT-E modulerne har ingen junktionboks og kan integreres fuldkommen i facaden som et ægte facadebygningselement. Isoleringsmateriale som stenuld kan lamineres ind i selve modulet. Standardsystemer fra flere fabrikater kan bruges, så man ikke betaler for montage af isolering. Ingen kodens.

(E) Manglende sikre tarifer for salg af overskydende strøm medfører en lang tilbagebetalingstid.

EUDP løsningen: Grundet at PVT-E modulerne både producerer op til 3 gange så meget energi og fordi de samtidigt kan erstatte udgifterne til et facade- eller tagbygningselement og er lette at montere, så er der tale om en økonomisk game-changer med en særdeles lav betalingstid.

(F) Solcellemoduler fremstilles kun i små enheder og kræver derfor for lang og kostbar montage.

EUDP løsningen: Udover at eksisterende montagesystem kan anvendes (RE-Air, STO skinner etc), så er der udviklet flere simple montagesystemer som reducerer montagearbejdet med en faktor 5. Der er også udtaget flere patenter i forlængelse af denne udvikling.

Samlet set har EUDP projektet vist så mange fordele at både teknologien og økonomien forventes at få et internationalt gennembrud.

Summary and conclusion

1 Indledning

1.1 Baggrund

Baggrunden for dette projekt er EUDP projektet "Udvikling af kombineret solcelle og solfanger modul (PVT) til etageejendomme" (J.nr. 1936-0014) som blev afsluttet i 2015 med slutrapport i december 2015. I dette projekt blev teknologien udviklet, mens ideen med nærværende projekt var at demonstrere teknologien hos andelsboligforeningen A/B Nørrebrogade 233-237.

Imidlertid opstod der en række hindringer for denne demonstration. Projektgruppen søgte derfor om tilladelse til at gennemføre demonstrationen på DTU på DTU-BYGs prøvestand og at foretage målinger og evalueringer på dette grundlag. Dette blev accepteret. A/B Nørrebrogade 233-237 har dog ikke opgivet projektet og arbejder fortsat på at komme videre med og har været i løbende kontakt med projektgruppen desangående.

1.2 Formål og indhold

Projektets formål var at demonstrere den i fase 1 udviklede teknologi.

I den planlagte demonstration på Nørrebrogade blev der allerede i fase 1 af projektet arbejdet på placering af moduler og udnyttelse af varme fra PVT panelerne. Det var her planlagt at der skulle PVT på gavlen og på taget, evt. kunne modulerne på gavlen være uden den termiske del da arealet til varmeproduktion eller ville blive for stort, mens den producerede el kunne udnyttes fornuftigt.

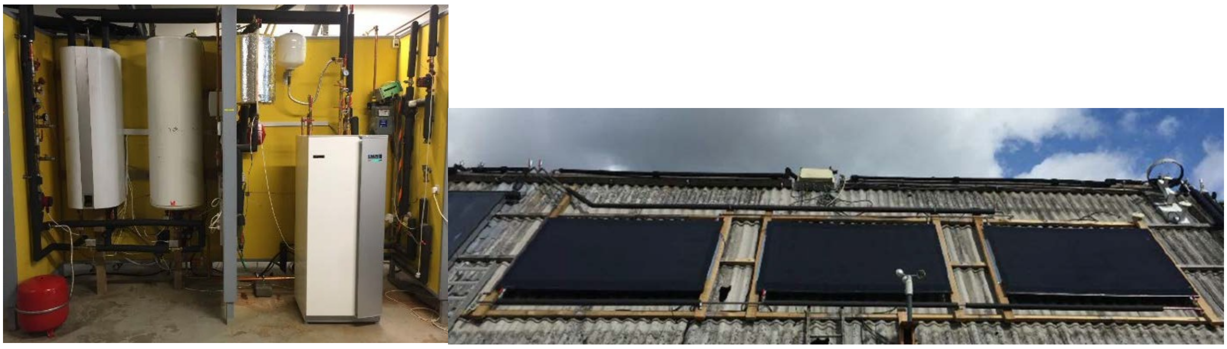
Udnyttelse af varmen var tænkt til forvarmning af varmt brugsvand i kælderen og til supplerende opvarmning af kælderen som i sommerperioden er kold og fugtig. Kælderen udnyttes delvist og der var allerede en vis opvarmning med fjernvarme. Det blev overvejet at indbygge en varmepumpe således at der kunne opnås en højere ydelse af PVT panelerne og leveres mere varmt brugsvand.

Da ønsket i fase II var at kunne demonstrere den nye type PVT i fuldskala og for at overkomme bureaukratiske problemer som byggetilladelser o.lign., blev demonstrationsopgaven opdelt i to dele:

(1) På DTU demonstreredes i hvilket omfang PVT anlægget kunne levere den ønskede energi til dynamiske forbrugsprofiler sv.t. en etageejendom og

(2) Bygningsintegration af store arkitektoniske moduler og udnyttelsen af disse blev demonstreret på en 5 etagers bygning i Gladsaxe både på skæve facader og på tag med diverse udtag.

På DTU var der opbygget et nyudviklet regulerbart saltanlæg, der præcist og dynamisk kunne simulere forbrugsprofilen fra de data der var blevet indsamlet fra etageejendommen på Nørrebrogade. Da der tilmed på DTU ikke var begrænsninger ift. fjernvarmeselskab, blev det besluttet at man udover at undersøge budraget fra traditionel solvarme til varmt vand, på anlægget på DTU også skulle medtage demonstration af PVT med en tilkoblet varmepumpe for at øge fleksibiliteten og udnyttelsen. Med varmepumpen blev der åbnet for at man også kunne måle, analysere og vurdere mulighederne for BIPVT i områder i Danmark, hvor der ikke er adgang til fjernvarme. Således kunne demonstrationen på DTU eftervise hvorvidt man udover produktion af varmt brugsvand også kunne producere rumvarme i rigelige mængder.



Figur 1 Forsøgsopstilling på DTU. Til venstre beholdere og varmepumpe. Til højre de 3 PVT-E moduler.

1.3 Hovedaktiviteter i projektet

Projektet bestod ifølge ansøgningen af følgende arbejdspakker.

Arbejdspakke 1 – Opstart

- Valg af design af PVT modul på grundlag af afprøvninger af prototype.
- Ansøgning om byggetilladelser mv.
- Afklaring af myndighedsforhold vedr. afregning, afgifter mv.

Arbejdspakke 2 - Analyse

- Modellering af PVT modul og beregning af el og varmeproduktion
- Model for beregninger af varmesiden, herunder også varmpumpe.
- Samlende teknisk økonomisk analyse af PVT moduler og system til udnyttelse af varme.
- Valg af system og komponenter til demonstration.

Arbejdspakke 3 - Opførelsesfase –

- Planlægning af målinger og måleprogram.
- Opførelse varetages af Racell i henhold til kontrakt med andelsboligforeningen afhængigt af EUDP projektet. EUDP projektets parter fungerer som rådgivere
- Måleudstyr etableres parallelt med opførelsen og iværksættes så snart der er data.

Arbejdspakke 4 – Analyse og erfaringsopsamling

- Opsamling af målinger og indsamling af driftserfaringer og brugerreaktioner.
- Analyse, konklusioner og rapportering.

Arbejdspakke 5 – Marked og formidling

- Videnskabelig formidling via papers mv., hovedsagelig DTU.
- Partnernes videre udvikling og realisering af potentialet.

Disse arbejdspakker blev gennemført med den ændring at demonstrationen foregik på DTU i stedet for på Nørrebrogade. Anlægget på Nørrebrogade blev delvist projekteret og der blev udført omfattende analyser som så kunne overføres til anlægget på DTU. Selve fuldskala eftervisningen af, at så store og tunge facademoduler kunne monteres og arkitektonisk integreres på en etagebygning blev eftervist på Bolig+ bygningen i Gladsaxe.

2 Projektresultater

2.1 Introduktion

Dette afsnit fokuserer på at dokumentere de resultater der er opnået på grundlag af forsøgsopstillingen eller demonstrationen på DTU. Vedr. de planlagte installationer i Nørrebrogade henvises til slutrapporten for 1 fase af projektet.

2.2 Tekniske løsningsmuligheder

Med de PVT moduler der er tilgængelige i dag vil man ikke opnå så høje temperaturer som med almindelige solfangere. Det betyder at man, selv i sommerperioden, ikke kan dække hele behovet for varmt brugsvand.
Hvis man medtager en varmepumpe i konceptet vi man kunne dække en større del af behovet. Analyser havde vist at man så ville kunne dække hele behovet for varmt brugsvand, også om vinteren, og det var et af formålene med demonstrationen at eftervise dette. Det skal så bemærkes at man med et almindeligt solvarmeanlæg til varmt brugsvand ikke kan dække behovet om vinteren uden back up.

Det skal bemærkes at projektgruppen imens nærværende projekt er gennemført har gået videre med udviklingen og er i gang med at udvikle og demonstrere et koncept hvor der også dækkes rumvarme og hvor der indgår et batteri så forholdet mellem varme og el kan optimeres. Det anlæg der beskrives her har i høj grad være inspiration hertil, ligesom de resultater der er opnået har dannet grundlag for ideen og optimismen, samtidig med at det har givet værdifulde data til analysen.

Figur 2 viser princippet for det afprøvede anlæg. Det kaldes nu et PVT-E anlæg og solfanger/solcelle modulet for et PVT-E modul (PV Termisk med Energiabsorber).

Anlægget består til et enfamiliehus af ca. 10 m² PVT-E moduler, en varmtvandsbeholder med en spiral i bundet til solfangeren og en spiral i toppen koblet til en varmepumpen som henter varme i en varmepumpebeholder som derved køles. Varmepumpebeholderen genopvarmes med PVT-E modulerne, enten ved at solen skinner og modulerne bliver varmere end væsken i varmepumpebeholderen, eller ved at beholderen er blevet koldere end udeluften, så der går varme fra luften til PVT-E modulet som derved opvarmes. Dette sidste er funktionen som energiabsorber.

I en sammenligning med et jordvarmeanlæg, erstatter PVT-E modulet jordslangerne.

PVT-E modulet har således 3 funktioner.

1. Det er en solcelle der producerer el.
2. Det er en solfanger der producerer solvarme der kan forvarme det kolde brugsvand.
3. Det er en energiabsorber der (via en beholder eller evt. en varmeveksler) leverer varme til en varmepumpe der producerer varmt brugsvand.

Funktionen er følgende:

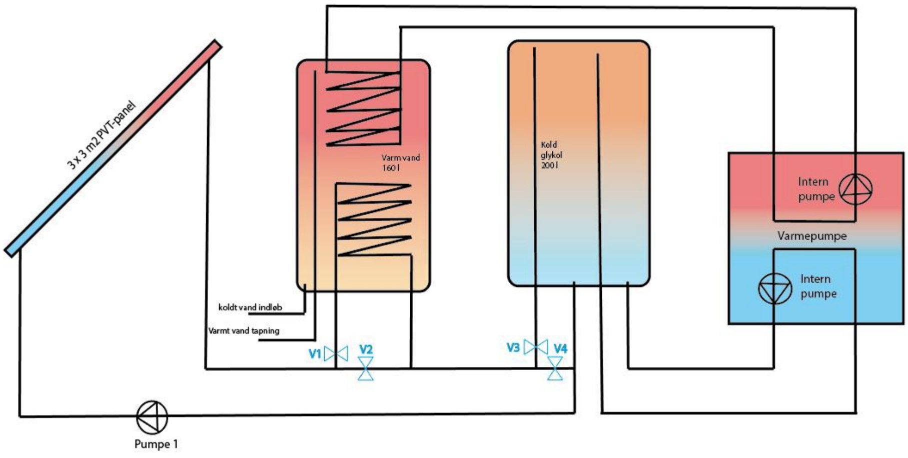
Sommer:

På meget solrige dage opvarmer anlægget stort set brugsvandet direkte til anvendelsestemperaturen og dækker hele behovet. Når varmtvandsbeholderen er varmet op opvarmer modulerne i stedet varmepumpebeholderen således at der opnås en høj COP når der senere, evt. dagen efter, bliver brug for varmepumpen. Der er dog her en øvre grænse idet de fleste varmpumper på markedet ikke kan hente varme ved en højere temperatur end 25-30 C. På mindre solrige dage kan PVT-E modulet forvarme det kolde brugsvand i bunden af varmtavndsbeholderen, mens varmepumpen opvarmer toppen, hvor varmen til varmepumpen så hentes ved en relativ høj temperaturen i varmepumpebeholderen som samtidig opvarmes af PVT-E modulerne.

Vinter:

I perioder med meget lidt sol vil PVT-E modulerne fortrinsvis virke som energiabsorber og varmepumpebeholderen vil overvejende genopvarmes ved varmeovergang fra luft til PVT-E modulet som så må være koldere end luften. Dette er selvsagt den kritiske periode hvor temperaturen i varmepumpebeholderen bliver meget lav. Det antages at hvis temperaturen i denne kommer under -10 C, så kan anlægget ikke mere levere noget.

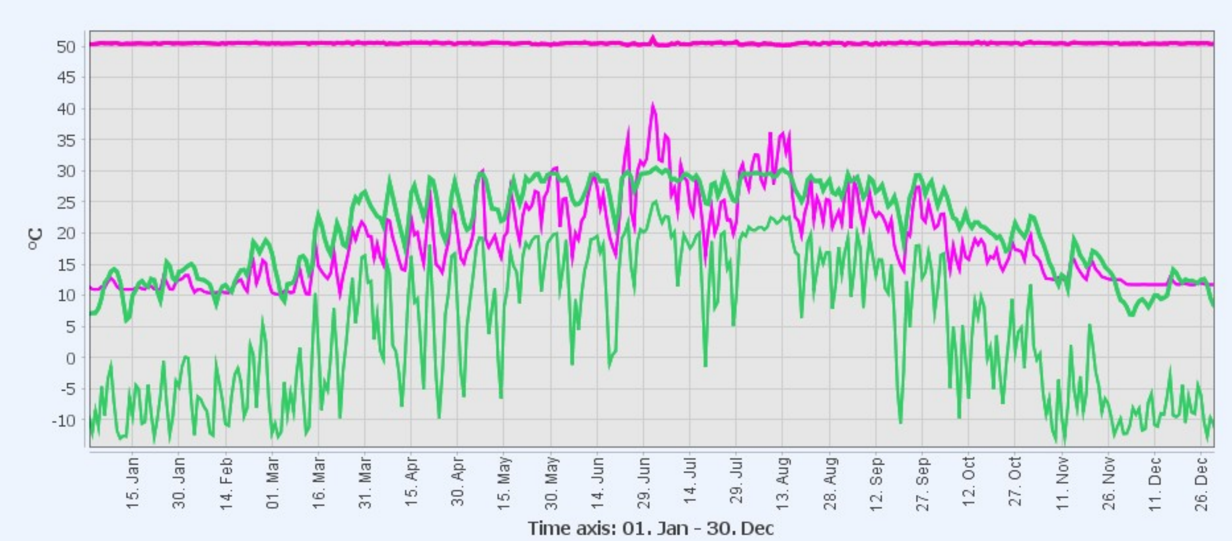
I perioder hvor der dertil kommer sne på modulerne kan det blive værre.



Figur 2 Anlæg med PVT og varmepumpe til opvarmning af brugsvand.

I en typisk driftssituation ser temperaturerne i beholderne ud som på Figur 3. Det fremgår her at temperaturen i toppen af varmtvandsbeholderen holdes på eller over den ønskede temperatur på det varme brugsvand, takket været varmepumpen. I bunden af beholderen forvarmes vandet med solvarme i sommerperioden hvorfor temperaturen her er højere end om vinteren hvor temperaturen er i nærheden af temperaturen på det kolde brugsvand.

I varmepumpebeholderen er temperaturen lav og mindre end 0 C i mørke kolde perioder om vinteren. Det er her anlægget kommer på den hårdeste prøve. Toppen af varmepumpebeholderen kommer dog ikke så langt ned som det fremgår.



Figur 3 Temperaturer i beholdere under en typisk drift af et PVT-E anlæg til varmt brugsvand. De lilla linjer viser temperaturen i top og bunde af varmtvandsbeholderen, de grønne i top og bund af varmepumpebeholderen.

2.3 Laboratorie test på DTU-BYG (fuld rapport i Bilag 1)

Et funktionsdygtigt anlæg blev opstillet på DTU, en nærmere beskrivelse af dette ses af Bilag 1. Det vigtigste at få klarlagt ved denne afprøvning var følgende:

1. Virker anlægget efter hensigten og er den udviklede styringsstrategi effektiv.
2. Kan man forsyne varmt brugsvand under alle forhold.
3. Hvad er effektiviteten af anlægget under forskellige driftsforhold, herunder sommer og vinter med forskellige belastning.
4. Hvordan virker det om vinteren når der er sne.

Konklusionen på målinger er følgende, idet der henvises til detaljerne i bilag 1:

Anlægget viste at det var muligt at levere varmt brugsvand under alle vejrforhold, året igennem, også om vinteren.

Der var som udgangspunkt installeret 3 moduler med i alt 9.3 m² PVT på anlægget. Beregninger havde vist at dette areal var mere end nødvendigt, men også valgt fordi elproduktionen så vil være højere. For at teste anlægget i den vanskelige situation om vinteren i kolde perioder blev 2 moduler frakoblet så anlægget kun kørte med 1 moduler på 3.1 m². Også i denne periode forsynede anlægget forbruget til varmt brugs på 4,5 kWh pr. dag. Temperaturen kom ned på ca. -10 C i varmepumpebeholderen, men stiger hurtigt igen.

Målingerne tyder på at panelerne virker rimeligt selv i perioder med sne, idet det dog er noget der skal undersøges nærmere idet det også tyder på at sneen har svært ved at smelte af når panelerne køles af en meget kold beholder. Under alle omstændigheder skal panelerne udføres så sne kan glide af. Det vil sige at der ikke skal være en forhøjet kant forneden. Evt. kan man indføre en procedure/metode for fjernelse af sne på taget.

Det er klart at der i mørke kun kan tilføres varme til varmepumpebeholderen når udetemperaturen er højere end beholdertemperaturen. Desuden skal varmepumpen kunne operer ved en brinetemperatur på i nærheden af de -10 C. Beregninger viser dog at selv i de koldeste perioder når bundet af varmpumpebeholderen kommer ned i nærheden af minus 10 så varmes den relativt hurtigt op igen så snart temperaturen stiger. Toppen af beholderen kommer i en simuleringsberegning på et anlæg svarende til forsøgsanlægget ikke under minus 5 C.

Styringen af anlægget, også beskrevet i bilagt, viste sig at fungere, idet der dog blev flyttet på nogle følere for at optimere driften. De ret omfattende og detaljerede målinger gjorde det muligt at identificere sådanne problemer og kontrollere at ny placeringer forbedrede driften.

Der blev forsøgt lavet en effektivitetsmåling af PVT-E modulerne ud fra de indsamlede data, se bilag 1. Denne er dog bestemt med stor usikkerhed og det er område hvor der mangler fortsat arbejde. Der er på internationalt plan ikke etableret en standard og praksis for angivelse af effektiviteten af sådanne paneler. Det er derfor meget vanskelig at udtrække koefficienter til at beskrive effektiviteten og overføre disse til det eksisterende simuleringsværktøj Polysun, der har været brugt til at foretage en analyse og sammenligning mellem målinger og beregninger. Denne analyse gengives nedenfor.

Den manglende praksis og standard gør det yderligere vanskeligt at markedsføre PVT-E moduler da det, selv for kyndige brugere, stort set er umuligt at sammenligne produkterne. En sammenligning kan kun foretages på grundlag af opbygning, anvendte materialer til absorber, solceller, samlingsmetoder mv. og bliver meget subjektiv. Der er altså i den nuværende situation ikke noget stærkt incitament for leverandører til at levere kvalitet og derfor er markedet for PVT også domineret af mange uheldige produkter. Almindelige solcellepaneler er let identificerbare på den peak effekt (W) som et panel kan yde og som oftest er verificeret.
Noget tilsvarende er langt fra tilfældet med PVT moduler og især med PVT-E moduler.

Som nævnt i bilaget har selve varmepumpen ikke kørt optimalt. Varmepumpen var ikke i fokus. Den er for stor, der er for lange rørstrækninger der giver store varmetab, specielt ved korte driftsperiode. Dette betyder tilsammen at varmepumpen har kørt dårligt hvilket dog ikke har påvirket testen af funktionen af anlægget med PVT som energikilde til varmepumpen.

En væsentlig konklusion vedr. varmepumpen er at den ikke skal have større kapacitet end nødvendigt, der skal være korte rørstrækninger mellem varmepumpe og beholder og styringen skal være så varmepumpen kører i længere driftsperioder, som udgangspunkt mindst 30 minutter og den skal ikke være behovsstyret. Varmepumpen skal endvidere kunne køre i det aktuelle temperaturområde og have sin bedste COP i det område der bruges mest. Dette er også et område der skal undersøges nærmere.

2.4 Sammenligning af målinger og beregninger

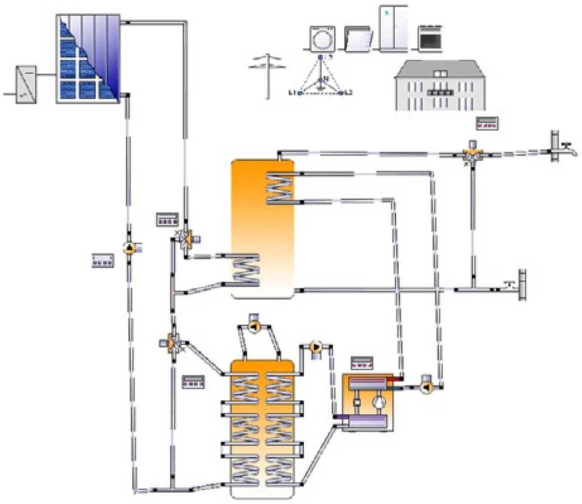
Der er opbygget en model i Polysun (version 10.0.11) der svarer til anlægget opført på prøvestanden. Det har ikke været muligt på det foreliggende grundlag at foretage en egentlig minutiøs sammenligning af de målinger og beregninger hvor dynamikken sammenlignes og verificeres.

Der er til simuleringen brugt de effektivitetsdata for PVT-E der kan bestemmes ud fra målingerne. En sammenligning af de opnåede termiske ydelser af PVT-E anlægget giver god overensstemmelse. Dette tyder på at de beregninger der fortages med modeller opbygget i Polysun giver brugbare resultater. Det er dog klart et område hvor der er behov for mere dybtgående forskningsarbejde.

Det næste afsnit vil på dette grundlag vise en mere generel analyse af PVT-E anlæg til forsyning af varmt brugsvand. I forsøgsanlægget var det daglige forbrug til varmt brugsvand på 4.5 kWh pr. dag og en temperatur på det kolde brugsvand på næsten 18 grader. I analysen nedenfor bruges et normal brugsvandsforbrug.

2.5 Beregninger på PVT-E anlæg med Polysun

De her præsenterede beregninger gælder for et forbrug af varmt brugsvand på 150 liter pr. dag (ca. 10 til 50 C), svarende til et mere normalt forbrug end det der var brugt i forsøgsanlægget. Opbygning af modellen ses af Figur 4.



Figur 4 Opbygning af model i Polysun. Varmevekslerne i varmepumpebeholderne vil ikke være nødvendige i et virkeligt anlæg, men er medtaget af regnetekniske grunde.

Figur 5 viser en beregning på et anlæg med 1 og med 3 moduler. Det fremgår af Figur 5 at der ikke er den store forskel på den termiske ydelse for et anlæg med 1 modul og et anlæg med moduler. Det skyldes at PVT-E modulet har rigelig kapacitet til at forsyne varmepumpen. Når der kun er et modul sker der det at temperaturdifferencen mellem PVT-E modul og omgivelser stiger når anlægget virker som energiabsorber, hvorved varmeoverføringen opretholdes. Der er dog med det lille areal alt andet lige større risiko for perioder om vinteren uden dækning.

Derimod er der jo stor forskel mht. elproduktionen. Her produceres der naturligvis mere el på det store anlæg pga. arealet. Der produceres også væsentlig mere el pr. arealenhed på det store anlæg, nemlig 179 kWh pr. m² mod 157 kWh pr. m² for det lille anlæg. Dette skyldes at PVT-E modulet gennemsnitligt er koldere med det store areal og PV cellers effektivitet falder ca. 0.5 % pr. grad temperaturen stiger.

Med 3 moduler opnås der altså en højere COP og samtidig en højere elproduktion. Det fremgår også at med 3 moduler opnås der et overskud af el fra anlægget, dvs. at der, på årsbasis produceres mere el end der bruges til varmepumpen.

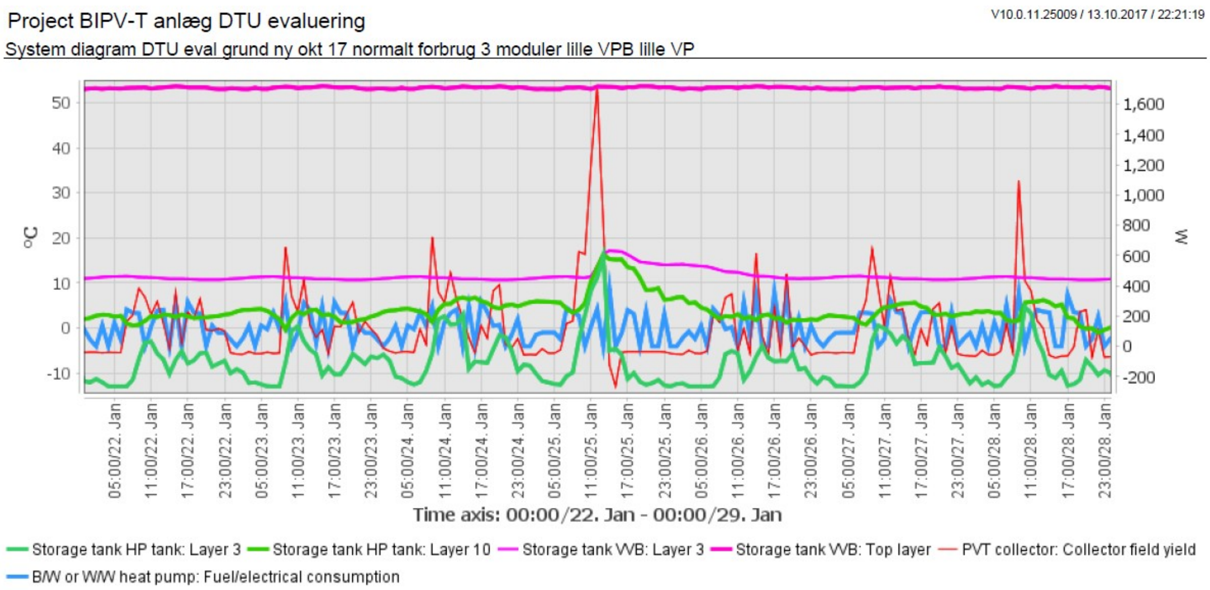
Ønsker man en højere dækning af elforbruget, kan anlægget suppleres med almindelig solceller, det vil ikke kunne betale sig at have et større areal af PVT-E til et anlæg til forsyning af varmt brugsvand.

Som nævnt arbejder projektgruppen videre i projekter med levering af varme og med udnyttelse af batterilagring. Dette er dog kun relevant i områder hvor PVT-E erstatter et oliefyr eller et gasfyr og ikke fjernvarmeområder.

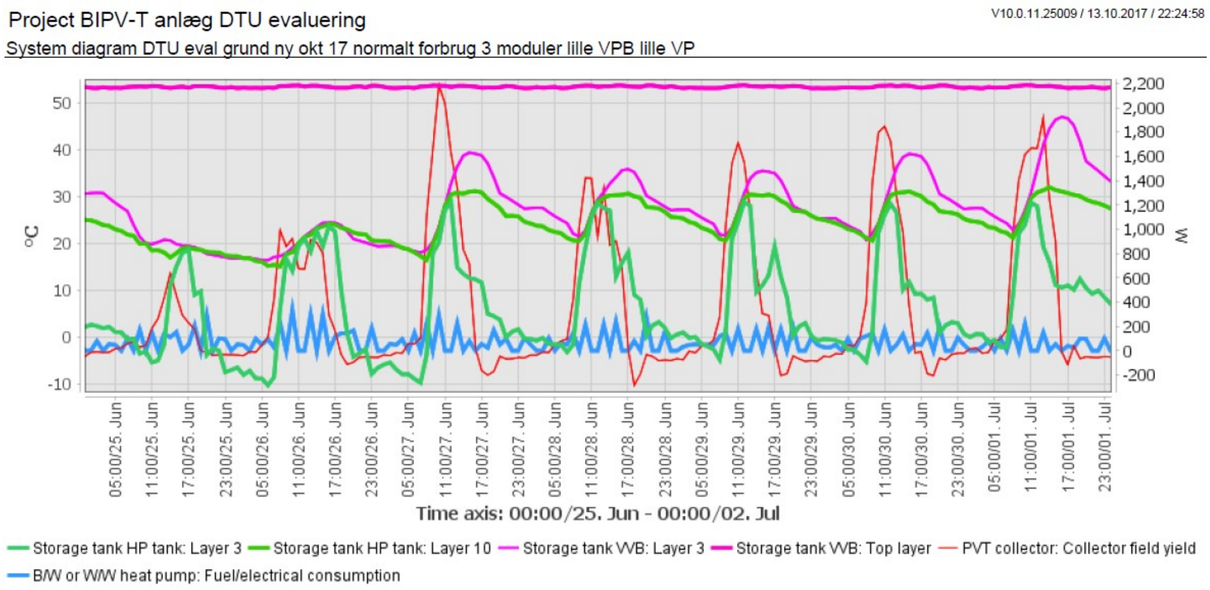
Varmepumpe effekt	kW varme	2	2	2
Varmtvandsbeholder volumen	l	300	300	300
Varmepumpebeholder volumen	l	500	500	150
PV areal	m^2	9	3	9
Varmt brugsvand, leveret	kWh/år	2,463	2,463	2,462
Varmepumpe elforbrug	kWh/år	1,008	1,119	993
Varmepumpe leveret til VVB	kWh/år	2,467	2,710	2,403
Solenergi til VVB til forvarmning	kWh/år	466	200	535
Solenergi til varmepumpebeholder	kWh/år	1,477	1,472	1,373
COP i forhold til leveret varmt brugsvand		2.4	2.2	2.5
Overskud af el på årsbasis	kWh/år	653	-633	660
Udnyttet solenergi	kWh/m^2	190	456	186
Produceret el	kWh/m131	179	157	178

Figur 5 Resultater af Polysun beregning for et BIPVT-E anlæg til varmt brugsvand.
Første beregning – anlæg med 3 moduler og stor 500 l beholder til varmepumpen.
Anden beregning – samme anlæg med kun et modul
Tredje beregning – som første, men med en mindre beholder til varmepumpen.

Figur 5 viser også funktionen forbedres når varmepumpebeholderen gøres mindre. Det er måske overraskende, men skyldes nok at de samlede varmetab fra beholdere bliver mindre. Det må derfor anbefales at se nærmere på dette i kommende anlæg, evt. helt at undgå beholderen og i stedet bruge en varmeveksler.



Figur 6 Beregning på anlæg med 3 moduler, 150 liter varmepumpebeholder og en 2 kW varmepumpe. Gælder for en kold uge i januar.
Det ses at om natten falder temperaturen i beholderen til varmepumpen, mens den hurtigt varmes op om dagen. På visse dage hjulpet af solen. Den 25 januar var der så meget sol at brugsvandet også er forvarmet og bunden i varmtvandsbeholderen stiger lidt.



Figur 7 Samme beregning som i Figur 6, for en dag i juni.
Her er temperaturen i varmepumpebeholderen højere og elforbruget til varmepumpen lavere. Brugsvnadet forvarmes med sol.

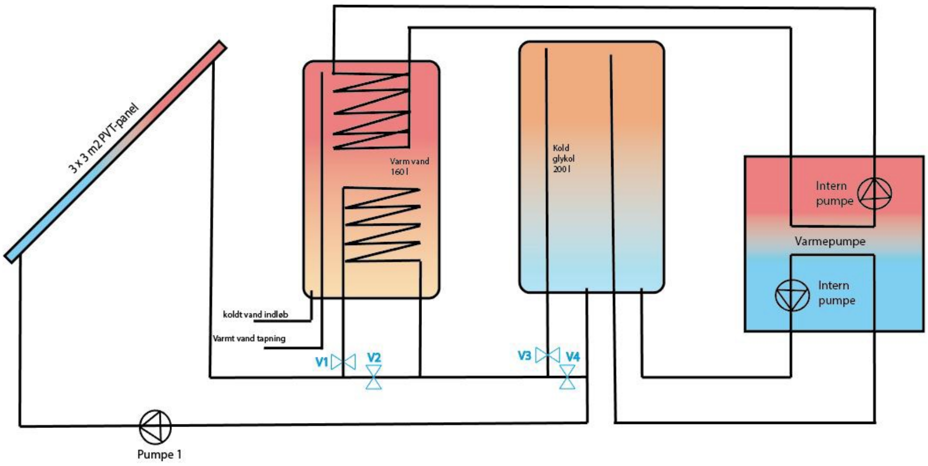
3 Kommercielle resultater

I forlængelse af de opnåede resultater og formidlingen er der opstået en stor interesse for projetets løsninger. Der er således i løbet af kort tid opbygget en pipeline med kommercielle ordrer på flercifrede millionbeløb.

5 Appendix 1 - Performance Test at DTU

Performance of a solar heating system with photovoltaic thermal hybrid collectors and heat pump

Authors: Mark Dannemand, Simon Furbo, Bengt Perers.



5.1 Abstract

A new system design of a solar heating system with two storage tanks and a liquid/water heat pump is presented. The system consists of PVT collectors that generate both heat and electricity. Heat from the collectors is transferred to a domestic hot water storage tank or to a cold storage tank, which is used as the source for the heat pump. When the heat pump charges the domestic hot water (DHW) storage tank, heat is extracted from the cold storage tank, which then easily can be reheated by the PVT collectors. The performance of the system with automated energy discharge over several months is evaluated. The focus was on the dynamic behavior between the components and the heat pump. The maximum temperature reached in the DHW tank when charged by the uninsulated PVT panels was 53 °C on a sunny summer day with no DHW draw off. The cold storage tank reached down to -9.8 °C in the winter when it was cooled by the heat pump. When the cold storage tank was cooled below the ambient temperature by the heat pump, the collector loop started and reheated the tank even when no solar irradiance was available.

5.2 1 Introduction

Smarter systems for space heating and domestic hot water preparation are needed to make energy consumption more efficient than it is today.

Hybrid PV panels and solar thermal collectors (PVT) produces both heat and electricity. The benefit of combining the two technologies includes the potential for increasing the efficiency of the solar cells as they are cooled by the thermal part of the collectors while the removed heat can be utilized for heating purposes. This lead to a better utilization of the solar exposed area available for the installation. Also the materials used fabricating the PVT panels may be reduced compared to individual PV and thermal systems side by side.

Heat pumps generate heat from electricity in an efficient way. Generally liquid/water heat pumps are more efficient than air/water heat pumps. Liquid/water heat pumps are typically installed with a tubing system either horizontally or vertically inserted into the ground. This requires space and has significant installations costs.

A new system design of a solar heating system with two storage tanks and a liquid/water heat pump is presented. Heat from the PVT collectors is transferred to a domestic hot water storage tank or to a cold storage tank, which is used as the source for the heat pump. When the heat pump charges the domestic hot water (DHW) storage tank, heat is extracted from the cold storage tank, which then easily can be reheated by the PVT collectors.

5.3 Method

5.3.1 System description

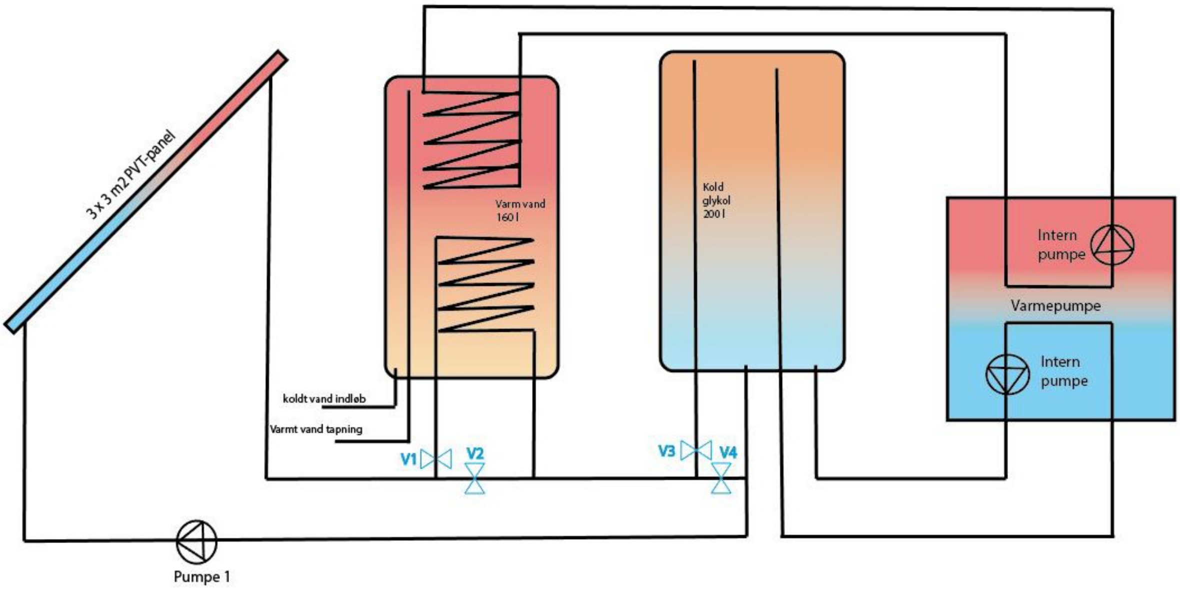
The system concept presented in this article is with a high efficient liquid/water heat pump in a system with PVT collectors. Instead of connecting the cold side of the heat pump to ground tubes, it was connected to a 200 liters cold storage tank with a 40% glycol/water mixture. The PVT collectors were uninsulated and could work as energy absorbers, which could extract low temperatures heat from the ambient when no solar radiation was available. As the heat pump charged the domestic hot water tank, energy was extracted from the cold storage, which could then be recharged by the PVT collectors.

The system consisted of three PVT collectors each with a gross collector area of 3.1 m2 (**Error! Reference source not found.**). The solar cells had a net area of 2.37 m2 on each PVT panel. The PVT panels were produced by RACELL Technologies. The PVT collectors faced south with a tilt of 45° and were installed at the Lyngby campus of Technical University of Denmark near Copenhagen, Latitude 56°N. The collectors were connected to two heat storage tanks located in an indoor test facility (see Figur 9). A 160 liters domestic hot water tank could be heated by a thermal loop for the PVT collectors via an internal heat exchanger spiral. A 200 liters cold storage tank with a water/glycol mixture could be heated by direct inlet of the heat transfer fluid into the tank. When the temperature level in the DHW tank dropped below the required comfort value, the heat pump heated it up. The installed heat pump was a Vølund F1155-6. This type of heat pump was designed to cover both a space heating and domestic hot water demand. In the present study, the solar heating system was only used for DHW. The heat pump was therefore oversized for the demonstration system presented in this report. The performance of the heat pump in this system should therefore not be evaluated in other ways than to prove the system concept. The focus of the investigations was to evaluate the yield from the PVT panels, both in terms of the high temperatures for coverage of DHW and as energy absorbers extracting low temperature heat as source for the heat pump. Further, the dynamic behavior of the storage tanks and the heat pump was of interest.

Figur 8. PVT collectors on roof.

Figur 9. Indoor installation of two storage tanks and a liquid/water heat pump.

Figur 10 shows a diagram of the solar heating system concept with the PVT panels DHW and cold storage tanks and a heat pump as the auxiliary heat source as well as the pipe connections.

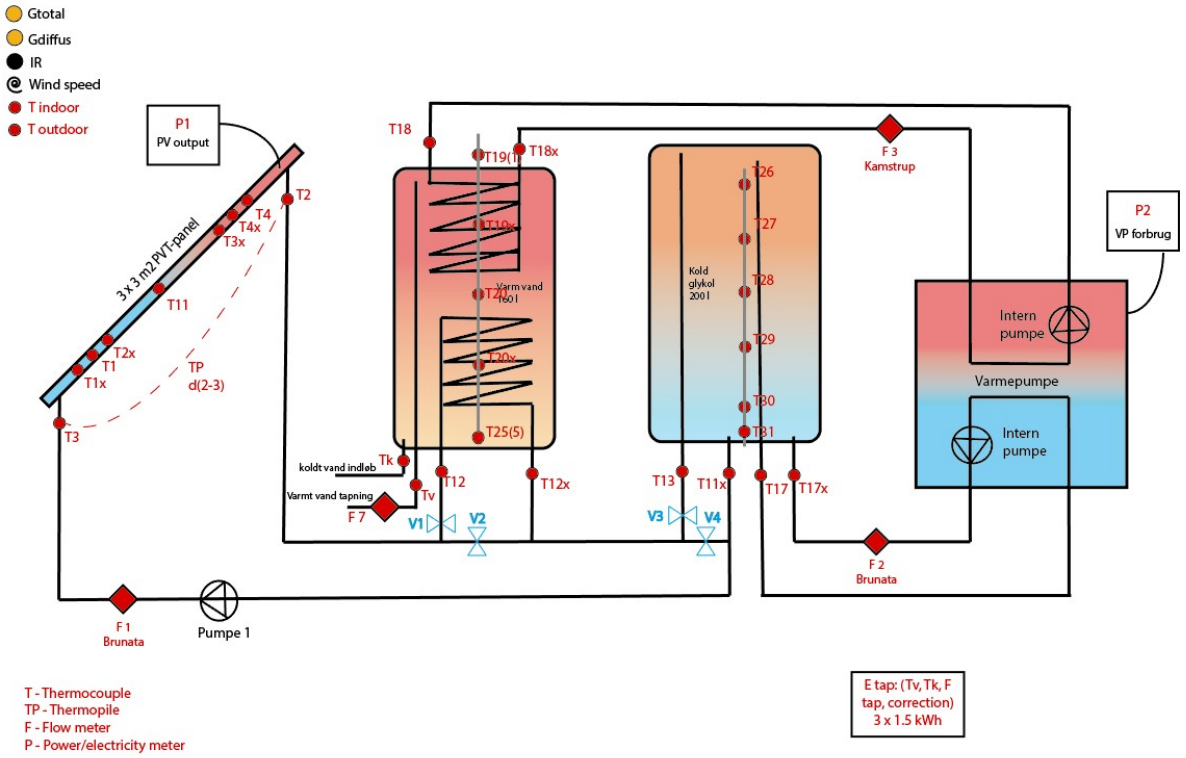


Figur 10. Simple diagram of system with PVT collectors, storage tanks and heat pump.

The PVT collectors were connected to the tanks via 20 m forward and 20 m return copper pipes with a outer/inner diameter of 22/20 mm. The pipes were insulated with Aeroflex with a thickness of 19 mm. The pipes connecting the heat pump to the storage tanks were each 4.5 meters. Automated draw offs of hot water were made three times per day to simulate an actual installation in a house. 1.5 kWh of energy was tapped three times per day at 7, 12, 18 hr. This corresponds to three times approximately 45 liters of water at 48-51 °C when the cold-water inlet temperature was 18-20 °C.
The PVT solar heating system ran continuously subject to real weather conditions for several months with various control strategies implemented to evaluate its performance. Minor changes in sensor placement and set point temperatures for the control of the heat pump were made during the test period to achieve better performance of the system.

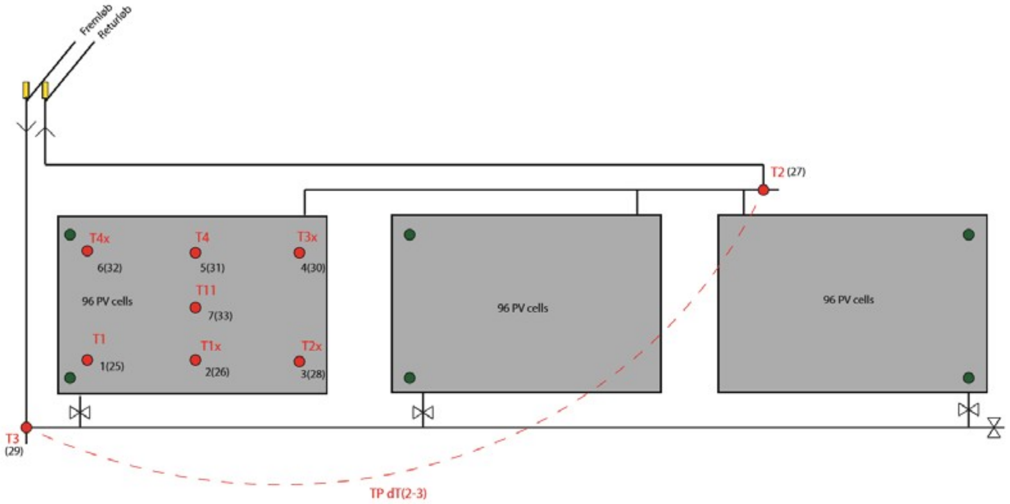
5.3.2 Measurements

Absolute temperatures in the tanks, liquid flow temperatures in the pipes, temperature differences, flow rates, electricity generation and electricity consumption at various key locations in the system and ambient were measured and logged. Five junction thermopiles made from thermocouples type TT were used to determine the temperature differences across in- and outlet of the collectors as well as across the hot and cold-water temperatures for the domestic hot water tapping. The total and the diffuse irradiances on the PVT panels were measured by pyranometers, the wind speed was measured with a cup star wind sensor and the infrared radiation exchange between the sky and the collector surface was determined by a pyrgeometer. Figur 11 shows an overview of the location of the thermocouples, thermopiles, flowmeters and energy meters in the system as well as global weather measurements.



Figur 11. System diagram with location of measurements equipment.

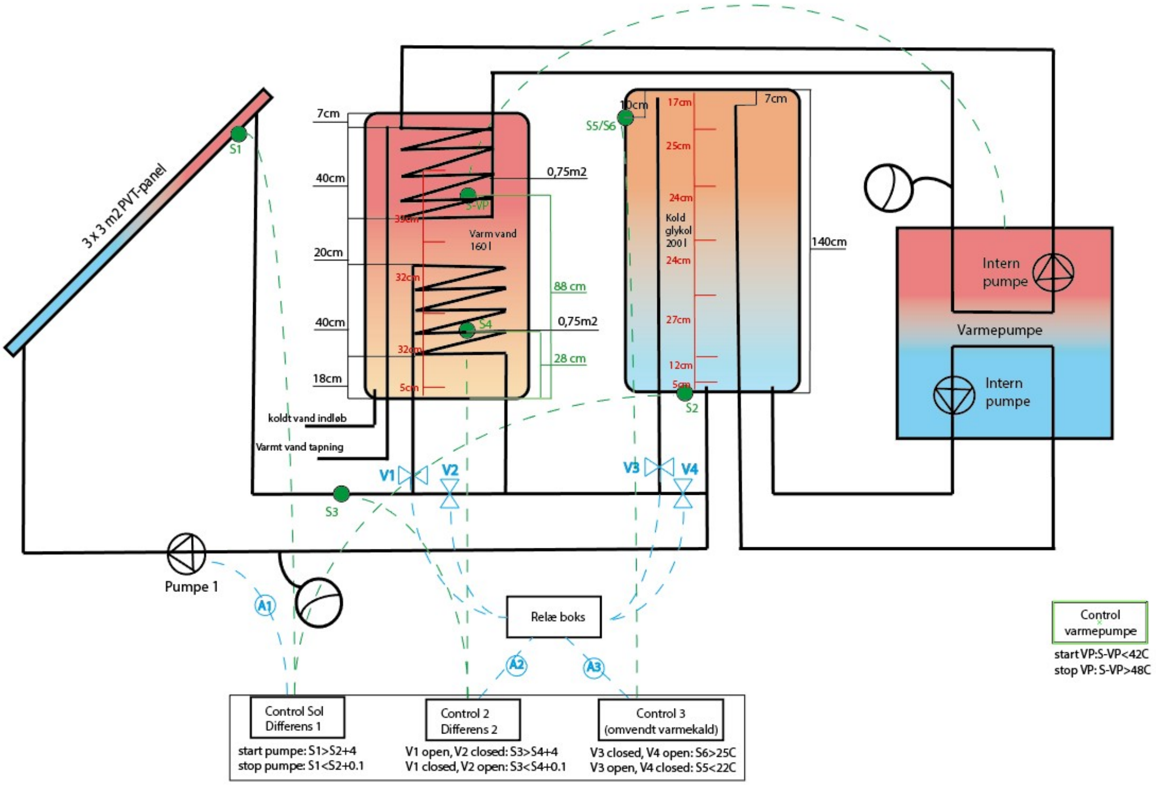
Figur 12 shows that the thermal part of the PVT collectors were connected in parallel and the location of thermocouples and thermopile relevant for the collector array.



Figur 12. Diagram of PVT collectors, pipe connections and location of temperature measurement equipment.

Control system

A UVR 63 from “Technische Alternative” controlled the system. Figur 13 illustrates sensor location and the control strategy of the thermal part of the solar heating system.



Figur 13. Control strategy and dimensions of system.

When the temperature on the back of the PVT panel near the outlet (S1) was 4 K higher than the bottom of the cold glycol tank (S2) the flow in the collector loop started by switching on Pump 1. The flow ran until the temperature of the PVT panel dropped below the temperature in the bottom of the glycol tank. If the temperature in the pipe immediately before the DHW tank (S3) was 4 K higher than in the lower part of the DHW tank (S4), then the flow was directed through the lower heat exchanger spiral of the DHW tank by opening the valve V1 and closing the valve V2. When the temperature in the pipe before the DHW tank dropped to the same as in the lower part of the DHW tank, then the flow bypassed the DHW tank by closing V1 and opening V2. As long as the temperature in the top of the glycol tank (S5/S6) was below 25 °C, then the flow of the solar collector loop was directed through the cold storage tank by having the valves V3 open and V4 closed. Otherwise, it was bypassed. The maximum temperature in the cold glycol tank was due to the maximum allowed inlet temperature in the cold side of the heat pump of 30 °C.

This control strategy allowed the collector loop to run even thou heat was not transferred to any tank in the case when the cold storage tank was fully heated to 25 °C, the temperature in the PVT was higher than the cold tank and the temperature in the bottom the DHW tank was higher than in the PVT.

When the temperature in the top of the DHW tank (S-HP) dropped below 42 °C, then the heat pump started and charged the top of the DHW tank to 50 °C via the top spiral.

Test periods

The energy flows in the different loops were calculated and accumulated values of selected periods were made to evaluate the performance of the system. The solar energy on the PVT panels accumulated over the periods were also determined to evaluate the efficiency of the collectors and system.

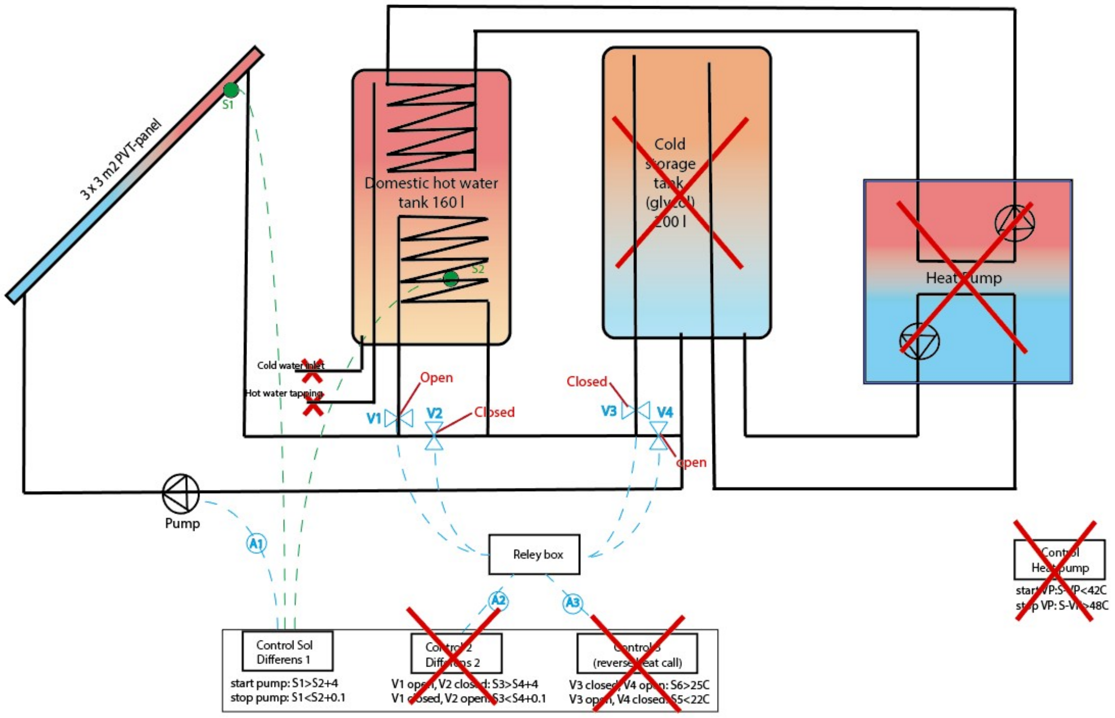
The system ran in periods between August 2016 and May 2017. The system was not in operation in some periods due to development of the system and maintenance of the measurement equipment. In the beginning of the test period, the PV generation was not active due to incomplete installation of the inverter for the PV part of the system. (August 2016 to November 2016).

Sensor S2 was located on the outer surface on the bottom of the cold glycol storage tank during the initial testing and was moved to a sensor pocket inside the lower part of the tank for the testing from 14/12/16 and onwards.

From February to May 2017 the thermal part of the PVT system ran on one PVT panel only.

From May to June two special operation modes for the system was applied. During this periods the sensor S2 for the control was moved from the cold storage tank to the lower part of the DHW tank, replacing S4. The solar collector loop was only supplying the DHW tank with heat from three PVT panels while bypassing the cold storage tank and the heat pump was stopped, see Figur 14.

In one period where DHW tapping was stopped. This was to elucidate the highest possible temperatures in the system with the current configuration. In another period, the DHW tapping ran continuously to dump the heat from the system to elucidate the performance of the PVT panels with low forward temperatures.



Figur 14. PVT system with configuration for alternative operation.

Flow distribution

To have the best performance of the solar collector array, the flow of heat transfer fluid should be equal in each collector. In this case, the collectors were parallel connected and the layout of the connecting pipes may have affected the flow distribution in each collector due to different hydraulic paths, which may have different pressure drops. The flow distribution in the collector array was evaluated by thermal imaging during operation in sunny conditions. Similar temperatures in the three collectors would indicate similar temperature increase across the collectors and therefore similar flow. A FLIR T-Series Thermal Imaging Camera was used for the evaluation.

Collector efficiency

The solar collector loop ran when the solar irradiance raised the temperature in the collector above the tank temperature. In these cases, the PVT panels worked as solar thermal collectors. The temperature of PVT panels were close to the ambient temperature when there was no solar irradiance. The solar collector loop also started when the temperature of the cold storage tank dropped below the collector temperature, also in the cases when there was no solar irradiance available. This happened typically after the heat pumps had been running and discharged the cold tank. In this case, the PVT panels extracted heat from the ambient and they worked as energy absorbers. In the analysis there was distinguished between when the PVT collectors worked as thermal collectors of solar irradiance and as energy absorbers where it extracted heat from the ambient when there was no solar irradiance available. When the total irradiance on the PVT panel was lower than 50 W/m^2 and the collector loop was running, it was defined as the PVT panels working as energy absorbers.

The thermal and electrical efficiency of the PVT collector was evaluated from the measurement of the system in operation. The dynamic of the system during operation did not allow for completely steady state conditions, which was needed for accurate evaluation of collector performance.

Therefore, periods of 10-30 minutes where the collector inlet temperature and the solar irradiance were more or less stable were selected for the collector efficiency evaluation. In the stable periods, the solar irradiance level was higher than 500 W/ m^2, varied less than 50 W/m^2 and the inlet temperature varied less than 1 K throughout the period.

The collector thermal efficiency was calculated as: $\eta_{th} = \frac{(T_{out} - T_{in}) \cdot V \cdot \rho \cdot c_p}{G_{total} \cdot A}$
where T_{out} is the collector outlet temperature, T_{in} is the collector inlet temperature, V is the volume flow rate, ρ is the density of the heat transfer fluid, c_p is the specific heat capacity of the heat transfer fluid, G_{total} is the total irradiance and A is the gross collector area.
The collector thermal efficiency was displayed as a function of the factor: $\frac{(T_m - T_a)}{G_{total}}$

where T_m is the collector mean temperature defined at the average of T_{out} and T_{in} and T_a is the ambient temperature. The wind speed at the collector surface affected the thermal efficiency of the PVT panels as it affected the convective heat losses. Each evaluated period was denoted as the average wind speed for the selected periods to show the effect of the wind speed on the efficiency.

Winter operation
During winter the PVT were covered by snowfall in periods. The snow on the collectors may affect the output from the PVT as snow on the collectors avoided electricity production. Heat transfer fluid from the cold storage tank at below 0 °C may hinder melting of the snow or build up ice on the collectors. Attention was given to snow on the PVT regarding melting behavior.

5.4 Results

5.4.1 Energy

:

- Solar radiation on the collector area
- Solar collector thermal output
- Energy absorber output (solar irradiance<50 W/m^2)
- Electrical output of the PV after the inverter
- Tapped energy for domestic hot water

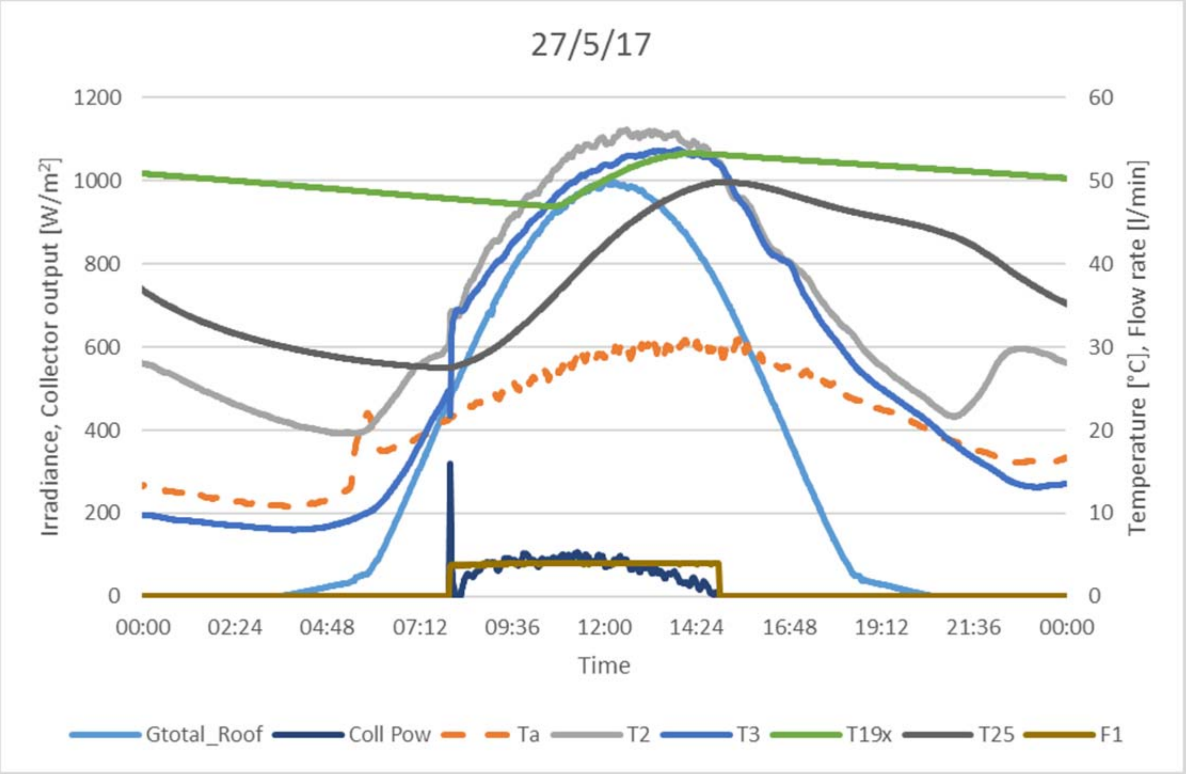
For the thermal calculations, the PVT area was 3.1 m^2 per panel. The total PV area for all panels was 7.1 m2 as the solar cells did not cover the entire absorber area.

Table 1. Accumulated energy quantities for the periods, thermal system running on three or one PVT collectors. * non optimal placement of control sensors

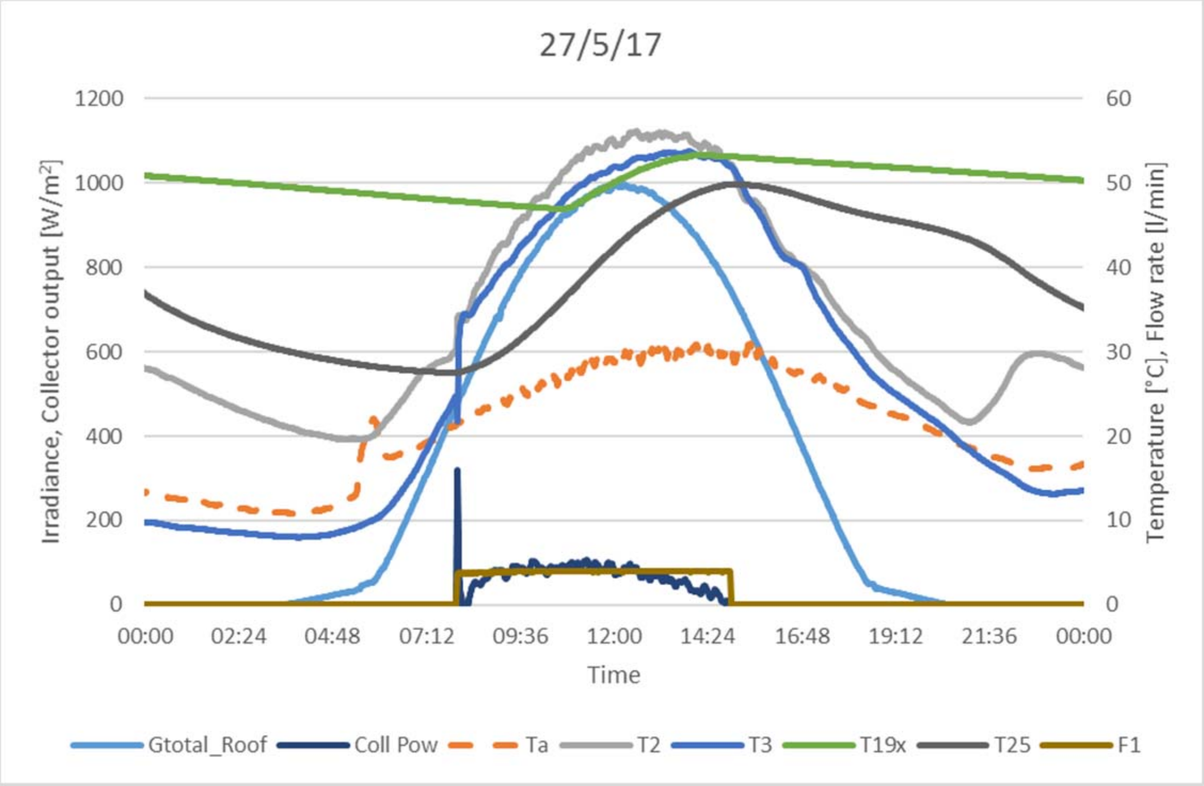
Operation period	**19/8/16 – 4/9/16**	**23/9/16 – 19/10/16**	**21/10/16 – 21/11/16**	**21/12/16 - 22/1/17**	**11/2/17 – 5/3/17**	**9/3/17 – 25/3/17**	**8/4/17 – 1/5/17**
Days	17	27	32	33	23	17	24
Active PVT panels in thermal loop	3	3	3	3	1	1	1
Solar radiation on PVT [kWh]	732	550	469	267	137	196	313
Solar radiation on PVT [kWh/day/m^2]	4.6	2.2	1.6	0.9	1.9	3.7	4.0
Collector thermal output [kWh]	106	117	138	102	65	68	94
Collector thermal output [kWh/day/m^2]	0.67	0.47	0.46	0.33	0.91	1.29	1.21
Energy absorber output (<50 W/m^2) [kWh]	0*	11.5*	20*	46	13	0.5	0.4
Energy absorber output (<50 W/m^2) [kWh/day/m^2]	0*	0.05*	0.07*	0.15	0.18	0.01	0.01
PV output (3 PVT) [kWh]	NA	NA	NA	28	40	62	86
PV output [kWh/day/m^2]	NA	NA	NA	0.12	0.17	0.26	0.37
Tapped DHW [kWh]	77	122	142	149	104	73	94
Tapped DHW [kWh/day]	4.53	4.52	4.44	4.52	4.52	4.29	3.76

The collector output was significantly higher per area when the system was operating with one PVT panel compared to when the system was operating with three PVT panels. It seem that the PVT worked as an energy absorber more frequently in the period December to February compared to March to April. This is most likely due to later period having more sun and heating the storage tanks more frequently so the cold tank was not so often cooled down below the ambient temperature.

5.4.2 No/Constant tapping



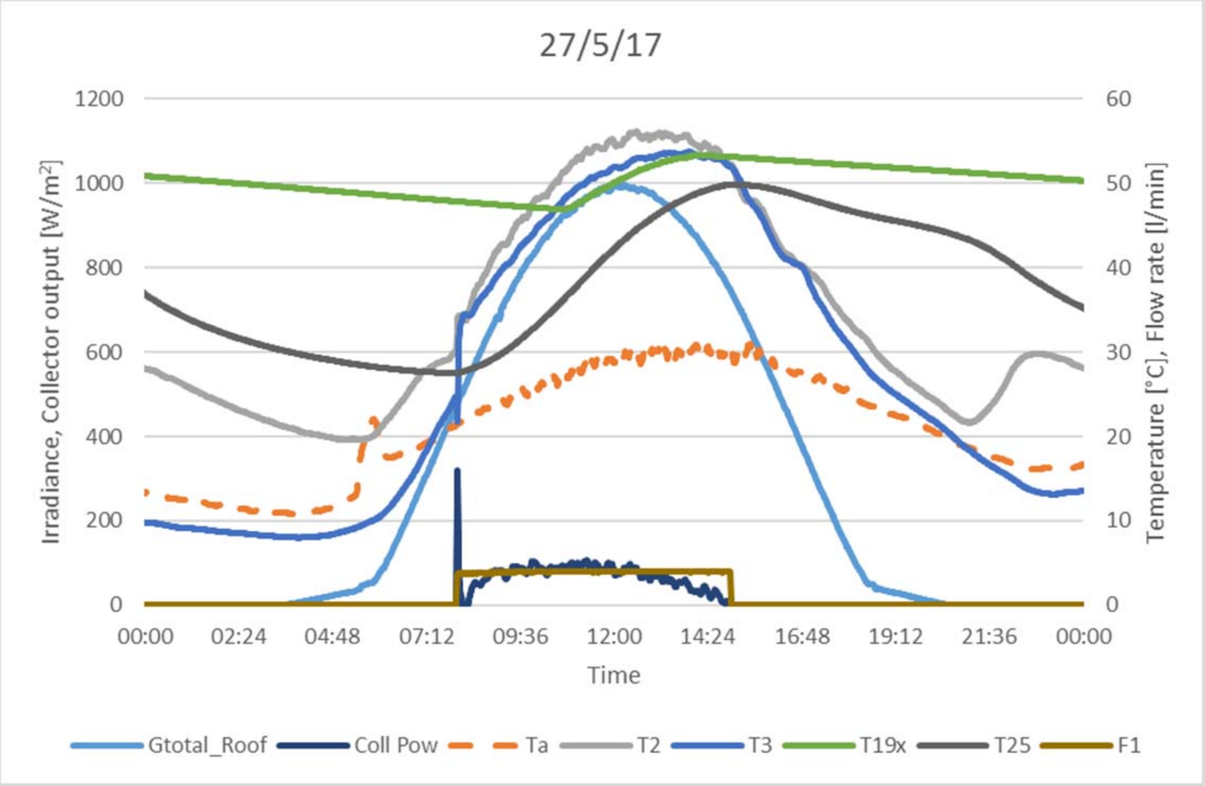
Figur 15 shows the total irradiance, the collector output, the flow rate and selected temperatures in the collector loop and the DHW storage tank on a very sunny day with no DHW draw off.



Figur 15. DHW tank and collector loop temperatures over a sunny day without DHW tapping, Temperatures in the top (T19x) and the bottom (T25) of the DHW tank. Collector outlet (T2) and inlet (T3)

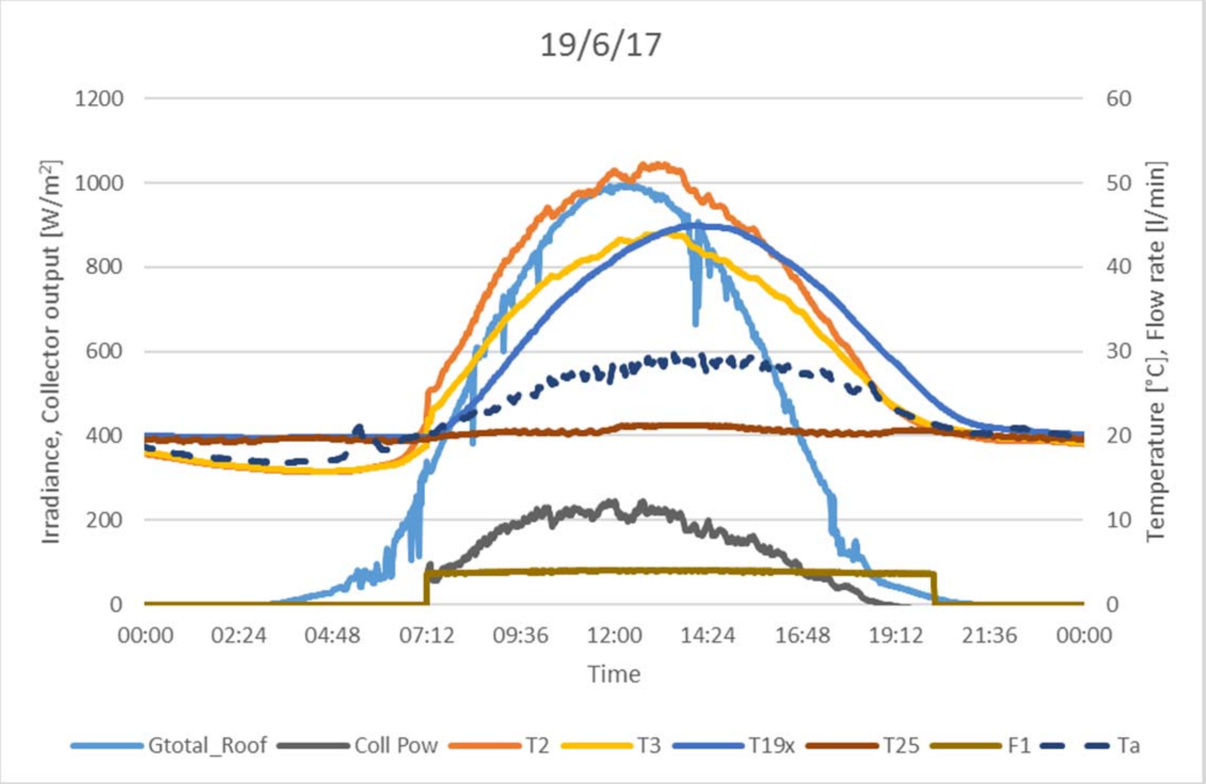
temperatures, Flow rate in collector loop (F1), Collector output power (Coll Pow), Ambient temperature (Ta) and total irradiance (Gtotal.Roof).

During this sunny day with no DHW tapping the top of the DHW tank reached 53 °C and the collector output temperature reached 56 °C. The heat added to the tank during the day was lost during the night due to heat loss to the ambient. The collector output power reached 104 W/m^2 in the middle of the day with an irradiance of 990 W/m^2.



Figur 15 shows that the temperature in the collector outlet (T2) increases around 21:00 and the temperature in the lower part of the DHW tank drops rapidly. This is most likely due to self-circulation/thermosyphoning in the collector loop at night.

Figur 16 shows the total irradiance, the collector output, the flow rate and selected temperatures in the collector loop and the DHW storage tank on a very sunny day with continuous DHW draw off.



Figur 16. DHW tank and collector loop temperatures over a sunny day with continuous DHW tapping, Temperatures in the top (T19x) and the bottom (T25) of the DHW tank. Collector outlet (T2) and inlet (T3) temperatures, Flow rate in collector loop (F1), Collector output power (Coll Pow), Ambient temperature (Ta) and total irradiance (Gtotal.Roof).

During the continuous tapping, the top of the DHW tank reached 45 °C and the collector outlet temperature reached 52 °C. The collector power reached 246 W/m^2.
Table 2 shows the measured energy quantities for the periods with out DHW tapping and with continuous tapping.

Table 2. Accumulated energy quantities for the period, thermal system running on three PVT collectors without tapping and constant tapping domestic hot water.

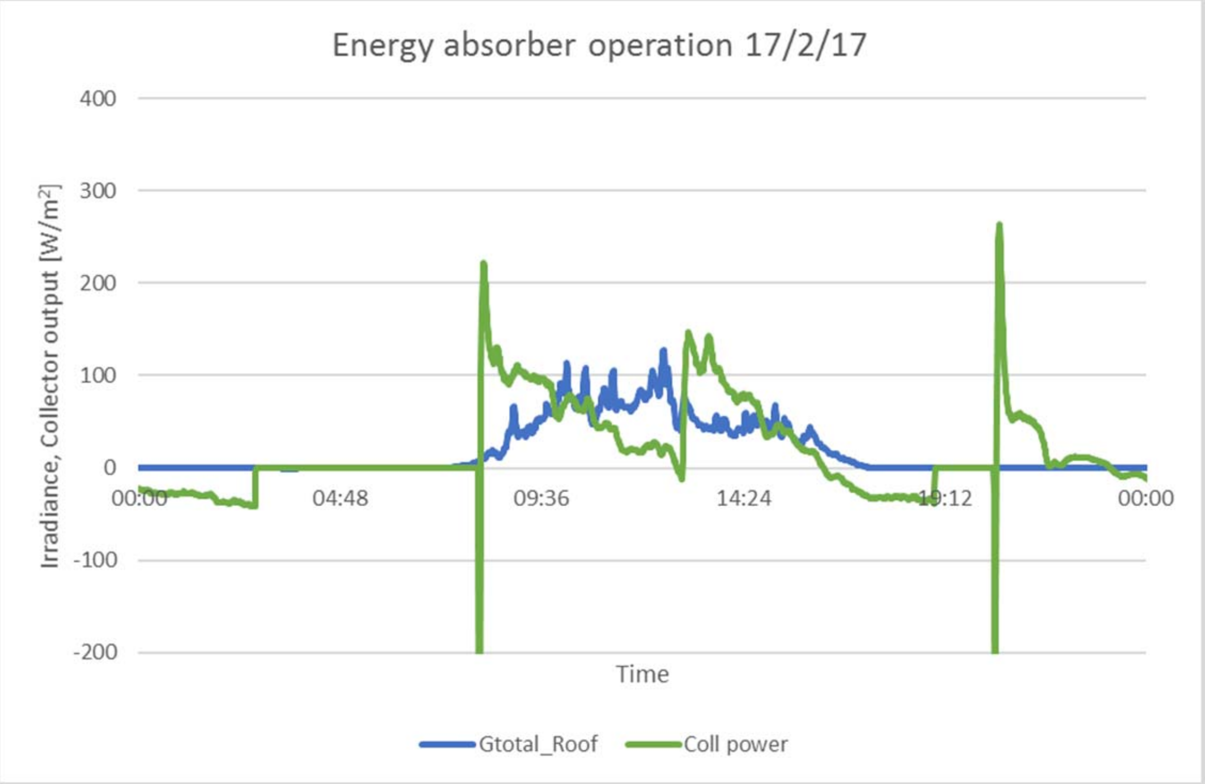
Operation period	**4/5/17 - 16/5/17**	**19/5/17 – 28/5/17**	**29/5/17 - 29/6/17**
Tapping conditions	**No tapping**	**No tapping**	**Continuous tapping**
Days	12	10	22
Active PVT panels in thermal loop	3	3	3
Solar radiation on PVT [kWh]	504	600	990
Solar radiation on PVT [kWh/day/m^2]	4.5	6.5	4.8
Collector thermal output [kWh]	24	32	142
Collector thermal output [kWh/day/m^2]	0.22	0.35	0.70
Energy absorber output (<50 W/m^2) [kWh]	NA	NA	NA
Energy absorber output (<50 W/m^2) [kWh/day/m^2]	NA	NA	NA
PV output (3 PVT) [kWh]	47	53	70
PV output [kWh/day/m^2]	0.55	0.75	0.45
Tapped DHW [kWh]	0	0	141.7
Tapped DHW [kWh/day]	0	0	6.4

5.4.3 Winter operation

5.4.3.1 Energy absorber

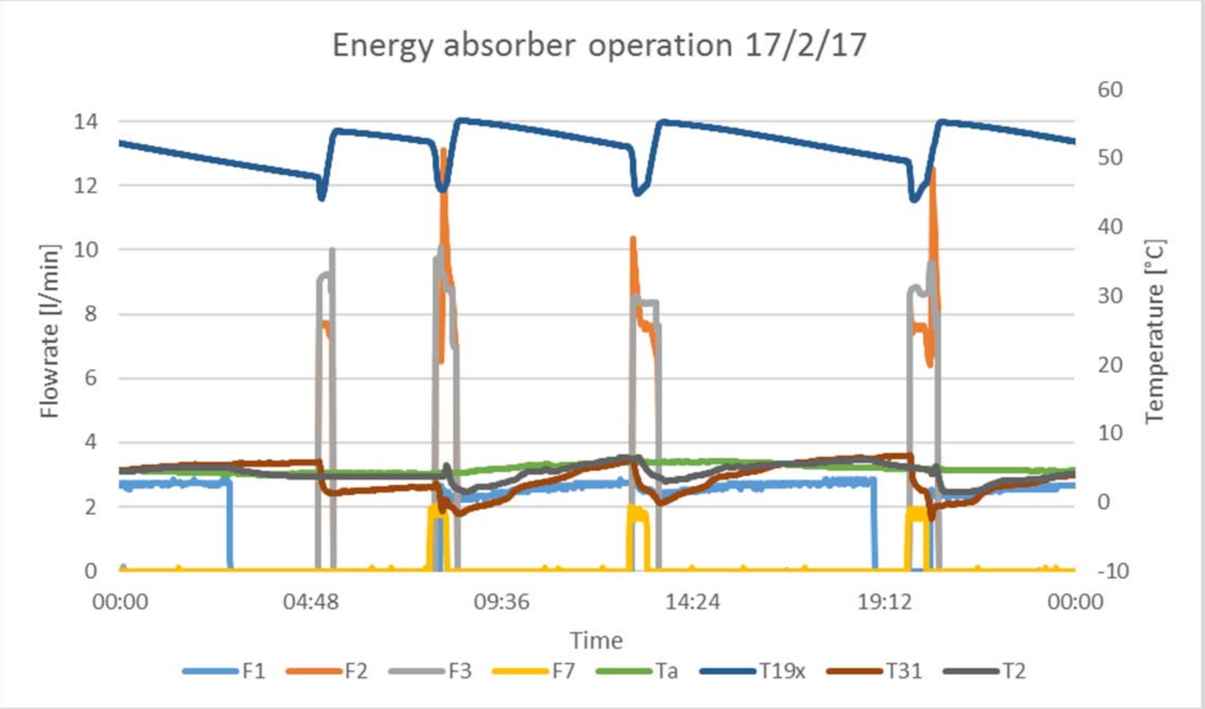
Figur 17 and Figur 18 represent a winter day (17/2/17) of operation without sunshine where the system operates with one PVT collector as energy absorber.

Figur 17 shows the measured irradiance and the thermal collector output per m^2 on the 17/2/17. *Gtotal_Roof* is the total irradiance on the collectors, *Coll power* is the thermal output of the PVT collector per m2.



Figur 17. Total irradiance on roof (Gtotal_Roof) and the collector thermal output from the PVT per m^2 (Coll power) for a winter day without sunshine.

Figur 18 shows the flow rates and temperatures at selected location in the system. *F1* is the flow rate in the collector loop, *F2* and *F3* are the flow rates on each side of the heat pump and *F7* is the flow rate during DHW tapping. *Ta* is the ambient temperature, *T2* is the collector output temperature, *T19x* is the temperature in the top of the DHW tank, *T31* is the temperature in the bottom of the cold storage tank.

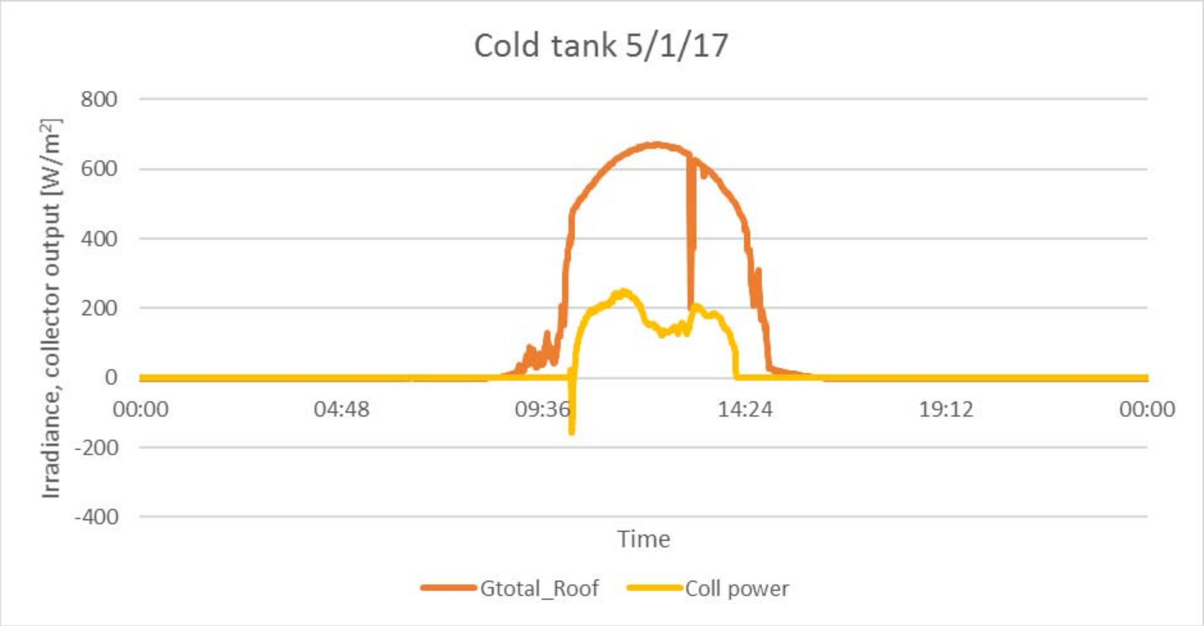


Figur 18. Flow rate in the collector loop (F1), flow rates on the cold/hot side of the heat pump (F2)/(F3), flow rate of DHW tapping (F7), ambient temperature (Ta), collector output temperature (T2), temperature in the top of the DHW tank (T19x), temperature in the bottom of the cold storage tank (T31) on 17/2/17.

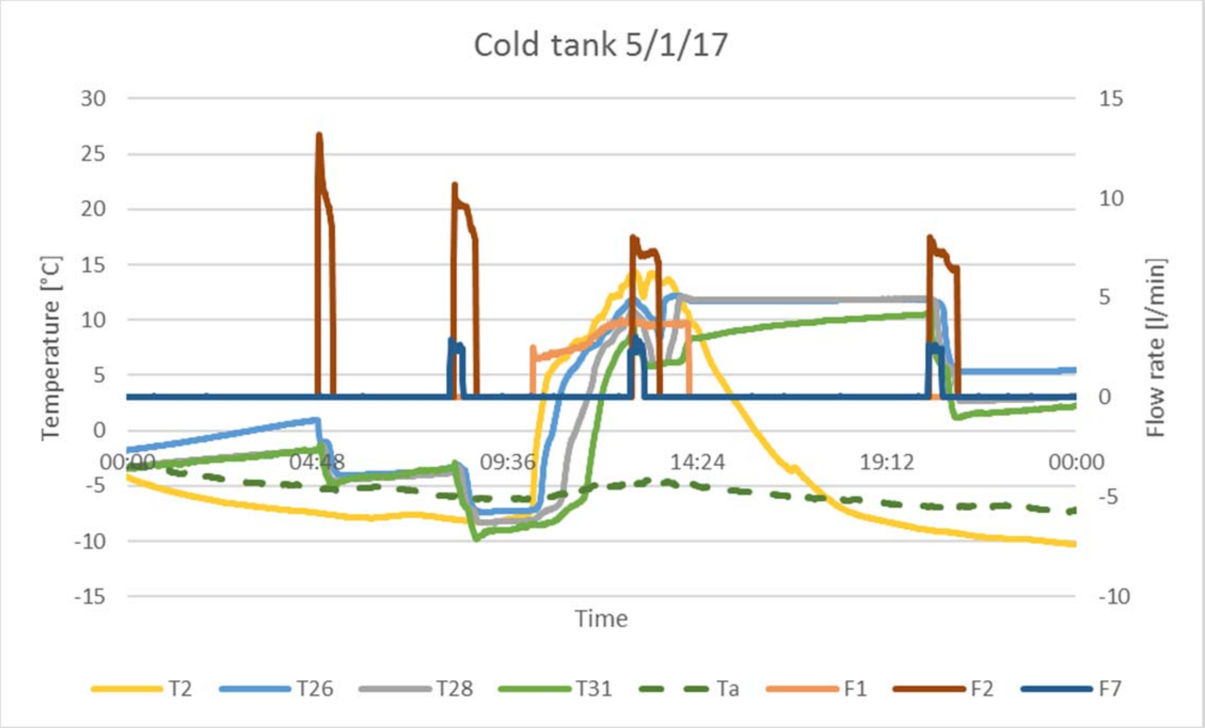
Negative collector output was observed from 17:00 to 19:00. An adjusted control strategy may avoid this. During this day 1.4 kWh of solar irradiance was accumulated on the 3.1 m^2 PVT collector and 1.4 kWh of thermal energy was removed from the collector. Some heat was removed from the collectors while there was no irradiance available, this shows that the PVT collectors absorbed heat from the ambient even when no solar irradiance was available.
The HP consumed 2.7 kWh electricity and 4.6 kWh of heat for the DHW was tapped. This corresponds to the COP of 1.7 for the system.

5.4.4 Minimum temperature in cold tank

The coldest temperature measured in the cold storage tank was -9.8 °C on the 5/1/17 at 8:51. Figur 19 shows the measured irradiance and the thermal collector output per m^2 on the 5/1/17. Figur 20 shows the temperatures in selected locations and flows in the system.



Figur 19. Total irradiance on roof (Gtotal_Roof) and the collector thermal output from the PVT per m^2 (Coll power) (3 PVT) for a winter day with sunshine.



Figur 20. Flow rate in the collector loop (F1), flow rates on the cold side of the heat pump (F2), flow rate of DHW tapping (F7), ambient air temperature (Ta), collector output temperature (T2), temperature in the top/middle/bottom of the glycol tank (T26)/(T28)/(T31) on 5/1/17.

During the morning, the temperature of the PVT panel (T2) was 2-3 K lower than the ambient air temperature (Ta) due to the infrared radiation to the sky. At 8:50 after the DHW discharge and the following operation of the heat pump, the temperature in the bottom of the cold tank (T31) was 1.5 K below the PVT and 3.5 K below the ambient air temperature. The control cut-in temperature difference between the PVT and the cold tank was 4 K. The collector loop pump started at 10:17 when the solar irradiance raised the temperature on the PVT panel above the cut-in temperature difference. Figur 20 shows that during the charge of the cold tank thermal stratification is built up. This is due to the heat from the PVT being delivered to the top of the tank with a flow rate of 2.0-3.6 l/min and the whole volume (200 liters) of the glycol tank is replaced in approximately one hour.

5.4.5 Snow of the PVT collectors

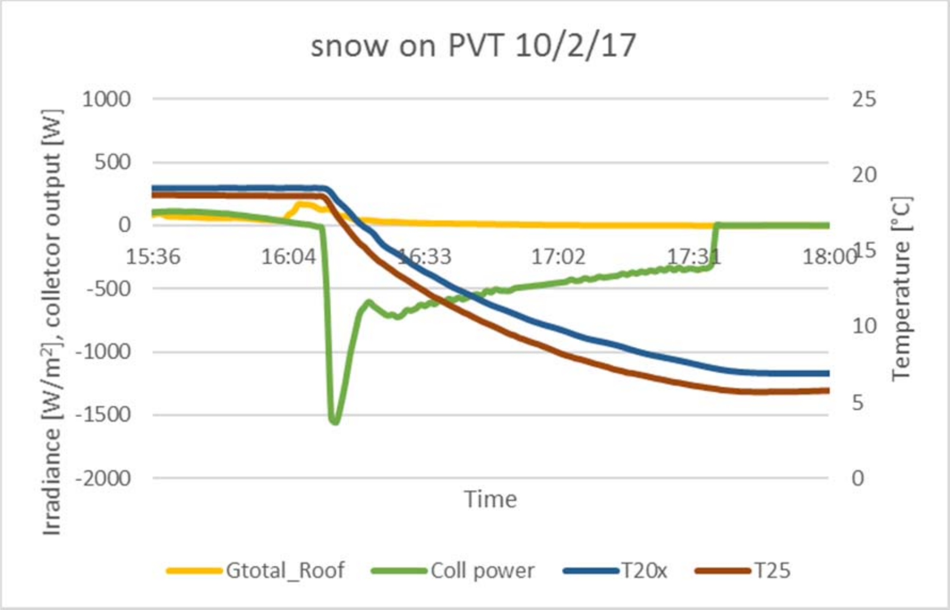
On the 9/2/16 there was 10-15 cm snowfall on the PVT collectors (Figur 21).

Figur 21. Snowfall on collectors 9/2/17 at 10:21

On the 10/2/16 there was little solar irradiance. Snow sled off thermal collector below PVT collectors and remained on PVT collectors (Figur 22).

Figur 22. Low level irradiance 10/2/17 at 16:14

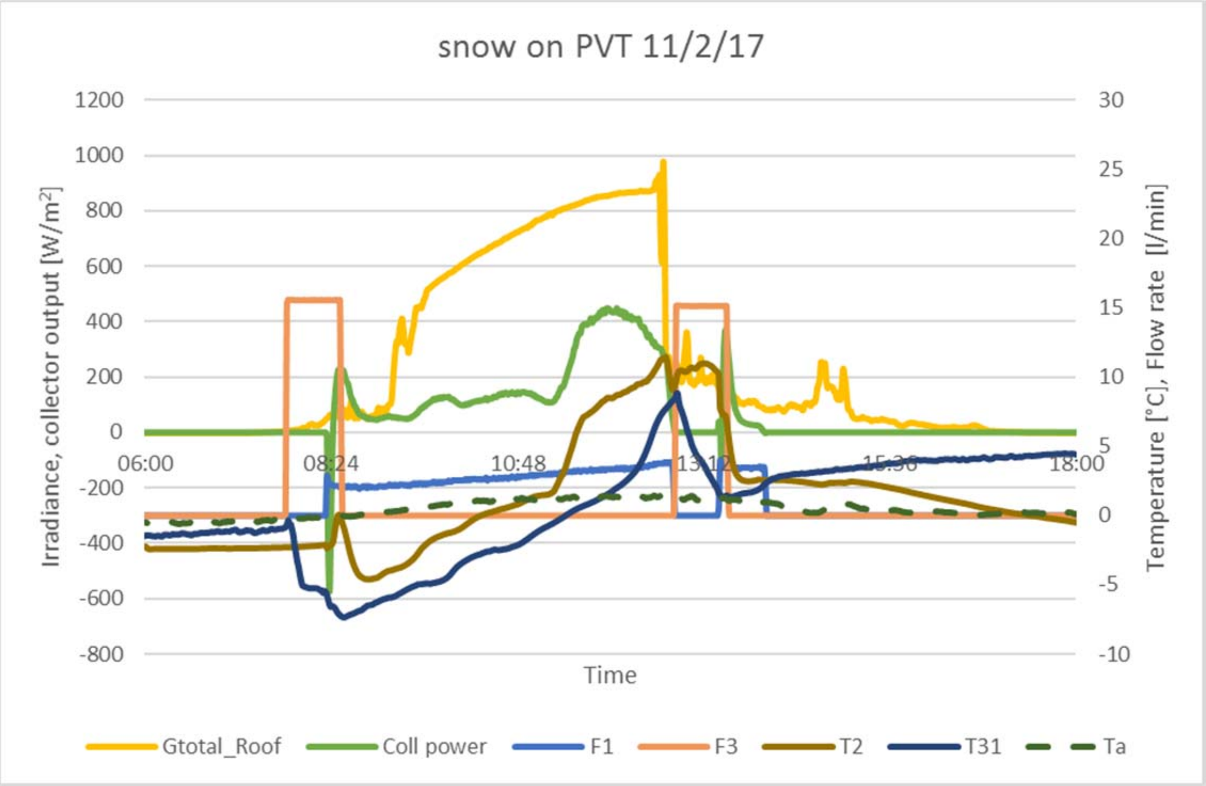
Between 16:13 and 17:36 heat was discharged from the DHW tank via the bottom spiral to the PVT collector on the right to melt the snow on the PVT collector. There was no solar irradiance at this time. The lower part of the DHW tank was cooled from 19 to 6 °C (Figur 23). A total of 0.75 kWh was discharged. The snow was only partly melted (Figur 24).



Figur 23. Discharge of heat from DHW to right PVT collector covered in snow. Total irradiance on roof (Gtotal_Roof) and the collector thermal output from the PVT used to melt the snow (Coll power). Bottom (T25) and lower middle (T20x) temperatures in the DHW tank.

Figur 24. Snow partly melted on right PVT collector at 17:34 on 10/2/17.

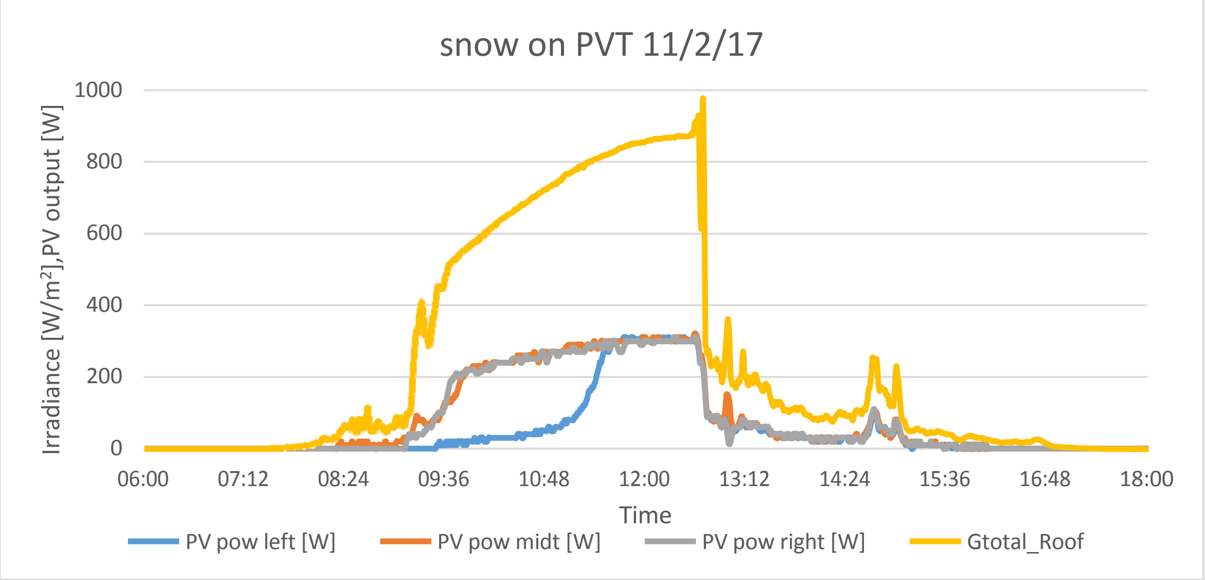
On the morning of the 11/2/17 the left and middle PVT were covered with snow. The PVT collector loop of the PVT system was set to operate on the left collector only by closing the valves to the middle and right PVT. After a DHW discharge at 7:30 the heat pump recharged the DHW tank while discharging the cold tank down to a temperature of -7 °C (Figur 25). The ambient temperature (Ta) was around 0 °C and the collector loop started to run (F1). There was sunny sky (Gtotal) and the snow on the middle PVT melted of rapidly, while the snow in the left PVT remained due to the heat transfer fluid circulated in the loop (T2) was below 0 °C (Figur 26).



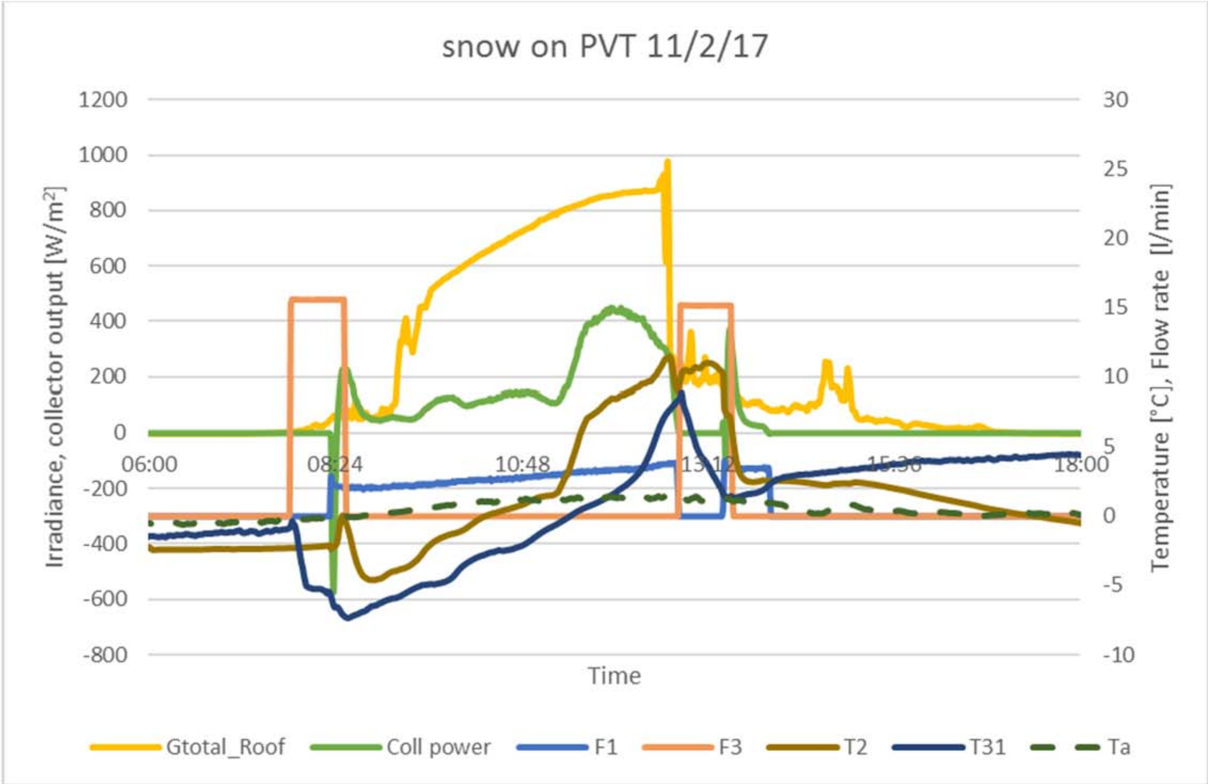
Figur 25. Operation of PVT system with melting snow on collectors. Total irradiance on roof (Gtotal_Roof) and the collector thermal output from the PVT (Coll power). Bottom temperatures in the cold tank (T31), ambient air (Ta), collector output (T2), collector loop flow rate (F1), heat pump flow rate hot side (F3).

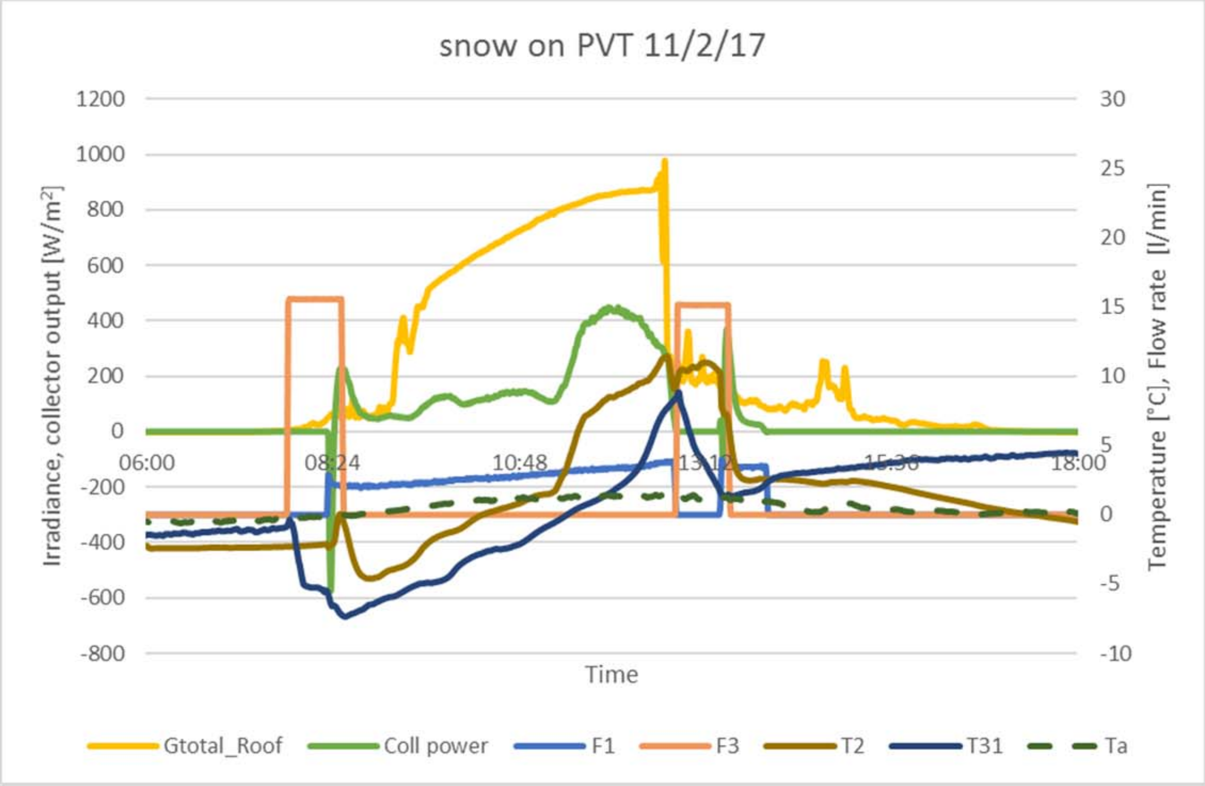
Figur 26. Left PVT covered with snow at 11:06 on 11/2/17.

Once the cold storage tank (T31) reached 0 °C at 11:30 the last snow melted off. The effect on the PV output of the left PVT collector being covered by snow in the first part of the day can be seen in Figur 27.



Figur 27. Irradiance and PV output with snow covered PVT part of 11/2/17.
The PVT on the left produced 0.6 kWh electricity and the two other PVT produced each 1.0 kWh of electricity on the 11/2/17. The thermal output power of the left PVT also increased after the snow melted off (Figur 25


snow on PVT 11/2/17
Irradiance, collector output [W/m2]
1200
1000
800
600
400
200
0
-200
-400
-600
-800
Temperature [°C], Flow rate [l/min]
30
25
20
15
10
5
0
-5
-10
06:00
08:24
10:48
13:12
15:36
18:00
Time
Gtotal_Roof
Coll power
F1
F3
T2
T31
Ta


snow on PVT 11/2/17
Irradiance, collector output [W/m2]
1200
1000
800
600
400
200
0
-200
-400
-600
-800
Temperature [°C], Flow rate [l/min]
30
25
20
15
10
5
0
-5
-10
06:00
08:24
10:48
13:12
15:36
18:00
Time
Gtotal_Roof
Coll power
F1
F3
T2
T31
Ta

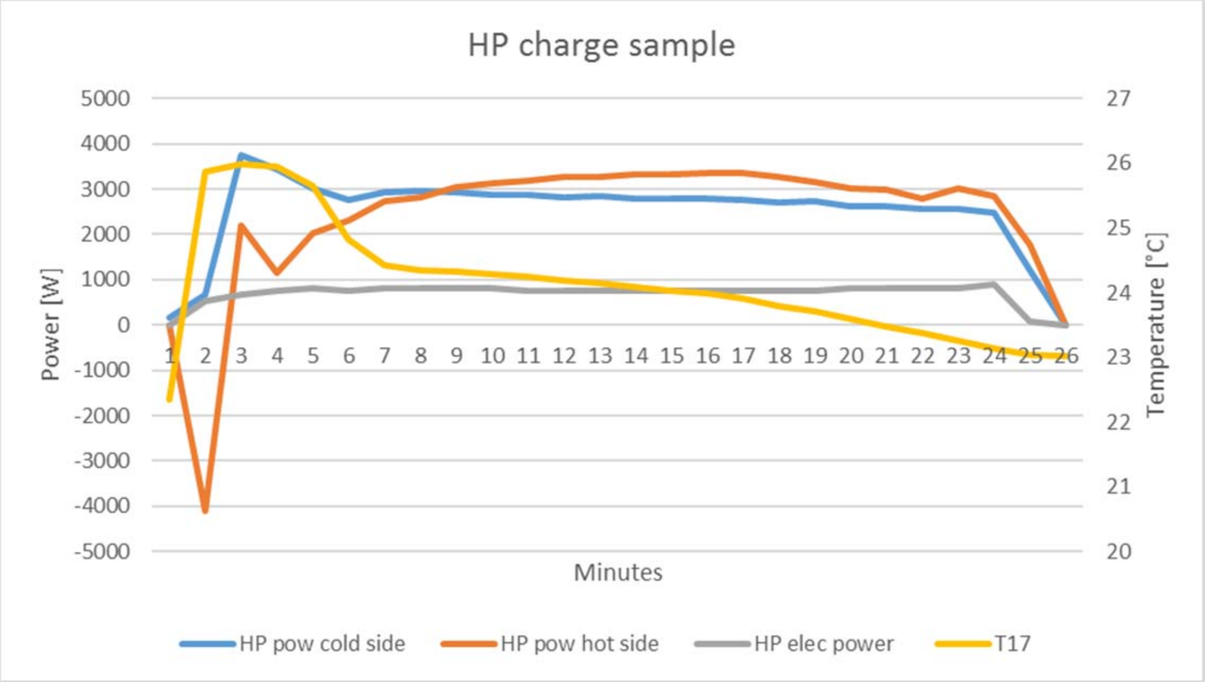
Figur 25).

Figur 28. PVT collectors 11/2/16 at 12:50

From the investigated case, it was found that the operation strategy of the PVT system hindered the snow to melt off fast as the cold heat transfer fluid in the loop cooled down the snow on the collector. The snow on the collector without active thermal loop melted faster. When the PVT panels were covered with snow and the temperature of the cold tank was below 0 °C allowing the snow to melt off before starting the collector loop pump would have led to a higher output over the day.

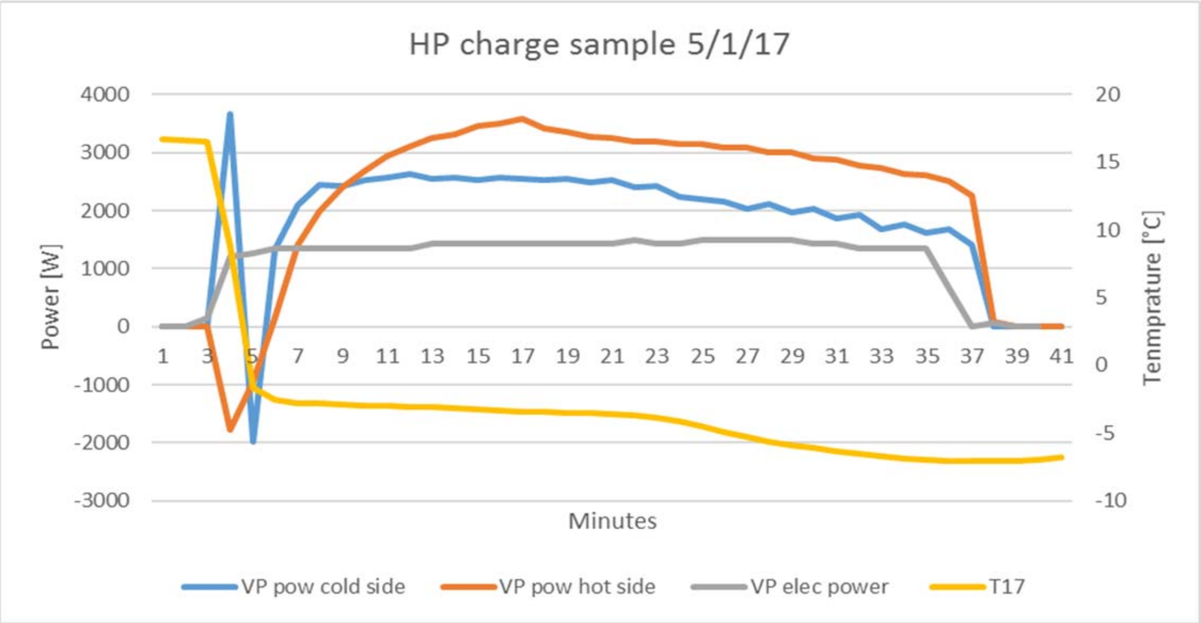
5.5 Heat pump

The montly COP of the heat pump was calculated to be 1.8 - 2.3 over the test periods as listed in Table 3 shows the accumulated energy quantities for the periods the heat pumps was running. The standby electricity consumption in the accumulated energy consumption from the heat pumps for the periods where it was not running. The thermal losses related the heat pump and the pipes connecting the storage tanks is defined as: $Q_{loss} = Q_{cold} - Q_{hot} + (Q_{el} – Q_{sb})$.
Table 3. The low COP was due to an average standby energy consumption for the heat pump of 23 W. Excluding this standby electricity consumption the COP could be estimated to 2.3 – 2.8, lowest in winter and highest in summer. The investigations also showed that the heat pump needed up to 10-15 minutes before it operated efficiently with a high COP. The average operation time of the heat pump was 19 minutes for the summer period. For more efficient system performance, longer operation periods of the heat pump are needed. The charge and discharge powers on the warm and cold side of the heat pump and the electricity consumption for periods where the heat pump was running are shown in Figur 29 and Figur 30. It can be seen that it takes approximately 10-15 minutes before the heat pump runs efficiently. The negative peak in the first minutes of the hot side HP is due to ambient temperature water in the pipes connecting the heat pump with the DHW tank. so the colder water in the pipes is circulated through the top spiral in the DHW tank giving this negative peak as the power was measured across the in- and outlet at the DHW tank. The instantaneous COP was up to 4.5 when the inlet to the heat pump was 24 °C (Figur 29). In the winter when the cold storage tank was the coldest (average -6 °C) the heat pump operated with a COP of 2.2 when it was running steadily (Figur 30).



Figur 29. Powers and electricity consumption of heat pump in operation summer (3/9/16). Inlet temperature to heat pump cold side/outlet temperature from cold tank to heat pump (T17).

Figur 30 show a running period of the heat pump in winter.



Figur 30. Powers and electricity consumption of heat pump in operation in winter (5/1/17), Inlet temperature to heat pump cold side/ outlet temperature from cold tank to heat pump (T17).

Table 3 shows the accumulated energy quantities for the periods the heat pumps was running. The standby electricity consumption in the accumulated energy consumption from the heat pumps for the periods where it was not running. The thermal losses related the heat pump and the pipes connecting the storage tanks is defined as: $Q_{loss} = Q_{cold} - Q_{hot} + (Q_{el} – Q_{sb})$.

Table 3. Data for heat pump operation.

Operation period	**19/8/16 – 4/9/16**	**23/9/16 – 19/10/16**	**21/10/16 – 21/11/16**	**21/12/16 - 22/1/17**	**11/2/17 – 5/3/17**	**9/3/17 – 25/3/17**	**8/4/17 – 1/5/17**
Days	17	27	32	33	23	17	24

Electricity consumption (Q_{el})[kWh/day]	1.4	2.2	2.5	2.8	2.7	2.2	2.1
Energy discharged from cold tank (Q_{cold})[kWh/day]	2.7	4.6	5.4	5.2	5.2	4.7	4.6
Energy charged to DHW tank (Q_{hot})[kWh/day]	2.5	4.9	5.6	5.8	5.9	5.3	4.6
Standby electricity consumption (Q_{sb}) [kWh/day]	0.5	0.3	0.3	0.3	0.2	0.2	0.3
Thermal losses (Q_{loss}) [kWh/day]	1.1	1.7	1.9	2.0	1.8	1.4	1.7
COP	1.8	2.2	2.3	2.1	2.2	2.3	2.2
COP running	2.8	2.6	2.6	2.3	2.4	2.6	2.6

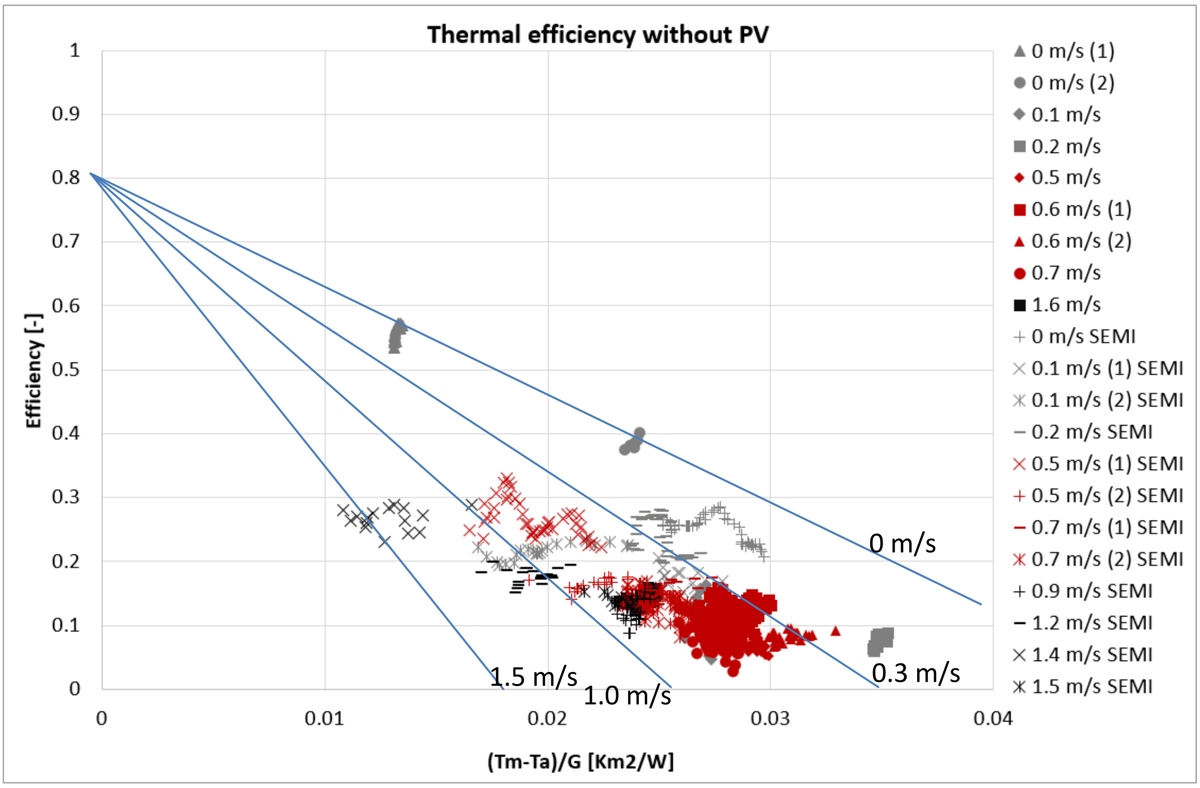
The thermal losses in the minutes where the heat pump was running was partly due to the relatively long pipes between the heat pump and the storage tanks. In as actual installation these components should be placed much closer to avoid these start and stop losses.

5.6 Thermal efficiently of collector

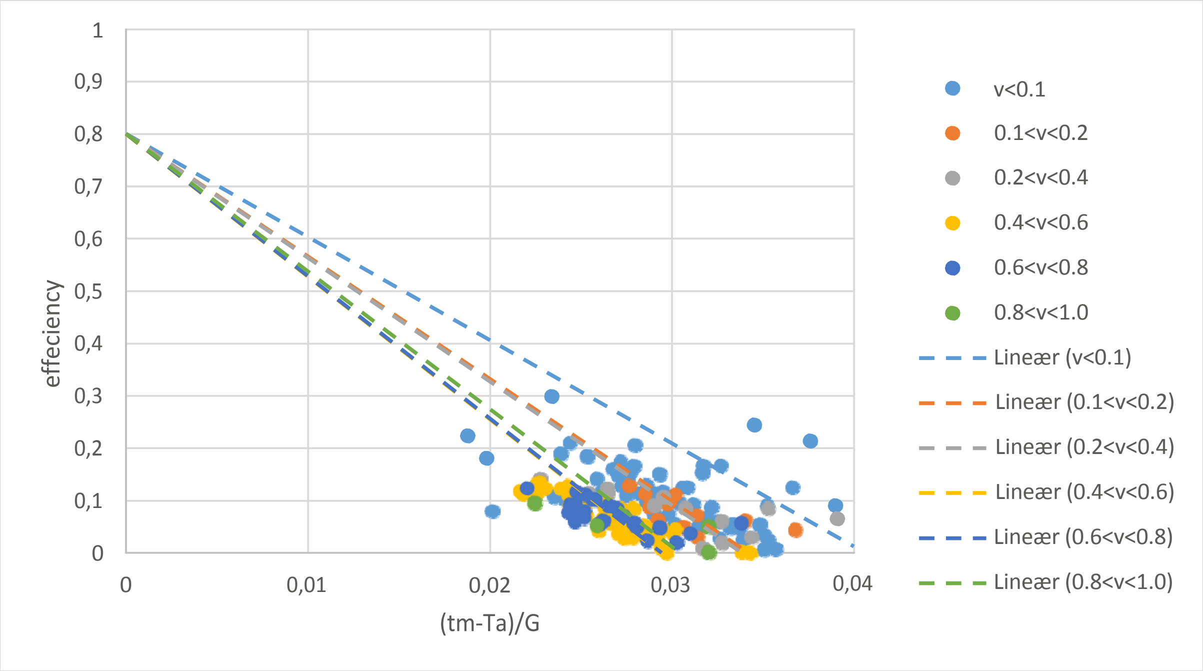
Figur 31 displays the measured thermal efficiency of the PVT collectors without the PV cells in operation. The efficiency is relatively low because the collectors were uninsulated and the wind caused significant heat losses. Guiding lines representing potential efficiency curves for different wind speeds assuming an optical efficiency of 0.8 are inserted in the figure.

In Figur 31, solid markers represents data from the more stable conditions and the thin markers represents data from measurement in the “SEMI” stable periods. Grey plots represents data for measurements with little or no wind, red plots a wind speed at the collector surface of 0.5 – 0.7 m/s and the black plots represents high wind speeds between 0.8 – 1.5 m/s.

Figur 32 shows the PVT collector thermal efficient calculated based in the measurement for the periods without DHW tapping and with continuous DHW tapping.



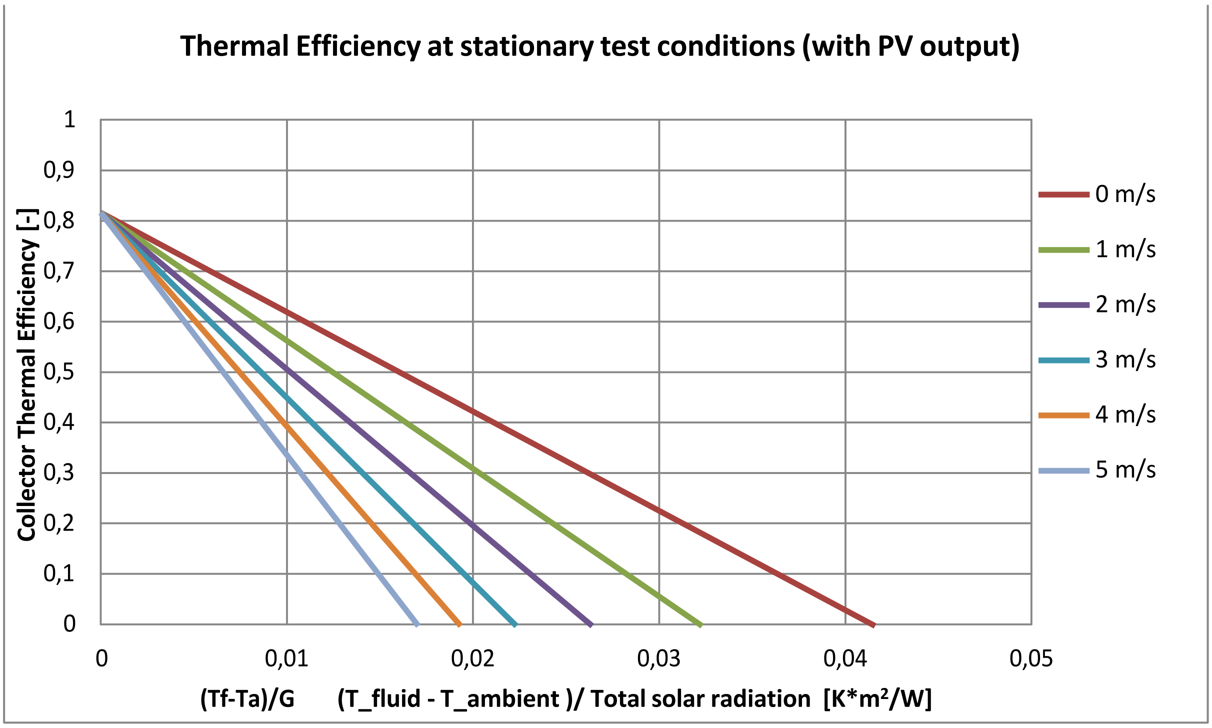
Figur 31. Measured thermal efficiency of PVT collectors in operation without electricity production.



Figur 32 Measured thermal efficiency of PVT collectors in operation without electricity production.

The tendency of the plots in Figur 31 and Figur 32 is that the measurement from periods with little or no wind show a higher efficiency compared the measurements from the periods with wind. This is as expected for the thermal part of the collector.

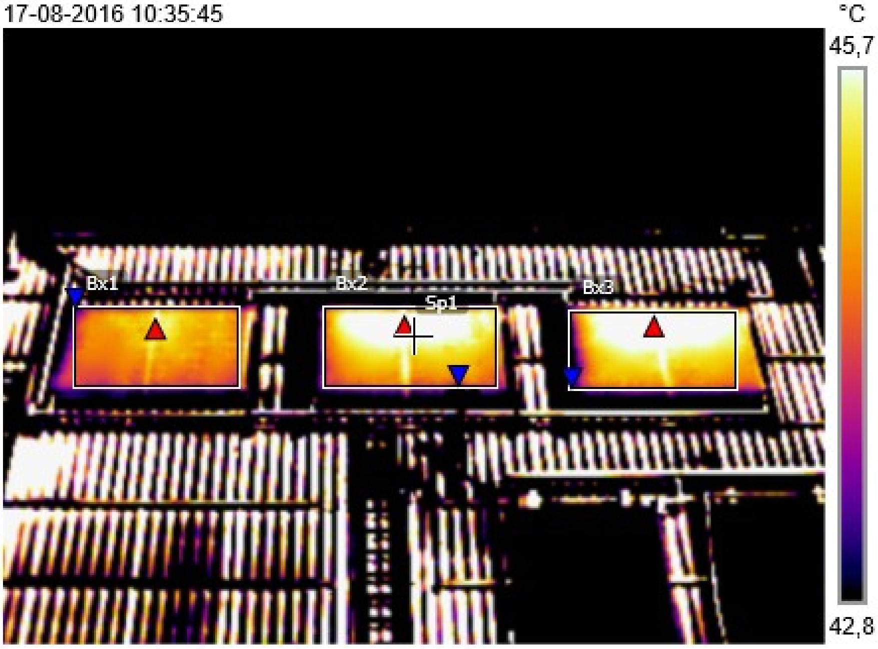
Figur 33 shows thermal efficiencies calculated based on the expressions derived in the report “Performance Test of Racell PVT” by Perers et al. 2014. The zero wind efficiency determined and displayed in Figur 32 is transferred to Figur 33. The dependency of the wind speed is then assumed to be similar as for the collectors analysed by Perers et al.



Figur 33.Thermal efficiency and wind dependency.

5.7 Flow distribution in collectors.

Figur 34 shows that the temperature in the left PVT collector was lower than the other two. This was because the flow rate was slightly higher through the left collector due to the pipe layout. In each collector the temperature was highest in the central upper area of the collectors due to the flow direction, the manifold and distribution pipe design.



Figur 34. Thermal vision image of PVT collectors during operation in sunny condition.

5.8 Conclusion

The investigations showed the concept with two storage tanks worked well in connection with the uninsulated PVT collectors. On sunny days in the summer, the collectors almost covered the heat demand for domestic hot water preparation. The thermal efficiency of the collectors was relative low as expected. The PVT panels were able to extract heat from the ambient when there was no solar irradiance available when the cold storage tanks was cooled below the ambient temperature by the heat pump. The heat pump showed a low performance due to the short periods it was operating. Longer operation periods and a lower standby consumption would lead to better system performance.

5.9 Acknowledgement

RACELL Saphire Technologies ApS has developed the PVT panels and the solar heating system concept was developed in collaboration with COWI A/S. The research was funded by the Danish Energy Agency through the EUDP programme grant no: 64014-0561.

Bilagsfortegnelse

Bilag A - Tilslutnings- og målepunkter for forsøgsopstilling på DTU

Bilag B - Patent for ophængsbeslag til facadeintegration

6 Bilag A

Målepunkter for PVT-system
Temperatur (thermocouples):

- 7 stk i PVT modul (T1x, T1, T2x, T4, T3x, T4x, T11) booth4
- 4 stk i brugsvand tank, glasstav (T19x, T20, T20x, T25) booth5
- 6 stk i kold glykol tank, glasstav (T26, T27, T28, T29, T30, T31) booth5
- 10 stk på rørkreds
    - Solfanger ud, (T2) booth4
    - Solfanger ind, (T3) booth4
    - Ind solfangerspiral brugsvandtank, (T12) booth5
    - Ud solfangerspiral brugsvandtank, (T12x) booth5
    - Ind topspiral, fra VP (T18) booth5
    - Ud tapspiral, til VP (T18x) booth5
    - Ind kold glykol tank, solfanger loop, (T13) booth5
    - Ud kold glykol tank, solfanger loop, (T11x) booth5
    - Ud kold glykol tank, til VP (T17) booth5
    - Ind kold glykol tank, fra VP (T17x) booth5
- 2 stk tappekreds
    - Kold vand indløb (Tk) booth5
    - Varmt vand udløb (Tv) booth5
- Ude temperatur Global
- Inde temperatur Global

Termosøjle:

- Solfangerkreds d(T2,T3) booth4 (K)
- Tappekreds d(Tv,Tk) booth4 (K)

Flowmeter: (l/s)

- Solkreds (F1) booth5
- VP tilgang fra kold glykol tank (F2) booth5
- Top spiral fra VP (F3) booth5
- Varmt vand tapning (F7) booth5

Energy/elektricitet:

- VP forbrug (E(1+2). E(3)) booth5
- PV output (E(5+6), EA1, Estyr) booth4
- tappet energi varmt vand (Edhw) booth5 (kWh)

NB: tappet energi mængde til brugsvand beregnes ud fra F 7, Tk, Tv og en korrektions faktor (tap i rør frem til målepunkter)

Vejrdata:

- Total stråling, pyranometer Global
- Diffus stråling, pyranometer med skyggering Global
- IR (AI1-CH2, AI1-CH3) Global
- Vind hastighed (AI2-CH28) Global

6 Bilag B

Patent udtaget for montage ophæng.

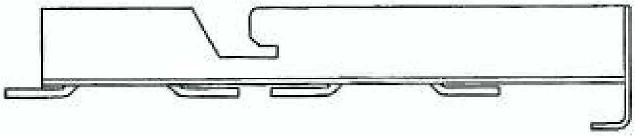
WIPO | HAGUE
The International
Design System

INTERNATIONAL REGISTRATION CERTIFICATE

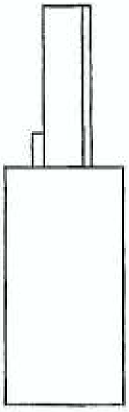
The International Bureau of the World Intellectual Property Organization (WIPO) hereby certifies that the particulars given below correspond to the recording made in the International Register of Industrial Designs, at the date of the international registration, under the Hague Agreement Concerning the International Registration of Industrial Designs.

Registration number	**DM/097 613**
Date of the international registration	**17.02.2017**
Filing date	17.02.2017
Name and address of holder	SAPHIRE SOLAR TECHNOLOGIES APS c/o Yakov Safir, Vester Voldgade 108, 3, DK-1552 Copenhagen V (Denmark)
Contracting Party of which the holder is a national	Denmark, European Union
Contracting Party of which the holder has a domicile	Denmark, European Union
Contracting Party of which the holder has an industrial or commercial establishment	Denmark, European Union
Contracting Party in which the holder has a habitual residence	Denmark, European Union
Applicant's Contracting Party	Denmark
Name and address of the representative	Budde Schou A/S Hausergade 3, DK-1128 Copenhagen K (Denmark)
Name and address of creator of designs	Yakov Safir, Vester Voldgade 108, 3, 1552, Copenhagen V, Denmark
Number of designs included in the international registration	3
Locarno Classification	Cl. 25-01
Indication of products	1.-3. Metal profiles.
Contracting Parties designated under the 1999 Act	European Union, Norway
Data relating to priority under the Paris Convention	for designs No(s) 1, 2, 3: 18.08.2016; DA 201600114; Denmark

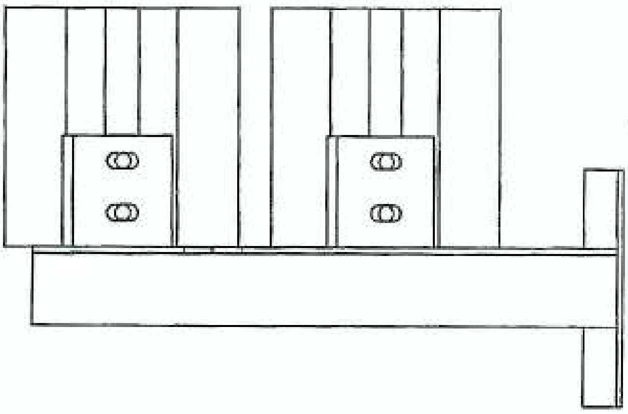
1.1



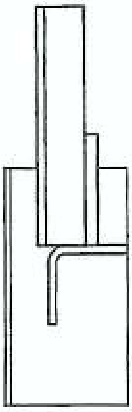
1.2



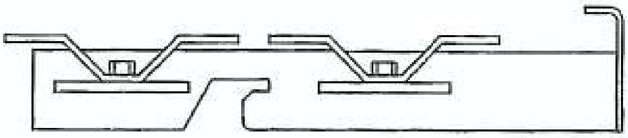
1.3



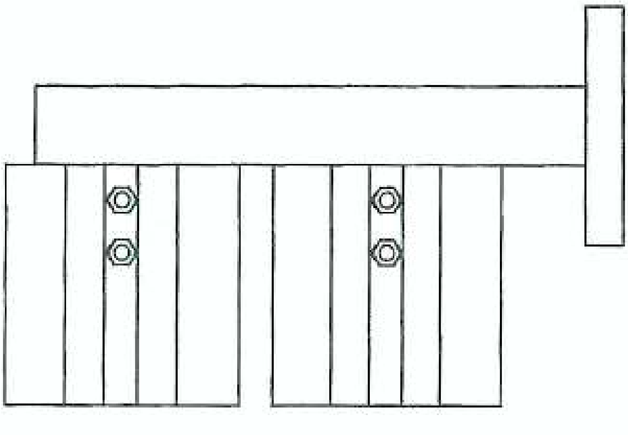
1.4



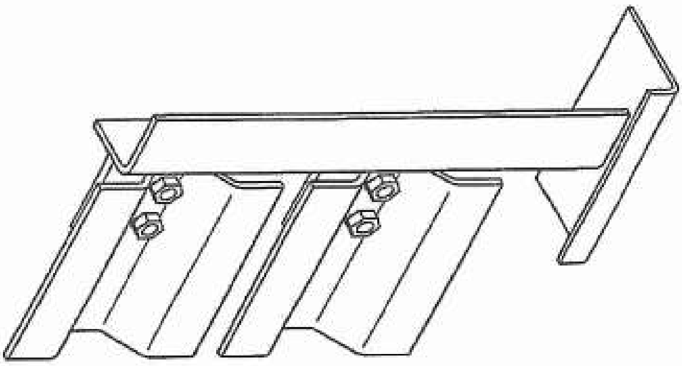
1.5



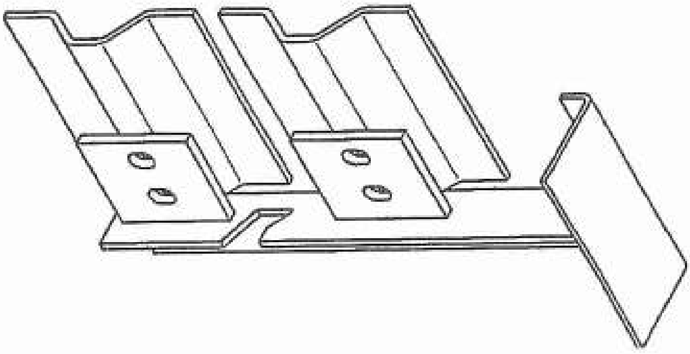
1.6



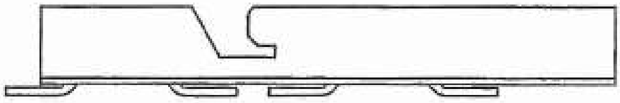
1.7



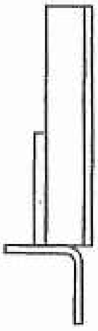
1.8



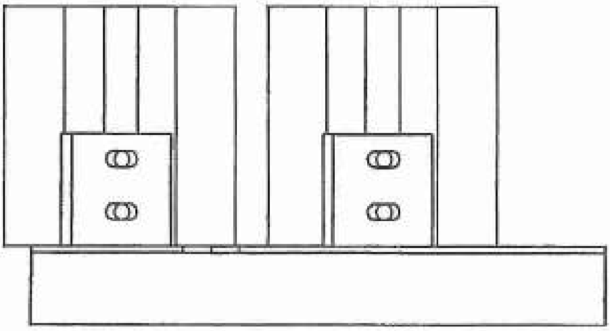
2.1



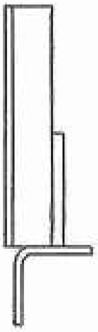
2.2



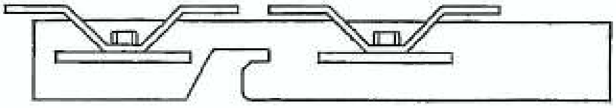
2.3



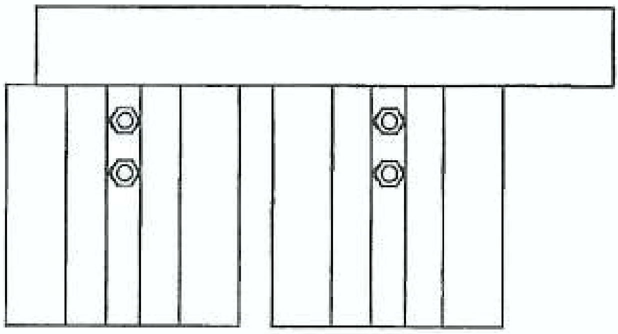
2.4



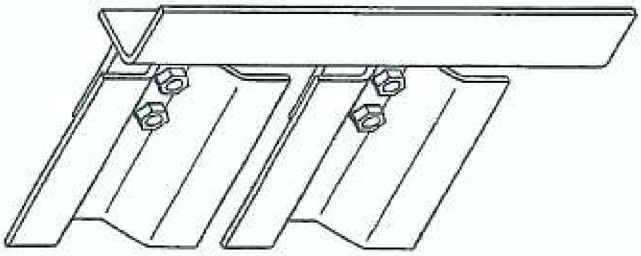
2.5



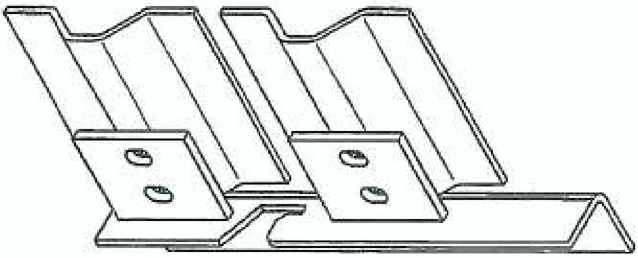
2.6



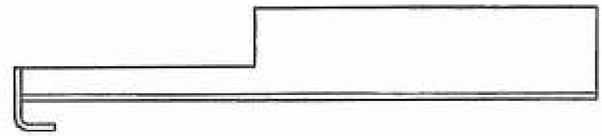
2.7



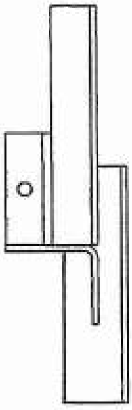
2.8



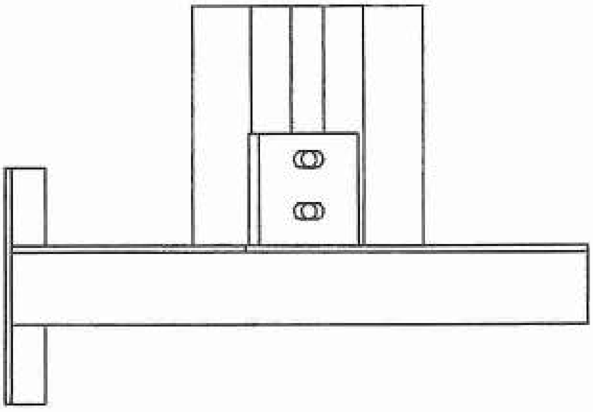
3.1



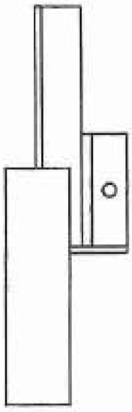
3.2



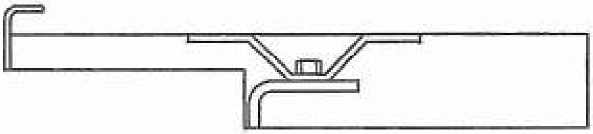
3.3



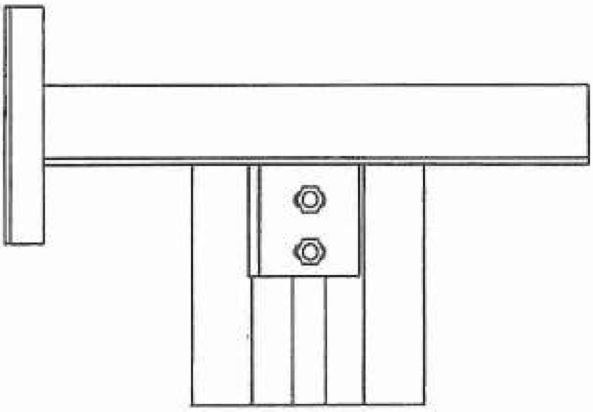
3.4



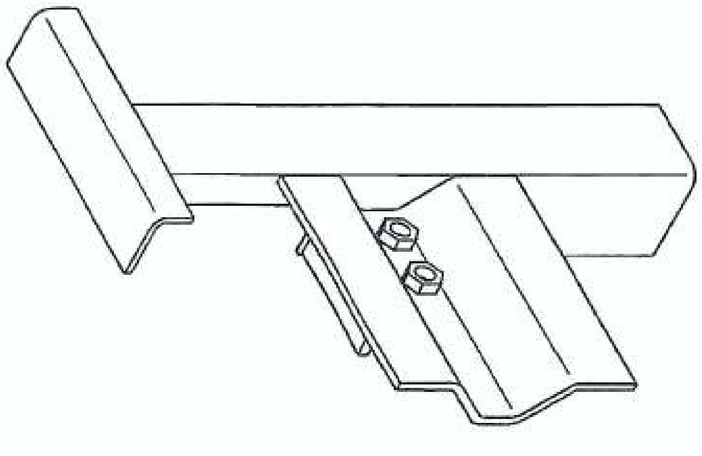
3.5



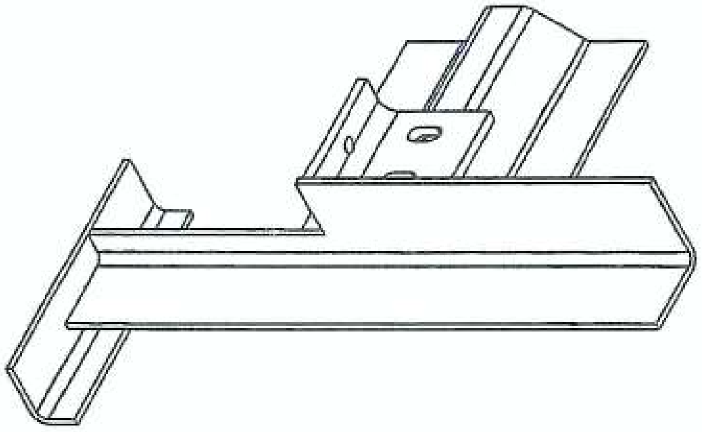
3.6



3.7



3.8



Quan-Ling SIM
Head, Operations Service
The Hague Registry
Brands and Designs Sector

Geneva, September 18, 2017