Solar CHP & C for Commercial buildings

Project details

Project title	**Solar Kraftvarme & Køling, CHP-C for erhvervs-bygninger og lokal forsyning**
Project identification (program abbrev. and file)	**SOLAR CHP-C** (ID# 64015-0614)
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	RACELL Saphire Technologies ApS, Roskildevej 22, DK-2620 Albertslund, Denmark
Project partners	DTU-Byg (CVR DK30060946), Albertslund Kommune (CVR DK66137112), Briggen/ Castellum (CVR DK33508832), ARKITEMA/ COWI (CVR DK15696230), MAP Architects (CVR DK21226343), Lithium Balance (CVR DK29391130), PlanEnergi (CVR DK74038212), Priedemann (VAT DE266306536), Solar City Denmark (CVR DK32872824)
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1. Short description of project objective and results

1.1 English

The project objective was to facilitate via new clean technologies that any typical commercial building can become its own actual energy source, a self-reliant building based on renewable energy only. The building becomes its own energy generator of electricity, heating and cooling.

This optimistic objective was to be reached by developing new types of Building Integrated PV Thermal hybrid panels "PVT". By designing the appropriate components (heat-pump, batteries, storage tanks and intelligent control) an independent local Combined Heat Power and Cooling System "Solar CHP-C" should be accomplished. The Solar CHP should also be beneficially integrated with district heating systems.

Many building types were investigated, and many system types developed. The results showed that special and cost-effective PVT modules could be produced and that surprisingly all energy consumption could be covered by the Solar CHP-C.

1.2 Danish

Projektets mål var at muliggøre at man med ny Cleantech teknologi vil kunne forvandle en hvilken som helst kommerciel bygning til at være dens egen energiforsyningskilde, en selvforsynende bygning baseret på kun vedvarende energi. Bygningen bliver sin egen generator af strøm, varme og køling.

Denne optimistiske målsætning skulle opnås ved at udvikle nye typer af bygnings Integrerede PV Termisk hybrid paneler "PVT". Ved at designe de passende komponenter (varmepumpe, batterier, varme- og køl-lagringstanke, ventiler, sensorer og intelligent styring) vil man kunne opbygge en lokal og uafhængig kraftvarme- og kølingsforsyningsanlæg, tilsammen kaldet "Solar CHP-C". Anlægget skal også kunne være fordelagtigt ved integration med fjernvarmenettet.

Mange bygningstyper blev undersøgt og mange systemtyper blev udviklet. Resultaterne viste at det var muligt at producere specielle og kosteffektive PVT paneler som overraskende kunne sikre forsyningen til hele bygningens samlede årlige energiforbrug via Solar CHP-C anlægget.

2. Executive summary

Four types of commercial buildings were considered: High rise office buildings, Shopping Malls, Production- or storage buildings and Hotels. The Solar CHP-C should provide as much energy coverage as possible to the building and generate the energy by the building's own facades and roof via the PVT panels. These four types should be analysed and simulated in different climates. Except for one building, the design of the PVT and components forming the Solar CHP-C, were to be based on theoretical energy consumptions only.

In the first phases of the project, it turned out that in order to cover the various energy consumptions in the different types of buildings and climates, the Solar CHP-C system had more than 60 different variants. Many different PVT panel types and many combinations of the components and controls of the heat-pumps, storage types, batteries banks, connections, sizes, controls etc. had to be analysed. Each building had its own separate Solar CHP solution. As verification tests were made and as new simulation-systems were developed the number of variants decreased.

A discovery of a new PVT module type "PVT-E", that could exchange energy with the surrounding air, changed the concept radically since energy now could also be harvested during the night or in shading conditions. The PVT module has thus turned into an energy unit that also achieves the same energy gains as ground pipes or energy wells. Thus the PVT-E module becomes the equivalent of both, a solar cell module, a solar thermal collector, a night sky radiation cooling collector and a ground pipe system collector. Four different energy harvesting units comprised. Multiple functions All-in-one element, energy production all year 24/7 all days and all nights.

Along with the project development and search for theoretical solutions, it turned out that several building project-owners and entrepreneurs were interested in the PVT and Solar CHP-C concept and thus were willing to provide to the project real and precise energy consumption data, along with the description of the buildings structure and building components. By developing and optimizing the Solar CHP-C components and concept based on real commercial building projects, the results became much more realistic and directly applicable.

Gradually it turned out that the capabilities of the PVT-E, tested and simulated for all the many building types (more than 68 variants) and associated designs of the Solar CHP-C systems, could eventually be comprised in just one single system configuration!! After this major simplification development, simulation and pre-design of a building could be accomplished within hours only instead of days.

The building owners, consultants, specialists and entrepreneurs challenged the new technology and successfully test results and simulations proved the validity of the Solar CHP-C. Some smaller systems were installed for proving separate issues such as mounting, PV and PVT efficiencies, energy gain by cooling, TABS, black body sky radiation, heat pump efficiencies etc. Thus the utilisation of the Solar CHP-C seems to have attracted a fair number of new future customers. Some of the buildings that were simulated for may still actually be realised as full scale orders for the partners in the EUDP project.

3. Project objectives

3.1 Objectives – Main objectives

The main objective for the project is to develop, demonstrate and provide a cost effective Solar “All-inclusive Multiple Energy Power Plant” or “Solar CHP-C” for Commercial buildings. The Solar powered Combined Heat Electricity & Cooling Power plant, should be easy to implement and consist of the advanced PVT solar units, heat pumps, storage and SMART Energy Control system.

Important objectives are that this “All-inclusive” Solar CHP-C System, shall be adaptable and scalable to various types of- and to large commercial buildings. Thus the PVT elements will be designed in order to (A) AESTETICS - fully fit the embedding and architecture of the building façade or the roof - (B) ENERGY CAPACITY - provide for the PVT cells and energy-absorber material structures enabling the dynamic energy flows 24/7 of the building - (C) SMART INTEGRATION - provide intelligent and modular Balance of System components - (D) EASYMOUNT - provide fast and cost effective installation - (E) QUALITY – ensure long lasting products, aim is more than 50 years, by using high quality materials and system components.

3.2 Objectives – Vital extra features

In the objectives were several extra features that should be included in the same system in order to make the building as self-sufficient as possible and all year round. These features also include (1) intelligent management and storage units (2) PVT panel energy harvesting at night via direct night radiative cooling source and (3) the direct intelligent linking between the PVT [the energy source] and Thermo-Active Building System heat/cool elements, such as capillary pipes or PCM slabs, for indoor room heat/cooling comfort [the energy consumer]. With these features the commercial building shall reach very high energy efficiency, meaning: (I) high energy harvest intensity per m2 per year, (II) high system components efficiencies such as high PVT yield, high COP for the heatpump, low losses from energy storage units and transmission pipes, (III) high flexibility in energy source supply meeting energy consumption in real-time, (IV) low maintenance and reliable high system up-time of nearly 100 percent.

3.3 Objectives – Overcoming technology barriers

The project objectives A, B, C and D are very much connected to overcoming the barriers that have existed for many years in the BIPV and PVT and BIPVT industry. So the present State-of-the-art has these failing features:

> For “on” roofs and “on” facades internationally several commercial buildings have solar modules. They are however separated either as PV modules for electricity only or as Thermal collectors for heating only. Also the mounting minimum 3 layers of expensive metal layers are required. The result is very high weight, large area demand and costly mounting components and installation works. The only “in” roof or “in” façade i.e. true BIPV used are Glass/Glass PV modules. However they require extra wide framing profiles because of ventilation needs for cooling of bypass diodes.

PVT modules exist on the market but only with the PV laminate glued or pressed to the absorber. The glue is unstable and cracks due to climatic frost-heat cycling. Apart from the high thermal resistance between the PV glass module and the glued thermal absorber, because of thermal expansion, the PV cells are stressed causing them to form micro-cracks and thus deteriorate. The state-of-the-art modules are also too small and thus require many of the costly pipe connections. Furthermore they require the standard very expensive installation works and material costs.

The goal of the Solar-CHP-C project is too overcome those barriers that are common in the state-of-the-arts today. That implies that the actual and innovative PVT panel is the most central and important element of the Solar CHP system.

3.4 Objectives – Innovate ▷ Develop ▷ Demonstrate

To meet the many and ambitious objectives and successful results for Solar CHP project, new innovations were necessary and needed to be developed, tested and demonstrated. The new innovative technologies seemed realistic, since the PVT module, components and connecting system had some important head-start and would be able to utilize the knowhow from former successful RACELL lead projects:

(I) "TeSiS - Teknisk Si til højeffektive Solceller", (II) "KIS – Kosteffektive Intelligente Solceller", (III) "Solar Production Technology Meets Architects" supported by Energinet.dk and three EUDP BIPV Projects: (IV) "Self-bearing roof Hercules PVT elements" and (V) "Isolation PVT wall for apartment blocks" and (VI) "COOL PVT".

For the project the expectations were: The 12m2 PVT panel "in" facade should produce electricity, heat and cooling from the very same area. Achievable Efficiency is between 60 to 80 percent for the RACELL PVT panels or PVT building element. Thus the name triple Energy, since compared to standard PV panels which produce 20% efficiency only , the innovative PVT panels produce at least 3 times more.

The efficiency enhancement will be achieved by using newly developed high efficiency parallel multi-channel aluminum absorbers as part of the PVT element. The heat or cold is transferred from fluid in the PVT element through the heat pump to the comprehensive capillary pipe system inside the building or to the thermal storage unit. The architecturally designed PVT modules add to the aesthetics of the building and are simple to integrate either as substitute of roof or façade elements.

By merely using safe and environmentally friendly batteries, Non degrading PVT module materials and mounting elements, the project will ensure quality, long lifetime and minimal maintenance. The battery types chosen for the project could be the innovative "salt water" batteries "AHI" Aqueous Hybrid Ion battery system or LiFePO4 and Lead Acid battery systems. The simulation and advanced control of the batteries was essential for the project in order to provide the necessary flexibility when the energy consumption rapidly changes.

During the night in warm climates and clear skies, the PVT modules are able to collect cooling energy from the sky and provide ice storage for the daytime cooling of buildings. The fluid from the PVT modules can be utilized directly for comfort heating or cooling inside the building via easily mounted wall, loft or floor Capillary tubes. A new SMART intelligent control system will efficiently manage all the components and energy-flows in the Solar CHP system incl. storages.

3.5 The Project Maturity and Risks

The complexity and extreme requirements for the aimed efficient, cost effective and scalable multiple technologies solar CHP system generate many risks. The risks could appear both in the actual structure of the PVT elements and in the other HVAC components (Heat-pump, flow-pumps, controllers, valves, sensors, storage systems etc.) and in the automated control management software for the complete system. There should be redundant facilities if some components mismatch others, since failures in keeping a building warm or cold, will make the stay in the building unbearable for people. Redundant heat and cooling systems are extremely expensive, so most of the risks of the building shut-down will all be allocated to the Solar CHP-C system itself.

The innovative PVT utilizing both BIPV-electricity-heat-cooling production requires new materials, designs and material combinations. These materials have different coefficients of expansion and also the fluid material can create deterioration issues in various system parts. Also the new control software has to manage material changes and fluctuations during operation.

Distortions to the central power, heat and cooling supply is a major risk, in particular for production equipment and for large scale shopping Malls. The scope of utilising the combined heating/ cooling and PVT driven power generation on large scale commercial buildings is a new concept, in particular in combining the PVT night cooling technology. All together the scalable design & sizing of the Solar CHP system for industrial production companies with high variation of energy intensities as well as sizing for office buildings in cold geographical regions and in warm regions requires risky innovative solutions. The combination with new battery storage systems is also risky when considering reliable supply and reliable indoor climate, especially in office buildings and hotels. If the system has to rely on high storage capacities and high instantaneous power for production equipment or ventilation system etc. the system control management and redundant capacities within the Solar CHP-C system must be available. Establishing very large storage units will be too expensive, so a redundant electricity supply and even an extra backup supply for the heating could be necessary. For that reason, the risks are minimized if the electrical grid and district heating are still connected. The dimensioning and the control management and the mutual benefit collaboration with the grid and District heating can minimize most of the risks.

Flow batteries and the innovative AHI batteries, nontoxic and with high capacity, by Aquion was very new and just starting as this project started. It turned out during that the company went bankrupt during the project period. Another flow battery system was investigated instead at the Bolig+ building, but the system used toxic liquid and was difficult to control.

The capillary system and TABS concept are well known but have not been used before in conjunction with PVT, but the failure risks are considered low. Any risk of leakage from the PVT could be avoided by having a heat-exchanger between the production part of the system and the storage and consumption part of the system.

Solutions to the complexity and risks were a major part of the project and were obtained by the 12 highly experienced partners of the project.

3.6 Implementation and Milestones

The main Milestones for the project and their implementation were developed as follows:

M1 PROGRESS REPORTS & COORDINATED WP PLAN UPDATES

This was standard procedures, but some difficulties occurred a few times, when the larger commercial partners made major changes for their internal business strategies or organization structure or merged with another company. However since the project was still of high interest, the companies returned to base and fulfilled their commitments.

M2: ARCHITECTURAL ILLUSTRATIONS & VISIUALISATION OF SOLUTIONS

Several architects were involved and the as the projects became more concrete with actual cases, the combination of simulation models and visualisation became very successful and proved the importance of the aesthetics of the otherwise complicated technology based Solar CHP-C system.

M3: OPTIMIZED PROTOTYPES AND MODELS READY

The first prototypes were changed several times as output came from simulation results and full-scale tests. In the first part of the project software tools were not fully developed and the four commercial building types (Industrial & storage building, Shopping Malls, Office Buildings and hotels) and variants (size, consumption, climate) were far too many. It would take several days to simulate every single variant system.
Gradually as the software was further developed and test results could be matched with the simulation models, results could be made within hours and the number of variants could be reduced dramatically from more than 60 to one general model only. This process generated new optimised prototypes for successful tests and implementations.

M4: DEMO SOLAR CHP SYSTEM FULLY INSTALLED

The Solar CHP-C project was directly responsible for the interesting implementation of some small and some large scale system in Denmark and Norway.

M5: TEST RESULTS & VERIFICATION OF ENERGY & COST MODELS

Utilizing the actual commercial examples that were made available for the project, it was possible to calculate and verify the systems. The variants were many and the political restrictions on energy prices, especially sales prices (excess energy produced by the Solar CHP-C) when interacting with the grid, introduced uncertainties for the cost models. However even with worst case scenarios, it seems that the Solar CHP-C provides very good ROI results compared to other alternative energy systems. Obviously, the price for the PVT modules is important and must be reduced, which is also expected by the fast learning curve for this product. In the cases of renovation or new building the ROI was always extremely good if the PVT is used as the actual self-bearing building elements of the roof or the façade of the commercial building.

M6: SIMULATION MODELS COMPLETED & VISUALISED
Three simulations programmes were developed during the project, Polysun, Transys and PV-Bat. In all three modelling programmes the new PVT-E element has been successfully implemented and new features have gradually been incorporated. Several commercial buildings were analysed and successfully simulated and visualised as shown in this report.

M7: SEMINARS, PAPERS & PRESENTATION TO PUBLIC & TO INTERNATIONAL DEVELOPERS
Because actual cases were implemented in the project, there were several opportunities for seminars and presentations. Most successful the presentations related to commercial bids or renovation projects provided the interest of many partners from the building industry also internationally. In particular, the self-reliance issue of the three types of energy, created major interest by developers and the public.

The Milestones M1-M7 became an integral part of the commercial milestones listed below

CM1: Architectural visualization & simulation Model presented

CM2: Complete Demo system can be presented

CM3: Reliable costs and regional adaption ready

As for CM3, some serious uncertainties still rely on the cooling part, since the market for this type of Solar CHP-C is enormous whereas the cooling on a larger scale is still not proven. Cooling by black body night sky radiation was tested on a smaller scale in the project and was clearly proven. It has also been tested by others on a large scale, but without PV.

CM4: Dissemination to International developers

A major problematic barrier with the Solar CHP-C project is that the technology is very new and unknown in the building industry. For commercial parties in the conservative building industry it is essential that the technology is proven and thoroughly demonstrated. Another barrier was that no party wishes to take responsibility for projecting and implementing such a new technology. Therefore, some prefabricated units must be developed in the future to ease the opening to the market. Finally, the customised designs were accepted, but involve high extra costs and many expensive consultants, engineers and high insurance fees. Therefore, the PVT elements must be standardised in the future, so that it will be easy to implement them as any other standard building element and to fulfil the national Building regulations etc. for the roof or the façade. In order to overcome these three important barriers, this requires another and new RTD project.

4. Project results and dissemination of results

The project results succeeded in realising the objectives of the project. The results were many and are best described through the actual cases. Technically and commercially , the most surprising results were that that the commercial buildings could be turned into self-reliant buildings on a yearly basis by using only the renewable energy produced by the building skin, i.e. by utilising the PVT and the proper dimensioning of heat-pumps, storage units and smart control system. Depending on the height and consumption of the building, often the roof in itself had enough area for providing the energy. Especially for high rise office buildings, it was necessary to utilise the façade area as well.

The project managed to introduce and develop several smart control systems, some of these were successfully proven, some failed because of complexity and lack of suitable heat pumps and other components. The configurator idea could however use the control systems for designing a complete Solar CHP-C system with all ideal components included. Along with the engineering design and dimensioning of the components, an architectural design was developed. Thus, the result was that if a customer with a commercial building is requesting a systems design and fairly precise numbers for the energy savings and degree of energy self-reliance and an architectural visualisation of the system, a first full description could be developed within a few days.

The fast configuration of a complete Solar CHP-C system for any given building has opened up for an unexpected market. Surprisingly, because one basic system formed the basis for all types of buildings and climates. The result is that the partners in the project have gained more interest for Solar CHP-C idea and have started promoting it along with their own products. They all expect that both increased turnover, exports and thereby employment will be the result within a couple of years. The breaking point is to prove the system with full scale references. This is happening now but needs a couple of years with firm long-term results in order to prove that the algorithms and the components work according to the simulated engineering and architectural models.

Because the partners in the project succeeded in promoting and disseminating the ideas and preliminary results, several commercial real cases turned up, some of them described in this report, and those real cases attracted several consulting engineering and architects and building owners. They automatically spred out the word to others, so that the project partners were invited to seminars and presentations, especially in Norway and Sweden. Recently international visitors and specialists from a new IEA PVT task group was visiting Denmark and some the installations related to the Solar CHP-C project. Without further attempts to promote because IPR and commercial reasons, of the concept outside Denmark, still a number of requests have come especially from Germany, France, Italy, the USA and Canada.

4.1 PVT-E, the “Energy-absorber” a new product discovered, producing energy from the surroundings day and night

A major discovery was made during and for the Solar CHP-C project, as the test measurements made on the various PVT construction types, indicated that exchanging energy directly with the surroundings: air, vapor, rain, wind, snow and ice. This important discovery proved that the PVT modules could also operate in darkness and simply harvest energy from the air. Because of the large area covered by the modules and the efficient liquid absorber, the energy harvesting resembled geothermal energy pipes collecting energy from the ground. The geothermal energy pipes are known for collecting the energy to be used in conjunction with a heat pump and thus providing energy for either cooling or heating.

It turns out that the absorber was most efficient when it rained. If there was Ice or snow, it could quickly form a liquid surface and the ice / snow would slide down.

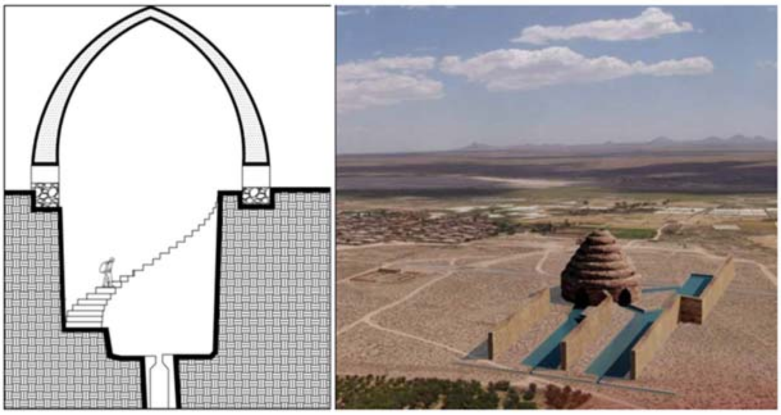
After this important discovery, absorbing energy from the surroundings, the new Racell PVT elements were called PVT-E. The “E” symbolising the “Energy absorber”, which before was only shown by the “T” which indicated the Thermal part of the module. It turned out to have vital implications for utilizing the facades of high rise buildings.

The energy absorber that is placed behind the solar cells consists of many thin multiple pipes in a aluminium structure. Thus, the energy absorber can collect energy from (I) the sun during daytime, (II) exchange energy from the air both day and night and (III) exchange energy with a clear sky at night by the black-body-sky-radiation phenomena.

At clear nights PVT units can absorb cooling energy by radiating heat directly to the clear cold Sky (Delta T at -25 ºC). In the day time the accumulated cooling energy can be used for cooling the building.

The night sky radiation cooling phenomena was used already in ancient Persia 2500 years ago to keep huge ice storages.

The ice was stored all year round in the hot desert areas.



The discovery of the efficient Energy absorber suddenly enabled using the façade for energy harvesting for cooling, instead of only using the roof for cooling by night sky radiation. In particular or high-rise buildings, the energy absorber is important. In the daytime when shading from other high-rise buildings stops the harvesting of PV electrical energy for any modules on the facade, much energy can still be absorbed, either for heating or for cooling. The potentials of the Solar CHP-C project ware certainly widely extended by making the module work in shading conditions or at night.

4.2 FACADES of Office buildings by Solar CHP-C

For high rise office buildings, a major issue is how to enable mounting of large scale units on the roof with strong winds and even worse, how to mount the PVT modules on the facades. The relative area on the roof is limited for the high rise buildings and therefore the façade areas must be used. Utilising the façade is of prime importance, especially in cities with high rise buildings that are shading for each other. The same cities that have the highest energy consumption, have limited light for solar cells because of shading. However, since during the project a new type of PVT module was developed, the PVTE, it turned out that the Solar CHP-C system could extract heating and cooling energy from the facades irrespective of the shading and thus also during the night. The major discovery gave the facades of the buildings a completely new role as an energy supplier.

The aesthetic issue is of prime importance and no compromise is accepted, whether for small façade units or the very large ones. The large modules are more cost-effective from the production point of view, because of faster mounting time and because there are less pipe interconnections.

In the project three types of CHP-C façade power modules were developed. The façade mounting could either (A) completely replace the existing façade elements or (B) be mounted on the façade or (C) become an integral part bearing element like the concrete cement blocks.

4.2 (A) Replacing the existing Façade elements

In Copenhagen a black & white structured office building, at Havneholmen 25 in Copenhagen, owned by Briggen/Castellum was analysed. The main issue was that the well-insulated multi-storey building was overheated when the sun was shining. The very comprehensive heat-exchanger ventilation system filled all the rooftop area. This cooling system was consuming most of the yearly energy needed by the office building. The existing cooling system also required high costs for maintenance. A famous Scandinavian architect had designed black & white façade and nothing could be changed if new PVT façade elements should replace the original elements.

Special absorbers and connectors were developed to fit in behind the coloured PVT modules mounting. First calculations showed that by replacing all the black and white façade elements with PVT-E module, the roof conditioning system could be drastically minimised and the new free area could be used for recreational purposes and some for energy storage.

The building is seen in fig. 4.2.1. The establishing of a PVTE Solar CHP-C system is still being evaluated by owner and expected to be implemented in 2021.

More information is shown in Annex 4.3.1D. The project is still being considered by the owner and major savings on both energy consumption and maintenance are expected.

Figure 4.2(A).1 Solar CHP-C Cooling planned via PVT-E resembling the original façade elements

Another office building owned by Briggen/Castellum, at Roholmsvej in Albertslund that contains offices and a large number of servers, was introduced for the project.

The building is only 30m tall but only but only the façade was available for use. Three different façade-elements were developed and it was possible to maintain the same mounting elements.

Figure 4.2(A).2 The office building at Roholmsvej

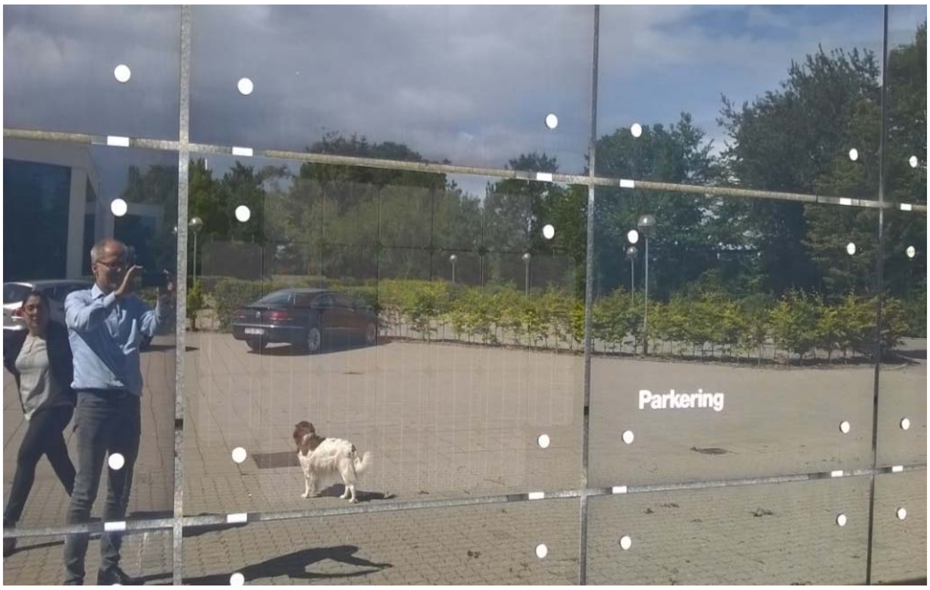


Figure 4.2(A).3 Replacing existing façade element without changing the mounting system or the Architectural Aesthetics

Again, here the PVTE element chosen was one that had no visual differences between the original façade elements and the Solar CHP-C replacement modules.

Both architecture and the unchanged mounting made the owner accept the solution. The losses by having a reflecting and thus less light absorbing glass surface, was compensated by the impact achieved from the heating and cooling energy gains by the PVT-E.

4.2 (B) Mounting PV modules on the Façade

In the case of placing large area façade elements as part of the façade, but mounted on the concrete, this was developed for a school and office building in Oslo on top of the Fjord area, the Nordseter School. Very strong winds and strict architectural aesthetics were the challenges for these large PV glass modules. A special mounting system, which was simple to mount, was developed in the project. It surpassed the static requirements and a 7m2 module could be mounted within minutes. The mounting units were an integral part of the module and could be hooked on two or three aluminium rails.

Spacing for absorber pipes could easily be arranged without changing the mounting structure. Thus this mounting system was designed to enable mounting of PVTE modules including the hidden header pipes for the energy source for a Solar CHP-C system.

The rail mounting and final façade is shown in figure 4.2.3 and 4.2.4 The solar façade modules were placed all around the school building.

Figure 4.2(B).4 New cost-effective Racell rail-mounting system of large modules on façade

Figure 4.2(B).5 Cost-effective aesthetic rail-mounting final result.

Another example was developed and tested for the Solar CHP project on the facade of a production and storage building in Stavanger. In this case the idea was to simply drill directly through the PVTE elements in order to fix them directly to the concrete wall. The modules are seen on figure 4.2(B).6. This system has seemingly had very high efficiencies and can be monitored directly by a link in real time. There are several sensors mounted, so that the temperature and flow can be registered in real time at www.vbus.net/scheme/26a2173d65f2529c068ad534d789b59f

Figure 4.2(B).6 Large PVTE modules fixed to the concrete façade by drilling through the modules

Systemet er blevet koblet sammen med nogle energibrønde for at vurdere samspillet og mulighederne for styring og selvforsyning hele året. Systemet er vist i figur 4.2(B).10 og har kørt siden 2017 uafbrudt. To artikler herom kan ses i Annex 4.2B.8 og Annex 4.2B.9.

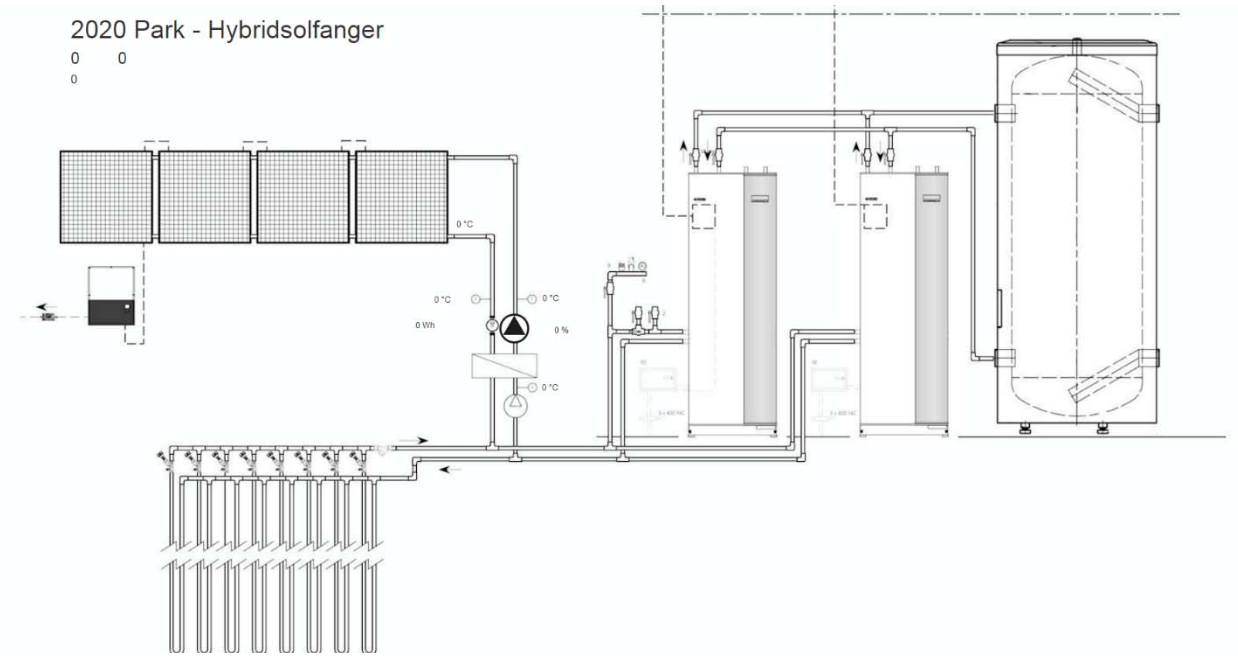


Figure 4.2(B).7 PVTE Solar CHP-C systemet har kørt siden 2017 uafbrudt i Stavanger

Based on the test results from the DTU data and the simulation software developed with COWI, a number of commercial buildings in Norway could be analysed. It was possible in all cases to make the building self-reliant on the energy from the PVTE and Solar CHP, except for when the buildings are high along with a very high energy consumption. This was the case in Trondheim where the façade had to be utilized. The NTNU building has a total area of 16900 m2 and is a combined university building including extensive sports facilities, offices, lecture halls etc. In order to get enough electrical power during the less sunny periods, The PVT could boost the electricity in the façade elements by cooling the cells and thus achieve 30% more electrical energy.

The design of the building is seen in figure 4.2(B).8 and the CHP-C energy flows in fig. 4.2(B). 9. The design was made by Henning Larsen Architects. The available effective roof area for the PVTE modules was only 2500 m2.

Figure 4.2(B).8 PVTE Solar CHP-C systemet for the Henning Larsen design for NTNU at Trondheim

The final simulation results showed that 36 geothermal wells could be abolished. In order to keep the architecture unchanged, the PVTE modules would have the same looks as the wooden structure designed by the architects, thus losing some 15% of the energyy provided by black modules. The results are shown below:

Forbruget på kun 85,000 kWh elektricitet til varmepumpen kan fastholdes.

Resultater på basis af beregningerne:

A. De 36 200m dybe energibrønde kan fravælges helt.
B. Arealer på tag og facade er fordelt om ift. krav fra arkitekterne
C. Spildvarme fra gråvand udnyttes og forbedrer varmepumpens kapacitet om vinteren
D. Der installeres PVT overalt, også på facaderne, således at cellerne yder 16% mere energi pga køling af selve cellerne via væsken i PVT absorberen.

Resultat af beregninger:

Leveret varme og køl fra PVT og varmegenvinding	Produceret, kWh pr. år
Leveret varme til rumopvarmning	178,000
Leveret køling til rumkøling	17,000
Leveret brugsvand med varmepumpe	201,000
Leveret brugsvand ved varmegenvinding	70,000
I ALT leveret varme og køl	**466,000**
Produceret el	
El produceret på PVT på 1500m2 tag 5. etage (hældn 30 grader)	246,100
El produceret på PVT på 975m2 tag 6. etage (hældn 20 grader)	145,700
El produceret på syd facade, 500 m²	64,300
El produceret på vest facade, 250 m²	23,200
El produceret på øst facade, 250 m²	23,500
I ALT produceret elektricitet med PVT	**502,900**
Balance eksklusive teknisk udstyr (+ er overskud)	+73,900

COP med varmegenvinding indregnet [1] 5.5

Elforbrug	kWh pr. år	Til CO_2 opgør-lse
Vifter	154,000	154,000
Pumper	20,000	20,000
Belysning	170,000	170,000
Varmepumpe	85,000	85,000
I ALT, eksl. tekn. udstyr	**429,000**	**429,000**
Teknisk udstyr (jf. HENT 4/1)	197,000	
I ALT, inkl. tekn. udstyr	**626,000**	

Udnyttelse af PVT på facaderne og et varmesæsonlager (jordslanger eller brønn) bevirker at solcellerne kan køles endnu mere og dermed producere tilsammen måske 21% mere elektricitet i de varme måneder. Denne 5% ekstra merproduktion af elektricitet kan bruges som sikkerhed for produktionen også i år med mindre solindstråling.

Beregningens resultat henover et fuldt år vises her, hvor de endelige arealforhold er indført og hvor også gråvand spildvarme udnyttes.

[1] Der er således antaget at 70 000 kWh kan genvindes fra brugsvandet. Man kan indregne dette i COP, så man kommer frem til en COP på 5.5. Denne del af COP er jo uden el til pumper mv.

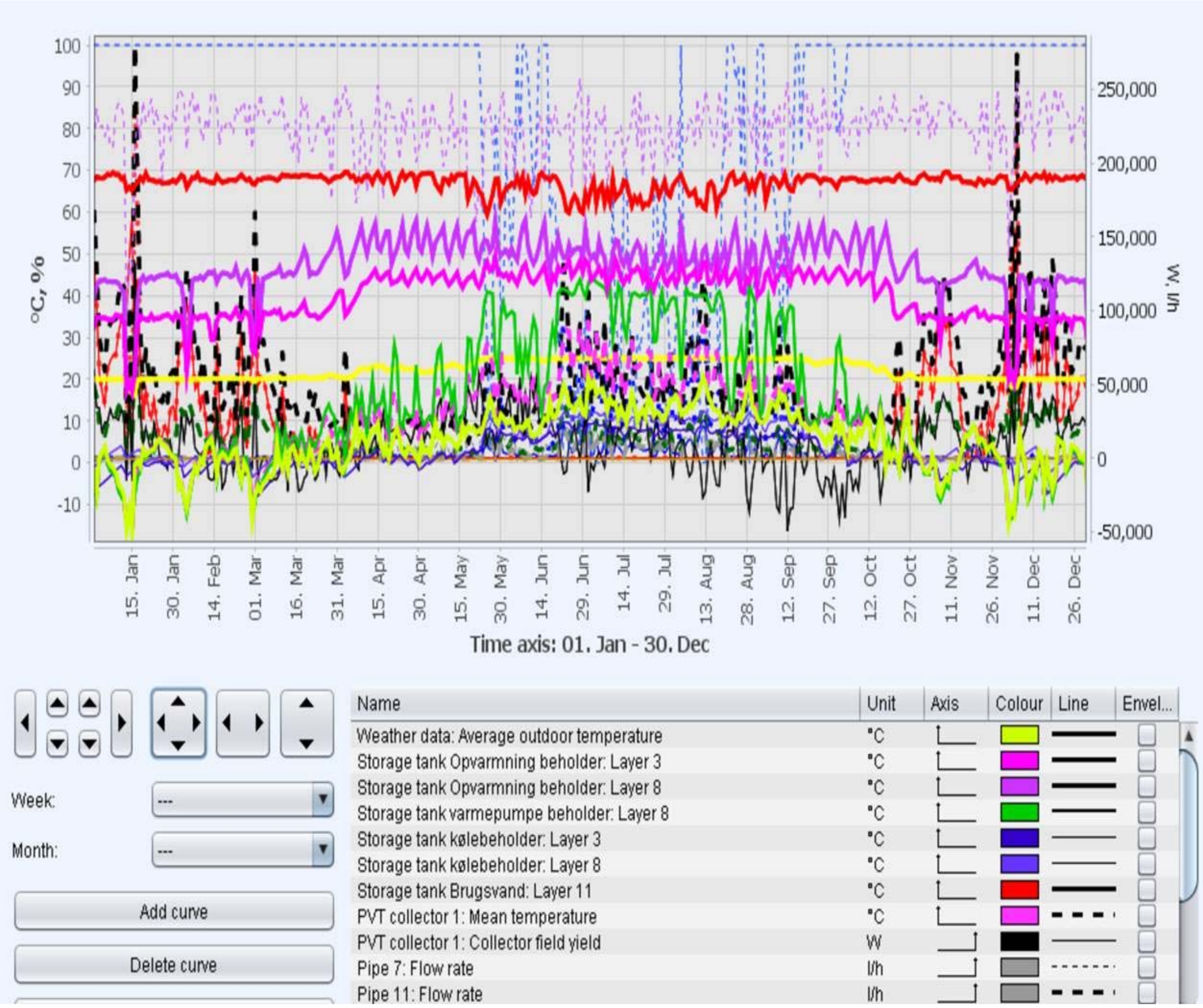


Figure 4.2(B). 9 Energy production results at the proposed university, NTNU in Trondheim with high efficiency PVT modules that cool the cells and thus increase the electricity yield by 22% .

4.2 (C) PVT Façade modules as part of the actual concrete wall

More and more new building projects are reducing costs by minimizing worktime on the actual building site. This also significantly reduces the costly necessary working area of the building site. Therefore more emphasis is made in pre-manufacturing. By pre-manufacturing also several risks are avoided and quality control is optimized.

The Solar CHP-C project has thus collaborated with a large international manufacturer, CRH plc, of Concrete elements. The aim was to incorporate PVTE and PV modules as part so it became a part of the concrete block while drying the cement. The PVTE from Racell is expected to melt into concrete elements of up to 12m in height. Various types of PVTE / Cement elements were created and the piping passages through the concrete block were developed.

One important issue regarding the unification of the PVTE module and the large concrete block is the energy storage that the concrete can accumulate from the modules. Also cooling of the module is provided by the massive mass of the concrete. The final test site is shown in fig. 4.2(C)10

Figure 4.2(C)10 PVT-E modules encapsulated concrete wall On the right steel PV modules.

The modules were made of steel and of aluminum in order to test the influence of the differences in the coefficient of expansion. For prefabrication and complete encapsulation in the cement, the steel solution is the only viable one. The system setup and test site is described in Annex 4.2C.8

One module had an isolation sheet between the concrete and the module. This module was considerably warmer than the others. Several sensors were incorporated and the details of the output from the modules made it possible to predict how they would contribute in a Solar CHP-C system.

The major benefits were both that extra cooling capacity was achieved by the mass of the concrete. Physically the other benefit was that the PVTE was very thin and when made in steel, it actually enforces the concrete block. The shallow thickness of the module is extremely important since the wall can keep it standard slim dimensions and does not need extra and costly concrete mass.

The tests of the temperature and thus the influence on the CHPC system turned out to be very complex. Several variables were influencing, not least the wind on one side and the concrete mass on the other. An article describing the tests and results for the concrete wall is given in Annex 4.2C.9.

The test system set-up as incorporated in a CHP-C system is shown in figure 4.2(C)11.

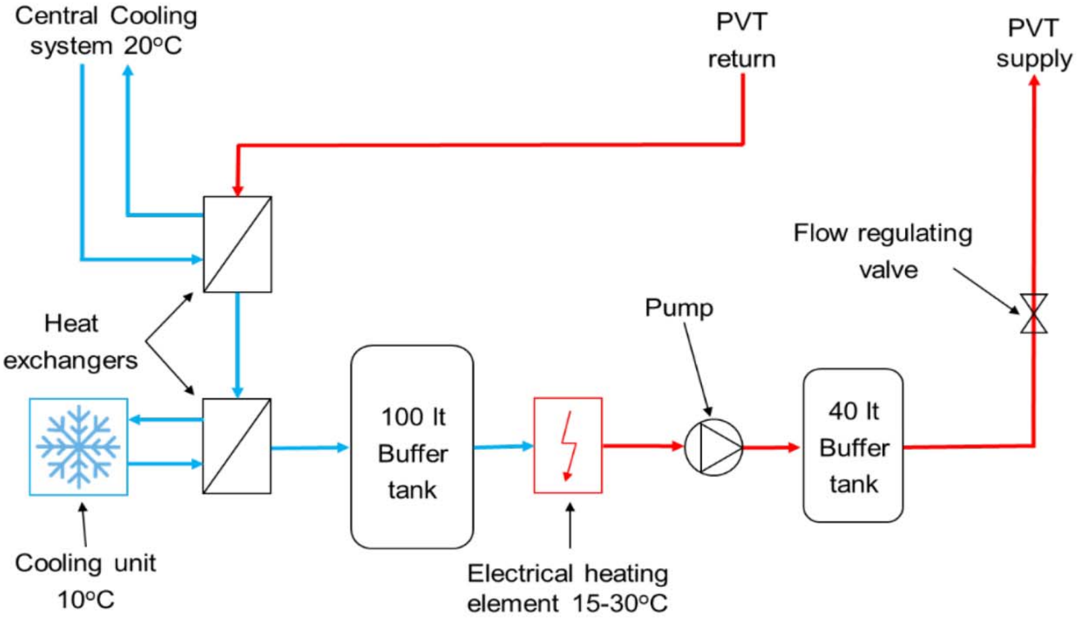


Figure 4.2(C)11 The CHP-C test system for the PVT-E modules in the concrete wall

4.3 Solar CHP-C Proof of Concept for various building types

As the project developed, various PVT-E roof systems were investigated. For buildings, contrary to office buildings, with a large roof area ratio, such as shopping Malls, Supermarkets, storage buildings and production buildings more space was available than needed. For hotels in recreational areas the buildings are low and this resemble the roof ratios of the other low rise building types. Office buildings and some hotel types have a low roof ratio and the facades must be used. The building types are illustrated in figure 4.3.

Figure 4.3 The chosen Solar CHP-C market in this project are (1) large industrial buildings and storage halls, (2) large office buildings, (3) shopping malls and (4) hotels.

Solar CHP-C is ideal for large commercial buildings due to the economy of scales. The PVT solar CHP-C technology dramatically reduces the needs for ventilation, air conditioning and technical installations and thus saves costs for high rise buildings both in hot and in cold climates.

Examples of the calculations for the various building types are given in Annexes 4.3 and shortly described here.

Annex 4.3.1A describes some of the features of the PVT technologies used in this project.

Extensive long-term testing of the various combinations of PVTE and Solar CHP-C was made at DTU and some of the results are described in Annex 4.31B. The tests were also used to change and update the simulation software programs, so that real time physical tests and theoretical simulations would fit the predictions and mathematical models.

4.3.1 Various roof solutions for 4 - 6 STORY BUILDINGS

Annex 4.3.1E shows the case in Norway for a specialized hospital. Instead of some very large air to air heat-pumps, the Solar CHP-C is investigated. The PVTE is considered to form the actual roof.

Another new building in Norway was investigated as to becoming self-reliant with a PVTE CHP-C energy system. The building called Tåsenhjemmet is still being considered. The project is described in Annex 4.3.1F

Figure 4.3.1.a Tåsenhjemmet in Norway, where simulations showed that Solar CHP-C could provide self sufficiency for covering all of the required energy consumption.

In general, it was proven that in Scandinavia it would be possible to achieve self-reliance on energy by PVTE and the solar CHP-C for multistory buildings without having to utilize the facades. The area required would normally be 50-100 % of the roof even if the geometrical directions of the building should be followed with Eat-West mounting or NE/SW or SE/NW. In the summertime for cooling, more electricity is needed for cooling, however in this season the electricity production is at its highest level, so that the balance is fine.

An example in humid and warm countries, is a calculation and simulation for a typical office building in Manila in the Philippines. Also in this case the building can become energy self-reliant as shown in Annex 4.3.1.G

HOTEL BUILDINGS

Two hotels in Morocco were also investigated, simulated and proved to have enough roof area for both electricity, cooling and heat production by PVT-E. The Solar CHP-C for the Agadir hotel is described below:

Hotellet Hotel Riu Tikida Beach tilhører en stor international hotelkæde og er typisk for luksus strandhoteller rundt om i verden der ligger ud til kysten i varme klimazoner. Der er typisk behov for både strøm, køling og varmt vand. Flere steder kan der også være behov for rumvarme, især hvis vintersæsonen i december/ januar er relativ kold. Det varme vand kræves til brusebad og til swimmingpools.

Dertil er der ofte store tekniske anlæg til rensning af vandet i svømmebadene og til faciliteter for de mange gæster. I de tilfælde hvor også brakvand skal renses stiger energibehovet markant. Ved dette hotel var udgangspunktet at man skulle sikre energi til varmt brugsvand og svømmebad.

KATEGORI:	HOTEL beligende ved stranden, men med egne svømmebade
ANVENDELSER:	3-400 værelser skal have varmt vand. Hotellet skal bruge masser af strøm
STØRRELSER:	Til PVT-E er der i første omgang kun 1.500 m2 tagareal til rådighed.
ENERGIBEHOV:	Elektricitet, Varmt vand, Komfortvarme, Køling
MÅL:	Selvforsyning med strøm og varmt brugsvand
EKSTRA:	Hotellet vil være interesseret i mere energi når de opdager mulighederne

Flere simuleringer blev udført og man kom frem til at på trods af det begrænsede tagareal til PVT-E (billede af taget til venstre) så kunne man dække al varmtvandsforbruget.

Den bedste case er tilfælde (B) hvor man får både dækket al varmtvandsforbruget og al varmetab fra cirkulation. Derudover bliver der ca. 305 MWh/år af elektricitet til overs som enten kan sælges til nettet eller bruges lokalt i hotellet til lys, TV, aircondition m.v. årsagen til denne store gevinst i strøm, er at solcellerne bliver kølet af returvandet og dermed producerer mere strøm. Den øvrige årsag til at man opnår så gode resultater er at Solar CHP modulerne via

den indbyggede energiabsorber arbejder hele døgnet, dvs. at de kan generere varme også om natten.

I tilfældet (C) hvor man ikke udnytter energiabsorberen, er der ikke så stor en gevinst som i (A) og (B) så det kun kan lade sig gøre at klare at forvarme vandet og dermed kun yde 55% til varmtvandsforbruget og 0% til cirkulationstab.
I tilfældet (A) hvor der er koblet en varmepumpe på, dækkes al varmtvandsforbruget 100% men i modsætning til (B), så dækkes 0% af cirkulationstabet. Til gengæld er der noget mere (80 MWh/år) overskydende elektrisk energi.

Antagelser

Modulvirkningsgrad (STC @ AM1.5)	188,3	Wp/m²
PVT nodulareal	1500	m²
Beholder til solvarme	20	m³
Beholder til varmepumpe	20	m³
Varmtvandsbeholder	10	m³

ÅRLIG PRODUKTION vs FORBRUG	(A) Uden cirkulation		(B) Med cirkulation		(C) Uden varmepumpe	
	MWh/år	kWh/m²/år	MWh/år	kWh/m²/år	MWh/år	kWh/m²/år
Produceret solvarmeenergi (V1+V2)	**758**	**505**	**1285**	**857**	**453**	**302**
(V1) Heraf solvarme til solbeholder	381	254	286	191	453	302
(V2) Heraf solvarme til varmepumpebeholder	377	251	999	666		
Produceret elektrisk energi (E1+E2+E3)	**502**	**335**	**652**	**435**	**502**	**335**
(E1) Heraf elforbrug varmepumpe	110	73	340	227		
(E2) Heraf diverse systemtab	7	5	7	5		
(E3) Oveskydende elektrisk energi	**385**	**257**	**305**	**203**	**502**	**335**
Tilført til varmtvandsbeholder fra varmepumpe	486		1340			
COP varmepumpe	4.4		3.9			
(F1) Forbrug til opvarmning af brugsvand	826		826		826	
(F2) Forbrug til dækning af Cirk. tab	0		825			
Total forbrug til varmt brugsvand (F1) + (F2)	826		1651			
Dækket procent af al varmeforbrug	*100%*		*100%*		*55%*	
Samlede produktion af Varme og El	**1260**	**840**	**1937**	**1292**	**955**	**637**

Total Investment costs	**800.000**	**euro**	**5.960.000**	**DKK**
Pr. år /kWh	0,63	€/kWh	4,73	DKK/kWh
På 15 år /kWh	0,04	€/kWh	0,32	DKK/kWh

Det fremgår at al forbrug dækkes når der er varmepumpe med.
Hvis ikke så dækkes kun 55% af forbruget til opvarmning af det varme vand.

På trods af ganske forbrugsdata fra besøg på hotellet, så lå det klart at selv uden yderligere optimering, å kunne man faktisk godt dække energiforbruget til opvarmning af vandet.

Ikke medtaget i beregningerne var igen muligheden for varmegenvinding ved udnyttelse af varmepumpen. Herved ville kunne reducere arealet for PVT-E og i stedet bruge supplerende rene solceller til produktion af supplerende strøm til andre tekniske anlæg på hotellet.

En egentlig 100% kraftvarme/køl selvforsyning vil muligvis også kunne lade sig køre ved yderligere optimering af anlægsdesignet. Optimeringerne og tilhørende simuleringer krævede dog flere præcise data.

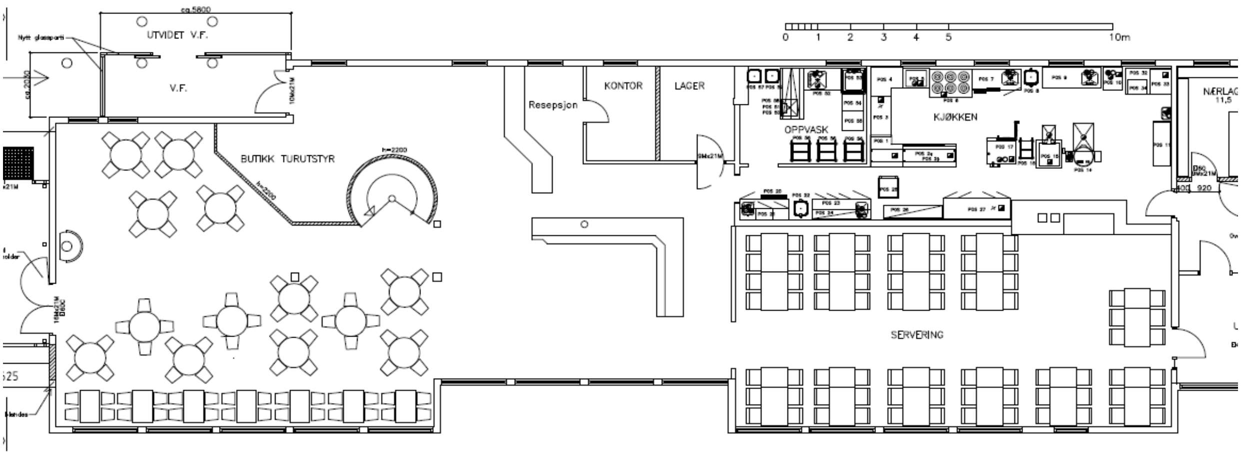
At another geografical position, a forthcoming hotel at Kerag in Norway was considered in order to eliminate the use of helicopters bringing in energy spply such as diesel and gas for the desolated but much visited hotel. A description is shown below.

HOTELS IN COLD CLIMATES in Norway and in Greenland

The forthcoming hotel is to be built on top of a high rise mountainous cliff providing an extraordinary view. More than 100 overnight visitors are expected to climb up every day in the accessible periods of the year. Normally such a hotel and restaurant needs frequent supply of diesel or gas flown in by helicopter. Thus this is one of the highest daily expenses for the hotel. These costs will disappear completely with the Solar C-CHP system as the hotel wil be completely energy self-reliant. Anlægget skal gøre hotellet selvforsynende med energi. Grundarealet er ca. 600m2 og etageareal ca. 1000m2.

Nogle af de krav man forventer bliver stillet til designet af hotellet bliver:

- Kafe/varmestue, serveringsdisk for servering over disk og buffet (ref Haukeliseter). Kapasitet 100 personer ved spisebord. Gasspeis som sentralt samlingspunkt (ref. viewpoint Snøhetta), basert på biogass.
- Oppholdsrom (peisestue) for overnattingsgjester, sittekapasitet 50 personer i sofa/lenestoler.



Udfra de første energiforbrugsprofiler og simulerede løsninger, blev det forløbigt besluttet at man skulle sigte efter en stejl facade, idet man således kunne undgå snelastprolemer. Det var klart at at arkitekten vil være meget afhængig af Solar CHP beregnigerne og orienteringen af PVT modulerne. Derfor bliver det et tæt samarbejde mellem PVT beregner og arkitekterne. Der undersøges muligheder for at opnå så høj udnyttelse ved efterår og forår, men ikke om vinteren hvor der ikke er gæster. Om sommeren er der særlig mange gæster, men der er god udnyttele af energien. Største problem er forbrug for tilberedning af mad til de måske flere hunderede gæster der muligvis kommer pr. dag. Løsningen bliver at bruge gas til dette.

A detailed report escribing the possible solutions with SolarCHP is shown in the confidential report in Annex 4.3.2A

Also a future hotel in Illulisat in Greenland was investigated reg. BIPVTE in two different colors. Also here the energy supply from the PVTE supply to the PVT-E would be sufficient to keep the hotel warm during the whole year and provide enough electricity to appliances and to run the heatpump. However in periods with temperatures in the clear nights below -25ºC, a suplementary gas CHP would have to be used.

Architecturaly the PVT-E modules were designed in two different colors. On one side the modules were made red to fit the local architecture and on the other side the modules were gray. For the PV elctricity production this results in losses of 10-15% only, wheras for the thermal energy no losses are expected.

The colored moduled are forming the actual facade and roof of the Illulisat hotel.

4.3.2 Solar CHP-C for Shopping malls and for Supermarkets.

In the project a number of detailed studies were made for Shopping Malls and for supermarkets, trying to make them self reliant on energy. Actual visits were made for cases in Malaysia, philipinnes, and Denmark.

SHOPPING MALLS IN ASIA

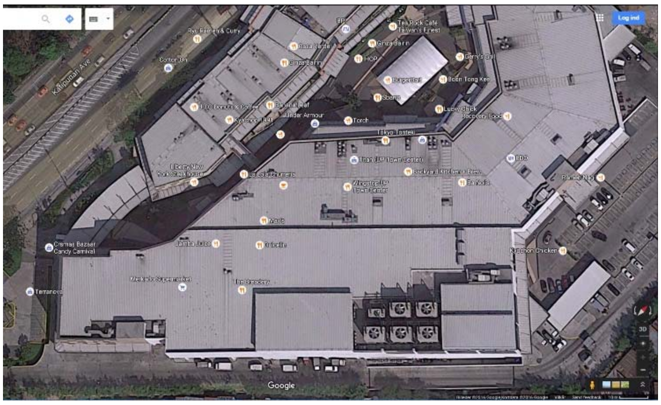
Figure 4.3.2B the shopping Mall Setia City Mall in Malaysia

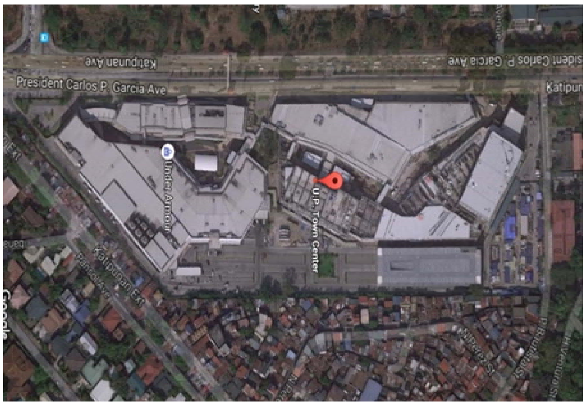
Five large scale Shopping malls with areas of 30 – 80.000 m2 were visited in Manilla in the Philippines and in Kuala Lumpur in Malaysia. Most of the energy supply costs, between 70 – 90 % were used for cooling energy. Thus the Solar CHP-C cooling units were further developed in a new patent pending design for the PVT-E modules and it turned out that the available roof areas were sufficient for self-reliance on renewable energy.

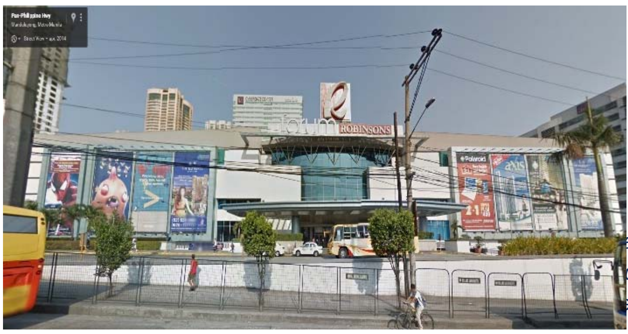
In Annex 4.3.2B the shopping Malls Setia City Mall in Malaysia seen left on the pictures and Robinsons Mall in Manila shown below, the results for the different cases are described.

After the visits to Manila, the calculations for two of the Shopping Malls in Asia were made as shown in Annex 4.3.2B, Setia City Mall near Kuala Lumpur in Malaysia. Below is shown the Ayla Robinsson Mall. One request was made for utilizing the façade as well as the roof, since the PV Starlight LED display PVTE modules could provide colorful advertising for the Mall and at the same time still provide a lot of cooling energy via the Solar CHP-C system.

Utilizing the façade areas fits well into maximizing the cooling energy, since it receives less sun during the daytime and can still utilize the black body sky radiation during the night time.







SUPERMARKETS IN DENMARK

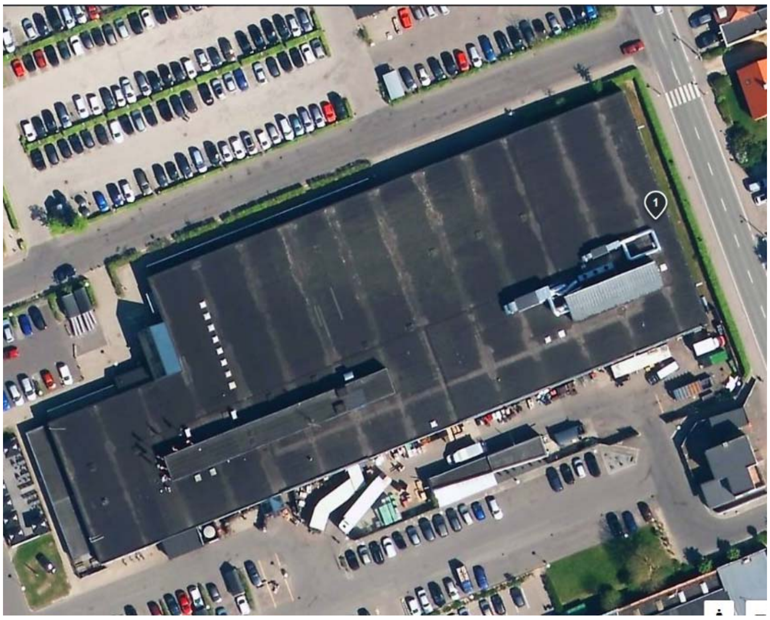


Figure 4.3.2D The 6000m2 COOP supermarket in Helsinge, Denmark

Most interesting was the case for the 6000 m2 supermarket Kvickly in Helsinge, Denmark, for some years the largest Danish supermarket including a bakery, a cafeteria, a butcher shop and many shelves of cooled or frozen food in display.
In the first rough simulations it seemed as if 5000 m2 of PVTE was needed. After several tests and analysis and pre-engineering, the final configurator and model calculations showed a much different result: having 1000 m2 PVT-E and 1000 PV on the roof was sufficient to produce all the needed CHP-C energy for the supermarket! It also turned out that the existing CO2 heatpump could be used. This way all the existing energy infrastructure in the supermarket could remain virtually untouched. Details are shown in Annex 4.3.2.C

The importance of the flexibility of the Solar CHP-C system clearly proved itself in this case, since the supermarket would normally be very hesitant in changing any positioning of the food displays or of the layout in the shop. Any reconstructions for achieving better energy efficiency and optimization would have much less importance than the maintaining the right display for the customers. Below is shown the energy flow of the system.

Financially, the supermarket is spending 1,6 mio. DKK per year today on electricity, cooling and heating. If the Solar CHP-C system with PVT-E of 1000 m2 and 1000 m2 PV is installed, the yearly energy costs will be reduced to zero with a ROI period of only 5 years. The energy flow for the CHP-C projection is shown in fig. 4.3.2E.

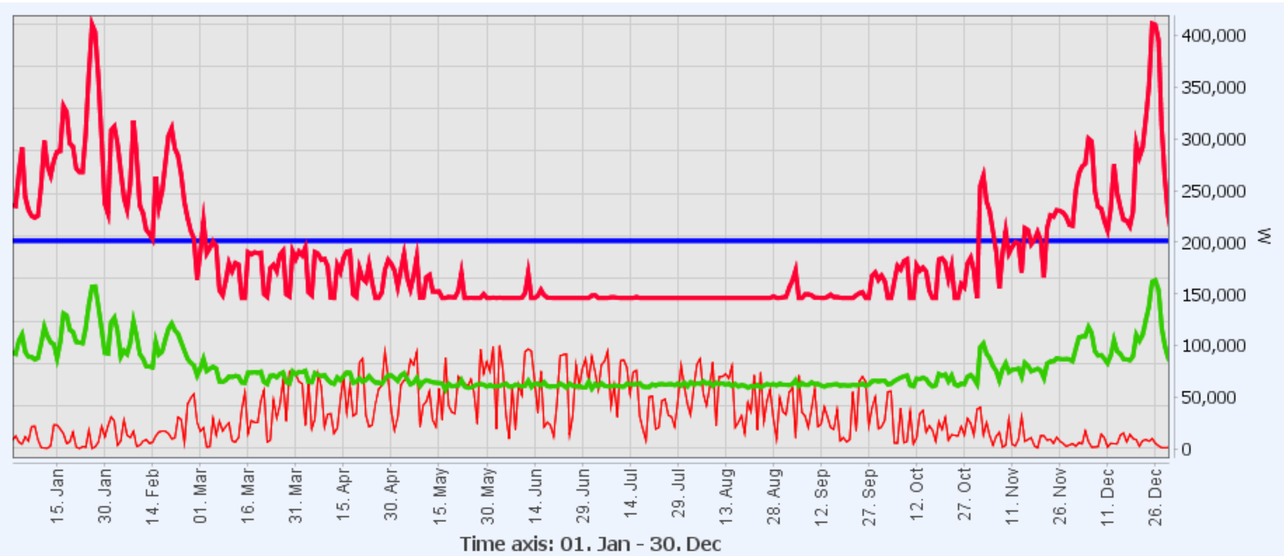


Figure 4.3.2E The energy flow with 1000 m² PVT-E for the Helsinge COOP supermarked.

Color coding:

- Thick red: Heat consumption (internal and sold to grid)
- Thick blue: Cooling consumption (variation small, therefore not visible).

Grøn: Electrical consuption by the heatpump.
Thin red: Electricity produced by the PVT-E.

4.3.3 Solar CHP-C for a Production Building near Copenhagen

A detailed investigation was made for the Castellum building where RACELL has a production facility. The main issues were to manage peak demand of energy and also supply excess energy to the Local district heating system. The best options were compared in the report from Plan Energy, Annex 4.3.3 which also considered the sizing of the tanks for storage capacities. The investigation was extended to also consider if the surplus PV electricity and surplus PVT-E heat and cooling energy from the Solar CHP-C could be used for supply to the next door 3 story office building and how the energy could be utilized by the district heating system.

Figure 4.3.3A: The factory bulding (1) is on the right, in the middle a storage building(2), canteen (3) and auditorium (4) and on the sides the office buildings. The PVT-E is to be placed on the middle buildings.

The analysis of the different possibilities for the integration of PVT modules was done through the development of scenarios in the software energyPRO with alternatives to the present situation. This was used as an alternative and for comparison to the other configurator programs, Transys, PolySun, PV& PVT-Bat. The use of different software for designing the Solar CHP-C gave a better basis for understanding the potentials and limitations of these design tools, which is also important for developing the future optimal intelligent control system for the Solar CHP-C concept.

The analysis assessed different possibilities for combining PVT modules with a heat pump and compares them to a heat pump as a standalone solution. The results show that when evaluating the feasibility of integrating the PVT modules it is important to consider the cost of displaced energy (incl. taxes). Operating PVT modules and a heat pump in parallel is more economically favorable than applying a heat pump alone. Moreover, connecting the PVT modules in series with a heat pump, thereby mutually supplementing their operation, could be a feasible solution.

This configuration entails one of the units preheating the water from the return temperature level and supplying it to the other unit, which raises the temperature level to the desired forward temperature. The PVT modules produce more heat and have higher thermal efficiency when preheating the water and feeding it into the heat pump.

Several scenarios were analyzed and among them the parallel and series connected systems;

Scenario 3: HP, PVT, and TES in parallel
The electricity produced by the PVT modules is first and foremost used to cover the electricity demand. The electricity consumption of the HP is given second priority and, as the last option, the electricity is sold to the grid.

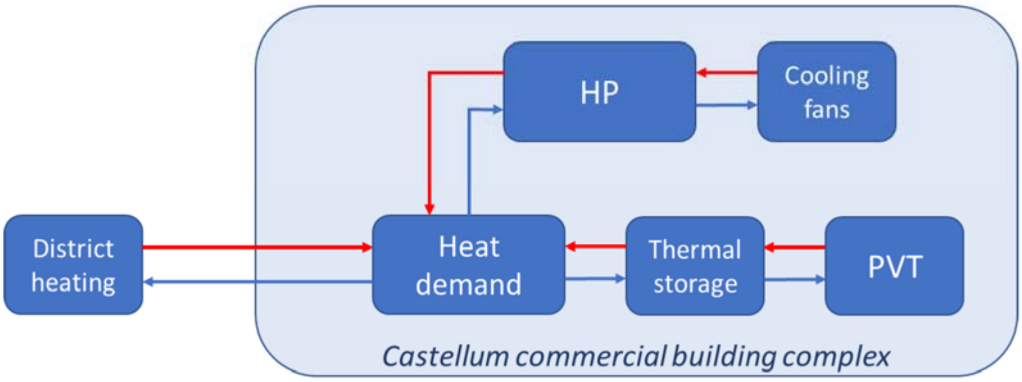


Figure 4.3.3B: Structure of scenario 3 Red and blue arrows represent supply and return heat flows respectively.

Scenario 4a: HP, PVT, and TES in series
In this configuration, the HP preheats the water from the return temperature and supplies it to the PVT modules, which increase the water temperature further, until it reaches the required supply temperature. The HP operates together with the PVT modules whenever possible, operating like in scenario 3 the remainder of the time. This configuration increases the performance of the HP while reducing the efficiency of the PVT modules.

Comparison with scenario 3:
- HP:
  - o Inlet temperature on condenser side: Unchanged.
  - o Outlet temperature on condenser side: Reduced.
  - o Performance: Improved.
- PVT:
  - o Inlet temperature: Increased.
  - o Outlet temperature: Unchanged.
  - o Performance: Reduced.

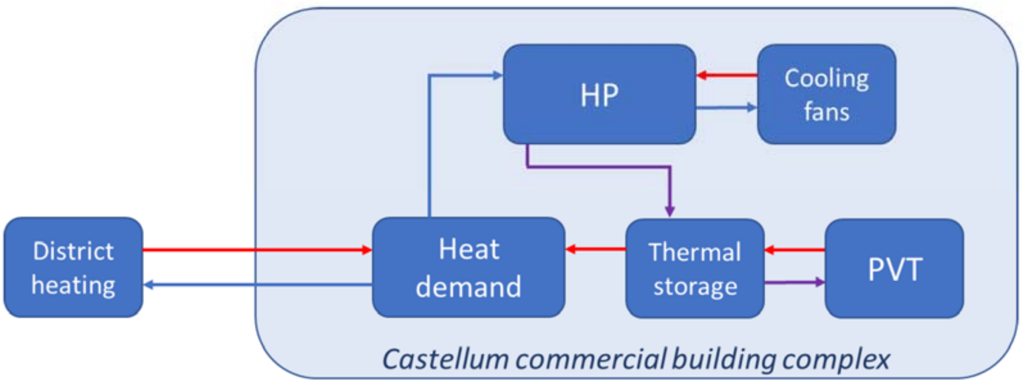


Figure 4.3.3C: Principal structure of scenario 4a. Red, purple and blue arrows represent supply, intermediate and return heat flows respectively.

In all scenarios with PVT modules, TES capacity is also assumed. This allows storing the excess heat production from the PVT modules, which improves the utilization of the PVT and TES system significantly. With the purpose of determining the most feasible storage size for the current system, an optimization procedure is performed, the results of which are shown in the next chapter.

The investment costs for the TES are assumed to be 9,000 DKK/m32 in the relevant capacity range for this project. It is assumed that the temperature range in the storage is the difference between the supply temperature and the return temperature.

District heating is assumed to have a variable share of the price of approx. 532 DKK/MWh and a fixed share amounting to approx. 148,600 DKK/year. The fixed cost for the connection to DH remains the same in all scenarios and will thereby not influence the results. Hence, only the variable share of the DH costs has an influence on the different scenarios.

Scenario no.	0	1	2	3	4a	4b
Scenario name	DH	PVT and TES	Heat Pump	HP and PVT Parallel	HP and PVT Series	PVT and HP Series
386 m^2 PVT modules		X		X	X	X
20 m^3 TES		X		X	X	X
180 kW air-to-water HP			X	X	X	X

Once all scenarios are modeled and simulated in energyPRO, relevant data relating to the annual energy production and fuel consumption is extracted from each scenario. The key parameters from the different scenarios are then compared. The results from this comparison are shown in detail in Table 3 and graphically represented in Figure 4.3.3D, to make them easier to compare.

		0 Castellum BAU	1 PVT + heat storage	2 Heat pump	3 PVT + Heat pump Parallel	4a Heat pump + PVT Series	4b PVT + Heat pump Series
Gross heat demand	MWh/year	1,070	1,070	1,070	1,070	1,070	1,070
Electricity demand	MWh/year	184	184	184	184	184	184
District heating delivery	MWh/year	1,070	943	81	72	74	72
Heat production, heat pump air-water	MWh/year	0	0	989	871	809	776
Heat production, PVT assisted heat pump	MWh/year	0	0	0	0	66	80
Heat production, PVT	MWh/year	0	157	0	157	148	188
Heat loss, PVT	MWh/year	0	-30	0	-30	-28	-46
Net heat production, PVT	MWh/year	0	127	0	127	121	142
Heat production, total	**MWh/year**	**1,070**	**1,070**	**1,070**	**1,070**	**1,070**	**1,070**
Electricity production, PVT	MWh/year		68		68	67	69
Electricity consumption, heat pump, air-water	MWh/year			291	263	245	236
Electricity consumption, PVT assisted heat pump	MWh/year					17	21
Coverage electricity, PVT	%		37%		37%	36%	38%
Coverage heat, PVT	%		12%		12%	11%	13%
Annual net heat production pr. m^2 PVT	kWh/m^2/year		329		329	313	368
Full load hours PVT el.	kWh/kW/year		988		988	975	1003
Coverage, air-water heat pump	%			92%	81%	76%	73%
Coverage, PVT assisted heat pump	%					6%	7%
Air-water heat pump, SCOP				3.40	3.31	3.30	3.29
PVT assisted heat pump, SCOP						3.91	3.88

Table 3: Energy production and consumption in all scenarios.

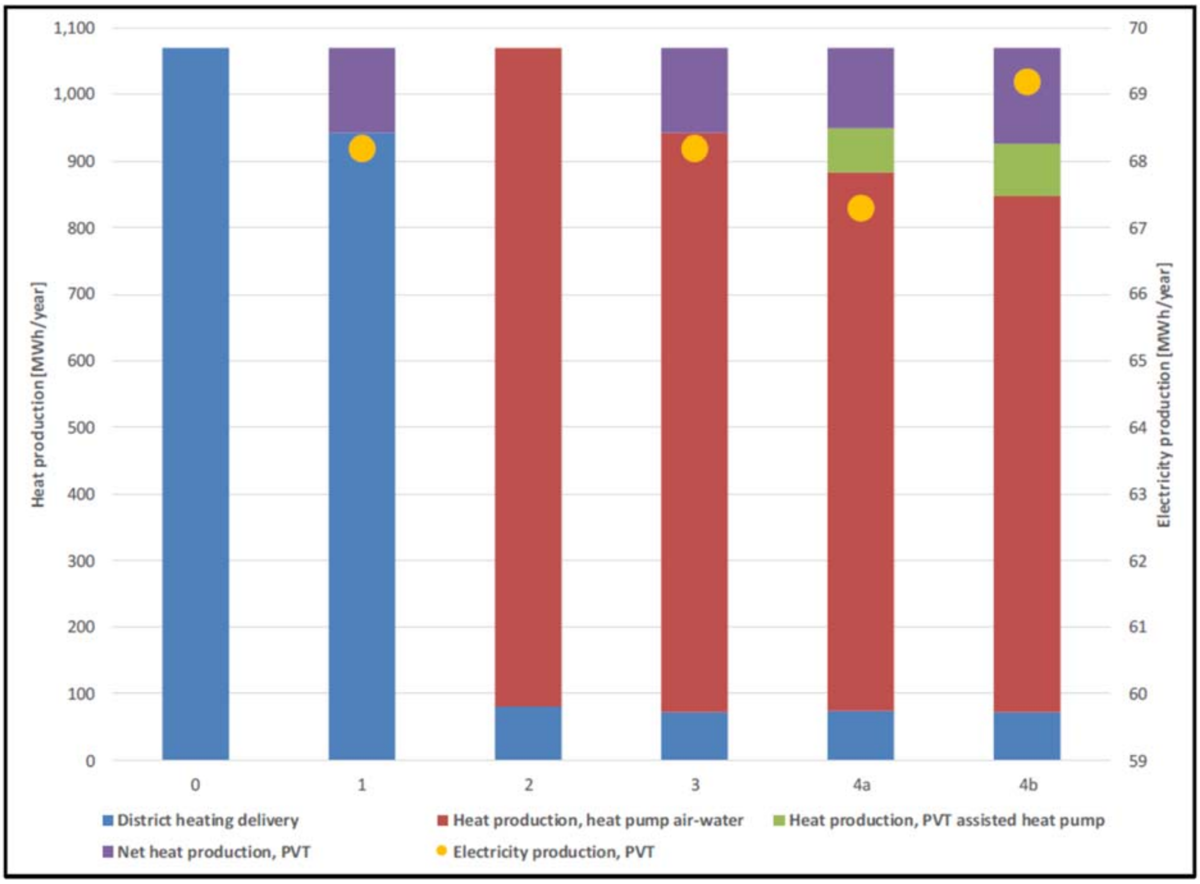


Figure 4.3.3D: Heat and electricity production in all scenarios

The different scenarios presented in the report of annex 4.3.3 show the possibilities for applying PVT modules in office buildings supplied by DH and the option of combining such PVT modules with a HP. In the report, the addition of either PVT modules, a HP or both to the energy mix, reduces the delivery of DH. It is therefore worth mentioning that the purpose of this report is not to replace DH in itself, but only to assess the technical and economic possibilities for the integration of PVT modules in buildings connected to DH.

In the scenarios where the PVT modules are combined with a HP, DH delivers only the peak load supply. The calculations does not reflect such a solution applied on a larger scale (i.e. for many DH customers), since there would be a high chance for an increase in the fixed DH costs in the long run, if DH was to be delivered in small amounts, thus making the DH peak load capacity more expensive. It would, therefore, be worth investigating in a future study how the solutions analyzed in the report could be applied on a larger scale where they could supplement DH instead of almost replacing it.

As seen in other report sections of this Solar CHP&C project, more advanced approaches in larger systems can provide more effective, profitable and flexible operation modes that fit both the immediate energy consumption, the forecasted consumption, and the consumption according to historical behavioral records.

Finally, the flexibility of the Solar CHP&C system could be further enhanced by using a mix of different types of PVT modules on the same roof or facade. Some modules could be insulated so that they provide high-temperature heat, while others are ventilated by built-in airflow in the module structure, so the module can absorb heat or cooling from the surrounding air.

4.4 Indoor Climate and Solar CHP-C in various buildings

The combination of low temperature energy form the PVTE fits specifically well with providing high comfort for indoor climate. Annex 4.3.1B provides literature reg. this. Several solutions for transferring the heat exist. The TABS analyzed in this project, made out of PCM elements (Phase Change Material), have been successful, but the price for these TABS elements is still very high. However the results and the same benefits from the TABS can be directly transferred to another much cheaper ceiling element namely the capillary systems with plastic pipes, which can be easily mounted anywhere.

An in-depth simulation analysis of the PVT for Copenhagen, Denmark showed the effect of flow rate, collector slope and inlet temperature on their cooling potential. Thus, a 90^0 South orientation was found to be optimum for cooling power production (cooling energy), as less solar radiation is present in early mornings and late evenings. Moreover, if the inlet temperature increases, the cooling output of the PV/Ts increases while the same effect was found if a turbulent flow was selected instead of a laminar one. By also analyzing the PV/T cooling potential for different European cities, a general trend of increase from south to north was found, most likely due to the overall lower air temperatures in northern climates. In Annex 4.4.1 the full study is described.

An indication of how much cooling energy can be achieved in various areas in Europe is shown below.

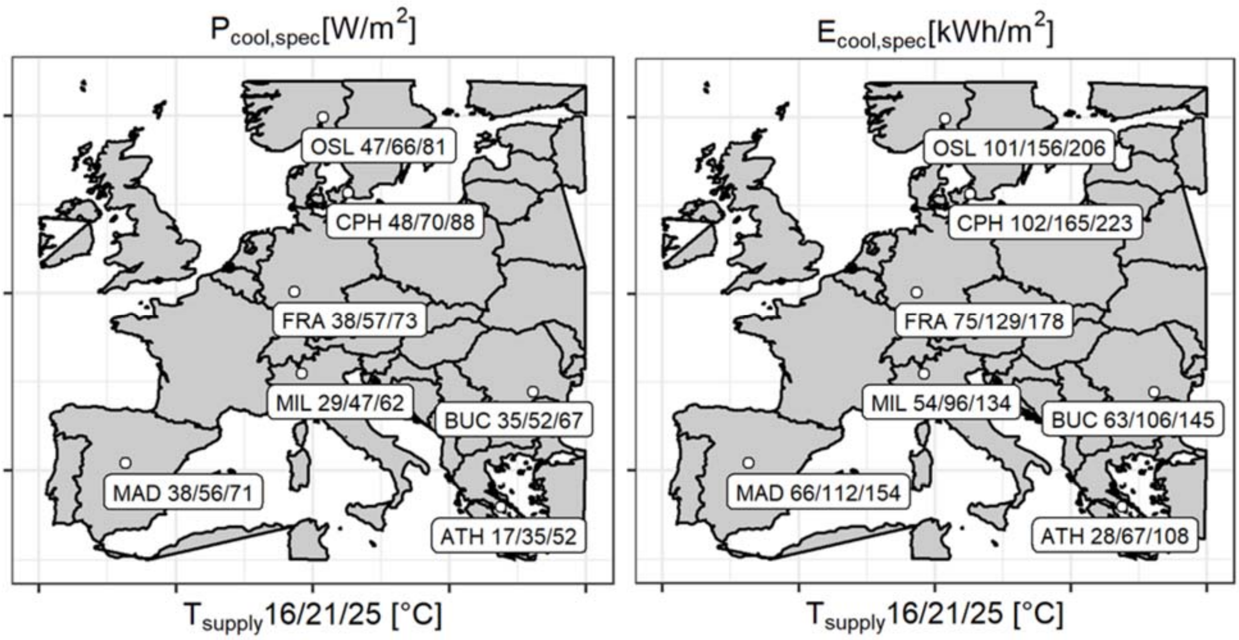


Figure 4.4A Specific cooling power and energy for European cities as a function of supply temperature.

The results showed a general increase in both power and energy from south to north. However, exceptions can be observed due to differences in climate. For example, although Madrid, Spain is at a lower latitude than Bucharest and Milan, the relative humidity is lower, which justifies the higher cooling energy. Moreover, Copenhagen, Denmark has oceanic influences as opposed to Oslo, Norway, which could justify a higher cooling potential.

The cooling phenomena by the black-body-night-sky-radiation was carefully investigated in specially designed chambers full of sensors and test facilities, also in combination with the PCBs. One test period gave the following results:

RACELL PVT panels were coupled with novel PCM ceiling panels as an alternative to TABS for cooling purposes in Copenhagen, Denmark. Although the experiment is ongoing, data available from the 20th of February to the 10th of May 2019 was analyzed and presented. In terms of average specific cooling power, the PVTs showed a cooling potential of 110 W/m2, slightly higher than results from the previous experimental setup, and a 151 kWh/m2 specific cooling energy for the analyzed period.

4.5 Battery storage and designs for Solar CHP-C

The principle for optimizing the efficiency and the costs of the PVT-E based Solar CHP-C is to have a large system covering many unalike energy consumption profiles. Simply because when one consumer is not using energy, then another does and thus the peak demand can be reduced.

4.5.1 Control System and battery storage capacity

PEAK DEMAND and STORAGE

If the consumer profiles in a building are all alike, the chances are there for a high peak demand. A peak demand requires a high production capacity which means that the costly area of the PVT-E must be increased sometimes dramatically. In order to compensate for one or more high peak demands, more storage capacity can be incorporated in the Solar CHP-C system. Expanding the tanks for cooling matter (salt, water or ice) and the tanks for heating energy (salt, liquid, or other matter) would provide means for managing the thermal peak loads. The thermal storage tanks are normally very cost effective, but as shown in section 4.3.3 the Heat Pump can play a significant role.

HEAT PUMP and STORAGE

The Heat Pump can reduce the demand for the large storage tanks whenever there is excess energy available from the PVT-E modules. The typical situation would be in the summer season, when there is too much electricity produced and consumption for electricity in the building is low. If t the same time selling electricity to the grid provides a very small revenue, the surplus electrical power can be utilized to activate the Heat Pump and produce direct thermal energy to the building, such as cooling energy during the day.

SURPLUS ELECTRICITY and HEAT PUMP

In periods where too much electricity is produced, the combination of the Heat Pump and thermal storage capacity is valuable, especially for producing Domestic Hot Water and for cooling capacity. The basics of the Solar CHP-C s really the flexibility of the smart system, on one hand having both “free” direct production, by the PVT-E, of electricity, heating- and cooling energy, and on the other hand the combination of Heat Pump and storage capacities to utilize the energy intelligently thereby reaching high COP and SCOP and less demand for large storage systems. This flexibility also affects the costliest part of the storage systems, which is the battery storage.

The battery storage is however more important than in normal much simpler systems, where considerations are made only for PV and the consumption of electricity. In the case of Solar CHP-C where direct heating and cooling energy is available from the thermal Energy absorber in the PVT-**E** modules in the daytime but also at nighttime, the provision of electricity for the Heat Pump is important. Thus, on one hand the need for battery capacity can be reduced because of the heat pump, on the other hand more battery capacity is necessary at night and in seasonal periods where there is less sun. In the cases analyzed in this project, it turns out that the Heat Pump normally absorbs 50% of the electricity produced by the PVT-E modules. This can be compensated for by installing extra areas with PV modules only and/or by expanding the battery capacity.

c

When a roof of a building has two different orientations, East/West or SE/NW, then it would typically be covered by PVT-E on the south side and with PV on the north side. This way the architectural aesthetic is provided with the same looks on both sides and the provision of extra electricity for the Heat Pump is available, so that the building can become energy self-reliant.

CONTROL SYSTEM

Another issue from which the battery storage system is important has been the control system. Because the battery typically has many cells and the cells deteriorate over time and cell temperatures start to vary, the control systems for some batteries has become quite advanced. Also, the battery control normally takes in to account the variations in the dynamic PV production variations, the varying building consumption profiles and in the inverters and in the energy production from other supplementary electricity sources, such as the grid, a local windmill and a diesel/gas generator.

In this project the control system from the project partner Lithium Balance has been developed and utilized in order to make it include intelligent and smart algorithms so that the heat pump, weather forecast, consumer habits and more could be incorporated. So, the battery control system has been developed by Lithium Balance is also taking care of the consumer habits with continuous optimizations and of all the components that have to do with the thermal energy flows in the Solar CHP-C system. The prototypes were tested on different sites and the control system that involves the Solar CHP-C components is expected to become an industrial product, that can rely on the present demonstration sites, in particular at DTI, in Ballen at Samsø Harbour and in Ringgården in Aarhus and Växjö where large PVT-E systems are installed.

The control system has been tested mainly with the battery type called Li-ion NMC and is mainly known from the cars produced by Nissan. The control system and the battery capacity together can also fulfill requirements such as those described in section 4.3.3 where up to 4 industrial machines require some electrical peak loads in the range of 100-150 A for approx. 5 minutes especially in the morning and then a few times during the day.

The features of the control algorithms, the battery management system, called BMS, are many and described here:

General
- modularity: storage power and energy adjustable to every need: Max power 1.6MW and 2.5MWh.
- low TCO, extraordinary safety, space-saving and minimum O&M cost;
- high efficiency, ultra-low auxiliary power consumption during standby for battery system and inverter;
- build in site controller manage the entire BESS and as an energy management system (EMS) providing power dispatch, assuring safe system operation, enabling communication with all system peripherals, data acquisition, communication with cloud, system diagnostics;

For industrial/Housing associations:
- improving renewable energy self-consumption (e.g. storing during the day for usage during the night);
- cloud connection allowing for system monitoring, control, data acquisition;
- ROI maximized by using advanced algorithms in the cloud considering consumption patterns as well as energy and weather forecast data.
- possibility of integrating external energy meters and other auxiliaries (e.g. heat pump and EV charging stations);

For Grid applications:
- providing grid support services by different operating modes: frequency, voltage regulation, peak shaving, transmission upgrade deferral, power on demand, energy arbitrage, synthetic inertia, black start;
- possibility of island operation (independence from the grid);
- other: selectable harmonic mitigation (up to 50th), load balancing, stepless reactive power compensation, dynamic active and reactive power control (possibility of individual power control of each individual phase).

More details are given in annex 4.5.A where the NMC battery is shown as the XOLTA product, that also has the inverter built in and thus is a Plug-and-Play system.

STORAGE CAPACITY
One very important issue is that the capacity expansion of a system is modular and Plug-and-Play like. This was developed through the project period and can thus be designed for very large buildings. One rack has 79 kWh and by combining up to 32 racks, a capacity of 2528 kWh can be achieved.

NMC prototype, outdoor version

6 racks installed together (474 kWh). Scalable to 32 racks

6 racks in other color and with customer logo (example)

The storage architectural design is of great importance for the Solar CHP-C, and therefore efforts were made together with Lithium Balance to provide system that could be placed outdoors and require as little space as possible (high energy density). Also because of reduced safety requirements, the modular stacking of the batteries have allowed the installation in almost any building or box design as created by architects, or as a supplementary part to the building itself. Thus, one of the aims of the project was reached.

4.5.2 Battery types, features and safety

In the project the aim was to test various battery technologies. The AHI was the favorite, but the developer a US company went bankrupt. The other favorite was LFP and was indeed tested during the project and successfully developed into a complete system prototype with a control system. The comparison to liquid Acid was tested and analyzed in the project and proved the benefits of the LFP, as shown in the report in Annex 4.5.B.

In the end, because of the technology features of the Li-Ion NMC type, this technology was chosen by Lithium Balance and was further developed to the Xolta battery system. The reason for this choice is as follows.

The original preference was LFP due to the Safety, price and life span of the cells, and the first prototype BESS plant was indeed made with this chemistry. However, since Li-Balance later managed to gain access to the NMC cells from Nissan, new battery features were now accessible:

- The NMC technology and batteries have been in use in cars and more without any incidents over many years and has thus proven themselves as exceptionally very safe. This is one of the most important issues compared to other types of Li based batteries, that have suffered several incidents with fire and explosions.

- They have a long service life and wide temperature range during operation.

- The NMC battery has double energy density, which meant that even though the cells were more expensive, the overall construction, which f. ex. includes cooling and exhaust facilities, would be cheaper because there was less mechanics, more simple temperature control, and less power electronics.

- This led to Nissan battery cells being selected for the final BESS construction, which has subsequently also been developed for the EU projects READY (FP7) and SMILE (H2020).

- Cost wise, during the project period, the component costs have been reduced so that the battery unit including the Inverter, has fallen from a sales price per kWh excl. VAT. VAT of 7.500 DKK to 4.500 KR, and with the volume and continued drop in battery prices, it is expected that in the near future the price could be further reduced by a third.

Much of the prototype work has focused on safety issues and regulations. This would then, unlike the other battery types available, make the NMC and BESS Xolta type be approved for installations within the Solar CHP-C systems offered in the near future.

It complies with Fire requirements as specified by the DBI - The Danish Institute of Fire and Security Technology. It thus complies to Fire Class 1, contains a Sprinkler system and an Alarm system. In practice the system can be installed inside a building as long as there is a simple air outlet for toxic gasses in the case of fire. In tests the system can withhold flames for more than one hour, which is normally something other constructions cannot.

In total the Battery system developed seems to fulfill all the goals originally aimed for in the project mile stones. The fairly large 700m^2 complete PVT-E test system at Ringaarden will show the first long term results. Three other systems with Solar CHP-C including this battery control system are expected soon in Scandinavia.

5. Utilization of project results

THE PROJECT PARTICIPANTS UTILIZING RESULTS

During the project a close collaboration between the participants has been developed and the knowledge obtained for the new concept is gradually developing through the networks into requests and inquiries for new orders. An example is Danfoss which finds the concept suitable for their products reg. control of indoor climate comfort. Although Danfoss has sold off its own production line of Heat Pumps, a collaboration has started together with the

Danish producer MetroTherm, Racell, Danfoss, COWI and Li- Balance for developing a commercial Solar CHP-C package for commercial buildings, building blocks and for one family houses.

After the results from this project we are considering the Solar CHP-C as a true game changer. This has led to a close collaboration between Racell, Danfoss, Rockwool, Cowi and more, for developing new standards for the building industry. On one hand we are starting to develop the multi hybrid PVTE module as a building element, with standard sizes which can readily fit in to BIM and to existing standard sizes for insulation bats, façade wind protection panels, standard roof elements etc. On the other hand, the approach is to deliver a complete prefabricated roof apartment and technical room that contains the PVTE modules and all the Solar CHP-C components. The principle has earlier on been tested by Velux, Danfoss and Racell under the name Solar Prism and Solar Solution. However, at the time the technology was not very advanced and took up too much space and was too costly. To day the same principle can get a real breakthrough and with hours, a multistory building can get a prefabricated extra floor level on the roof (lifted with a crane) and at the sam time all the whole building will become energy self-reliant by the built in Solar CHP-C system. The partners Rockwool, Danfoss, Cowi, Metrotherm, Lithium Balance and Racell are all expecting to develop, demonstrate some full scale models, so that this could be a proven concept within 2 years and ready for the market.

THE NEW COMMERCIAL ACTIVITIES AND PRODUCTS

The surprising and good results from the now proven Solar CHP-C technology for the 4 different commercial building type, has opened up with new customers contacting in particular Racell, asking for offers for specific buildings, both for renovation and for forthcoming new buildings. The new PVT-E module has become a new product line and, since the ROI and NOI and the idea of self-reliance by renewable energy. Whereas before it was mostly the aesthetics that formed the attraction, today it is first of all the financial benefit that attracts the building owners, secondly it is the independence of energy supply from outside. Total energy self-reliance is new phenomena which is also used by companies to show their sustainability and green marketing.

From the discovery of how little an area is actually needed for PVT-E to provide cooling for large scale shopping malls (100.000 m2 or more), the product has started to attract also the PV solar park providers. Instead of providing “only” 2 MWp per Hectare of electricity, the PV park developer can 6 MWp on the same area an sell the surplus costly 4 MWP cooling-energy for local district cooling. This new economy of scale has now been implemented in the Racell activities and new business plans. It can be implemented on large area buildings, like data centers or shopping malls or as ground based Solar CHP-C (PVT_E) parks. The market potential is overwhelming, especially for cooling purposes and thus partnerships with other Danish companies that are operating on the international markets (Danfoss, Metrotherm, Rockwool, 3XN, Arkitema, Henning Larsen, COWI, European Energy and more) have become important partners for the future markets penetration. The competition is still non-existing within this technology, since no other company can produce these types of elements. The major competition are large heat pumps combined with the low-cost PV modules. But since the SCOP for the Solar CHP-C is extremely high, the competition is only dependant on having more reference projects, that can prove that this “too-good-to-be-true” actually exists and works. Racell have applied for a number of new patents which are useful in particular for Solar CHP-C concept. The most important ones have already been accepted

THE CONTRIBUTIONS TO REALIZING ENERGY POLICIES AND TO DISSIMINATION

As a gamechanger within renewable energy, it is obvious that the future contributions from this project will be important both in the building industry and in the utility sector. The association C40 is an example of where the Solar CHP-C gamechanger will change the rules, ones the large cities realize the existence of the technology. During the project period a handful of students have efficiently incorporated the Solar CHP-C in their PhDs and the interest is high at international Universities and research institutions.

6. Project conclusion and perspectives

The Solar CHP-C project has proven that the newly developed and demonstrated technology, especially when based upon the newly developed PVT-E modules, has now become a proven concept with proven technology for changing the way we think about energy production in our cities.

It is well known that the energy consumption in the cities around the world, is the single and most dominant factor in our ever-growing energy consuming mankind. The climate warnings are well-known, and the role of the urban areas on large are well described below:

From “UN HABITAT for a Better Urban Future” :

> **UN-Habitat is the United Nations programme working towards a better urban future. Its mission is to promote socially and environmentally sustainable human settlements development and the achievement of adequate shelter for all.**
>
> *Regardless of the source, energy is a major factor for development. It is needed for transport, industrial and commercial activities, buildings and infrastructure, water distribution, and food production. Most of these activities take place in or around cities, which are on average responsible for more than 75 per cent of a country's Gross Domestic Product (GDP) and therefore the main engines of global economic growth. To run their activities, cities require an uninterrupted supply of energy. They consume about 75 per cent of global primary energy and emit between 50 and 60 per cent of the world's total greenhouse gases.*
>
> *A sustainable urban energy system will need low carbon technologies on the supply side, and efficient distribution infrastructure as well as lowered consumption on the end-user side. Cities therefore need to shift from the current unsustainable fossil fuel energy generation towards using renewable energy sources, not only because of looming resource depletion but also to curb the negative externalities such as pollution and greenhouse gas emissions. At the same time, energy consumption must be reduced by changing consumption patterns and adopting energy saving techniques.*
>
> *To tackle intermittency, several renewable energy sources should be combined to overcome source-specific shortages, such as solar at night, or wind during doldrums. Solutions can also come from waste and heat recovery technologies that can be used to bridge supply gaps.*

From NREL & DOE report 2016:

> *Building energy use—primarily electricity and natural gas consumption—accounts for about 40% of U.S. greenhouse gas emissions (EPA 2015). Cities can reduce building-related emissions through the implementation of new building energy codes or through measures to maximize energy savings from existing building energy codes. Our analysis finds that city building energy code actions can reduce building-related carbon emissions by about 60-120 MMT CO2/year by 2035, representing about 0.9%-1.9% of 2013 U.S. greenhouse gas emissions. It is important to note that the short-term carbon abatement potential of building energy codes is limited by the long life and slow turnover of building stock; however, the longer-term carbon abatement potential may be significantly greater (Schwartz et al. 2016).*

This EUDP project was intending to prove that the combination of PVT supportive supply of both electricity and thermal energy would be a <u>supplementary</u> to the Smart City approach with energy efficiency savings enabling the reduction of energy consumption in buildings. The Solar CHP should also assist in reducing the peak load demand for the grid on thermal and electrical energy via coordination with the existing grid. That overall objective has been reached.

Technically the project managed to prove that it is possible to design and to simulate an renewable Solar CHP-C system for several building types and in different climates and predict the energy production match to the energy consumption of the building.

What has happened during the Solar CHP-C project has been a major surprise: It turned out that for almost any building, it is possible to make it a producer of its own energy and even supply more energy than it needs. This is a completely different approach than the normal energy savings in energy efficiency mindset approach. Instead on focusing on saving energy in buildings, which is a difficult long term and demanding process, the new mindset with the Solar CHP-C says:

> Do not worry about saving energy; the building itself will produce all the energy you need.
> The game changer Solar CHP-C has it. Lots of free renewable energy and no CO2 emissions.

Obviously, it is definitely still worthwhile to make energy savings and utilize energy efficiency and Smart City technologies. The more energy savings, the less area is needed by the PVT-E modules.

The impact is influencing the whole energy sector: suddenly the PVT-E combined with the Solar CHP-C components makes the building the energy source for all energies: electricity, heating, cooling, domestic hot water. Masses of noisy Air-Condition units hanging all the buildings are no longer needed. Energy is available also when there is no sun. The city buildings are generating energy day and night and do not need massive district heating and district cooling networks. All energy is produced locally by the buildings themselves.

International investors have recently started to become active by getting involved with direct contacts and are seriously looking forward to supporting the forthcoming breakthrough of this new Gamechanger in the global energy market, the Solar CHP-C concept. It is indeed with the support from the Danish EUDP support program that this new energy adventure has been lifted up from ideas and small-scale tests to a forthcoming massive sustainable energy revolution.

7. Annexes

- Annex 4.2.B.6_Article Hybridsolceller kan erstatte energibrønner.pdf
- Annex 4.2.B.7_Article 2019 Hybridsolceller kan erstatte energibrønner.pdf
- Annex_4.2.C.8_REPORT_Solar_CHP_PVT_modules_inside_a_concrete_wall.pdf
- Annex_4.2.C.9_Article_PVT_inside_a_Concrete_block_&_INSULATION.pdf
- Annex_4.3.1.A_REPORT_RACELL_iTM_energy_roof_&facade_systems.pdf
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- Annex_4.3.2.A_REPORT_FORTROLIG Solar C-CHP for Kjeraghytten i Norge.pdf
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- Annex_4.3.3_REPORT_Production_building_Solar CHP&C PlanEnergi.pdf
- Annex_4.4.1_REPORT_Solar CHP-C Cooling_by_PVTE_Final_Report_DTU.pdf
- Annex_4.5.A_DataSheet_NMC_Battery-Energy_Storage_System_BESS.pdf
- Annex_4.5.B._REPORT_Presentation_LA_vs_LFP_battery.pdf